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September 14-19, 2013 Durbach, Germany

Editors: Ulrich Husemann, Hannes Mildner, Frank Roscher

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Preface

The 6th International Workshop on Top-Quark Physics (TOP 2013) took place in Durbach, Germany, between September 14-19, 2013. Physicists from all over the world reported on the latest theoretical and experimental results on the physics of the top quark and discussed perspectives for the research field. While the weather in Durbach didn't always keep the promise, the scientific program certainly did: the 125 participants followed 50 plenary presentations in 15 topical sessions, complemented by a poster session in picturesque Staufenberg castle, in which 20 young scientist discussed their work over tarte flambée and and a glass of wine in front of their posters. All participants could vote for the best poster and the three best posters received prizes. In two question-and-answer sessions young physicists had the opportunity to meet world experts on top-quark physics in an informal atmosphere. The excursion brough the participants to the city of Strasbourg, France, with a boat trip on the Ill river and strolls through Strasbourg's beautiful old town.

The TOP 2013 conference was co-organized by Karlsruhe Institute of Technology (KIT), DESY, and the University of Hamburg. We gratefully acknowledge the financial support the conference received from the DFG, the Helmholtz Alliance "Physics at the Terascale", the KIT Center Elementary Particle and Astroparticle Physics and from Blue Yonder. The conference would not have been possible without many helpers. First and foremost, we would like to thank our conference secretary, Mrs. Bärbel Bräunling. We would also like to thank the technical support team for the sessions (Martin Görner, Steffen Röcker, Frank Roscher, Eike Schlieckau, Markus Seidel, Shawn Williamson), and the staff at Hotel Vier Jahreszeiten. We also thank Britta Liebaug for the design of the poster and the web page and Kirsten Sachs for her support in publishing these proceedings. Last but not least, the German top physics community supported this conference in many ways, from the proposal phase over the conference program to chairing sessions at the conference.

Alexander Grohsjean, Ulrich Husemann, Judith Katzy, Thomas Schörner-Sadenius, Georg Steinbrück

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Search for vector-like quarks with the ATLAS detector

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A cornerstone of the Standard Model (SM) is the formulation of the electroweak interactions as arising from a spontaneously broken gauge symmetry, which has been confirmed during the past four decades. However, the SM cannot be considered as a complete description of nature since there are several open questions that still need to be solved. For example, there is no explanation for the number of fermions and there are quadratic divergences in the Higgs boson mass terms. There are several beyond the SM models which try to answer these questions and in some of them the existence of new vector-like quarks, which are defined as quarks for which both chiralities have the same transformation properties under the gauge symmetry group, is a feature.

In the present note, four analyses (Ht + X) same-sign leptons, Zt/b + X and Wb + X) targeting the pair production of vector-like quarks with different decay modes are presented. These analyses use a dataset corresponding to 14.3 fb⁻¹ of pp colisions at a center of mass energy of 8 TeV recorded in 2012 with the ATLAS detector [1] at the CERN Large Hadron Collider. Two vector-like quark models (singlet and doublet [2]) and flavors (T and B with electric charges of 2/3|e| and -1/3|e| respectively) have been studied, testing them for different vector-like quark masses ranging from 350 GeV up to 850 GeV in 50 GeV steps.

In the Ht+X [3] analysis $(T\bar{T} \rightarrow Ht+X)$, final states with one lepton and a high multiplicity of jets (≥ 6) and b-tagged jets (≥ 2) are compatible with signal hypothesis. The backgrounds for this analysis are primarily $t\bar{t}$ +jets, W+jets (for which the normalization is derived from data) and multijet processes (derived using data-driven techniques). Small contributions arise from single-top, Z+jets, diboson (WW, ZZ, WZ) and $t\bar{t} + V$ (V = W, Z) production.

The final selection is defined as those events in which there are ≥ 6 jets, ≥ 2 b-tagged jets, missing tranverse momentum $(E_{\rm T}^{\rm miss})$ above 20 GeV and $E_{\rm T}^{\rm miss} + m_{\rm T} > 60$ GeV, where $m_{\rm T} = \sqrt{2p_{\rm T}^{\ell}E_{\rm T}^{\rm miss}(1-\cos\Delta\Phi)}$, $p_{\rm T}^{\ell}$ being the transverse momentum of the lepton and $\Delta\Phi$ the azimuthal angular separation between the lepton and the direction of the missing transverse momentum. The sample is divided in three regions based on the b-tagged jet multiplicity: 2, 3 and ≥ 4 b-tagged jets. The higher signal to background ratio is found in the last region and therefore it is the one which drives the sensitivity of the analysis. The regions with 2 and 3 b-tagged jets, that have low signal contamination, are used to better estimate the $t\bar{t}$ background and constrain the systematic uncertainties.

The discriminant variable for the Ht + X analysis is $H_{\rm T}$, shown in Figure 1a, which is defined as the scalar sum of the transverse momenta of the jets, the lepton and $E_{\rm T}^{\rm miss}$. In the absence of evidence for signal, limits are set assuming a branching ratio corresponding to the





Figure 1: Discriminant variables for (a) the Ht + X, (b) Zt/b + X and (c) Wb + X analyses are shown. As illustration a signal distribution is shown for a vector-like quark with a mass of 600 GeV.

The same-sign lepton analysis [4] is not only intended to look for pair production of vectorlike quarks but it has a broader scope in which the interesting final states are those with a pair of same-sign leptons. There are several processes in which this signature is expected, such as chiral b' quark pair production, vector-like quark pair production, SM production of four top quarks or two positively charged top quarks. In the case of vector-like quarks this search is sensitive to both B and T quarks, being more sensitive to the W and Higgs boson decay modes in the case of vector-like B and T quarks respectively.

The selected events are those in which there is a pair of same-sign leptons (ee, $\mu\mu$ or $e\mu$), ≥ 2 jets, ≥ 1 b-tagged jet, $E_{\rm T}^{\rm miss} > 40$ GeV and $H_{\rm T} > 500$ GeV, where $H_{\rm T}$ is defined as the scalar sum of the transverse momenta of the selected leptons and jets. Two requirements in the mass of the leptons are also applied when they have the same flavor: $m_{\ell\ell} > 15$ GeV and $|m_{\ell\ell} - m_Z| > 10$ GeV to reduce the contribution from resonances in which one lepton's charge was mismeasured.

There are two main sources of background for the same-sign analysis: processes with real same-sign leptons in the final state and processes in which one of the leptons has been misidentified or misreconstructed. Processes with same-sign leptons in the final state include diboson production with a heavy flavor jet and $t\bar{t}$ pair production with an associated vector boson. The contribution of these processes is evaluated through Monte Carlo simulation. Background contributions from misidentified leptons are derived using data-driven techniques and can be separated in two categories: events in which a jet is misidentified as a lepton and opposite sign leptons in which the charge of a lepton is mismeasured, which is estimated using a $Z \rightarrow ee$ sample. The latter background is negligible for muons.

After the final selection 2.7 ± 0.5 , 4.4 ± 0.9 and 2.3 ± 1.2 background events are expected and 3, 10 and 2 events are observed for the *ee*, $e\mu$ and $\mu\mu$ channels respectively. The signal efficiency ranges from 0.01% for *B* pair production with a mass of 350 GeV in the *ee* channel to 0.34% for *T* pair production with a mass of 850 GeV in the $e\mu$ channel. In the absence of evidence

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for signal, 95% confidence level limits are set assuming branching ratios corresponding to the singlet model and masses below 0.59 (0.54) TeV are excluded for pair production of vector-like B(T) quark.

The Zt/b + X analysis [5] (searching for $Q\bar{Q} \rightarrow Zq + X$, with Q = T, B and q = t, b respectively) is sensitive to high branching ratio to the Z boson decay channel which is a phase-space region not covered by any of the previous analyses.

The main background in this analysis is Z+jets, with some contribution from $t\bar{t}+\text{jets}$ and a small contribution from $t\bar{t} + V(V = W, Z)$ production, single top, diboson and W+jetsproduction. Two corrections are applied to the Z+jets background. The first one aims to correct the *b*-tagged jet multiplicity, defining a control region with a Z boson candidate with $p_{\rm T} < 100$ GeV and ≥ 2 jets. The second one corrects the $p_{\rm T}(Z)$ distribution, which is derived in a control region with a Z boson candidate, ≥ 2 jets and 1 *b*-tagged jet.

In this analysis events with ≥ 2 opposite-sign, same flavor leptons are selected (*ee* and $\mu\mu$) with $|m_{\ell\ell} - m_Z| < 15$ GeV to reconstruct the Z boson candidate. The events must have ≥ 2 jets and ≥ 2 *b*-tagged jets. Two control regions for 0 and 1 *b*-tagged jets are defined to better describe the main background of the analysis and derive systematic uncertainties associated with the Z+jets corrections. The Z boson candidate is required to have $p_T(Z) > 150$ GeV to reduce the Z+jets background contribution. The scalar sum of the transverse momenta of the jets is required to be higher than 600 GeV.

The mass of the Zb system, shown in Figure 1b, is used as the discriminant variable. The *b*-tagged quark with highest transverse momentum is chosen to define the Zb system. In the absence of signal, limits are set and masses below 680 (725) GeV are excluded at a 95% confidence level for the T (B) quark.

In the Wb + X analysis (searching for $TT \to WbWb$) the main background processes are very similar to the ones in the Ht + X analysis: $t\bar{t}$ +jets, W+jets and multijet events, with W+jets and multijets treated in the same way as in Ht + X. Small contributions arise from single-top, Z+jets and $t\bar{t} + V(V = W, Z)$ production. The high mass of the T quarks results in energetic W bosons and b quarks with large angular separation between them and small angular separation between the decay products of the boosted W boson. This is different from the signature of $t\bar{t}$ events in which the boost of the SM top quark translates into closer W boson and b quark than in the vector-like case.

Two selections, *loose* and *tight*, are defined. The *loose* selection is defined by requiring ≥ 4 jets, ≥ 1 hadronic W boson candidate and $H_{\rm T} > 800$ GeV, where $H_{\rm T}$ is defined as the scalar sum of $E_{\rm T}^{\rm miss}$, the transverse momentum of the lepton and the transverse momenta of the four highest- $p_{\rm T}$ jets. This loose selection is used to study background modeling. The *tight* selection adds the isolation requirements that allow better suppression of $t\bar{t}$ events: min $[\Delta R(W_{had}, b_{1,2})] > 1.4$ and min $[\Delta R(\ell, b_{1,2})] > 1.4$.

The discriminant variable used is the reconstructed mass of the vector-like T, reconstructed with a hadronic W boson and one of the 2 *b*-tagged jets as shown in Figure 1c. The W - b pairing is chosen as the one giving the smallest difference between the mass obtained using the leptonic and hadronic W boson candidates.

Figure 2 summarizes the exclusion regions from the four analyses for vector-like T and B quarks respectively in the BR plane.

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JUAN PEDRO ARAQUE

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Figure 2: A summary of the exclusion regions obtained by the different analyses is shown (a) for the vector-like T and (b) vector-like B [7].

Measurement of the top polarization in the lepton+jets decay channel with the D0 detector

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1 Introduction

Top quark and its properties play an important role in the Standard Model (SM) and may probe for the new physics. The recent results for the top forward-backward asymmetry from the Tevatron [1, 2] showed tension between the SM and measurements. Various models can address that tension with regards to the top polarization and the spin correlation of the topantitop pairs. The SM predicts top quark pairs produced unpolarized at the Tevatron, while various models beyond Standard Model (BSM) expect non-zero polarization of the top pairs. As the matter of fact, the polarization quantity itself is distinctive for different models and thus the experimental result of the top polarization can confirm the SM calculation or various models BSM.

This on-going measurement of the top quark polarization uses lepton+jets decay channel of the top quark pair produced at the Tevatron collider in proton-antiproton collisions. The study analyzes data detected by the DØ detector with integrated luminosity of 9.7 fb⁻¹. Top quark polarization can play important role in confirmation of the Standard Model theory or in understanding BSM models as it supplements the measurements of forward-backward asymmetry. The polarization is studied by angular distribution of the lepton in beam basis and helicity basis, furthermore, the transverse part of the polarization is studied.

2 Method

Top polarization $P_{\hat{n}}$ can be measured in the top rest frame by the angular distribution of the top decay products with respect to a chosen axis \hat{n} [3, 4]:

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_{i,\hat{n}}} = \frac{1}{2} (1 + P_{\hat{n}} \kappa_i \cos\theta_{i,\hat{n}}), \tag{1}$$

where *i* is the decay product (that is lepton, quark, neutrino) and κ_i its spin analyzing power, that equals 1 for lepton, -0.4 for *b*-quark, and -0.3 for neutrino. As one can see, the lepton is the most sensitive product of the top quark decay to its polarization. Thus, this measurement is focused on the polarization information that is carried by the lepton¹,

¹In this article, by lepton are denoted only electron and muon.

which is detected and reconstructed by the DØ detector with a high accuracy. The downtype quark has also analyzng power close to 1 [5], however its identification is complicated.

The polarization is measured with respect to following axes:

- **beam** axis is given by the direction of the proton (antiproton) beam and is optimal for the Tevatron energy.
- helicity axis is given by the direction of the parent top quark in $t\bar{t}$ rest frame. This is preferred by the LHC energies, but can be measured at the Tevatron.

The axes and the respective polarization angles using lepton as the analyzing particle are shown in Figure 1. One can define the net polarization using cosines of the polarization angles as

$$P_{\hat{n}} = \frac{N(\cos\theta_{l,\hat{n}} > 0) - N(\cos\theta_{l,\hat{n}} < 0)}{N(\cos\theta_{l,\hat{n}} > 0) + N(\cos\theta_{l,\hat{n}} < 0)}.$$
 (2)



Figure 1: Visualization of the helicity $(\theta_{i,\hat{h}})$ and beam $(\theta_{i,\hat{b}})$ polarization angles using lepton as the analyzing particle in the top quark decay topology at the Tevatron.

To extract the polarization value from data, a fit using templates for polarized top quarks is performed. The polarized samples are produced by reweighing signal Monte Carlo sample with weight derived from Eq. 1, $(1 + \cos \theta_{l,\hat{n}})$ for positive and $(1 - \cos \theta_{l,\hat{n}})$ for negative polarization of the top quarks. The polarization is expected to be close to zero in the SM and a very small polarization is generated by the electro-weak interaction.

The bases mentioned above are longitudinal, but one can also study polarization **transverse**, perpendicular component to the production plane [6, 7]. Such polarization is allowed to be non-zero in the SM and has different values for various BSM models. Measurement of transverse polarization of the top quarks has never been performed.

3 Selection and samples

The measurement is performed with an integrated luminosity of 9.7 fb⁻¹ of proton-antiproton collisions at the center-of-mass energy of 1.96 TeV, recorded during Run II by the DØ detector [8] at the Tevatron collider. The events in the l+jets channel have exactly one isolated lepton with $p_T > 20$ GeV and $|\eta| < 1.1$ in case of electron, or $|\eta| < 1.5$ in case of muon. Events are required to have four or more jets identified by cone algorithm, each jet with transverse momentum of $p_T > 25$ GeV and $|\eta| < 2.5$. The leading jet has to satisfy $p_T > 40$ GeV criterium and at least one of the jets is required to be tagged as *b*-quark jet by multivariate tagging algorithm. The top quark pair decay topology in l+jets channel contains undetected neutrino, therefore additional selection criteria on the imbalance in the transverse momentum, $\not{E}_T > 20$ GeV, is applied. Additional quality cuts are applied to encrease signal-to-background ratio in selection of the $t\bar{t}$ events. Details about selection requirements, particle reconstruction, and identification are described in [9, 10].



Figure 2: Distributions of the cosines of the polarization angles with respect to the beam axis (a), to the helicity axis (b), and to the transverse component (c). The signal is modeled by leading order generator ALPGEN, the background samples are described in Sec. 3

Both data-driven techniques and Monte Carlo (MC) simulations are used to estimate the sample composition of the data. Each MC sample is processed through full simulation of the DØ detector based on GEANT. Signal $t\bar{t}$ events are simulated using various MC generators, a next-to-leading generator MC@NLO combined with HERWIG showering and a leading order generator ALPGEN combined with PYTHIA. The dominant background is W+jets, followed by multijet (MJ) contribution, where jets are misidentified as leptons, and small contributions from single top quark, Z+jets, and diboson are also calculated. Background samples are simulated using ALPGEN (W+jets, Z+jets), PYTHIA (diboson), COMPHEP (singletop), or from control samples from DØ data (MJ). The measurements uses various axigluon models for comparison, generated with MADGRAPH+PYTHIA. For direct comparison a $t\bar{t}$ signal with zero polarization was also generated using the same MC generators.

4 Results

To study angular distributions with the respective axes mentioned in Sec. 2, one needs entire information about kinematic of the top quark decay to reconstruct the top quark kinematic parameters. For this purpose, kinematic reconstruction is utilized to handle the assignments and combinatorics. The kinematic fit is constrained with the mass of the top quark and the mass of the W boson, and only the assignment with the lowest χ^2 is kept right now.

Cosines of the polarization angles are then evaluated as shown on the control plots for the

MEASUREMENT OF THE TOP POLARIZATION IN THE LEPTON+JETS DECAY CHANNEL ...

beam axis (a), helicity axis (b), and transverse component of the polarization (c) (Fig. 2).

Being "work in progress", this paper is able to report only MC results for the top quark polarization. Table 1 summarizes net polarizations for different MC simulations of $t\bar{t}$ signal after selection in comparison with axigluon models. Uncertainties are from MC statistics. For the first two SM MC generators, the dependency of the polarization on $M_{t\bar{t}}$ is shown. In case of data, the net polarization will be measured after the background subtraction.

	beam axis		helicity axis		transverse axis	
	$M_{t\overline{t}} < 450$	$M_{t\overline{t}}>450$	$M_{t\overline{t}} < 450$	$M_{t\overline{t}}>450$	$M_{t\overline{t}} < 450$	$M_{t\overline{t}}>450$
SM ALPGEN	-0.001(3)		-0.024(3)		-0.005(3)	
	0.002(3)	-0.005(4)	0.004(3)	-0.068(4)	-0.004(3)	-0.007(4)
SM mc@nlo	-0.008(1)		-0.043(1)		0.002(1)	
	-0.001(2)	-0.018(2)	-0.008(2)	-0.096(2)	0.003(2)	0.001(2)
SM madgraph	-0.007(11)		-0.020(11)		-0.015(11)	
$200 \text{ GeV} \text{ axigluon}_L$	-0.083(11)		-0.080(11)		-0.011(11)	
$200 \text{ GeV} \text{ axigluon}_R$	0.065(11)		0.013(11)		0.013(11)	
$2000 \text{ GeV} \text{ axigluon}_L$	-0.068(11)		-0.092(11)		-0.003(11)	
2000 GeV axigluon _{R}	0.041(11)		-0.01	1(11)	0.014	4(11)

Table 1: Summary of Monte Carlo predictions of the net polarization after selection. The SM signal is modeled using ALPGEN, MC@NLO, and MADGRAPH, axigluon models are simulated with MADGRAPH. Uncertainties are statistical.

Template fit with weighted MC samples (+1 and -1 polarized signal templates) will be used to measure the polarization in data.

5 Conclusion

The described measurement is an on-going study of the top polarization using the full Run II dataset from the $D\emptyset$ detector. The motivation is to provide result that will help to resolve whether there is new physics associated with the top quark or the SM holds true. This measurement is the first attempt to measure transverse part of the top quark polarization.

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Measurement of the leptonic $t\bar{t}$ charge asymmetry in the dilepton channel with the D0 detector

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1 Introduction

At next-to-leading order, quantum chromodynamics predicts a $t\bar{t}$ pair production asymmetry. The top quark is predicted to be emitted preferentially in the direction of the incoming quark, while the top antiquark in the direction of the incoming antiquark. The magnitude of the asymmetry has been computed to be around 9% for proton-antiproton collisions at Tevatron within the SM [1] including electroweak corrections. In 2011 results from CDF and D0 [2, 3] have driven a lot of attention because some of the measured asymmetries were significantly higher than the predictions based on the SM.

In this note, we report a new measurement [4] accepted by PRD of the $t\bar{t}$ asymmetry based on leptons produced in $t\bar{t}$ events in the dilepton channel with the full dataset collected by the D0 Collaboration in Run II of the Tevatron corresponding to an integrated luminosity of 9.7 fb⁻¹, and we compare our results with the most recent predictions based on the standard model [1]. We use the two observables $q \times \eta$ and $\Delta \eta$, where q and η are the charge and pseudorapidity of the lepton, and $\Delta \eta = \eta_{\ell^+} - \eta_{\ell^-}$ is the difference in lepton pseudorapidities. The pseudorapidity η is defined as a function of the polar angle θ with respect to the proton beam as $\eta = -\ln(\tan \frac{\theta}{2})$. Positive (negative) η corresponds to a particle produced in the direction of the incoming proton (antiproton). The single-lepton asymmetry A_{FB}^{ℓ} and dilepton asymmetry $A^{\ell\ell}$ are defined as

$$A_{\rm FB}^{\ell} = \frac{N(q \times \eta > 0) - N(q \times \eta < 0)}{N(q \times \eta > 0) + N(q \times \eta < 0)}, \quad A^{\ell\ell} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)}$$
(1)

where N corresponds to the number of leptons satisfying a given set of selection criteria.

2 Simulation and backgrounds

Monte Carlo (MC) events are processed through a GEANT-based [5] simulation of the D0 detector. $t\bar{t}$ events are generated with the NLO generator MC@NLO [6]. Electroweak backgrounds such as Drell-Yan process associated with jets and diboson production are simulated using ALP-GEN [7] and PYTHIA [8] respectively. The so-called instrumental background arises mainly from multijets and W+jets events in which one or two jets is misidentified as electrons or where muons or electrons originating from the semileptonic decay of a heavy flavor hadron appear isolated. This instrumental background is estimated directly in the data by the mean of the "matrix method".

3 Event selection

The selection of events follows the approach developed for the measurement of the $t\bar{t}$ cross section in the dilepton channel at D0 [9]. We require at least two high p_T isolated leptons and missing energy due to the two neutrinos escaping the detector. We define three channels requiring at least two jets: dielectron channel (*ee*) with two electrons, electron-muon channel $(e\mu)$ with one electron and one muon, and dimuon channel $(\mu\mu)$ with two muons. We define an additional channel requiring exactly one jet, one electron and one muon $(e\mu \ 1 \ \text{jet})$. The final selection is performed in two dimensions using informations from the *b*-quark identification and the topological variables such as $H_T = p_T^{lepton} + \sum_{i=1}^2 p_T^{jet}$ or the significance in missing transverse energy $\mathcal{S}(\not{E}_T)$. The numbers of predicted background events, as well as the expected numbers of signal events, in the four channels are given in Table 1 and show high signal purity of the selected sample.

Table 1: Numbers of total expected (N_{expected}) and observed (N_{observed}) events from backgrounds and $t\bar{t}$ signal. Expected numbers of events are shown with their statistical uncertainties.

	$Z \to \ell \ell$	Dibosons	$\begin{array}{ll} \text{Multijet} & \text{and} \\ W+\text{jets} \end{array}$	$t\bar{t} \to \ell\ell jj$	$N_{\rm expected}$	$N_{\rm observed}$
ee	$17.2^{+0.6}_{-0.6}$	$2.4\substack{+0.1 \\ -0.1}$	$4.7_{-0.4}^{+0.4}$	$127.8^{-1.4}_{-1.4}$	$152.1^{+1.6}_{-1.6}$	147
$e\mu$ 2 jets	$13.7_{-0.5}^{+0.5}$	$3.9^{+0.2}_{-0.2}$	$16.3^{+4.0}_{-4.0}$	$314.7^{+1.1}_{-1.1}$	$348.6^{+4.2}_{-4.2}$	343
$e\mu$ 1 jet	$8.7^{+0.6}_{-0.6}$	$3.4_{-0.2}^{+0.2}$	$2.9^{+1.7}_{-1.7}$	$61.7^{+0.5}_{-0.5}$	$76.7^{+1.9}_{-1.9}$	78
$\mu\mu$	$17.5_{-0.6}^{+0.6}$	$1.9^{+0.1}_{-0.1}$	$0.0\substack{+0.0\\-0.0}$	$97.7^{+0.6}_{-0.6}$	$117.1_{-0.8}^{+0.8}$	114

4 Measurements

Figure 1 presents the $q \times \eta$ and $\Delta \eta$ distributions for dilepton events after applying the event selection. To measure A_{FB}^{ℓ} and $A^{\ell\ell}$ we restrict the distributions to the so-called visible phase space. This region is defined such as the statistical uncertainty on the asymmetry within the full phase space is minimized using ensemble of pseudo datasets: $|\eta| < 2.0$ and $|\Delta \eta| < 2.4$. Within each of the four channels we perform a bin-by-bin subtraction of the estimated background contributions to the data. We then correct bin-by-bin the background subtracted distribution for the selection efficiency to get back to the production level result using MC@NLO $t\bar{t}$ sample. Figure 2 shows the corrected distributions for data compared to the predictions from MC@NLO. Finally, we extrapolate the measured production asymmetries from the visible phase space to the full phase space by multiplying the asymmetries within the visible phase space with the so-called extrapolation factor. We compute this extrapolation factor by taking the ratio of the generator level SM $t\bar{t}$ asymmetries from MC@NLO without selections to asymmetries within the visible phase space.



Figure 1: Distributions in (left) $q \times \eta$ and (right) $\Delta \eta = \eta_{\ell^+} - \eta_{\ell^-}$, for the sum of *ee*, $e\mu$ and $\mu\mu$ channels, along with predictions of the backgrounds and $t\bar{t}$ signal. The black points show data events and the error bars indicate the statistical uncertainty on the data.

5 Uncertainties

The main sources of systematic uncertainties are related to the modeling of the background and the signal as well as instrumental uncertainty such as energy scale of jets and leptons. The overall systematic uncertainties on A_{FB}^{ℓ} and $A^{\ell\ell}$ are small compared to the statistical uncertainties (see Sec. 6). Further details about each category of uncertainty may be found in [4].

Table 2: The measured asymmetries defined in Eq. (1) for all channels combined within the visible and full phase spaces, compared to the predicted SM NLO asymmetries [1] for inclusive $t\bar{t}$ production. The first uncertainty on the measured values corresponds to the statistical and the second to the systematic contribution. All values are given in %.

	Visible phase space	Full phase space	Prediction
$A_{\rm FB}^{\ell}(\%)$	$4.1 \pm 3.5 \pm 1.0$	$4.4 \pm 3.7 \pm 1.1$	3.8 ± 0.3
$A^{\ell\ell}(\%)$	$10.5 \pm 4.7 \pm 1.1$	$12.3 \pm 5.4 \pm 1.5$	4.8 ± 0.4

6 Results

We combine the four channels taking into account the correlations of the different systematic uncertainties using the BLUE method [10, 11]. Table 2 shows the combined results within the visible and the full phase space as well as the more recent predictions based on the standard model [1]. The measured A_{FB}^{ℓ} and $A^{\ell\ell}$ within the full phase space are consistent with the predictions.

We measure the statistical correlation between A_{FB}^{ℓ} and $A^{\ell\ell}$ to be of 0.82 as explained in [4] in order to compute the ratio of these two asymmetries which allow to achieve a better



Figure 2: Distributions in (left) $q \times \eta$ and (right) $\Delta \eta$, for the combined *ee*, $e\mu$, and $\mu\mu$ channels after subtraction of background and correction for selection efficiency within the acceptance. The error bars indicate the statistical uncertainty on data. The dashed lines show the predictions from MC@NLO outside the analysis acceptance.

sensitivity with ratio to the individual asymmetries due to systematic uncertainties cancellation. We measure a ratio equal to 0.36 ± 0.20 consistent at the level of 2 standard deviations with the prediction of 0.79 ± 0.10 . This predicted ratio is found to be almost the same for the different tested models as can be seen in Fig. 3(left).

CDF and D0 both recently measured A_{FB}^{ℓ} in the lepton+jets (ℓ +jets) final state [12, 13] to be $(9.4^{+3.2}_{-2.9})\%$ and $(4.7^{+2.6}_{-2.7})\%$, respectively. CDF also reported measurements of A_{FB}^{ℓ} and $A^{\ell\ell}$ in the dilepton final state [14] to be $(7.2 \pm 6.0)\%$ and $(7.6 \pm 8.1)\%$, respectively. We are able to compare our measurements performed in the dilepton channel at D0 with the results in the dilepton and ℓ +jets at CDF since they all are extrapolated to the full phase space. The measured A_{FB}^{ℓ} on one hand and $A^{\ell\ell}$ (dilepton only) on the other hand are in agreement.

The A_{FB}^{ℓ} measurement in the ℓ +jets channel at D0 is restricted to the region $|\eta_{lepton}| < 1.5$ and not extrapolated to the full phase space. We cannot then compare directly with our A_{FB}^{ℓ} measurement. Nevertheless in the dilepton channel at D0 we found that the ratio of A_{FB}^{ℓ} measured within the full and visible phase space ($|\eta_{lepton}| < 2.0$) is at the order of ~ 1.1 . The small extrapolation correction allows to compare the two D0 A_{FB}^{ℓ} results which we observe to be in agreement. Figure 3(right) shows a summary of the Tevatron measurement.

The combination of the CDF and D0 results will be the last step to build the legacy measurement from the Tevatron. We can perform the combination in different ways. One of them could be to combine and extrapolate the measurements at the same time. Using the distributions of the asymmetry as a function of the lepton pseudorapidity from each CDF and D0 measurements, we can fit them separately and then combine the parameters of the fit function using the BLUE method. It is then straightforward to extract the asymmetry in the full phase space (as well as in any restricted phase-space regions). The statistical uncertainty of the combined measurements are expected to be $\sim 1.5\%$ for A_{FB}^{ℓ} and $\sim 4.6\%$ for $A^{\ell\ell}$.



Figure 3: (left) D0 dilepton extrapolated A_{FB}^{ℓ} versus $A^{\ell\ell}$ asymmetries in $t\bar{t}$ data, the predictions from MC@NLO, axigluon models, and from the latest SM NLO prediction [1]. The ellipses represent contours of total uncertainty at 1, 2, and 3 SD on the measured result. Predicted asymmetries are shown with their statistical uncertainties. The predictions from MC@NLO differ from the SM ones because MC@NLO does not include the electroweak corrections. (right) Summary of the A_{FB}^{ℓ} and $A^{\ell\ell}$ measurements at the Tevatron.

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Stop and other searches

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The latest results from LHC on direct pair production of third-generation squarks are reviewed. We present searches performed for different decay modes of stop and sbottom using the full set of 8 TeV LHC data recorded in 2012 (corresponding to 20/fb).

1 Introduction

The search for the third-generation squarks, namely the stop \tilde{t}_1 and sbottom \tilde{b}_1 , is of particular interest in the frame of Natural SUSY which tends to accommodate a Higgs boson of 125 GeV. Stop and sbottom can be produced directly by pair through the $pp \to \tilde{t}_1 \tilde{t}_1^*$ and $pp \to \tilde{b}_1 \tilde{b}_1^*$ processes, with a cross section rapidly falling with an increasing value of their mass $(m_{\tilde{t}_1} \text{ or } m_{\tilde{b}_1})$ [1]. If the gluino is not too heavy to be produced at the LHC, the gluino-mediated production mode is also possible, and in that case, is dominant.

The analyses performed on the subject by the ATLAS [2] and CMS [3] Collaborations are done mainly in the frame of R-parity conservation (RPC), which implies that SUSY particles are pair-produced and decay up to the lightest supersymmetric particle (LSP). As the LSP is stable, it provides a clear signature in the detector by a large missing transverse energy (MET). In contrast, for R-parity violation (RPV), the LSP will decay into Standard Model (SM) particles leading to final states of larger multiplicity and without significant MET.

In all analyses, a strong effort is put on validating and estimating the SM contributions with data-driven methods. The absence of deviation in the data with respect to the SM processes leads up to now to the extraction of exclusion limits. Simplified models of Supersymmetry (SMS) are commonly used to set such limits on specific SUSY processes, as they allow describing a process with a limited set of free parameters, typically the masses of the SUSY particles which appear in the process. They also assume a branching ratio (BR) to a dedicated decay mode of 100%.

We present here only the most recent results for direct pair production of \tilde{t}_1 or \tilde{b}_1 , assuming RPC, based on the full 2012 data set corresponding to an integrated luminosity of $\sim 20/\text{fb}$.

2 Search for sbottom decaying into a bottom quark and the lightest neutralino

The study of the $\tilde{b}_1 \to b \tilde{\chi}_1^0$ process with the lightest neutralino $\tilde{\chi}_1^0$ as LSP has been performed [4] by ATLAS. The events are selected with 0 lepton, 2 jets identified as originating from a *b* quark ("b-tagged jets") and MET>150 GeV in the final state and categorized into two signal regions.

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The first signal region is defined for large mass differences $\Delta m(\tilde{b}_1, \tilde{\chi}_1^0)$ between the \tilde{b}_1 and the $\tilde{\chi}_1^0$, with a veto on any additional jet. It makes use of the contransverse mass m_{CT} displayed on Fig. 1 (left):

$$m_{CT}^2(v_1, v_2) = \left[E_T(v_1) + E_T(v_2)\right]^2 - \left[p_T(v_1) - p_T(v_2)\right]^2 \tag{1}$$

which tends to reconstruct the mass of a heavy particle, pair-produced and decaying semiinvisibly, from the information on the two visible particles (v_1 and v_2 , i.e. the b-tagged jets here). To consider also smaller mass differences $\Delta m(\tilde{b}_1, \tilde{\chi}_1^0)$ ($\leq 100 \text{ GeV}$), a second signal region is defined, asking for a leading jet coming from an initial state radiation (ISR) not b-tagged, the b-tagging criteria being only applied on the 2^{nd} and 3^{rd} jets.

As the data in these two signal regions are in agreement with the expected SM predictions, exclusion limits are extracted. They extends considerably the previous results from Tevatron [5, 6] as displayed on Fig. 1 (right) in the 2D plane $m_{\tilde{\chi}_1^0}$ vs $m_{\tilde{b}_1}$: $m_{\tilde{b}_1}$ up to 620 GeV are excluded at 95% of confidence level (CL) for $m_{\tilde{\chi}_1^0} < 120$ GeV; and $\Delta m(\tilde{b}_1, \tilde{\chi}_1^0) > 50$ GeV are excluded up to $m_{\tilde{b}_1}$ of 300 GeV.



Figure 1: Left: Distribution of m_{CT} . The different backgrounds are represented by colored histograms, the shaded band includes statistical, detector-related and theoretical systematic uncertainties. For illustration the distributions expected for two signal models are displayed. Right: Exclusion limits at 95% CL in the $(m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0})$ plane for the $\tilde{b}_1 \rightarrow b \tilde{\chi}_1^0$ process. Previous results from Tevatron are also shown.

3 Search for sbottom decaying into a top quark and the lightest chargino

The $\tilde{b}_1 \to t \tilde{\chi}_1^{\pm}$ process is studied by CMS with an event selection based on the presence of 2 leptons of same sign and at least two jets [7]. A veto on events with a third lepton is applied,

if this lepton is identified as coming from the Z decay. This analysis defines multiple signal regions, with different requirements on the jet multiplicity, the scalar sum H_T of the transverse momenta of the jets, the b-tagged jet multiplicity and MET, to maximize the sensitivity to many models. No excess with respect to the SM predictions is observed and the results are therefore interpreted in the frame of $\tilde{b}_1 \to t \tilde{\chi}_1^{\pm}$, with $\tilde{\chi}_1^{\pm} \to W \tilde{\chi}_1^0$, depending on the mass of the 3 SUSY particles. Figure 2 (left) shows the 95% CL exclusion limits in the 2D plane $m_{\tilde{\chi}_1^{\pm}}$ vs. $m_{\tilde{b}_1}$ for $m_{\tilde{\chi}_1^0} = 50$ GeV and Fig. 2 (right) presents these limits as a function of $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{b}_1}$ for the mass hierarchy $m_{\tilde{\chi}_1^0}/m_{\tilde{\chi}_1^{\pm}} = 0.5$. A similar analysis has been performed by ATLAS, leading to similar results [8].



Figure 2: Exclusion regions at 95% CL for the $\tilde{b}_1 \to t \tilde{\chi}_1^{\pm}$ process, in the 2D planes (left) $m_{\tilde{\chi}_1^{\pm}}$ vs. $m_{\tilde{b}_1}$ for $m_{\tilde{\chi}_1^0} = 50$ GeV and (right) $m_{\tilde{\chi}_1^0}$ vs. $m_{\tilde{b}_1}$ for $m_{\tilde{\chi}_1^0}/m_{\tilde{\chi}_1^{\pm}} = 0.5$.

4 Search for stop decaying into a charm quark and the lightest neutralino

The search of the $\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$ decay mode performed by ATLAS is only feasible in presence of an ISR jet, in order to identify the signal events from the large multijet background [9]. For small values of $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$, the monojet signature is designed, requesting a leading ISR jet of transverse momentum $p_T > 280$ GeV, a low jet multiplicity (≤ 3) and MET>220 GeV. For moderated values of $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$ (~ 20 to 80 GeV), the selection uses a c-tagging technique to identify jet originating from a *c* quark, which is based on a MVA algorithm using information from the impact parameters of displaced tracks and on secondary and tertiary decay vertices. In addition to a cut on MET>410 GeV, at least 4 jets are requested for this c-tagged signature. The leading jet with $p_T > 270$ GeV coming from ISR is not tagged, a b-veto is applied on the 2^{nd} and 3^{rd} jets and the c-tagging is applied on the 4^{th} jet for which the discriminant is presented on Fig. 3 (left).

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These two signatures do not present any excess in the data with respect to the SM expectations. The limits extracted in the $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ plane are shown on Fig. 3 (right): $m_{\tilde{t}_1}$ up to 200 GeV are excluded at 95% CL for $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < 85$ GeV; $m_{\tilde{t}_1}$ up to 230 GeV are excluded for $m_{\tilde{\chi}_1^0} = 200$ GeV. This extends significantly previous results from Tevatron [10, 11] and LEP [12] experiments.



Figure 3: Left: Distribution for the 4th leading jet, of the discriminator against jet identified as originating from a light parton. Data are compared to MC simulations for the different SM processes, the error band includes the statistical and experimental uncertainties in the predictions. Right: Exclusion plane at 95% CL as a function of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$ for the $\tilde{t}_1 \to c \tilde{\chi}_1^0$ process. Results from previous experiments are also displayed.

5 Search for stop decaying into a top quark and the lightest neutralino

The razor analysis [13] performed by CMS tends to estimate the mass scale of a process when moving from the lab frame to the frame in which particles are clustered into two "mega" jets of same momentum. The razor variables are defined as

$$M_R \equiv \sqrt{(p^{j_1} + p^{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2},$$

$$M_T^R \equiv \sqrt{\frac{\text{MET}(p_T^{j_1} + p_T^{j_2}) - \text{M\vec{E}T} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}.$$
(2)

 M_R depends only on the momenta \vec{p}^{j_i} of the 2 mega jets $(j_1 \text{ and } j_2)$, with p^{j_i} being the absolute value of the 3-momentum of the i^{th} jet and $p_z^{j_i}$ $(p_T^{j_i})$ its longitudinal (transverse) component, whereas the transverse variable M_T^R depends also on MET. Figure 4 shows how SUSY signal (top left) differs from SM background (top right) in the plane $R^2 = (\frac{M_T^R}{2})^2$ versus M_T

(top left) differs from SM background (top right) in the plane $R^2 = (\frac{M_T^R}{M_R})^2$ versus M_R . The final states, which contain 0 or 1 lepton and at least 1 b-tagged jet, are used for the search, they are separated into categories depending on the lepton and jet multiplicities. In

each category, the background is estimated from a 2D fit on R^2 and M_R in side-band regions (low M_R or low R) as shown on Fig. 4 (bottom) and extrapolated to the search region.



Figure 4: Top: Event distribution in the (M_R, R^2) plane for (left) the $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ signal and (right) the SM processes. Bottom: Projection of the sideband fit result on R^2 (left) and M_R (right). The separate background contributions from 1 b-tagged jet and ≥ 2 b-tagged jets are also shown.

No deviation is observed in any category, allowing to exclude at 95% CL $m_{\tilde{t}_1}$ between 340 and 740 GeV for light $\tilde{\chi}_1^0$ as presented on the left part of Fig. 5. This analysis is complementary to the search [14] from CMS which extends the exclusion limits to lower values of $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$.

The right part of Fig. 5 shows the exclusion limits obtained by ATLAS. New results [15] based on a selection of two leptons of opposite sign and at least two jets, complete the previous measurements with 0 lepton [16] and 1 lepton [17] in the final state with 8 TeV LHC data.



Figure 5: Summary of exclusion limits obtained by CMS (left) and ATLAS (right) with $\tilde{t}_1 \to t \tilde{\chi}_1^0$ searches, in the plane $m_{\tilde{\chi}_1^0}$ versus $m_{\tilde{t}_1}$.

6 Search for stop decaying into a bottom quark and the lightest chargino

The search by ATLAS for $\tilde{t}_1 \to b \tilde{\chi}_1^{\pm}$ with $\tilde{\chi}_1^{\pm} \to W \tilde{\chi}_1^0$, with 2 leptons of opposite sign and at least 2 b-tagged jets selected in the final state [15], makes use of the stransverse mass:

$$m_{T2}(p_T^1, p_T^2, q_T) = \min_{\substack{q_T^1 + q_T^2 = q_T}} \left\{ max \left[m_T(p_T^1, q_T^1), m_T(p_T^2, q_T^2) \right] \right\}$$

with $m_T(p_T^1, p_T^2) = \sqrt{2|p_T^1||p_T^2|(1 - \cos(\Delta\phi))}$ (3)

where p_T^1 and p_T^2 are the transverse momenta of 2 particles separated in the transverse plane by an angle $\Delta \phi$. The minimization for $m_{T2}(p_T^1, p_T^2, q_T)$ is performed over all the possible decompositions of q_T in the q_T^1 and q_T^2 vectors such as $q_T^1 + q_T^2 = q_T$.

The m_{T2} variable can be constructed from the two leptons and MET as in [18], such as $m_{T2}(\ell_1, \ell_2, \text{ MET})$ is bounded at m_W for the $t\bar{t}$ and WW processes and is correlated to $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ for the $\tilde{t}_1 \tilde{t}_1^*$ signal, providing interest for the region with large $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$.

On the contrary, in [15], the m_{T2} variable is constructed using also the momenta of the btagged jets: $m_{T2}(b_1, b_2, \ell_1 + \ell_2 + \text{MET})$, as represented on Fig. 6 (left). For the $t\bar{t}$ background, a bound is observed at m_t , whereas for the $\tilde{t}_1 \tilde{t}_1^*$ signal it is correlated to $\Delta m(\tilde{t}_1, \tilde{\chi}_1^{\pm})$ leading sensitivity to large $\Delta m(\tilde{t}_1, \tilde{\chi}_1^{\pm})$ and low $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$. In order to set up a selection orthogonal to [18], one requests $m_{T2}(\ell_1, \ell_2, \text{MET}) < 90$ GeV and $m_{T2}(b_1, b_2, \ell_1 + \ell_2 + \text{MET}) > 160$ GeV.

Figure 6 (right) presents the exclusion limits at 95% CL in the plane $m_{\tilde{\chi}_1^0}$ versus $m_{\tilde{\chi}_1^\pm}$ combining the two analyses [15, 18].

combining the two analyses [15, 18]. The search for $\tilde{t}_1 \to b \tilde{\chi}_1^{\pm}$ with $\tilde{\chi}_1^{\pm} \to W \tilde{\chi}_1^0$ performed by CMS on events with 1 lepton in the final state [14], makes use of the boosted decision tree technique after a cut on $m_T(\ell, \text{MET}) >$



Figure 6: Left: Distribution of $m_{T2}(b_1, b_2, \ell_1 + \ell_2 + \text{MET})$ after selection. SM backgrounds are represented by colored histograms, the bands representing the total uncertainty. Three different models are also shown for comparison. Right: Exclusion limits at 95% CL in plane $m_{\tilde{\chi}_1^0}$ versus $m_{\tilde{\chi}_1^\pm}$ for $m_{\tilde{t}} = 300$ GeV.

120 GeV as defined by Eq. (3). Exclusion limits at 95% CL are presented on Fig. 7 in the $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ plane, for different values of the mass parameter x characterizing $m_{\tilde{\chi}_1^\pm} = \mathbf{x} \cdot m_{\tilde{t}_1} + (1 - \mathbf{x}) \cdot m_{\tilde{\chi}_1^0}$. For completeness, a summary of the limits extracted by the different ATLAS analyses, with different $m_{\tilde{\chi}_1^\pm}$ hypotheses, is also displayed on Fig. 7.

7 Study on Polarization

The signal acceptance depends on the polarization of the decay products: the top in the $\tilde{t}_1 \to t \tilde{\chi}_1^0$ mode and the W and $\tilde{\chi}_1^{\pm}$ in the $\tilde{t}_1 \to b \tilde{\chi}_1^{\pm}$ mode, which depends on the L/R mixing of the \tilde{t}_1 and on the mixing matrices of the $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^{\pm}$. Based on events selected with 1 lepton in the final state ("1-lepton channel"), the variations on the exclusion limits obtained by CMS when varying the polarization are displayed on Fig. 8 [14]. This study has also been performed by ATLAS for the $\tilde{t}_1 \to t \tilde{\chi}_1^0$ mode for a fixed mass of the $\tilde{\chi}_1^0$ [17]. Unlike the 1-lepton channel, the $\tilde{t}_1 \to t \tilde{\chi}_1^0$ search in the 0-lepton channel is insensitive to the top polarization [16].

8 Study on the Branching Ratio

All the SUSY analyses present now their results in the context of SMS, with a BR of 100%. Limits for smaller BR can be extrapolated from the $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ results assuming that the analysis is only sensitive to this mode, as it is shown on Fig. 9 for CMS (left) [14] and ATLAS (right) [16], for example if the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$ are nearly mass-degenerated (i.e. with a mass parameter x~0).

For larger mass differences $(m_{\tilde{\chi}_1^{\pm}} > m_{\tilde{\chi}_1^0})$, a conservative approximate cross section limit can be obtained as $\sigma(pp \to \tilde{t}_1 \tilde{t}_1^*) < \min \left[\sigma_0 / B^2, \sigma_+ / (1-B)^2 \right]$ where $\sigma_0 (\sigma_+)$ is the cross section limit for the 100% $\tilde{t}_1 \to t \tilde{\chi}_1^0$ ($\tilde{t}_1 \to b \tilde{\chi}_1^{\pm}$) scenario and $B = \text{BR}(\tilde{t}_1 \to t \tilde{\chi}_1^0)$.



Figure 7: Exclusion limits at 95% CL for the $\tilde{t}_1 \rightarrow b \tilde{\chi}^{\pm}$ process as a function of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$ for a mass parameter of (top left) x=0.25, (top right) x=0.5 and (bottom left) x=0.75 used by CMS (the color scale indicates the observed cross section upper limit), and (bottom right) for different $m_{\tilde{\chi}_1^{\pm}}$ hypotheses by ATLAS.

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Figure 8: Effect of the polarization on the observed excluded regions in the 1-lepton channel. Left: For the $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ mode, limits are displayed for unpolarized, right-handed and left-handed t quarks. Right: For the $\tilde{t}_1 \rightarrow b \tilde{\chi}_1^{\pm}$ mode with x=0.5, the nominal scenario is compared to right-handed vs. left-handed $\tilde{\chi}_1^{\pm}$ ($\tilde{\chi}_R$ and $\tilde{\chi}_L$, respectively), and right-handed vs. left-handed $W \tilde{\chi}_1^0 \tilde{\chi}_1^{\pm}$ couplings.



Figure 9: Observed excluded region as a function of $BR(\tilde{t}_1 \to t\tilde{\chi}^0)$ for CMS (left) and ATLAS (right), assuming that the analysis has no acceptance to other decay modes.

STOP AND OTHER SEARCHES

9 Conclusions

Natural SUSY motivates the search for light squarks of third generation. The ATLAS and CMS Collaborations address the question of \tilde{t}_1 and \tilde{b}_1 through several analyses, covering different decay modes with different signatures and techniques. The latest results have been discussed here. There are still work ongoing in order to cover more and more phase space. For example, the kinematical region where $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \sim m_t$ is hardly accessible by direct \tilde{t}_1 pair production, but some exclusion limits can however be extracted with the $\tilde{t}_2 \rightarrow \tilde{t}_1 Z$ channel [19]. More SUSY scenarios are also investigated, like \tilde{t}_1 searches in RPV [20] or in GMSB [19, 21, 22]. Let us hope that with next LHC run, we will not continue to set up further limits but rather discover the first signs of SUSY.

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Alternative methods for top-quark mass determination at the Tevatron and LHC

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I am summarizing here the determination of the top-quark mass from the CDF and D0 Collaborations at the Tevatron and the ATLAS and CMS Collaborations at the LHC using non-conventional methods. I am concentrating on the extraction of the top-quark mass from the top-antitop cross-section, on the mass measurement using the so-called endpoint method and on the top-quark mass determination from the *b*-lifetime.

1 Motivations

The top-quark mass is now measured with a remarkable precision around 0.5 % both at the Tevatron and at the LHC using well-developed "standard" methods based on templates, matrix elements or ideogram.Despite this precision, some questions remain. Indeed since the top quark is a color object, it is non trivial to know which mass is really measured using these standard methods. In all standard methods, Monte Carlo (MC) is used to calibrate the measurements. This mass implemented in MC generators is different from a well-defined mass in theory. A way to get some hints about these points experimentally is to determine the top-quark mass using alternative methods. Such methods can use less inputs from MC or can have different sensitivity to systematic uncertainties than the standard analyses. In this article I will concentrate on the extraction of the top-quark mass from the top-antitop $(t\bar{t})$ cross-section, on the mass measurement using the so-called endpoint method and on the top-quark mass determination from the *b*-lifetime.

Before studying methods which rely differently on MC, it is interesting to look at the dependence of the measured top-quark mass using standard methods with the event kinematics and to compare the data measurements with the predictions from MC. This allows to test the description of the top-quark mass by MC in various phase space regions and to detect potential large deviations due to the pole mass definition problem described above. This has been looked at by the CMS Collaboration [1] in the ℓ +jets final state asking for two *b*-tag jets using 5 fb⁻¹ of LHC at 7 TeV [5]. For these comparisons, the top-antitop final state is fully reconstructed and the top-quark mass is measured using the ideogram technique either solely or together with the jet energy scale. The measurements are compared to Madgraph [2] with different Pythia [3] tunes and to MC@NLO [4]. Differential measurements as a function of several variables have been performed [5] that are sensitive to different physics effects. For instance, the top-quark mass distribution as a function of the opening angles between the two light jets (see Figure 1) or as a function of the pseudo-rapidity (η) of the hadronic decaying top is sensitive to color

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reconnection. The influence of initial and final state radiation can be investigated by looking at the top-quark mass as a function of the invariant mass of the $t\bar{t}$ pair or as a function of the transverse momentum (p_T) of the $t\bar{t}$ pair. To test the sensitivity to the *b*-quark kinematics, the top-quark mass is measured as a function of the transverse momentum or the pseudo-rapidity of the *b*-jet assigned to the hadronic decaying top quark. The mass distribution as a function of the distance between the *b*- and \bar{b} -jets ($\Delta R_{b\bar{b}} = \sqrt{\Delta \eta^2 + \Delta \phi^2}$) is also scrutinized (see Figure 1). Even if the statistical error on these differential measurements is still large, there is currently no indication of specific biases due to the choice of generators.



Figure 1: Differential top-quark mass measurements as a function of the separation of the lightquark jets (left) and of the b-quark jets (right) performed by CMS [5] compared to several MC predictions.

2 Mass extraction from the $t\bar{t}$ cross section

The principle for the mass extraction from the $t\bar{t}$ cross section is to compare the experimental measured $t\bar{t}$ cross section with the one computed theoretically. Both the experimental and theoretical cross sections depend on the top-quark mass but the dependence is different in the two cases. In the experimental case, the dependency comes from the acceptance cuts while in the theoretical case, it originates from the matrix element. The advantage of this alternative method lies in the fact that it allows to extract a top-quark mass in a well-defined renormalization scheme (the one that in used in the theory computation) in contrast to the one that is implemented in the MC generators. This method has however the drawback that it is less precise than direct measurements.

This determination of the top-quark mass has been performed by the D0 Collaboration using the $t\bar{t}$ cross section measured in the ℓ +jets channel using *b*-tagging requirement with 5.4 fb⁻¹. This measured cross section is the one that exhibits the weakest dependence on the top-quark mass. The variation of the measurement as a function of the MC mass $(m_t^{\rm MC})$ is parameterized using a third-order polynomial divided by the mass to the fourth power. As theory input cross section, the next-to-leading order (NLO), the NLO including next-to-leading log (NLL) resummation computations and some approximation of the next-to-next-to-leading order (NNLO) calculations. The mass is extracted from the maximum of a normalized likelihood distribution defined as:

$$L(m_t) = \int f_{\exp}(\sigma|m_t) \left[f_{\text{scale}}(\sigma|m_t) \otimes f_{\text{PDF}}(\sigma|m_t) \right] \, d\sigma,$$

where f_{exp} comes from the experimental measurement which uncertainties are assumed to be Gaussian distributed, f_{scale} represents the theoretical scale uncertainty, taken to be flat and f_{PDF} represents the uncertainty of parton density functions (PDF) taken to be a Gaussian function. The mass determination is performed assuming that m_t^{MC} corresponds to the pole mass (m_t^{pole}) and assuming that m_t^{MC} corresponds to the $\overline{\text{MS}}$ mass ($m_t^{\overline{\text{MS}}}$). The experimental and theoretical $t\bar{t}$ cross sections used in the extraction are shown in Figure 2. With this technique, D0 measures the top-quark pole mass shown in Table 1 [6]. These values are compatible but slightly lower than the top-quark mass world average [7]. The $\overline{\text{MS}}$ mass is also extracted [6].



Figure 2: Experimental and theoretical $t\bar{t}$ cross sections used by D0 to extract the top-quark mass [6].

A similar method has been developed by CMS. In that analysis, CMS uses the $t\bar{t}$ cross section measured in the dilepton channel using 2.3 fb⁻¹ at 7 TeV as experimental input. This cross section is the most precise one measured by CMS with a total uncertainty of 4.1 %. As for D0, it is parameterized using a third-order polynomial divided by the mass to the fourth power. The full NNLO prediction including next-to-next-to-leading log (NNLL) resummation is employed as theoretical input. The mass is extracted using a probability function similar to
Theoretical prediction	m_t^{pole} (GeV)	$\Delta m_t^{\rm pole} \; ({\rm GeV})$
MC mass assumption	$m_t^{\rm MC} = m_t^{\rm pole}$	$m_t^{\rm MC} = m_t^{\overline{\rm MS}}$
NLO	$164.8^{+5.7}_{-5.4}$	-3.0
NLO+NLL	$166.5_{-4.8}^{+5.5}$	-2.7
NLO+NNLL	$163.0^{+5.1}_{-4.6}$	-3.3
Approximate NNLO	$167.5^{+5.2}_{-4.7}$	-2.7

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Table 1: Values of the pole top-quark mass m_t^{pole} , with their 68% C.L. uncertainties extracted for different theoretical predictions by D0 [6].

the D0 analysis. A 1 GeV addition uncertainty is added to the experimental result to cover the possible difference between m_t^{MC} and m_t^{pole} . CMS also studies the interplay of the mass extraction with the value of the strong coupling constant α_s (see [8] for more details).



Figure 3: Experimental and theoretical $t\bar{t}$ cross sections used by CMS to extract the top-quark mass [9].

The experimental and theoretical $t\bar{t}$ cross sections used in the extraction are shown in Figure 3. The extracted top-quark pole mass by CMS are shown in Table 2 for different PDFs [9]. These values are compatible but slightly higher than the top-quark mass world average [7]. The same kind of extraction has been also performed by the ATLAS Collaboration [10] using the first 35 pb⁻¹ of LHC data leading to a top-quark mass of $m_t^{\text{pole}} = 166^{+7.8}_{-7.3}$ GeV [11].

To summarize, the top-quark pole mass has been extracted from the $t\bar{t}$ cross section by D0 leading to a precision of 3 % (where the input experimental cross section has a precision of 12 %, and the input theoretical cross section of 3 %), by ATLAS with a precision of 4.5 % (where the experimental input has an uncertainty of 13 % and the theory input of 5 %) and by CMS with a precision of 2 % (where the experimental input has an uncertainty of 4 % and the theory input of 4 %). Looking at the current theoretical uncertainty on the $t\bar{t}$ cross section and

	Most likely m_t^{pole}	Uncertainty (GeV)		
	value (GeV)	Total	From $\delta \alpha_S$	From $\delta E_{\rm LHC}$
ABM11	172.7	$+3.8 \\ -3.5$	$^{+1.0}_{-1.0}$	$^{+0.8}_{-0.8}$
CT10	177.0	$+4.3 \\ -3.8$	$^{+0.8}_{-0.8}$	$^{+0.9}_{-0.9}$
HERAPDF1.5	179.5	+4.3 -3.8	$+1.2 \\ -1.1$	+1.0 -1.0
MSTW2008	177.9	+4.0 -3.6	+0.9 -0.9	+0.9
NNPDF2.3	176.7	$+3.8 \\ -3.4$	$+0.7 \\ -0.7$	$+0.9 \\ -0.9$

Table 2: Results obtained by CMS for m_t^{pole} by comparing the measured $t\bar{t}$ cross section to the NNLO+NNLL prediction with different NNLO PDF sets [9].

assuming no experimental errors, one can estimate the ultimate uncertainty on the top-quark mass achievable with this method to be around 3 GeV (1.7 %).

3 Mass measurement using the endpoint method

The endpoint method employed for the first time by CMS to measure the top-quark mass [12] was originally developed to measure masses of potentially pair produced new particles with two cascade decays each ending in an invisible particle, like neutralino. It is thus also applicable to the $t\bar{t}$ dilepton final state which contains two escaping neutrinos. This method relies on the end distribution of the variable named M_{T2} used as mass estimator. This M_{T2} is a generalization of the usual transverse mass and is defined as:

$$M_{\rm T2} \equiv \min_{\vec{p}_{\rm T}^{\rm a} + \vec{p}_{\rm T}^{\rm b} = \vec{p}_{\rm T}} \left\{ \max(M_{\rm T}^{\rm a}, M_{\rm T}^{\rm b}) \right\}.$$

This variable corresponds to the minimum parent mass consistent with the observed kinematics for the hypothetical \bar{p}_{T}^{a} and \bar{p}_{T}^{b} . To limit the sensitivity to the transverse momentum of the $t\bar{t}$ system $(p_T(t\bar{t}))$, the variable $M_{T2\perp}$ is rather used. It is computed with the p_T components perpendicular to $p_T(t\bar{t})$.

Three variables are needed to solve the dilepton event kinematics. The chosen variables are $M_{T2\perp}$ computed at the lepton level ($\mu_{\ell\ell}$) after the W-boson decays, $M_{T2\perp}$ computed at the b-jet level (μ_{bb}), ignoring that leptons are in fact observed and the invariant mass between the b-jet and the lepton (M_{lb}) which is very correlated with $M_{T2\perp}$ constructed with the b-jet+lepton combined.

In the analysis, the physics background is estimated using MC while the background with mistag *b*-jets is evaluated using antitag events. The combinatoric background is suppressed using a dedicated selection algorithm [12]. The top-quark mass is extracted using a maximum likelihood fit of the endpoint of the three chosen variables taking the object resolution into account. Indeed in the limit of perfect object measurements, the maximum of the $\mu_{\ell\ell}$ distribution is equal to the W-boson mass (assuming zero neutrino mass), the maximum of the μ_{bb} distribution is equal to the top-quark mass while the maximum of M_{lb} can be expressed analytically using the energies and momenta of the daughter of $t \to Wb$ in the top-quark rest frame. The fitted distributions are shown in Figure 4. Using this technique, CMS measures [12]: $m_t = 173.9 \pm 0.9(\text{stat})^{+1.7}_{-2.1}(\text{syst})$ GeV. The precision of this result is comparable to the one from the standard measurement in the same channel. As can be seen in Table 3, the largest systematic uncertainty comes from the uncertainty on the jet energy scale.



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Figure 4: Results for the endpoint fit in CMS where the red line represents the full fit while the green and blue curves are for the signal and background shapes respectively [12].

4 Mass measurement using the B-hadron lifetime

The top-quark mass can also be measured using different observables. For instance the lifetime and decay length of the B-hadrons from the top-quark decay depends almost linearly on the top-quark mass as can be seen in Figure 5. Alternatively the lepton p_T from the decay of the *W*-boson from the top quark can also be used as a mass estimator. The advantage of such estimators is that they minimally rely on the calorimeter-based uncertainty like the jet energy scale uncertainty. However these methods can potentially be rather sensitive to the modeling of the top production kinematics or to the calibration of the *b* decay length or the *b* fragmentation model.

Source	$\delta m_t \; (\text{GeV})$
Jet Energy Scale	$^{+1.3}_{-1.8}$
Jet Energy Resolution	± 0.5
Lepton Energy Scale	$^{+0.3}_{-0.4}$
Fit Range	± 0.6
Background Shape	± 0.5
Jet and Lepton Efficiencies	$^{+0.1}_{-0.2}$
Pileup	< 0.1
QCD effects	± 0.6
Total	$^{+1.7}_{-2.1}$

Table 3: Summary of the systematic uncertainties affecting the CMS measurement of the topquark using the endpoint method [12].



Figure 5: Median of the transverse b decay length distribution between the primary and the secondary vertex as a function of the simulated top-quark mass for three final states studied by CMS [13].

4.1 Measurement using the B-hadron lifetime at CDF

These alternative methods were first developed at CDF in the ℓ +jets channel with at least one *b*-tagged jet using 1.9 fb⁻¹ [14]. The top-quark mass was simultaneously extracted from the B-hadron lifetime and from the lepton p_T . The main difficulty of this analysis appears to be the calibration of the transverse decay length. Indeed corrections for the inaccuracy of the fragmentation simulation in EVTGEN has been necessary as well as corrections for the tracker modeling in the simulation. These corrections are determined using a sample of $b\bar{b}$ events (with 95% purity) as a function the p_T of jets reconstructed only in the tracker. These track-based jets are previously calibrated using γ +jets events. The uncertainty on the calibration of the transverse decay length are the dominant systematic uncertainty on the final result. In the case of the measurement using the lepton p_T , the understanding of the lepton p_T scale is the largest systematic uncertainty. Constructing a combined likelihood shown in Figure 6 with the two observables, CDF measures [14]: $m_t = 170.7 \pm 6.3(\text{stat}) \pm 2.6(\text{syst})$ GeV. Details on the systematic uncertainties limiting the measurements are presented in Table 4.

4.2 Measurement using the B-hadron lifetime at CMS

CMS has adapted CDF method using both the ℓ +jets and dilepton final state using 19 fb⁻¹ of LHC data at 8 TeV. In this analysis, the chosen observable is the median of the distribution of secondary vertices with maximal transverse decay length (L_{xy}) . The calibration for L_{xy} is cross-checked using dijet events with one muon-tagged jet, taken to be the tag jet, while the second jet is taken to be the probe. The distribution of the secondary vertex mass of this



Figure 6: Likelihood constructed from 23 m_t test points using the transverse B-hadron decay length and the lepton p_T in the top-quark decay by CDF [14].

probe jet is then compared with the prediction after fitting the light, c and b-jets fractions. The agreement appears to be good as shown in Figure 7.

The top-quark mass extraction using the median values of L_{xy} after calibration leads to [13]: $m_t = 173.5 \pm 1.5(\text{stat}) \pm 1.3(\text{syst}) \pm 2.6(p_T(t))$ GeV. As can be seen in Table 5, the modeling of the top-quark p_T , which is mass dependent, has a huge influence on the result. A systematic uncertainty based on reweighting the simulation to the unfolded top-quark p_T spectrum from data is assigned. This is currently the limiting uncertainty. In the future, the possibility to use an invariant quantity like the lepton-vertex invariant mass could be studied since it would keep the information on the top-quark mass while being less dependent on the top-quark kinematics.

Systematic $[\text{GeV}/c^2]$	Lxy	Lepton p_T	Simultaneous
Background Shape	1.0	2.3	1.7
QCD Radiation	0.5	1.2	0.7
PDF	0.3	0.6	0.5
Generator	0.7	0.9	0.3
Lepton p_T Scale	0	2.3	1.2
Lxy Calibration	2.5	0	1.1
Multiple Interactions	0.2	1.2	0.7
Calorimeter JES	0.4	0.4	0.3
Systematics Total	2.9	3.8	2.6

Table 4: Final systematic uncertainties for the transverse B-hadron decay length and the lepton p_T CDF measurement [14].

	Source		$\Delta m_t [\text{GeV}]$	
		μ +jets	e+jets	$e\mu$
Statistical		1.0	1.0	2.0
	Jet energy scale	0.30 ± 0.01	0.30 ± 0.01	0.30 ± 0.01
	Multijet normalization $(\ell + jets)$	0.50 ± 0.01	0.67 ± 0.01	-
Experimental	W+jets normalization $(\ell + jets)$	1.42 ± 0.01	1.33 ± 0.01	-
	DY normalization $(\ell \ell)$	-	-	0.38 ± 0.06
	Other backgrounds normalization	0.05 ± 0.01	0.05 ± 0.01	0.15 ± 0.07
	W+jets background shapes $(\ell + jets)$	0.40 ± 0.01	0.20 ± 0.01	-
	Single top background shapes	0.20 ± 0.01	0.20 ± 0.01	0.30 ± 0.06
	DY background shapes $(\ell \ell)$	-	-	0.04 ± 0.06
	Calibration	0.42 ± 0.01	0.50 ± 0.01	0.21 ± 0.01
	Q^2 -scale	0.47 ± 0.13	0.20 ± 0.03	0.11 ± 0.08
Theory	ME-PS matching scale	0.73 ± 0.01	0.87 ± 0.03	0.44 ± 0.08
Theory	PDF	0.26 ± 0.15	0.26 ± 0.15	0.26 ± 0.15
	Hadronization model	0.95 ± 0.13	0.95 ± 0.13	0.67 ± 0.10
	B hadron composition	0.39 ± 0.01	0.39 ± 0.01	0.39 ± 0.01
	B hadron lifetime	0.29 ± 0.18	0.29 ± 0.18	0.29 ± 0.18
	Top quark p_T modeling	3.27 ± 0.48	3.07 ± 0.45	2.36 ± 0.35
	Underlying event	0.27 ± 0.51	0.25 ± 0.48	0.19 ± 0.37
	Color reconnection	0.36 ± 0.51	0.34 ± 0.48	0.26 ± 0.37

Table 5: Statistical, experimental and theoretical systematic uncertainties on the measured topquark mass based on the median of the transverse B-hadron decay length distribution between the primary and the secondary vertex by CMS [13]. ALTERNATIVE METHODS FOR TOP-QUARK MASS DETERMINATION AT THE TEVATRON ...



Figure 7: Inclusive fit to the flavor content of a dijet sample based on the secondary vertex mass distribution to check the calibration of L_{xy} in CMS B-hadron lifetime measurement [13].

5 Conclusion

Now that the precision on the direct top-quark mass measurements reaches 1 GeV, alternative methods that are less sensitive to MC (and so less sensitive to the top-quark mass scheme implemented in MC) or with different sensitivity to systematic uncertainties need to be developed. Some of these alternative approaches have been described here. For some of them the achieved precision is still modest. However with plenty of statistics forseen, the LHC Run 2 will enable to improve them allowing in particular to study the systematic limitation using data.

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Search for rare top quark decays

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The top quark is the heaviest elementary particle known and has such a small lifetime that it decays before hadronization occurs, almost exclusively to bW, within the Standard Model (SM). These properties make it a good object to test quantum chromodynamics (QCD), in production, and electroweak sectors, in decay or single top production, of the SM of particle physics. In the SM, due to the GIM mechanism [1], Flavour Changing Neutral Current (FCNC) decays are forbidden at tree level and the decay rates are much smaller than the rate of the dominant decay mode $t \rightarrow bW$ at loop level. Figure 1 shows the dominant decay of the top quark, as well as possible FCNC decays. However, several SM extensions predict higher branching ratios (BR) for the top quark FCNC decays [2] (Table 1) which make the search for FCNC decays a good window into physics beyond the SM. Examples of such extensions are the quark-singlet model (QS), the two-Higgs doublet model with (FC 2HDM) or without (2HDM) flavour-conservation, the minimal supersymmetric model (MSSM), SUSY with R-parity violation, the Topcolour-assisted Technicolour model (TC2) [3] or models with warped extra dimensions (RS) [4].



Figure 1: Top quark decays. The dominant SM decay channel $t \to bW$ and the FCNC channels of SM extensions

The present experimental limits on the branching fractions of the FCNC top quark decay channels established by experiments at the LEP, HERA, Tevatron and LHC colliders are shown in Table 2. Here, three searches $(t\bar{t} \text{ production with FCNC } t \rightarrow qZ \text{ and } t \rightarrow cH$ decays, and direct single top production $qg \rightarrow t$) with the ATLAS detector [14] at the LHC [15] and its

Process	\mathbf{SM}	QS	2HDM	FC 2 HDM	MSSM	R SUSY	TC2	RS
$t \to qZ$	$\sim 10^{-14}$	$\sim 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$\sim 10^{-6}$	$\sim 10^{-5}$	$\sim 10^{-4}$	$\sim 10^{-5}$
$t \to q\gamma$	$\sim 10^{-14}$	$\sim 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-6}$	$\sim 10^{-6}$	$\sim 10^{-9}$
$t \rightarrow qg$	$\sim 10^{-12}$	$\sim 10^{-7}$	$\sim 10^{-4}$	$\sim 10^{-8}$	$\sim 10^{-5}$	$\sim 10^{-4}$	$\sim 10^{-4}$	$\sim 10^{-9}$
$t \rightarrow qH$	$\sim 10^{-15}$	$\sim 10^{-5}$	$\sim 10^{-3}$	$\sim 10^{-5}$	$\sim 10^{-5}$	$\sim 10^{-6}$		

Table 1: FCNC decays branching ratios of several SM extension. See text for references.

	LEP	HERA	Tevatron	LHC
$BR(t \to q\gamma)$	2.4% [5, 6, 7, 8, 9]	$0.47\% (tu\gamma) [10]$	3.2% [11]	
$BR(t \to qZ)$	$7.8\% \left[5, 6, 7, 8, 9 ight]$	$30\% \; (tuZ) [10]$	3.2%[12]	0.07%[13]

Table 2: Present experimental 95% CL upper limits on the branching fractions of the FCNC top quark decay channels.

sensitivity within the High Luminosity LHC (HL-LHC) at 3000 fb⁻¹ for the decays $t \to qZ$ and $t \to q\gamma$ are presented.

The qZ analysis [16] is performed on data collected in pp collisions during 2011 at the LHC, corresponding to an integrated luminosity of 2.1 fb⁻¹ at a centre-of-mass energy of $\sqrt{s} = 7$ TeV. Only leptonic decays from Z and W are considered leading to a final topology with three isolated leptons, two jets (from the light quark and the b quark) and missing transverse energy from the undetected neutrino. Leptons are selected either using the full ATLAS identification criteria (ID) or using high quality inner detector track (TL) and events were divided into events with three ID leptons (3ID) or two ID leptons and one TL (2ID+TL). In a pre-selection exactly three leptons are required with two of them being reconstructed within 15 GeV of the Z boson mass. At the final selection at least two jets are required and $E_T^{\text{miss}} > 20$ GeV. Since the neutrino longitudinal momentum is unknown, the event kinematics is determined by minimising a χ^2 function. After the reconstruction, 40 GeV and 30 GeV window mass cuts around the top quark and W boson masses are applied, respectively. Table 3 shows the number of events after the final selection. No evidence for the $t \to qZ$ decay mode was found and upper limits at 95% CL on the number of signal events were derived using the modified frequentist likelihood method (CLs). In pseudo-experiments the expected event numbers are fluctuated according to Poisson distributions. All statistical and systematic uncertainties of the expected backgrounds and signal efficiencies were taken into account. The limits on the number of signal events were converted into upper limits on the corresponding BRs using the approximate NNLO calculation [17] and its uncertainty for the $t\bar{t}$ cross section, and constraining $BR(t \to Wb) = 1 - BR(t \to Zq)$. The observed upper limit at 95% CL on the FCNC $t \to Zq$ BR is 0.73%, after combining the 3ID and 2ID+TL results.

The $qg \rightarrow t$ analysis [18], is performed on data collected in 2012, corresponding to an inte-

	3ID	2ID+TL
	51D	21D 1 L
ZZ, WZ	9.5 ± 4.4	$1.0\pm^{0.5}_{0.6}$
ttW, ttZ	0.51 ± 0.14	0.25 ± 0.05
$t\bar{t}, WW$	0.07 ± 0.02	
Z+jets	1.7 ± 0.7	7.6 ± 2.2
Single top	0.01 ± 0.01	1.0 ± 2.2
2+3 fake leptons	$0.0\pm^{0.2}_{0.0}$	
Total bckg	11.8 ± 4.4	8.9 ± 2.3
Data	8	8
Signal efficiency (%)	0.205 ± 0.024	0.045 ± 0.007

Table 3: Number of events after the final selection [16].

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grated luminosity of 14.2 fb⁻¹ at 8 TeV. FCNC $t \to qg/qg \to t$ is searched for in the production of single top-quark events, since the corresponding decay is nearly indistinguishable from the multijet background that arises from QCD processes. Again, only leptonic W boson decays are used leading to a final state topology with a single jet, a single lepton and missing transverse energy $(qg \rightarrow t \rightarrow b\ell\nu)$. The event selection requires exactly one electron or muon, one jet that is b-tagged and $E_T^{\text{miss}} > 30$ GeV. To reduce multijet background events, characterised by low E_T^{miss} and low $m_T(W)$, the event selection requires $m_T(W) > 50$ GeV. The analysis defines a signal and a control region both requiring the preselection and one tagged jet. Events in the signal region have jets tagged by the default tagger with a tagging efficiency of 50%. The events in the control region have jets tagged with a less stringent tagger and a looser working point with a tagging efficiency of 85% and vetoing events from the signal region. This control region ensures the resulting sample is dominated by W+ jets. To provide sufficient discrimination between signal and background a neural-network method is used. All possible discriminating variables such as momenta, relative angles, pseudorapidity, reconstructed particles masses and lepton electric charge are explored. To reconstruct the neutrino momenta, a constraint on the invariant mass of the lepton and the neutrino to the W mass is imposed, $(p_W)^2 = (p_\ell + p_\nu)^2 = m_W^2 = (80.4 \text{ GeV})^2$, and the solution with the smaller $|p_\nu^z|$ is chosen. The resulting neural network output distributions for the various processes in the control region and signal region are shown in Figure 2. No evidence of FCNC single top-quark production is found and the upper limit at 95% CL on the production cross section is 2.5 pb. Using the NLO predictions for the FCNC single top-quark production cross-section and assuming $BR(t \to Wb) = 1$, the measured upper limit on the production cross-section is converted into limits on the coupling constants which in turn can be converted into limits on the branching fractions: $BR(t \rightarrow ug) < 3.1 \times 10^{-5}$ and $BR(t \rightarrow cg) < 1.6 \times 10^{-4}$.

For the $t \to cH$ analysis [19], 20 fb⁻¹ of 8 TeV and 5 fb⁻¹ of 7 TeV data collected by the ATLAS experiment were analysed. Both hadronic and leptonic decays of the W boson were



Figure 2: Neural-network output distributions for (a) the signal region and (b) the control region, in the $qg \rightarrow t$ analysis [18].

considered with the Higgs boson decaying to $\gamma\gamma$. The event selection is divided into candidates which contain exactly one lepton (leptonic analysis) and events having no leptons (fully hadronic analysis). Events with two or more leptons are rejected. At 7 TeV all events were processed through the fully hadronic analysis, independently of the number of leptons. Since the leptonic fraction at 8 TeV is of the order of 2%, the impact at 7 TeV is expected to be very small. The analysis is conducted in three steps. First, diphoton candidates are selected on the basis of photon information only. Second, for the hadronic final state, events are required to have at least four jets. Once four jets are selected, four combinations of pairs $(m_{\gamma\gamma j}, m_{jjj})$ using the three jets are formed, and only combinations with $m_{\gamma\gamma i}$ and m_{iji} within [156,191] GeV and [130,210] GeV, respectively, and with a b-tagged jet are accepted. For the lepton analysis events are required to have one lepton, two or more jets and $E_T^{\text{miss}} > 30$ GeV. The two possible pairs are considered. The momentum of the neutrino, required for the reconstructed mass of $m_{\ell\nu i}$, is estimated using the W boson mass constraint. The mass windows are [156,191] GeV for $m_{\gamma\gamma i}$, as before, and [135,205] GeV for $m_{\ell\nu j}$. Again, the event is selected if one b-tagged jet is present. In the last step, the background events are estimated from the diphoton mass distribution using a sideband technique and the signal events are obtained by subtracting the backgrounds from the data events. A maximum likelihood fit using the product of the likelihoods for the search channels has been performed on the selected data sample, consisting of 50 events in the hadronic channel (7 + 43 at 7 and 8 TeV respectively) and one event in the leptonic channel. The diphoton mass spectrum in the hadronic channel is shown in Figure 3(a), together with the fitted background shape and the signal shape for a Higgs boson mass fixed at 126.8 GeV. No evidence for a signal is found and a limit on $BR(t \to cH)$ is set. The evolution of the signal confidence level CLs as a function of BR is shown in Figure 3(b) for the same Higgs boson mass. Pseudo-experiments have been used to determine the distributions of the test-statistic under the signal+background and the background only hypotheses. The observed (expected) limit on BR is 0.83% (0.53%) at the 95% confidence level.

Foreseen for the early 2020's is an upgrade of the LHC accelerator and detectors to handle luminosities of $\sim 5 \times 10^{34}$ cm⁻²s⁻¹ (HL-LHC operation [20]), and a total integrated luminosity



Figure 3: Relevant distributions for the $t \to cH$ analysis [19]: (a) the distribution of $m_{\gamma\gamma}$ for the selected sample in the hadronic channel and (b) the evolution of CLs as a function of BR for the observation (full line) and the expectation in the absence of signal (dashed line), together with the 1σ and 2σ bands around the expected curve.

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Figure 4: The present 95% CL observed limits, as well as the expected ATLAS sensitivity. For the $t \to qZ$ and $t \to q\gamma$ channel [20].

of 3 ab^{-1} is expected to be reached. The sensitivity for the FCNC decays at the HL-LHC is evaluated by extrapolation from the numbers at 7 TeV. For the $t \to \gamma q$ channel, the dominant backgrounds are $t\bar{t}$, Z+jets and W+jets events. For the $t \to Zq$ channel, the background is mainly composed of $t\bar{t}$, Z+jets and WZ events. In the absence of FCNC decays, limits on production cross-sections are evaluated and converted to limits on BRs using the SM $t\bar{t}$ cross section. The HL-LHC expected limits at 95% CL for the $t \to q\gamma$ and the $t \to qZ$ channels are in the range between 10^{-5} and 10^{-4} [20]. Figure 4 shows the present 95% CL observed limits on the BR($t \to q\gamma$) vs. BR($t \to qZ$) plane as full lines for the LEP, ZEUS, H1, D0, CDF, ATLAS and CMS collaborations. The expected sensitivity at ATLAS is also represented by the dashed lines. Limits are represented for an integrated luminosity of L = 3 ab^{-1} and L = 300 fb⁻¹.

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Tau (or no) leptons in top quark decays at hadron colliders

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Measurements in the final states with taus or with no-leptons are among the most challenging as they are those with the smallest signal-to-background ratio. However, these final states are of particular interest as they can be important probes of new physics. Tau identification techniques and cross section measurements in top quark decays in these final states are discussed. The results, limited by systematical uncertainties, are consistent with standard model predictions, and are used to set stringent limits on new physics searches. The large data samples available at the Fermilab and at the Large Hadron Collider may help further improving the measurements.

1 Introduction

Many years after its discovery [1, 2], the top quark still plays a fundamental role in the program of particle physics. The study of its properties has been extensively carried out in high energy hadron collisions. The production cross section has been measured in many different final states. Deviation of the cross section from the predicted standard model (SM) value may indicate new physics processes. Top quarks are predominantly produced in pairs, and in each top quark pair event, there are two W bosons and two bottom quarks. From the experimental point of view, top quark pair events are classified according to the decay mode of the two W bosons: the all-hadronic final state, in which both W bosons decay into quarks, the "lepton+jet" final state, in which one W decays leptonically and the other to quarks, and the dilepton final state, in which both W bosons decay leptonically. The word "lepton" here refers to electrons and muons, whereas τ s are generally treated separately. When talking about τ s, we are referring to hadronic tau decays, τ_h . At the moment, the case where the τ s decay to leptons cannot be distinguished experimentally from prompt electrons or muons.

Cross section measurements have been performed both at the Tevatron and at the LHC and the accuracy of the experimental results rivals that of theory expectations [3]. After the first few years of proton-proton collisions for the first data-taking period at the LHC energies of 7 TeV (in 2010 and 2011) and 8 TeV (in 2012), thousands of top quark events have already been reconstructed and selected. Measurements of the inclusive top quark pair production cross section have been performed at the LHC in the dilepton and lepton+jet channels using electrons and muons and provide the most precise results; most of the results obtained are limited by systematic uncertainties.

Here, we will address the final states with τ s or with no leptons. Since the first measurement

using hadronic tau decays at a hadron collider [4], tau identification techniques have improved thanks to more sophisticated particle detectors, to advanced reconstruction algorithms, and to much increased data samples. The selection and the study of these final states continues to be challenging as they are those with the smallest signal-to-background ratio. However, these decay modes are potentially interesting on their own as their branching ratios are large and could signal the presence of new physics. As an example, the $t\bar{t}$ "tau dilepton" decay mode containing one τ (in which one W decays to an electron or a muon, and the other to a τ) has a similar branching fraction to the "standard" dilepton final states with electrons and muons. As the τ s are heavier than electrons or muons, their coupling to new physics processes could be enhanced. The case of the all-hadronic final state is more complicated, as the backgrounds are even larger. However, despite the large backgrounds, measurements have also been performed in this final state with reasonable precision. The measurement in the all-hadronic final state is complementary to other measurements and is interesting in its own right.

2 Tau and *b*-jet identification

Identification of τ s and *b*-jets is not only essential in providing the necessary tools to study the final states with τ s or no leptons, but also important because an efficient *b*-jet identification can suppress the large backgrounds and isolate the signal sought of these final states.

2.1 Tau identification

At hadron colliders various important processes involve the emission of high- p_T electrons and muons. Examples are W, Z, and top quark production. Collider detectors have specialized in detecting electrons and muons from these events. On the other hand, τ leptons decay predominantly into charged and neutral pions and suffer from large backgrounds from jet production, and are more difficult to signal. Hadronic tau decays produce narrow and more collimated jets when compared to quark or gluon jets. Since the first attempts to detect taus at a hadron collider [4], the performance of tau lepton reconstruction and identification algorithms have improved thanks more refined particle detectors, and to sophisticated techniques/algorithms yielding an improved understanding of the data. Overall, signal efficiencies and background rejection have improved.

Tau leptons decay promptly either to lighter leptons or to hadronic jets. The hadronic and leptonic branching fractions are $\mathcal{B}(\tau \to h\tau_{\nu}) \simeq 64\%$ (50% one-prong, and 14% three-prong decays) and $\mathcal{B}(\tau \to \ell \nu_{\ell} \nu_{\tau}) \simeq 36\%$, respectively. Tau leptons that decay into one or three charged hadrons are identified using final-state particles reconstructed in the tracker and in the calorimeters, both electromagnetic and hadronic. In order to reduce the contamination from quark and gluon jets, it is required that the τ candidate is isolated around the reconstructed τ momentum direction. Alternative identification methods are used to discriminate tau leptons from QCD jets or other backgrounds. Either cut-based discriminants, particle-flow (PF), or boosted decision tree (BDT) algorithms are used [5, 6]. As an example, the τ reconstruction is seeded by considering each jet as a tau candidate; a list of identification variable calculated from the tracking and calorimeter information are then combined into multivariate discriminants to reject misidentified QCD jets and electrons or muons. Finally, the number of τ leptons in the selected samples is extracted by fitting the distributions of BDT outputs to background and signal templates [6]. Alternatively, the algorithms use decay mode identification techniques and hadronic τ decays are reconstructed starting with the clustering of all PF particles into jets [5]. For each jet, a charged hadron is combined with other nearby charged hadrons or photons to identify the decay modes. The identification of π^0 mesons is enhanced by clustering electrons and photons in "strips" along the bending plane to take into account possible broadening of calorimeter signatures by early showering photons. Then, strips and charged hadrons are combined to reconstruct the following combinations: single hadron, hadron plus a strip, hadron plus two strips and three hadrons. Tau energy scale is derived using *in situ* calibration based on the $Z \to \tau \tau$ peak position. Overall, the τ identification algorithms efficiently discriminate against potentially large backgrounds from quarks and gluons that occasionally hadronize into jets of low particle multiplicity. The reconstruction efficiency of the algorithms is measured using tau leptons produced in Z-boson decays. The tau lepton misidentification rates for jets and electrons are also determined from multijet data samples. Tau identification efficiencies of 60–70% are obtained with a few percent ($\simeq 1-2\%$) background contamination due to "fakes", i.e. where a jet is misidentified as a tau.

Some forms of tau identification have been implemented at the trigger level. However, requiring one tau alone may not be sufficient to reduce the trigger rates or to collect a tauenriched sample of events to study a given final state and, wherever possible, the tau trigger is used in combination with other objects, such as electrons or muons, or jets, or other specific event topologies. Alternatively, inclusive electron or muon or multi jet triggers are used, and the tau lepton is only selected "offline".

2.2 *b*-jet identification

Top quark pair events contain at least two jets from the hadronization of *b*-quarks from the $t \rightarrow Wb$ decays. In order to select top quark events, *b*-jet identification is therefore important, as it can be used as an additional suppression of non- $t\bar{t}$ backgrounds. All experiments use multivariate techniques combining information from lifetime (displaced tracks and/or vertices), mass (associated to the secondary vertex), decay chain reconstruction, in order to discriminate *b*-jets from *c*- and light-flavor (i.e. u, d, s, g) jets. Several alternative algorithms have been developed. The efficiency of the algorithms is measured in multijet events where a muon is reconstructed inside a jet, or are calibrated in other data samples. For jets originating from the hadronization of light-flavor jets, the misidentification efficiency is estimated using the distribution of the negative tags in jet samples, i.e. those resulting from tracks produced upstream with respect to the primary interaction vertex. A typical performance is obtained with a *b*-tagging efficiency of approximately 70%, and a fake rate from light-flavor jets of $\simeq 1\%$ [7].

3 Taus in top quark decays

Besides the final states with electrons and muons in the "dilepton" or "lepton+jet" final states, measurements are also performed in the final states containing at least one tau, i.e. "tau+lepton" and "tau+jets". The interest of determining the cross section in these channels is mainly to check the consistency of the measurements with the results from the other final states. Abnormal rates of taus with respect to the SM predictions can be an important manifestation of new physics. For example, the existence of a charged Higgs with a mass smaller than the top quark mass $m_H < m_t$ could give rise to anomalous tau lepton production directly observable in these decay channels, via $t \to H^+b$. A $t\bar{t}$ cross section measurement in the final

state with taus makes it possible to probe flavor-dependent effects in top quark decays. Other possible non-SM processes that can enhance the top-quark-to- τ -lepton branching fraction are R-parity violating decays of the top quark in supersymmetric models [8] and new Z' bosons with non-universal couplings [9]. Furthermore, the $t \to (\tau \nu_{\tau})b$ decay exclusively involves third generation leptons and quarks, and directly probes interactions between members of the third generation family.

3.1 Tau+lepton channel

Among the final states including taus is the $t\bar{t}$ "tau dilepton" channel, i.e. where one W boson decays into $e\nu$ or $\mu\nu$ and the other into the hadronically decaying τ lepton and ν_{τ} , in the final state $t\bar{t} \to (\ell\nu_{\ell})(\tau_{h}\nu_{\tau})bb$, where $\ell = e, \mu$. The expected fraction of events of the τ dilepton channel is approximately 5% (4/81) of all $t\bar{t}$ decays, i.e. similar to the fraction of the "light" dilepton channels (ee, $\mu\mu$, $e\mu$) which is equal to 4/81 of all $t\bar{t}$ decays. Events are selected with one W decaying to a charged lepton (either an electron or a muon, either prompt or from a τ leptonic decay) and a neutrino, and the other W decaying to a τ lepton and a neutrino with the τ lepton in turn decaying hadronically, τ_h . In addition, at least one jet is tagged (b-tag) as originating from a b quark (b-jet) by means of an algorithm that can identify b-jets with "high" efficiency while maintaining a good rejection of light-quark jets. Missing transverse momentum is also required, signaling the presence of energetic neutrinos. After the final event selection, the largest background contributions come from events where one W boson is produced in association with jets, and from $t\bar{t} \to W^+ bW^- \bar{b} \to (\ell \nu_\ell b)(qq'\bar{b})$ events, where one jet is misidentified as the τ_h . This large background is estimated using control data samples by determining the τ misidentification probabilities in jet-dominated samples (these are orthogonal to the samples of selected events and are used to determine the "per-jet" τ misidentification probability); the misidentification rates are then applied to every jet in the $W + \geq 3$ jet sample of selected events [10]; alternatively, in order to determine the background contribution it can be exploited the fact that events with lepton and τ candidates with electric charge of opposite sign (OS) contain real τ leptons while those with same sign (SS) charge are pure background [11]. The top quark pair production cross section is measured in dilepton events with one electron or muon, and one hadronically decaying τ lepton from the decay $t\bar{t} \to (\ell \nu_{\ell})(\tau_h \nu_{\tau})bb$, (with $\ell =$ e, μ [10, 11]. The measured cross section in this channel is consistent with the value measured in the other final states, and the total uncertainty of approximately 13-18% is dominated by systematics. The limiting sources of uncertainty come from the determination of the τ -fake determination and from the b-tagging efficiency uncertainties. These results are used to set stringent limits on charged Higgs production [12, 13, 14].

The top quark pair production and decay into leptons with at least one hadronically decaying τ lepton is also studied at the Tevatron proton-antiproton collider at Fermilab. The top quark pair production cross section at 1.96 TeV is measured together with the top branching ratio into τ lepton, $\mathcal{B}(t \to \tau \nu_{\tau} b)$ [15]. Furthermore, in order to discriminate the signature of the tau+lepton decay from the di-tau processes and perform a measurement of the branching ratio of top quark decay in tau, a second log-likelihood ratio discriminant method is implemented to separate the two processes. Measurements are in good agreement with the expectations of the SM (and with lepton universality) within the experimental uncertainties, and with the results obtained using other decay channels of the top quark at the Tevatron. Due to the smaller production cross section at the Tevatron, the results are limited by statistical uncertainties, and the total uncertainty is approximately 30%.

3.2 Tau+jets channel

The top quark pair production cross section in the final state with one hadronically decaying tau lepton together with additional jets is also measured. The tau+jets final state, i.e. $t\bar{t} \rightarrow$ $(\tau_h \nu_\tau b)(q\bar{q}b)$ is expected to be the largest ($\simeq 15\%$) among those with τ leptons in the final state, but it also has large background contributions. At the LHC, data for this measurement are collected either with a dedicated b-jet or with a multijet trigger, depending on the analysis. The trigger efficiencies have been measured in data, determining separately the efficiency of a single jet and a single τ_h to pass the trigger requirements. Events with at least four (or five) jets are selected, where one (or two) of the jets are identified as having originated from b quarks. One hadronically decaying tau is selected, exploiting tight identification criteria to best suppress the large multijet backgrounds. The presence of any additional lepton is vetoed. Given the small expected signal over the background ratio, a neural network has been developed to separate the top quark pair signal from the W+jets and multijet backgrounds. The multijet background is estimated from data by using the same selection as the preselected sample except that a veto is applied on the presence of a b-tagged jet. A set of different variables is used to build the neural network discriminator. In order to reduce the uncertainties, the full discriminator output is fit with a likelihood in order to extract the signal and background yields [16]. Alternatively, the τ_h contribution is separated from quark- or gluon-initiated jets with a one-dimensional fit to the distribution of the number of tracks (n_{tracks}) associated with the τ_h candidate. Since the τ_h decays preferentially to one or three charged particles (and other neutral decay products), this variable provides good separation between hadronically decaying tau leptons and jets, as the latter typically produce a large number of charged particles. To extract the signal from the $n_{\rm tracks}$ distribution, the data sample is fitted with three probability density functions (templates): a tau/electron template, a gluon-jet template and a quark-jet template. The electron and τ_h templates are combined into a single tau/electron template, using Monte Carlo predictions to determine their relative contributions. The tau/electron template is obtained from simulated $t\bar{t}$ events. The remaining significant contributions come from mis-identified jets, and are separated into two templates: the gluon-jet template describes the QCD multijet processes which are dominated by gluon-initiated jets, and the quark-jet template describes the remaining processes ($t\bar{t}$, single- top quark and W + jets) that are enriched in quark-initiated jets. They are both determined from data, from a control region of the multijet sample (gluon-jet template) and from a $t\bar{t}$ control sample (for the quark-jet template). A binned likelihood is used to extract the different contributions from the n_{tracks} distribution [17]. The main backgrounds come from multijet events, $t\bar{t}$ events with a different final state or signal events where the wrong jet is chosen as the τ_h candidate. A small contribution from single-top, and W + jets events is also present. Dominant sources of systematic uncertainties are due to tau identification, jet energy scale, and initial- and final-state radiation jets. The cross section measurements are consistent with SM predictions, and the total uncertainty (dominated by systematics) is approximately 21% [16] and 25% [17].

At the Tevatron the $t\bar{t}$ cross section $\sigma_{t\bar{t}}$, and the top quark mass m_{top} are also measured in this final state. A neural network is used to reduce the large QCD multijet background contribution. A binned likelihood fit based on the predicted and observed number of events is used to measure $\sigma_{t\bar{t}}$ [18, 19]. Then, to extract the top quark mass m_{top} , a likelihood function built from signal and background probabilities is used [18]. The cross section measurement is combined using all measured $t\bar{t}$ channels with leptons in the final state (τ_h +jets, e/μ +jets, "light" dileptons), and repeat the negative log-likelihood fit for the number of $t\bar{t}$ signal and multijet background events by fixing the $t\bar{t}$ branching fractions to their SM values, but this time fit for all $t\bar{t}$ channels simultaneously [19]. Furthermore, the cross section times the branching fraction, $\sigma_{t\bar{t}} \times \mathcal{B}_{t\bar{t}\to\tau_h+\text{jets}}$, is also measured. The cross section measurements are limited by statistical uncertainties, as only a handful of events are selected at the Tevatron.

4 All hadronic final state

The all-hadronic final state $(t\bar{t} \to W^+ b W^- \bar{b} \to 6 \text{ jets})$ is the most common with a branching fraction $\mathcal{B}_{t\bar{t}\to all-hadronic} \simeq 46\%$, but it competes with very high backgrounds from QCD multijet events. This final state, where both W bosons decay hadronically, is characterized by a six-jet topology. As an example, the cross sections for this QCD process at the Tevatron is higher than the top cross section by approximately three orders of magnitude. Despite the extremely high background levels, it is possible to isolate a top quark signal in this mode after applying further kinematical cuts and identifying the b quark(s) in the final state. Furthermore, it does not suffer from the presence of neutrinos of large transverse momentum p_T that escape detection. Events are selected with a multijet trigger and are required to have two reconstructed jets tagged as b-jets to identify $t\bar{t}$ event candidates. In addition, kinematical and topological characteristics are also exploited. The all-hadronic $t\bar{t}$ channel nominally has six jets and does not contain intrinsic missing transverse momentum (E_T^{miss}) or isolated leptons in the final state. Therefore, a veto against the presence of isolated leptons and significant E_T^{miss} is applied. After the event selection, a kinematic fit is performed to compute the top quark mass in the selected events. The kinematic fit is based on a likelihood approach to find the correct association of jets with the final state partons of the fully hadronic $t\bar{t}$ decays. The requirement of b-jets in the event selection reduces the combinatorics in the jet-parton assignment. In the mass distribution, the number of $t\bar{t}$ events remaining after the final selection is determined through an unbinned maximum likelihood fit of contributions from $t\bar{t}$ signal and multijet background. The results correspond to a signal fraction of approximately 31% [21] and 35% [20]. The cross section measurements in this channel are consistent with the other measurements in dilepton and lepton+jets final states, as well as with the predictions of the SM. The measurements have a total uncertainty of 20% [20] and 37% [21]. Dominant sources of uncertainty are the jet energy scale, and the b-tagging and mistagging rates on the efficiency of the event selection.

5 Summary

Measurements in the final states with taus or no leptons are some of the most challenging to be performed in top quark physics but are certainly possible. Since the first measurements, the much larger number of selected events has allowed for an improved understanding of these final states. Some of the latest and most relevant measurements have been presented and discussed. The precision of the measurements achieved both at the Tevatron and in the first few years of operation at the Large Hadron Collider have demonstrated a good understanding of the data, and have shown good consistency with expectations. Results are limited by systematical uncertainties and, with some optimism, it is natural to expect in the years to come further improvements in the understanding of these final states.

In conclusion, we have learned that, however difficult, tau detection is possible at hadron collider experiments. Taus can extend the sensitivity in searches for both known and "new" physics. Hadron colliders have an enormous discovery potential and new physics can show up

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as an excess of tau production. It is essential that detector upgrades and new detector designs consider tau detection as an additional handle to new physics searches.



Figure 1: A day without rain in the vineyard.

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Inclusive single top cross section at the LHC

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The three single-top-quark production modes are presented. The t-channel, established at the Tevatron, has the highest production rate and its cross-section has been measured at the LHC at 7 and 8 TeV. Evidence of the tW associated production was presented with 7 TeV data by ATLAS and CMS and observation was achieved at 8 TeV by the CMS experiment. An upper limit on the s-channel cross-section was set with 7 TeV data by ATLAS.

1 Introduction

At hadron colliders, top quarks are mostly produced in pairs via strong interaction. Top quarks can also be produced singly, via electroweak interaction involving a tWb vertex. The three modes of single top production are: t-channel, tW associated production and s-channel. While



Figure 1: Leading order (LO) diagrams for single top production: t-channel (Left), tW associated production (Center), and s-channel (Right).

the t-channel was established by the Tevatron experiments, the tW associated production can only be studied at the LHC.

Single top processes are interesting for many reasons. They are sensitive to many models of new physics affecting the Wtb vertex like Flavor Changing Neutral Currents (FCNC) and Anomalous couplings; or involving new particles, like W' or charged Higgs bosons. They also provide a complementary scenario in which to perform Standard Model (SM) measurements like top polarization, W helicity fractions, top mass, or the CKM matrix element $|V_{tb}|$. Finally they are also background to different searches. In the following, measurements of the inclusive cross-section of the t-channel and tW associated production are presented, as well as the first approach to the study of the s-channel, at the LHC experiments, ATLAS and CMS.

2 t-channel

The t-channel production is the mode with the highest cross-section at the LHC. ATLAS and CMS have studied the process at 7 and 8 TeV. The signal events are characterized by a leptonic decay of a top quark: one isolated lepton, electron or muon, missing transverse energy (MET) due to the neutrino and a central jet coming from a b decay; and an additional light-quark jet from the hard scattering process that is often forward. A second b-jet, produced in association to the top quark, can be present as well, but leading a softer p_T spectrum with respect to the b-jet from the top decay. The main backgrounds to this signature are W+jets production, $t\bar{t}$, and multijet events.

2.1 Cross-section at $\sqrt{s} = 7$ TeV

With the data delivered by the LHC at a center of mass energy of 7 TeV, ATLAS and CMS measure the t-channel cross-section. ATLAS performs an analysis based on a Neural Network (NN), using $1.04fb^{-1}$ of integrated luminosity [1]; while CMS carries out three different analyses [2]: one based on a NN, another based on a Boosted Decision Tree (BDT), and finally an analysis that uses the kinematic distribution of the pseudorapidity of the recoiling jet, $|\eta_{j'}|$. The integrated luminosity used by CMS is $1.17fb^{-1}$ in the μ final state and $1.56fb^{-1}$ in the e final state.

The object selection is similar in both cases. In ATLAS muons (electrons) are required to be isolated and with a p_T (E_T) > 25 GeV and $|\eta| < 2.5$ (2.47); similarly, in CMS they are required to have a $p_T > 20$ (30) GeV and $|\eta| < 2.1$ (2.5). Jets are reconstructed using the anti k_t algorithm with a parameter size of 0.4 (0.3) in ATLAS (CMS). The ATLAS measurement selects jets with $p_T > 25$ GeV and $|\eta| < 4.5$; the CMS experiment selects jets with $p_T > 30$ GeV and $|\eta| < 4.5$. Both experiments use b-tag algorithms to identify jets coming from b-decays.

Events are selected if they have exactly one isolated lepton (e or μ) and at least 2 jets. ATLAS uses events with exactly 2 or 3 jets, that define either the signal region, if one them is b-tagged, or the 'pre-tagged' sample, used as control region if no b-tag is applied. CMS makes use of several N_{jet} - M_{b-tag} regions: the NN and BDT analyses are performed on the 2jet-1tag and 3jet-1tag regions, but more regions (4jet-1tag, 2jet-2tag, 3jet-2tag, and 4jet-2tag) are included in the statistical fit to constrain nuisance parameters. The $|\eta_{j'}|$ analysis on the other hand, uses the 2jet-1tag, further separated using the invariant mass of the lepton, the jet and the neutrino, $m_{l\nu b}$, into 'signal region' (130 < $m_{l\nu b}$ < 220 GeV) and 'sideband region' (outside the signal region).

To reduce the contribution of multijet processes, ATLAS requires that MET > 25 GeV and that the transverse mass of the W boson, $m_T(W)$, built using the lepton and MET of the event, fulfills that $m_T(W) > (60 - MET)$. CMS requires $m_T(W) > 40$ GeV in the μ channel and for final states with electrons, MET > 40 GeV instead.

The optimal simulation of the multijet processes with enough statistics is complex, and therefore the estimation of this background is carried out in a data-driven way. A maximum likelihood fit is applied to the MET distribution (or the $m_T(W)$ for the μ channel in CMS) with templates obtained from data, either inverting the isolation criteria (CMS, μ channel), requiring the events to fail some conditions on the lepton selection (CMS, e channel), or replacing the electron by a jet. The latter is referred to as 'jet-electron model' and it is used in ATLAS in all the final states. Another important background is the W+jets production. For this background, the analysis carried out by ATLAS uses the shape of the distributions from simulation and

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derived the normalization from data. CMS estimates this background in the $|\eta_{j'}|$ analysis, from the sideband to the signal region. Simulation is used for the remaining backgrounds.

For the ATLAS measurement, the t-channel cross-section is obtained performing a maximum likelihood fit to the shape of the NN discriminant, that is built using 12 variables for events with exactly 2 jets and 18 variables for the events with 3 jets, the most discriminant being $m_{l\nu b}$ and $m_{j_1j_2}$. In the case of CMS, the statistical fit uses either the shape of the NN, built with 37 or 38 variables (μ or e final state); or the BDT discriminant, that uses 11 variables; or the shape of the $|\eta_{j'}|$ distribution inside the signal region. All the possible sources of systematic uncertainty are taken into account in each case. For ATLAS, the main systematic uncertainty comes from the initial and final state radiation (ISR/FSR) and the b-tagging; while for CMS are b-tagging, background estimations and generators. ATLAS measures a single top t-channel



Figure 2: Distributions of the NN output for the 2-jet b-tagged sample in ATLAS (Left), and BDT discriminator output in the muon channel for the '2-jets 1-btag' region in CMS (Right).

inclusive cross-section of:

$$\sigma_{t-channel}^{ATLAS} = 83 \pm 4(stat)_{-19}^{+20}(syst) \ pb = 83 \pm 20 \ pb \tag{1}$$

CMS has results in each analysis that are combined into:

$$\sigma_{t-channel}^{CMS} = 67.2 \pm 3.7(stat) \pm 3.0(syst) \pm 3.5(th) \pm 1.5(lumi) \ pb = 67.2 \pm 6.1 \ pb \qquad (2)$$

The measured values are in agreement within uncertainties with the SM expectation for this channel:

$$\sigma_{t-channel}^{th} = 65.9^{+2.1}_{-0.7}(scale)^{+1.5}_{-1.7}(pdf) \ pb = 65.9^{+2.4}_{-1.9} \ pb \tag{3}$$

estimated at approximate NNLO derived from NNLL resummation [3]. From the t-channel cross-section a value of the CKM matrix element $|V_{tb}|$ can be extracted as $|V_{tb}| = \sqrt{\sigma^{exp.}/\sigma^{th.}}$. ATLAS measures a $|V_{tb}|$ value of $1.13^{+0.14}_{-0.13}$, and CMS measures $|V_{tb}| = 1.020 \pm 0.046 \pm 0.017$; assuming unitarity of the CKM matrix ($|V_{tb}| \le 1$), the values are $|V_{tb}| > 0.75$ and $|V_{tb}| > 0.92$ respectively for ATLAS and CMS at 95% CL.

2.2 Charge ratio at $\sqrt{s} = 7$ TeV

Since the density of 'u' quarks in the proton is about twice as the density of 'd' quarks, the production cross-section of single t quarks is expected to be also twice as large as the production cross-section for single \bar{t} quarks. Therefore, the experimental study of the charge ratio $R = \sigma_t / \sigma_{\bar{t}}$ is interesting to understand the internal structure of the proton. At 7 TeV, ATLAS measures the t-channel charge ratio using 4.71 fb^{-1} of integrated luminosity [4]. The analysis is based on [1], with some modifications. The same objects are used, though forwards jets are now selected if they have $p_T > 50$ GeV. The event selection applies slightly different kinematic requirements: the MET threshold is raised to 30 GeV and the triangular cut on $m_T(W)$ is substituted by $m_T(W) > 30$ GeV. The multijet background is estimated in the same way as in the inclusive cross-section analysis, while the W+jets contribution is estimated using simulation with the different flavor fractions normalized from data. The analysis uses a NN, built using 15 variables in the 2 jet bin and 19 in the 3 jet bin. The training is done in 4 channels: the two regions defined by the jet content, separated by the charge of the lepton $(l^+ \text{ or } l^-)$.

A maximum likelihood fit to the NN is performed, with the following results:

$$\sigma_t = 53.2 \pm 1.7(stat) \pm 10.6(syst) \ pb = 53.2 \pm 10.8 \ pb \tag{4}$$

$$\sigma_{\bar{t}} = 29.5 \pm 1.5(stat) \pm 7.3(syst) \ pb = 29.5^{+7.4}_{-7.5} \ pb \tag{5}$$

in agreement with the SM expectation of $\sigma_t = 43.0^{+1.6}_{-0.2} \pm 0.8 \ pb$ and $\sigma_{\bar{t}} = 22.9 \pm 0.5^{+0.7}_{-0.9} \ pb$ [3]. The measured charge ratio is therefore:

$$R = 1.81 \pm 0.10(stat)^{+0.21}_{-0.20}(syst) = 1.81^{+0.23}_{-0.22} \tag{6}$$

presented in Figure 3 compared to the values obtained from different next-to-leading order (NLO) pdf sets.



Figure 3: Calculated charge ratio values for different NLO PDF sets.

2.3 Cross-section at $\sqrt{s} = 8$ TeV

At a center of mass energy of 8 TeV, ATLAS and CMS measure the t-channel production crosssection. ATLAS performs a NN analysis using 5.8 fb^{-1} of integrated luminosity [5]. CMS uses

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the shape of the $|\eta_{i'}|$ distribution, using only final states with muons and 5.0 fb^{-1} [6].

In ATLAS muons (Electrons) are required to be isolated and with a p_T (E_T) > 25 GeV and $|\eta| < 2.5$ (2.47). Muons in CMS are required to have a $p_T > 26$ GeV and $|\eta| < 2.1$. The ATLAS (CMS) analysis selects jets with $p_T > 30$ (60) GeV and $|\eta| < 4.5$.

The analysis at 8 TeV follows the same scheme as at 7 TeV. ATLAS performs the same kinematic cuts as in the charge ratio analysis, raising the $m_T(W)$ threshold to 50GeV. The signal region is defined by events with exactly 2 or 3 jets, one of them b-tagged; and loose b-tag requirements are used to define control regions. CMS performs the $|\eta_{j'}|$ analysis under similar conditions as the 7 TeV analysis, with a requirement on $m_T(W) > 50$ GeV. Events are again separated in 'signal region' and 'sideband' by means of the $m_{l\nu b}$ variable.

The background estimation also follows a similar strategy than the 7 TeV analysis. Multijet background is estimated via maximum likelihood fit to the $m_T(W)$ in CMS and to the MET in ATLAS. The templates come from data in the case of CMS, by inverting the isolation, while ATLAS applies the 'jet-electron' model on a multijet sample simulated using PHYTIA. The W+jets background is estimated in the same way as in the charge ratio analysis at 7 TeV in ATLAS, and is extrapolated from the sideband to the signal region in CMS. Additionally, CMS also has a data-driven estimation of the $t\bar{t}$ background, using normalization from simulation and the template from the $t\bar{t}$ enriched 3jet-2tag control region.

The ATLAS analysis builds a NN using 11 variables, trained independently in the 2 jet and 3 jet events. CMS uses the shape of the $|\eta_{j'}|$ distribution in the signal region of the 2jet-1tag events; both presented in Figure 4. The systematic uncertainties that have a larger effect on the ATLAS measurement are IRS/FSR and b-tagging; for CMS, the most important systematic is the jet energy scale (JES). The ATLAS experiment measures a cross-section of the t-channel



Figure 4: Distributions of the NN output for the 2-jet b-tagged sample in ATLAS (Left), and $|\eta_{i'}|$ in the signal region in CMS (Right).

single top production at 8 TeV of:

$$\sigma_{t-channel}^{ATLAS} = 95.1 \pm 2.4(stat) \pm 18.0(syst) \ pb = 95.1 \pm 18.1 \ pb \tag{7}$$

and the CMS experiment measures a value of:

$$\sigma_{t-channel}^{CMS} = 81.0 \pm 5.7(stat) \pm 11.0(syst) \pm 4.0(lumi) \ pb \tag{8}$$

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From the cross-section measurements, $|V_{tb}|$ values are obtained: $|V_{tb}| = 1.04^{+0.10}_{-0.11}$ ($|V_{tb}| > 0.80$ at 95% CL) for ATLAS, and $|V_{tb}| = 0.96 \pm 0.08(exp) \pm 0.02(th)$ ($|V_{tb}| > 0.81$ at 95% CL) for CMS. The cross-section measurements are combined [7] using the iterative best linear unbiased estimator (BLUE) technique, to give the LHC t-channel cross-section measurement at 8 TeV:

$$\sigma_{t-channel}^{LHC} = 85 \pm 4(stat) \pm 11(syst) \pm 3(lumi) \ pb \tag{9}$$

All the measurements are in agreement with the SM expectation [3]:

$$\sigma_{t-channel}^{th} = 87.2^{+2.8}_{-1.0}(scale)^{+2.0}_{-2.2}(pdf) \ pb = 87.2^{+3.2}_{-2.4} \ pb \tag{10}$$

2.4 Charge ratio at $\sqrt{s} = 8$ TeV

The charge ratio is also measured at 8 TeV by the CMS experiment, using the $|\eta_{j'}|$ analysis with $12.2 f b^{-1}$ of integrated luminosity [8].

The analysis extends the one presented in [6] including electrons and using a larger dataset. Electrons are selected with $E_T > 30$ GeV and $|\eta| < 2.5$; and the p_T threshold of the jets is raised to 40GeV. The event selection is unchanged, with a requirement on the MET of the event in the electron channel, MET > 45 GeV. The background estimation follows also the same description as in the 8 TeV cross-section analysis.

The charge ratio is obtained performing a maximum likelihood fit to the $|\eta_{j'}|$ distribution in the signal region in events with 2 jets, one of them b-tagged, separated in final states with a positive or negatively charged lepton. The main systematics that affect the R measurement are the pdf uncertainties and the background estimation.

The measured production cross-sections for single t and \bar{t} are:

$$\sigma_t = 49.9 \pm 1.9(stat) \pm 8.9(syst) \ pb \tag{11}$$

$$\sigma_{\bar{t}} = 28.3 \pm 2.4(stat) \pm 4.9(syst) \ pb \tag{12}$$

that are in agreement with the SM expectation of $\sigma_t = 56.4^{+2.1}_{-0.3} \pm 1.1 \ pb$ and $\sigma_{\bar{t}} = 30.7 \pm 0.7^{+0.9}_{-1.1} \ pb$ [3]. The measured charge ratio is therefore:

$$R = 1.76 \pm 0.15(stat) \pm 0.22(syst) \tag{13}$$

and is presented in Figure 5 compared to the values obtained from different next-to-leading order (NLO) pdf sets.

3 tW associated production

Single top tW associated production is the process with the second largest cross-section at the LHC. ATLAS and CMS have presented evidence of the process at 7 TeV and CMS achieved the first observation at 8 TeV. Leptonic decays of the top quark and W boson are studied. Therefore, signal events are characterized by having two opposite-sign, isolated leptons, MET due to the undetected neutrinos in the final state, and a jet coming from the decay of a b-quark. The main source of background is $t\bar{t}$ production, that not only has a cross-section about ten times higher than tW production, but also produces identical final states ($t\bar{t}$ and tW diagrams mix at NLO in QCD); followed by Z+jets.

3.1 Evidence at $\sqrt{s} = 7$ TeV

With the data collected by the LHC at 7 TeV, ATLAS and CMS presented the first evidence of the process. Both measurements are based on a BDT, ATLAS performs the analysis with an integrated luminosity of $2.05 f b^{-1}$ [9], while CMS uses $4.9 f b^{-1}$ [10].

Central, isolated leptons, electrons and muons, are used. ATLAS requires that the muons (electrons) fulfill p_T (E_T) > 25 GeV and $|\eta| < 2.5(2.47)$; while CMS requires the leptons to have $p_T > 20$ GeV and $|\eta| < 2.4$ in the case of electrons and 2.5 for muons. Jets are reconstructed using the anti- k_t algorithm with a parameter size of 0.4 (ATLAS) or 0.3. Jets are selected if $p_T > 30$ and $|\eta| < 2.5$ (ATLAS) or 2.4 (CMS). Additionally, CMS uses b-tagging to identify jets coming from b-quarks. Events are selected with exactly two, opposite-charge, isolated leptons, therefore, three final states are studied: ee, $e\mu$ and $\mu\mu$. ATLAS and CMS



Figure 5: Comparison of the measured charge ratio in the t-channel single top production with the prediction obtained using different PDF sets.



Figure 6: Distributions of the BDT output in ATLAS (Left), and CMS (Right).

have similar approaches to the event selection with some differences. ATLAS selects events with MET > 50 GeV, outside the Z mass window in the ee and $\mu\mu$ final states (vetoing events with $81 < m_{ll} < 101$ GeV), and that fulfill $\Delta \Phi_{l_1,MET} + \Delta \Phi_{l_2,MET} < 2.5$ (against $Z \rightarrow \tau \tau$). CMS requires $m_{ll} > 20$ GeV in all the final states to remove events from low invariant mass Drell-Yan, and in the ee and $\mu\mu$ final states, events within the Z mass window are removed in the same way as in the ATLAS analysis, and min(MET, TrackerMET) > 30 GeV is required. Tracker MET is an estimator of the MET in the event using only tracker information. Then, ATLAS selects events with at least one jet. The signal region is then defined in ATLAS by the events that have exactly 1 jet. CMS defines the signal region as events with exactly 1 jet, b-tagged, called the '1jet-1tag' region, and also uses events with exactly 2 jets, either 1 or 2 of them b-tagged, '2jet-1tag' and'2jet-2tag' control regions.

The $t\bar{t}$ production is the most important background and both experiments have dedicated control regions included in the statistical fit. ATLAS uses events with exactly 2 jets and 3 or more, while CMS includes the 2jet-1tag' and 2jet-2tag' regions. For the Z+jets background, data-driven scale factors are used. ATLAS obtains the scale factors from control regions defined by means of the MET and m_{ll} ; CMS has MET-dependent scale factors obtained by inverting the m_{ll} cut. ATLAS estimates also the background contribution from events with fake leptons (< 1%) using the matrix method, and the $Z \to \tau \tau$ inverting the cut.

ATLAS uses 22 variables to build a BDT discriminator, CMS uses 4, presented in Figure 6. The most discriminant variable in both cases is the p_T of the system composed by the 2 leptons, the jet and the MET. Performing a maximum likelihood fit over the BDT distribution, the tW signal is extracted with an observed (expected) significance of 3.3σ (3.4σ) by ATLAS and 4.0σ ($3.6^{+0.8}_{-0.9}\sigma$) by CMS, constituting evidence of the process. The measurement is most affected by the JES, and either parton shower modeling (ATLAS) or matching thresholds (CMS).

The measured production cross-sections are:

$$\sigma_{tW}^{ATLAS} = 16.8 \pm 2.9(stat) \pm 4.9(syst) \ pb \tag{14}$$

$$\sigma_{tW}^{CMS} = 15^{+5}_{-4} \ pb \tag{15}$$

in good agreement with the SM expectation of $\sigma_{tW}^{th} = 15.6 \pm 0.4(scale) \pm 1.1(pdf) \ pb$ [3]. From the ATLAS measurement, a value of $|V_{tb}| = 1.03^{+0.16}_{-0.19}$ is exacted, and for CMS, $|V_{tb}| = 1.01^{+0.16}_{-0.13}(syst)^{+0.03}_{-0.04}(th)$, or $|V_{tb}| > 0.79$ at 90%CL.

3.2 Observation at $\sqrt{s} = 8$ TeV

At 8 TeV the CMS experiment has established the tW process observing it with more than 5σ of significance [11]. The CMS analysis uses $12.2 f b^{-1}$ of data and a similar approach to the 7 TeV analysis [9]. A new category of jets is defined in this case, 'loose jets' are defined as those that pass the regular quality criteria but fail either the p_T or the η requirements ($p_T > 30$ and $|\eta| < 2.4$), while passing looser thresholds: $p_T > 20$ and $|\eta| < 4.9$. These jets are key to identify $t\bar{t}$ background where one the two hasn't been properly identified.

The event selection is similar as in [9] but the MET requirement is raised to MET > 50 GeV, removing largely the Z+jets contribution in the 8 TeV analysis. The same regions and background estimations are used, however, the BDT is built in different way: 13 variables are used, the ones related to the 'loose jets' being the most sensitive. The distribution of the BDT output is presented in Figure 7. The main systematics affecting this measurement are related

to theoretical uncertainties: matching thresholds and factorization and renormalization scales (Q^2) .

Performing a binned likelihood fit on the three final states in the three regions, the tW associated production is observed with 6.0σ of significance $(5.4^{+1.5}_{-1.4}\sigma \text{ expected})$. The measured cross-section value is:

$$\sigma_{tW}^{CMS} = 23.4^{+5.5}_{-5.4} \ pb \tag{16}$$

from which a value of $|V_{tb}| = 1.03 \pm 0.12(exp) \pm 0.04(th)$ (or $|V_{tb}| > 0.78$ at 95% CL) can be extracted.

At 8 TeV, ATLAS also has measured the tW associated production, using a BDT with $20.3 fb^{-1}$ using only the $e\mu$ channel [12]. Events are selected in this case if they have a $e\mu$



Figure 7: Distribution of the BDT output in the 1jet 1tag region for all the final states together in CMS.



Figure 8: Distribution of the BDT output in events with 1 jet in ATLAS.

pair and exactly 1 or 2 jets, one of them b-tagged. The matrix method is used to estimate the background coming from events with fake leptons and no other data-driven method is used. The analysis is based on a BDT with 19 variables in events with 1 jet and 20 in events with 2 jets, presented in Figure 8. The largest systematic effect comes from the generators and flavor tagging. ATLAS measures a cross-section of the tW associated production of:

$$\sigma_{tW}^{ATLAS} = 27.2 \pm 2.8(stat) \pm 5.4(syst) \ pb \tag{17}$$

with a significance of 4.2σ (4.0 σ expected). The $|V_{tb}|$ value that can be extracted is $|V_{tb}| = 1.10 \pm 0.12(exp) \pm 0.03(th)$ or $|V_{tb}| > 0.72$ at 95%CL.

All the results are in good agreement with the SM expectation of $\sigma_{tW} = 22.2 \pm 0.6(scale) \pm 1.4(pdf) \ pb$ [3].

4 s-channel

The s-channel single top production provides a challenging signature with one lepton, MET and two jets coming from b quarks. It is very complicated to disentangle s-channel from W+jets and $t\bar{t}$, backgrounds able to provide identical signatures. Only ATLAS has results on this channel, using $0.70 f b^{-1}$ at 7 TeV [13]. The analysis is based on a set of cuts, optimized against S/\sqrt{B} , and it is statistically limited. The same objects, event selection and background estimation as in [1] were used, with the exception that, in this case, only central jets were used.

An observed (expected) 95%CL upper limit of $\sigma_{s-channel} < 26.5$ (20.5) pb is set on the s-channel cross section, in agreement with the SM expectation of of $\sigma_{s-channel} = 4.56 \pm 0.07(scale)^{+0.18}_{-0.17}(pdf) pb$ [3].

5 Summary

ATLAS and CMS have a wide catalog of single-top studies. The t-channel was rediscovered at the LHC with early 7 TeV data, and its cross-section and charge ratio where measured at 7 and 8 TeV. Evidence of the tW associated production was reported with 7 TeV data, and the process was observed with a significance of more than 5σ by CMS at 8 TeV. The s-channel, which is very challenging to observe at the LHC, is under study in both experiments and ATLAS has determined an upper limit on this cross-section at 7 TeV.

So far, everything is in agreement with the Standard Model expectations.

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Measurement of the longitudinal polarization of the top quark in top-antitop events with the ATLAS experiment.

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In the Standard Model (SM), top-antitop quark pair production $(t\bar{t})$ is generated from both strong and weak interactions. At the Large Hadron Collider (LHC), the strong interaction is the dominant mechanism for producing top-antitop pairs. Parity conservation in the strong production of $t\bar{t}$ renders un-polarized top quarks, meanwhile, parity-violating weak interactions generate a negligible contribution to the polarization [8]. The anomalous forward-backward asymmetry (A_{FB}) results from the Tevatron experiments, D0 [9, 10] and CDF [11], have motivated theorists to explain the result using Beyond the Standard Model (BSM) mechanisms, such as axi-gluons, which produce non-zero longitudinal polarization of top quarks in topantitop production [12, 13, 14]. The measurement of the longitudinal polarization of the top quark may be used as a check for the SM and as a way to probe the existence of BSM physics given the discrepancy between the SM and BSM predictions.

The analysis presented in this article measures the longitudinal polarization of the top quark in $t\bar{t}$ production using the single lepton channel. In addition, the single lepton channel and dilepton channel are used to produce a combined measurement.

With a lifetime of 3.29×10^{-25} s [15], the top quark decays before hadronization can occur, allowing the spin information of the top quark to be accessed through its decay products. By utilizing this property of the top quark, its longitudinal polarization can be determined by analyzing the angular distribution of its final state decay products. The distribution of the polar angle, θ_i , of each of the top quark's final state decay products, labeled by *i*, is given by

$$W(\cos\theta_i) = \frac{1}{2} \left(1 + \alpha_i P \cos\theta_i \right), \tag{1}$$

α_i	Particle Type
1.0	Charged Lepton
1.0	Down and Strange Quarks
-0.4	b Quark
-0.3	Neutrino
-0.3	Up Type Quark

Table 1: Predicted tree level values of the spin-analyzing power, α_i , for the top quark final state decay products.

where P represents the degree of polarization along the chosen quantization axis and α_i is the spin-analyzing power of the final state decay product [16, 17], which is a measure of the sensitivity of the daughter particle to the parent particle's spin state. Table 1 shows the tree level values of the spin-analyzing power for the final state particles of the top decay. For this analysis, the helicity basis is used, where the parent top quark's momentum direction in the $t\bar{t}$ center-of-mass frame is chosen as the quantization axis. Due to its α_i value being 1, which gives it maximal sensitivity to the top quark's spin state, the charged lepton is utilized in this analysis to determine the longitudinal polarization of the top quark. The polar angle of the charged lepton, θ_{ℓ} , is determined by measuring the angle between the quantization axis and the charged lepton's momentum direction in its parent top quark's rest frame, as depicted in Figure 1. Templates of $\cos \theta_{\ell}$, which require $t\bar{t}$ event reconstruction, are produced and fit to the data using a binned maximum likelihood fit. Results for the single lepton and combined fits are quoted as the product of α_i and P.

The full 2011 dataset of proton-proton (pp) collisions collected by the ATLAS detector [18] at a center-of-mass energy of $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of 4.7 fb⁻¹, is used for this analysis [19]. The single lepton channels considered for this analysis are the electron and muon channels. Selection cuts on event and object kinematics are performed to enhance the signal to background ratio for $t\bar{t}$ events. The cuts used in this analysis are as follows: exactly one high- p_T isolated electron or muon, at least four jets; with at least one *b*-tagged, large missing transverse energy from the neutrino, and a large transverse mass of the leptonically decaying *W*-boson, defined as

$$m_{\rm T} = \sqrt{2p_T^{\ell} E_{\rm T}^{\rm miss} [1 - \cos(\phi^{\ell} - \phi(E_{\rm T}^{\rm miss}))]},$$
 (2)



azimuthal angle of the charged lepton, and $\phi(E_{\rm T}^{\rm miss})$ is the



Figure 1: The Helicity Basis.

azimuthal angle of the missing transverse energy. Monte Carlo (MC) simulated samples are used to determine the signal and background contributions, with the exception of the nonprompt(NP)/fake lepton contribution arising from QCD multi-jet events. The $t\bar{t}$ signal MC was simulated using the next-to-leading order (NLO) MC@NLO 3.41 [7] generator with the NLO parton density function (PDF) set CT10 [6], assuming a top mass of 172.5 GeV. Parton showering is modeled with HERWIG 6.510 [5] and the underlying event is generated using JIMMY 4.31 [4]. Single top events were simulated using the MC@NLO generator for the Wt and s-channel, while the ACERMC [2] generator was used for the t-channel. Diboson (WW, WZ, ZZ) events were simulated using the HERWIG generator. The production of W and Z bosons in association with jets were simulated using the ALPGEN [1] generator interfaced with HERWIG and JIMMY. The shapes of the kinematic distributions produced from the W+jets background are taken from the MC, however, the overall normalization of the events is scaled using the most recent ATLAS measurement of the cross section of this process [20]. The NP/fake lepton contribution is estimated using a data driven matrix method based on the ratio of jets passing loose lepton selection to those passing tight lepton selection [21, 22]. Table 2 shows the expected signal and background yields compared to data, after selection, for both of the single lepton channels.

The four momentum of both the top and antitop are needed in order to determine the quantization axis for the calculation $\cos \theta_{\ell}$, requiring a full reconstruction of the $t\bar{t}$ system. A kinematic likelihood fit, which utilizes *b*-tagging information, is employed to determine the longitudinal momentum of the neutrino and to assign the selected jets to the top (antitop)

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Table 2: Expected signal and background rounded yields compared to data for each of the single lepton channels considered. The total systematic and statistical uncertainties are reported.

Source	e+jets	μ +jets
$t\bar{t}$	16200	26500
Background	5100	9400
Total	21300	35900
Uncertainty	± 1300	± 1700
Data	21956	37919



Figure 2: Comparison of the data to expectation based on MC and data driven predictions. The hatched error bands are formed from the statistical and systematic uncertainties.

decay [23]. Figure 2 depicts the performance of the kinematic fitter by displaying the data to expectation agreement after reconstruction for the neutrino p_z and $\cos \theta_{\ell}$.

After event reconstruction is performed, templates of $\cos \theta_{\ell}$ for signal and background are produced and then fit to the data. The MC available for this analysis lacks polarized top quarks, requiring that the signal MC be reweighted to induce longitudinal polarization. Each MC signal event is reweighted based on the double differential cross section given by [24]

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1d\cos\theta_2} = \frac{1}{4}\left(1 + \alpha_1 P_1\cos\theta_1 + \alpha_2 P_2\cos\theta_2 - C\cos\theta_1\cos\theta_2\right),\tag{3}$$

where $\alpha_1 P_1$ ($\alpha_2 P_2$) corresponds to the spin-analyzing power of one of the final state decay products of the top (antitop) quark times the longitudinal polarization of the top (antitop) quark and C represents the $t\bar{t}$ spin correlation. The angle θ_1 (θ_2) corresponds to the polar angle of the final state decay product used to determine $\alpha_1 P_1$ ($\alpha_2 P_2$) of the top (antitop) quark. The polar angle is defined as the angle between the helicity basis' quantization axis and the final state decay products momentum direction in its parent top quark's rest frame. The


Figure 3: CPC and CPV fits and templates for the single lepton channel.

truth information of each MC signal event is used to reweight the event. After applying the weight, the parton level distributions of the top (antitop) final state decay products, labeled by the index i, follow the relationship:

$$W(\cos\theta_i) \propto 1 + \alpha_i \cos\theta_i. \tag{4}$$

The value of C is taken from the signal $t\bar{t}$ MC (MC@NLO) and is valued at 0.307, with the value of $\alpha_i P$ chosen as ± 0.3 to ensure that the cross section in eq. (3) remains positive. Two scenarios for top quark polarization are considered in this analysis: CP conserving (CPC) and CP violating (CPV). The CPC case corresponds to $\alpha_1 P = \alpha_2 P$, meanwhile, the CPV case corresponds to $\alpha_1 P = -\alpha_2 P$.

Templates of the reconstructed $\cos \theta_{\ell}$ are created for the CPC and CPV scenarios, each requiring two sets of templates: a positively polarized and a negatively polarized template. For each scenario, a binned maximum likelihood fit to the data is performed to extract the longitudinal polarization of the top quark. The $t\bar{t}$ cross section is simultaneously fit to reduce the normalization uncertainty. The fits are performed on all considered channels using charge separated templates. The single lepton result is obtained by multiplying the electron and muon likelihoods together. Similarly, the combined result is obtained by multiplying the single lepton and dilepton channel likelihoods together. The product of the spin-analyzing power and the magnitude of the longitudinal polarization is quoted as the result. Figure 3 shows the CPC and CPV fits and templates.

Templates are created for each source of systematic uncertainty. The systematic uncertainty for the up and down variations is quoted as the mean of the distribution of differences between the central fit value and the systematic template fit to 1,000 pseudo-datasets. The sources of uncertainty that do not depend on the charge of the lepton dramatically reduce the uncertainty in the CPV scenario. This is due to the fit parameters being pushed in opposing directions for the oppositely charged templates. The tension created in the fit leads to the reduced uncertainty.

Table 3 displays the results for $\alpha_{\ell}P$ in the single lepton channels. The combined result of the single lepton and dilepton channels for the CPC scenario is

$$\alpha_{\ell} P_{\rm CPC} = -0.035 \pm 0.014 (\text{stat}) \pm 0.037 (\text{syst}) \tag{5}$$

and in the CPV scenario the result is

$$\alpha_{\ell} P_{\rm CPV} = 0.020 \pm 0.016 (\text{stat})^{+0.013}_{-0.017} (\text{syst}).$$
(6)

Channel	$\alpha_\ell P_{\rm CPC}$	$\alpha_\ell P_{\rm CPV}$
e+jets	$-0.031 \pm 0.028^{+0.043}_{-0.040}$	$0.001 \pm 0.031^{+0.019}_{-0.019}$
μ +jets	$-0.033 \pm 0.021^{+0.039}_{-0.039}$	$0.036 \pm 0.023^{+0.018}_{-0.017}$
$\ell + jets$	$-0.034 \pm 0.017^{+0.038}_{-0.037}$	$0.023 \pm 0.019^{+0.012}_{-0.011}$
SM Prediction	0.003 [8]	0.0

Table 3: Summary of fitted $\alpha_{\ell}P$ in the individual single lepton channels for the CP conserving and CP violating fits. The uncertainties quoted are first statistical and then systematic.

Table 4: Summary of the systematic uncertainties on $\alpha_{\ell}P$. The systematic uncertainties have been added in quadrature to obtain the total systematic uncertainty.

Source	$\Delta \alpha_{\ell}$	$P_{\rm CPC}$	$\Delta \alpha_{\ell} l$	CPV
Jet reconstruction	+0.031	-0.031	+0.009	-0.005
Lepton reconstruction	+0.006	-0.007	+0.002	-0.001
$E_{\rm T}^{\rm miss}$ reconstruction	+0.008	-0.007	+0.004	-0.001
$t\bar{t}$ modeling	+0.015	-0.016	+0.005	-0.013
Background modeling	+0.011	-0.010	+0.005	-0.007
Template statistics	+0.005	-0.005	+0.006	-0.006
Total systematic uncertainty	+0.037	-0.037	+0.013	-0.017

The major sources of uncertainty in the combined result are due to jet energy scale, top mass uncertainty, *b*-tagging efficiency, and NP/fake lepton estimation. Table 4 lists the sources of systematic uncertainty for both the CPC and CPV scenarios.

In conclusion, the top quark longitudinal polarization in the CP conserving and CP violating scenarios have been measured and are found to be in agreement with the Standard Model predictions.

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Heavy resonances and top production Overview of top tagging techniques

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Events containing hadronically decaying top quarks with large momentum are playing an increasingly significant role, both in searches for new physics and measurements of Standard Model processes at the Large Hadron Collider. Such events are not fully described by traditional reconstruction techniques, because boosted top decays are very collimated, leading to merged jet topologies. We review top tagging techniques that can contribute to the identification of boosted top jets. We also point out some issues that may arise in searches that make use of such substructure information.

1 Introduction

The study of substructure of boosted massive jets gives insight into the fundamental structure of QCD and an opportunity to tune the various Monte Carlo (MC) event generators. These exotic jets are also becoming increasingly important at the Large Hadron Collider (LHC), with the experimental searches entering a kinematic regime in which a significant fraction of heavy Standard Model (SM) particles are produced at high transverse momentum (p_T). Of particular interest are boosted top quarks, as many models of new physics that address the hierarchy problem predict states with a large decay rate to top quark pairs (see for example Refs. [1, 2, 3, 4, 5, 6, 7]).

At high p_T , the decay products of heavy objects tend to be collimated in the lab frame and are not adequately described by standard reconstruction techniques. As a rule of thumb, one can estimate the opening angle of decay products of a boosted object as $\Delta R \gtrsim 2M/p_T$, where M is the mass of the decaying resonance (top or W) and p_T its transverse momentum. Consequently, by using usual jets with a radius R = 0.4 or R = 0.5, the decay products of the W in $t \rightarrow bW \rightarrow bq\bar{q}$ may not be resolved if $p_T^W \gtrsim 300$ GeV. Using smaller R to directly resolve the subjets results in significant loss of gluon radiation from the $W \rightarrow q\bar{q}$ system, giving poor mass resolution.

An alternative method is to cluster the resulting hadrons into "fat jets" with large radius parameter (R = 1.0 or R = 1.5), in order to collect all decay products [8, 9, 10]. This gives us the flexibility to solve some combinatorial issues while also ensuring the capture of interesting gluon radiation from decay products. The leading order (LO) three prong decay structure of a boosted top and the correlations therein can be employed to distinguish top quark jets from, say, light parton QCD jets, which typically have a two prong topology. Many different approaches have been developed to exploit these differences and will be the focus of this review. HEAVY RESONANCES AND TOP PRODUCTION OVERVIEW OF TOP TAGGING TECHNIQUES

2 Jets and jet substructure

Understanding jets and why they are important phenomenological tools is a critical step to understand jet substructure and its applications. Jets are the objects that enable us to connect long-distance effects with perturbatively describable short-distance physics. The property of QCD that allows this is called factorization. It can be used to write hard scattering crosssections as convolutions of separate hard, jet, and soft functions. The soft and jet functions are the only ones that are associated to the particular jet and its definition. Reasonable calculations of these functions from the jet functions, which are related to radiation from the parton that originated the jet, and ignore the soft functions, which depend on large-angle radiation from other final-state partons and from the initial-state partons.

2.1 Sequential recombination algorithms

Jets, however, are not unambiguous objects. To be able to compare experimental observations to theoretical predictions, jets have to be defined in an infrared safe way, i.e. insensitive to the emission of soft or collinear particles. This is because the QCD matrix elements have singularities whenever a soft gluon or collinear pair of massless partons is emitted. Many jet clustering algorithms have been proposed for the analysis of hadronic final states in hadronhadron collisions. Of course, when comparing experiment with theory, it is important to use the same algorithm to ensure consistency in the results.

Some of the jet algorithms that are in widespread use at the LHC are sequential recombination algorithms. Here jets are constructed by iteratively recombining final state particles pairwise according to some measure d_{ij} . The three most popular sequential jet algorithms are the k_T [11], the Cambridge/Aachen (CA) [12] and the anti- k_T [13] algorithms. Their measure is given by

$$d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{T,i}^{2p}, \tag{1}$$

where p = 1, 0, -1 for the k_T , CA and anti- k_T algorithms, respectively, and R is the jet resolution parameter. These algorithms sequentially merge the pair of protojets (by combining their four vectors) which are closest according to d_{ij} , unless one of the d_{iB} is smaller than all d_{ij} , in which case the protojet *i* is deemed a jet and the procedure continues on the remaining objects.

The choice of jet algorithm and resolution parameter R depends on the topology and experimental context of interest. A jet algorithm may be preferred because of its larger background rejection rate, insensitivity to contamination, or, as we will se below, because it is able to highlight certain aspects of the substructure of jets. Determining an optimal jet radius R is a compromise between taking it large enough to catch the bulk of gluon radiation and small enough to avoid too much contamination from the underlying event (UE) and pileup. ATLAS and CMS have many different jet finding algorithms and choices of jet radii, ensuring some degree of flexibility at the time of performing an analysis.

2.2 The importance of jet mass

While looking for a resonance massive jet, the jet mass is a good indicator of its origin. Assuming a given jet p_T , and working in the collinear regime (small R), the leading-order differential QCD

jet-mass distribution is given by [16, 17]

$$\frac{1}{\sigma} \frac{d\sigma}{dm_J^2} \approx \frac{\alpha_s C_F^2}{\pi m_J^2} \left(\ln \frac{R^2 p_T^2}{m_J^2} + \mathcal{O}(R^2) \right)$$
(2)

where C_F are the color factors associated with the representation of the particle initiating the jet. In the region of interest for boosted object studies, $m_J \ll p_T$, the logarithmic term in Eq. (2) can be large even when electroweak scale jet masses are considered. An accurate description of massive jets therefore requires to consider variables that can resolve finer details of the substructure of jets, beyond the jet mass and p_T .

Subjet techniques aim to identify relatively hard, symmetric splittings which are most likely associated to a heavy particle decay. In the leading log approximation, we can describe a massive jet composed of two subjets by

$$\frac{m_J^2}{p_{T,J}^2} \sim z(1-z)\Delta R_{j_1j_2}^2, \qquad \text{with } z = \frac{\min p_{T,j_i}}{p_{T,J}}.$$
(3)

If one of these splittings corresponds to $t \to bW$ or $W \to jj$, we expect symmetric decays with $z \sim 0.5$. For a given mass, QCD subjets also tend to be symmetric but much less so, owing to the different nature of the splittings. This provides us a way of placing cuts on the z fractions, so as to eliminate backgrounds. Once a small angular scale $\Delta R_{j_1j_2}$ has been found, it can be used for resolving the jet at a even smaller scale to remove soft radiation and further improve on jet mass resolution.

2.3 Jet grooming

At the large luminosities present at the LHC, additional energy depositions from the UE, pileup or initial state radiation may hinder substructure studies. These additional contributions are uncorrelated with the hard-scattering process that originated the event and introduce a background of soft diffuse radiation. The soft diffuse pileup/UE background can have a large impact on the jet mass, p_T and other jet substructure observables, especially for large-R jets. It is thus important that measurements of jet substructure be able to remove this extra energy from the reconstructed jets.

Several grooming techniques are available to mitigate the effects of pile-up and UE. The purpose of these methods is to remove particles in a jet which are most likely associated with uncorrelated sources of radiation. The most commonly used grooming techniques are filtering [8], trimming [14] and grooming [15]. Jet filtering and trimming work in a similar fashion by re-clustering the constituents of a fat jet using a k_T jet algorithm with smaller radius $R_{\rm sub}$ to find subjets of the original jet. Only a subset of these subjets is kept. Filtering keeps a fixed number n_f of subjets. Trimming, instead, keeps only the subjets which satisfy $p_{T,i} > f_{\rm cut} \times p_T^{\rm jet}$, where $f_{\rm cut}$ is an adjustable parameter.

Likewise, pruning tries to clean jets from soft and wide angle radiation. Unlike the case of filtering and trimming, pruning works instead by discarding particles at each recombination step of a k_T or CA jet algorithm. At each recombination step $ij \rightarrow a$, the algorithm checks for either two conditions,

$$z = \frac{\min(p_{T,i}, p_{T,j})}{|\vec{p}_{T,i} + \vec{p}_{T,j}|} < z_{\text{cut}}, \qquad \Delta R_{ij} > D_{\text{cut}},$$
(4)

where z_{cut} and D_{cut} are two parameters that have to be optimized for each process of interest. If both conditions are met then one drops the softer of i, j, and continues the process. The algorithm continues until all constituents have either been combined or else removed.

It has been shown that grooming techniques improve the jet's mass resolution [18]. This property can be used to increase the sensitivity of a resonance search. One should only be aware that the cuts are placed on infrared safe observables, so as not to spoil the infrared safety properties of the original, ungroomed jets.

3 Techniques to reconstruct boosted top jets

In this Section we present a very brief overview of some of the most popular top tagging techniques, focusing on the ones that are already in use by the LHC experiments. These methods can be grouped into two broad categories. The first class includes methods that characterize signal events by subjets that would correspond to the decay of heavy particles. The second class employs jet shape observables to probe the energy radiation pattern within jets. The choice of a top tagger is a compromise between maintaining a high signal efficiency or delivering a large background rejection. Thus, the question of which top tagger is the "best" depends on the search or measurement in question.

3.1 k_t splitting scales, d_{ij}

One widely used class of substructure observables are the splitting scales in the last stages of jet clustering by a k_T jet algorithm. They were applied by ATLAS in combination with jet mass as a simple way of tagging tops [19]. The method is optimized to work at larger tagging efficiencies, where basic event selections already remove a large fraction of the background. The k_T distance of the final clustering step defines a splitting variable $\sqrt{d_{12}}$:

$$\sqrt{d_{12}} = \min\left(p_{T,j_1}, p_{T,j_2}\right) \Delta R_{j_1 j_2},\tag{5}$$

Similarly, one can define a splitting scale $\sqrt{d_{23}}$ of the next-to-final clustering step. The ordering of clustering in the k_T algorithm implies that decay products of massive particles are typically combined in the last steps of recombination. Thus, one expects $\sqrt{d_{12}} \approx m_t/2$ and $\sqrt{d_{23}} \approx m_W/2$ for a fat jet containing all top decay products $t \to bW \to bq\bar{q}$, while QCD jets typically give much smaller splittings.

3.2 John Hopkins top tagger

The "Hopkins" top tagger [20] is inspired by the BDRS algorithm [8] applied to boosted Higgs identification. The fat jet is found using the CA algorithm with R = 0.8. This jet is then decomposed by reversing the clustering history, iteratively splitting each jet into two objects $j \rightarrow j_1 + j_2$. The softer of the two objects is thrown out if min $p_{T,j_i} < \delta_P p_T^{\text{jet}}$, for some parameter δ_P , and the procedure continues on the harder objects. The declustering step is repeated until an interesting splitting is found such that

$$\Delta R_{j_1 j_2} > \delta_R, \qquad \min p_{T, j_i} > \delta_P \, p_T^{\text{jet}}, \tag{6}$$

where δ_R is an additional parameter. The next step is to successively uncluster both j_1 and j_2 to find jets with 3 or 4 subjets. If the resulting subjets satisfy several kinematical constraints

consistent with a boosted top decay (e.g. the total invariant mass of all subjets should be near m_t , two of the subjets are required to reconstruct m_W and their helicity angle should not be too small,) the jet is deemed a top candidate. The "Hopkins" top tagger has been modified by CMS [21], where the kinematic cuts have been replaced by a single cut on the minimum pairwise subjet mass.

3.3 HEPtopTagger

Similarly to the John Hopkins tagger, the HEPTopTagger [22, 23] is another tagger inspired by the BDRS method. It was originally designed to efficiently identify mildly-boosted top jets, with $p_T \gtrsim 200 \text{ GeV}$. The algorithm begins by clustering the event using a CA algorithm with an extremely large angular scale R = 1.5, and requiring the jet to have $p_T > 200 \text{ GeV}$. The next step is to iteratively uncluster the jet while looking for some interesting substructure. The criterion for an interesting splitting $j \rightarrow j_1 j_2$ is that the subjets must satisfy a mass drop condition $m_{j_i} < 0.2m_j$. If the splitting fails this criterion, the lightest subjet is discarded and the procedure continues recursively on the heavier object. The procedure ends when all the subjets satisfy $m_{j_i} < 30 \text{ GeV}$. The next step is to apply jet filtering on the constituents of the surviving subjet's $\{j_i\}$, with a small angular resolution scale $R_{filt} = \min(0.3, \Delta R_{ij})$, and retain five subjets. This step is performed in order to reduce sensitivity to pileup/UE. These five filtered subjets are then once more reclustered into exactly three subjets, which are the candidates for the top decay products. Finally, the invariant mass combinations of the three subjets are reconsidered in the $(m_{23}/m_{123}, \arctan(m_{13}/m_{12}))$ plane. For tops, one of the combinations is required to satisfy,

$$0.85 \frac{m_W}{m_t} \lesssim \frac{m_{23}}{m_{123}} \lesssim 1.15 \frac{m_W}{m_t}, \quad 0.2 \lesssim \arctan \frac{m_{13}}{m_{12}} \lesssim 1.3.$$
(7)

These kinematic cuts pick out top jets, while the background is typically concentrated on small pairwise invariant masses.

3.4 Template Overlap Method

The Template Overlap Method [24] differs from the above approaches in that it does not manipulate the jet constituent list, nor does it require a special clustering algorithm for substructure analysis. Instead, the method compares the jet to a set of parton level states built according to a fixed-order distribution of signal jets called templates. The comparison makes use of an "overlap function" which evaluates the level of agreement between each measured jet and a set of templates.

Let us consider the case of a boosted top quark decay $t \to bW \to bq\bar{q}$. The phase space for this decay is determined by four independent parameters, which can be chosen as the rapidity and azimuthal angle of the W decay daughters, $(\eta, \phi)_{i=1,2}$ in the lab frame. Each top template consists of a set of three momenta (p_1, p_2, p_3) at fixed total p_T obtained by sequentially scanning over the phase space given by the above four angular variables.

Following the notation of Ref. [25], here we consider the definition of *hadronic peak template* overlap in terms of longitudinally boost invariant quantities:

$$Ov_3 = \max_{\{f\}} \left\{ \exp\left[-\sum_{a=1}^N \frac{1}{\sigma_a^2} \left(\epsilon \, p_{T,a} - \sum_{\Delta R(i,a) < r_a} p_{T,i} \right)^2 \right] \right\},\tag{8}$$

where $p_{T,a}$ is the transverse momentum of the a^{th} template parton and $p_{T,i}$ is the transverse momentum of the i^{th} jet constituent. The functional is maximized over the set of templates fconstructed by the above procedure. The weight σ_a defines the energy resolution of the peak template overlap which we set to $\frac{1}{3}p_{T,a}$, while the coefficient ϵ serves to compensate for the radiation which falls outside the template sub-cones.

It has been shown that Ov_3 is a good discriminant between top jets and QCD light parton jets [24, 26]. In addition, placing limits on the distributions of the best matched templates gives additional information on the likelihood that the jet is signal or background. The templatebased observables by themselves are robust against pileup up to 50 interactions per bunch crossing, without the use of additional pileup correction techniques [25, 26]. The relative insensitivity of the Template Overlap Method to pileup may thus serve to study the systematic effects of other pileup correction techniques.

3.5 Other top tagging approaches

Methods that employ a different approach to probing the substructure of jets also exist. The jet observable N-subjettiness [27, 28] is designed to classify jets as being N-prong-like without any reference to jet algorithms. Given N axes \hat{n}_i , N-subjettiness is defined by

$$\tau_N = \frac{1}{d_0} \sum_{k \in J} p_{T,k} \min\{\Delta R_{1,k} \cdots \Delta R_{N,k}\},\tag{9}$$

with

$$d_0 = \sum_{k \in J} p_{T,k} R_0.$$
 (10)

Here the index k runs over all the jet's constituents. τ_N measures the extent to which the N-subjet description provides a good characterization of the energy distribution within jets. This provides an useful handle to disentangle heavy-object jets from light parton QCD jets. It was shown that the real discrimination power of N-subjettiness occurs when considering ratios of N-subjettiness, $r_N = \tau_N/\tau_{N-1}$. For heavy particles with N-prong decays, r_N is expected to peak at larger values compared to the QCD case. One should be aware that these ratios by themselves are not infrared and collinear safe for generic jets. In particular, r_N is infrared safe only when applied to jets with a N-prong substructure, which can be guaranteed through a cut on r_{N-1} . A simple top tagger can be constructed using as input variables the jet mass, τ_2/τ_1 and τ_3/τ_2 .

More recently, shower deconstruction method [29, 30] appeared as a variant of the matrix element method to classify jets with the help of approximations to hard matrix elements and the parton shower. The method attempts to identify boosted hadronic tops by computing the ratio of the likelihood for a jet to have been originated from a top decay to the likelihood for the same jet to have been originated from a light QCD parton. These likelihoods are computed by summing over all possible shower histories leading to the observed final state, using first principle QCD, in a similar fashion to what full event generators do. The results presented in Ref. [30] show an improvement on the top taggers described previously.

4 Asymmetric $t\bar{t}$ production from higher-order amplitudes

The first area where top tagging has proved fruitful is in searches for new physics decaying to top quark pairs. The $t\bar{t}$ topologies we observed in the detector depend strongly on the kinematic regime, as quantified by the H_T of the event (here we define $H_T = \sum_j p_{T,j}$, where j runs over all final state particles in the event.) Low-energy events, the top and anti-top are produced nearly back to back with about the same p_T . Yet, high energy events often involve extra hard radiation in the final state as well as a non-negligible gluon splitting function to heavy flavors, all of which can result in an imbalance between the transverse momenta of the top and anti-top [26, 31]. The contributions from these categories of events are depicted in Fig. 1.



Figure 1: Three categories of $t\bar{t}$ events. Figure from Ref. [26].

Contributions from asymmetric events belonging to class (ii) and (iii) in the SM $t\bar{t}$ production are of great importance to measure the SM top differential p_T distribution. However, including these asymmetric events into the event sample might cause the gluon jet to be misidentified as the hadronic top, and an inaccurate reconstruction of the event. On the other hand, the rejection of asymmetric events is of particular relevance in searches for new physics. For instance, top quark pairs produced in heavy resonance decays typically belong to class (i). Hence, rejecting asymmetric events implies that the SM $t\bar{t}$ is not an irreducible background anymore and a further improvement in signal to background can be achieved. All of this stresses the importance of using a good top tagger, with relatively high efficiency and better background rejection.

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Inclusive top pair production at Tevatron and LHC in electron/muon final states

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Recent measurements of the inclusive top pair production at the Tevatron and LHC collider in the electron/muon final states are discussed. Measurements at the Tevatron use up to 9.7 fb⁻¹ of data, and at the LHC up to 4.9 fb⁻¹ of data at $\sqrt{s} = 7$ TeV and up to 20.3 fb⁻¹ of data at $\sqrt{s} = 8$ TeV. For the experiments at both colliders these corresponds to the full data sets at the given center-of-mass energies. Overall results are in agreement between the experiments at the Tevatron and between the experiments at the LHC. All measurements are in agreement with recent theory calculations at NNLO QCD. Individual LHC measurements are challenging the precision of the theory calculations.

1 Introduction

The top quark is the heaviest known elementary particle and was discovered at the Tevatron $p\bar{p}$ collider in 1995 by the CDF and DØ collaboration [1, 2] with a mass around 173 GeV. At the Tevatron the production is dominated by the $q\bar{q}$ annihilation process with 85% as opposed to gluon-gluon fusion which contributes only 15%, whereas at the LHC fractions are approximately opposite. The top quark has a very short lifetime, which prevents any hadronization process of the top quark. Instead bare quark properties can be observed by measuring top quark properties.

Theoretical predictions of the $t\bar{t}$ production process exist at various orders of perturbative QCD (pQCD). The most recent prediction is a fully re-summed next-to-next-to-leading log (NNLL) at next-to-next-to-leading order (NNLO) pQCD calculation [3]. Table 1 summarizes these predictions for the Tevatron and the LHC center-of-mass energies (using $m_t = 173$ GeV and the MSTW2008NNLO PDF). The total uncertainty from factorization and renormalization scale variation and PDF uncertainties is approximately 3.5% for the Tevatron and approximately 4.3% at the LHC.

1.1 Measurement of cross sections

The measurements presented here are performed using either the dilepton $(\ell \ell)$ final state or the lepton+jets $(\ell+jets)$ final state, where ℓ can be an electron or a muon. The branching fraction for top quarks decaying into Wb is almost 100%. Within the $\ell+jets$ final state one of the W bosons (stemming from the decay of the top quarks) decays leptonically, the other Wboson decays hadronically. For the dilepton final state both W bosons decay leptonically. The main background contribution in the $\ell+jets$ decay channel originates from W+jets production,

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Collider			
	$\sigma_{\rm tot} ~[{\rm pb}]$	$\delta_{\rm scales}$ [pb]	$\delta_{\rm pdf} \ [{\rm pb}]$
Tevatron ($\sqrt{s} = 1.96$ TeV)	7.164	+0.110 (1.5%) -0.200 (2.8%)	+0.169 (2.4%) -0.122 (1.7%)
LHC ($\sqrt{s} = 7 \text{ TeV}$)	172.0	$\begin{array}{c} +4.4 & (2.6\%) \\ -5.8 & (3.4\%) \end{array}$	+4.7 (2.7%) -4.8 (2.8%)
LHC ($\sqrt{s} = 8$ TeV)	245.8	+6.2 (2.5%) -8.4 (3.4%)	+6.2 (2.5%) -6.4 (2.6%)

Table 1: Total $t\bar{t}$ production cross sections and their uncertainties [3] at the Tevatron and the LHC.

whereas the dilepton decay channel suffers most from contributions from Z+jets production. At the LHC also single top quark production is one of the dominant background contributions for the $\ell\ell$ and ℓ +jets channel. Jets originating from a beauty quark (*b*-jets) are usually identified by means of multivariate discriminants built by the combination of variables describing the properties of secondary vertices and of tracks with large impact parameters relative to the primary vertex.

The measured cross section can be calculated by using

$$\sigma_{\rm tot}(t\bar{t}) = \frac{N^{\rm obs} - N^{\rm bg}}{\epsilon \cdot \mathcal{A} \cdot \mathscr{L} \cdot \mathscr{B}} \ . \tag{1}$$

The number of observed data events N^{obs} is subtracted by the number of expected background events N^{bg} and then corrected for the detector efficiency ϵ and acceptance \mathcal{A} , the total integrated luminosity \mathscr{L} that corresponds to the selection requirements, and for the branching fraction \mathscr{B} into the decay channel under consideration. Thus any measurement of a cross section relies on Monte-Carlo (MC) samples to correct the data for the detector efficiency and also in order to extrapolate from the fiducial cross section to the total cross section. For this purpose all cross section measurements (also differential) use currently theory predictions at leading-order or next-to-leading order pQCD.

2 Dilepton channel (CDF)

CDF uses all available data corresponding to 8.8 fb⁻¹ in the dilepton decay channel to measure the $t\bar{t}$ production cross section [4]. The data is selected by requiring exactly two leptons and the accompanying missing transverse energy $\not\!\!E_T$ originating from the non-reconstructed neutrinos from the leptonic decays of the two W bosons. Leptonic decays of τ are included, whereas hadronic ones are not considered here. At least one isolated electron with $E_T > 20$ GeV is required, whereas the second electron does not need to be isolated. Muons are required to have at least $p_T > 20$ GeV, again at least one muon needs to be isolated. Furthermore at least two jets with $p_T > 15$ GeV and pseudorapidity $|\eta| < 2.5$ are required, with at least one jet identified to originate from a *b*-quark (*b*-tagged). Figure 1 shows the selected data in the a) pre-tag or b) *b*-tagged case. The total cross section (see Equation 1) assuming $m_t = 172.5$ GeV is measured from this *b*-tagged event selection to $\sigma_{tot}(t\bar{t}) = 7.09 \pm 0.49(\text{stat}) \pm 0.52(\text{sys}) \pm 0.43(\text{lumi})$ pb. The systematic uncertainty is dominated by the modeling of the *b*-tagging and the total uncertainty for this measurement is 12%. If no requirement on *b*-tagging is applied a cross section of $\sigma_{tot}(t\bar{t}) = 7.66 \pm 0.44(\text{stat}) \pm 0.52(\text{sys}) \pm 0.47(\text{lumi})$ pb is measured. Table 2 shows a comparison to other CDF measurements in the ℓ +jets channel not presented at TOP2013 [5, 6] and to DØ



Figure 1: Selected data in the dilepton channel for the a) pre-tag or b) *b*-tagged case compared to the background contributions.

measurements (see Sec. 3). The measurements are in good agreement with the most recent pQCD prediction at NNLO, which yields a cross section of $\sigma_{tot}(t\bar{t}) = 7.24^{+0.23}_{-0.27}$ (scales \oplus pdf) pb.

3 Dilepton and ℓ +jets channel (DØ)



Figure 2: The *b*-tagging discriminant output is shown in a) for the ee + 2 jets sample, where the expected $t\bar{t}$ cross section is normalized to 7.45 pb. The sample composition of the selected ℓ +jets data as a function of the jet multiplicity for b) zero *b*-tagged jets and c) more than 1 *b*-tagged jet.

b-tagging discriminant distribution is shown in Figure 2 a), where the expected $t\bar{t}$ cross section is normalized to 7.45 pb. The cross section is measured to be $\sigma_{tot}(t\bar{t}) = 7.36^{+0.90}_{-0.76}(\text{stat} + \text{sys})$ pb.

The measurement in the ℓ +jets channel uses 5.4 fb⁻¹ of data [8]. Events compatible with the ℓ +jets signature are selected by requiring at least 2 jets with $p_T > 20$ GeV and within $|\eta| < 2.5$, in addition an isolated lepton with $p_T > 20$ GeV is required. Electrons are selected

within $|\eta| < 1.1$, whereas for muons $|\eta| < 2.0$ is required. Additionally $\not{E}_T > 20 (25)$ GeV is required in the e+jets ($\mu+\text{jets}$) channel. The selected data are used for a combined measurement using *b*-tagging and kinematic information splitted in different channels by number of *b*-tags and jets. In addition to the $t\bar{t}$ cross section the heavy flavor contribution is fitted as well. Figure 2 b) and c) shows the sample composition of the selected data as a function of the jet multiplicity for 0 and more than 1 *b*-tagged jet. As one expects the background contributions rise towards lower jet multiplicity and the $t\bar{t}$ contribution rises strongly with number of *b*-tags (and also with number of jets). The cross section is measured to be $\sigma_{\text{tot}}(t\bar{t}) = 7.78 \pm 0.25 (\text{stat}) \pm_{0.58}^{0.65} (\text{sys} + \text{lumi})$ pb, which is in good agreement to the theory prediction and other measurements by DØ or CDF.



Figure 3: The scalar sum H_T of the p_T of the jets for the a) e+jets and b) μ +jets channel, the expected $t\bar{t}$ cross section is normalized to the measured cross section of 8.27 pb.

the scalar sum H_T of the p_T of the jets for the e+jets and μ +jets channel, respectively. Thus the established sample composition in the ℓ + 4 jets bin is used to measure differential $t\bar{t}$ cross section by first performing a kinematic fit to identify the top quarks. The output is subtracted by the background and the cross section is determined according to equation 1, where data is corrected by means of a regularized matrix unfolding. The total $t\bar{t}$ cross section is then measured to be $\sigma_{\text{tot}}(t\bar{t}) = 8.27 \pm 0.68(\text{stat}) \pm 0.50_{-58}^{0.61}$ (sys) $\pm 0.50(\text{lumi})$ pb, which is somewhat higher than the SM prediction but given the uncertainties still in agreement.

A comparison of all the discussed measurements at the Tevatron is presented in Table 2. More information about other Tevatron top quark measurements can be found here [11]. The uncertainties of a single measurement at the Tevatron are significantly larger than the uncertainties

Measurement	\mathscr{L} [fb ⁻¹]	$\sigma_{ m tot}(tar{t})$ [pb]	total rel. unc.
CDF $(\ell\ell, b\text{-tag})$	8.8	$7.09 \pm 0.49(\text{stat}) \pm 0.52(\text{sys}) \pm 0.43(\text{lumi})$	12%
CDF $(\ell + jets [5])$	4.6	$7.82 \pm 0.38(\text{stat}) \pm 0.37(\text{sys}) \pm 0.15(\sigma_Z)$	7.0%
CDF $(\ell + jets [6])$	4.3	$7.32 \pm 0.35 (\text{stat}) \pm 0.59 (\text{sys}) \pm 0.15 (\sigma_Z)$	9.6%
$DO(\ell\ell)$	5.4	$7.36^{+0.90}_{-0.76}(\mathrm{stat}\oplus\mathrm{sys})$	11%
$D\emptyset$ (ℓ +jets, b-tag)	9.7	$8.27 \pm 0.68(\text{stat}) \pm \substack{0.61\\0.58}(\text{sys}) \pm 0.50(\text{lumi})$	12.5%
$DO(\ell + jets, b-tag)$	5.3	$7.78 \pm 0.25 (\mathrm{stat}) \pm \overset{0.65}{_{0.58}} (\mathrm{sys} \oplus \mathrm{lumi})$	9.1%
Theory:			
NNLO pQCD [3]	NA	$7.24^{+0.23}_{-0.27}(\mathrm{scales}\oplus\mathrm{pdf})$	3.5%

Table 2: Summary of presented and discussed measurements of the total $t\bar{t}$ production cross sections and their uncertainties at the Tevatron. The DØ measurement in ℓ +jets using 9.7 fb⁻¹ is not optimized to measure the total cross section, hence the larger total uncertainty.

of the most current pQCD calculation ($\approx 3.5\%$), and only the combination of all available Tevatron cross section measurements [10] yields an uncertainty closer to the theoretical one.

4 Dilepton and ℓ +jets channel (ATLAS)

The production of $t\bar{t}$ pairs at the LHC is strongly enhanced by the higher energy, resulting in 20 – 30 times higher cross sections if compared to the Tevatron. Thus measurements in the dilepton and ℓ +jets channel are not statistically limited and the uncertainties are dominated by systematic uncertainties. Both channels can be selected with high purity, with the dilepton $e\mu$ channel being almost background free.

ATLAS performed a measurement of the $t\bar{t}$ cross section in the ℓ +jets channel using 5.8 fb⁻¹ of data at $\sqrt{s} = 8 \text{ TeV}$ [12]. Events are triggered by the single electron or muon trigger and verified off-line by requiring a reconstructed isolated e or μ with $p_T > 40$ GeV and $|\eta| < 2.5$, electrons in the region $1.37 < |\eta| < 1.52$ are excluded. A second lepton is vetoed. For electrons (muons) a cut of $\not\!\!\!E_T > 30 (20)$ GeV, as well as a cut on the transverse mass of the W of $M_T(W) > 30$ GeV is required. For muons the sum of $M_T(W) + \not\!\!\!E_T$ is required to be larger than 60 GeV. Furthermore at least three jets with $p_T > 25$ GeV and $|\eta| < 2.5$ are required, and at least one of the jets needs to be b-tagged. Additional quality cuts are applied [12]. The $t\bar{t}$ cross section is measured from a fit to a likelihood discriminant $D_i = L_i^s / (L_i^s + L_i^b)$ based on the lepton η and the transformed event aplanarity A', which is given by $A' = \exp(-8 \cdot A)$ (the aplanarity A is based on the momenta of all jets and the lepton). Figure 4 shows the likelihood discriminant for the a) e+jets channel and b) for the μ +jets channel. Both channels are well described by the background contributions and in contrast to $t\bar{t}$ production in $p\bar{p}$ collisions, single top quark production is amongst the dominant background contributions. The total $t\bar{t}$ cross section assuming $m_t = 172.5$ GeV is then measured to be $\sigma_{tot}(t\bar{t}) = 241 \pm 2(\text{stat}) \pm 31(\text{sys}) \pm 9(\text{lumi})$ pb. The dominant systematic uncertainties arise from the modeling of the signal implemented in MC, the jet and E_T reconstruction and calibration followed by the lepton trigger, identification and reconstruction. The measurement agrees with CMS measurements (see Table 3) and is in agreement with the latest theory prediction of $\sigma_{tot}(t\bar{t}) = 252.9^{+13.3}_{-14.5}$ (scales \oplus pdf $\oplus \alpha_s$) pb [3].

The ATLAS measurement in the dilepton channel $(e\mu)$ uses the full data set available at



Figure 4: The likelihood discriminant based on lepton η and the aplanarity A' is shown in a) for the e+jets and in b) for the μ +jets channel. The expected $t\bar{t}$ cross section is normalized to the measured cross section.

 $\sqrt{s} = 8$ TeV [13]. It is a sample with very high purity comprising $\mathcal{O}(10^4) t\bar{t}$ pairs. Events are selected by the single electron or muon trigger and verified off-line by requiring a reconstructed isolated lepton with $p_T > 25$ and $|\eta| < 2.5$. At least one jet with $p_T > 25$ and $|\eta| < 2.5$ is required and exactly one or exactly two of the jets needs to be *b*-tagged. The level of agreement



Figure 5: Comparison of data to signal and background contributions as a function of the lepton p_T for the a) electron and for the b) muon.

between data and MC is very good and shown in Figure 5 a) for the electron p_T and in b) for the muon p_T . The $t\bar{t}$ cross section is measured from a simultaneous determination of $\sigma_{tot}(t\bar{t})$ and the efficiency to reconstruct and b-tag jets. The measurement strategy is aimed to reduce the related systematic uncertainties of jets and b-tagging. The samples with exactly one b-jet (N_1) and two b-jets (N_2) are simultaneously fitted with $N_1 = \mathscr{L} \cdot \sigma_{t\bar{t}} \cdot \epsilon_{e\mu} \cdot 2\epsilon_b (1 - C_b \epsilon_b) + N_1^{bg}$ and $N_2 = \mathscr{L} \cdot \sigma_{t\bar{t}} \cdot \epsilon_{e\mu} \cdot C_b \epsilon_b^2 + N_1^{\text{bg}}$, where $\epsilon_{e\mu}$ is the efficiency to pass the $e\mu$ preselection and ϵ_b is the combined probability for a jet from the $t \to Wq$ to be within acceptance, reconstructed as jet and b-tagged. The correlation between two b-tagged jets is taken into account by C_b . Employing this new approach and assuming $m_t = 172.5$ GeV yields a total $t\bar{t}$ cross section of $\sigma_{\text{tot}}(t\bar{t}) = 237.7 \pm 1.7(\text{stat}) \pm 7.4(\text{sys}) \pm 7.4(\text{lumi}) \pm 4.0(\text{beam energy})$ pb. The latter uncertainty is estimated from a 0.66% uncertainty on the beam energy, which translates to a 1.7% uncertainty on the $t\bar{t}$ cross section. The combined fit of the $t\bar{t}$ cross section, the lepton, and the jet efficiencies (including b-tagging) significantly reduces the systematic uncertainties from these sources. Thus the measurement is dominated by signal model, the electron identification and the PDF uncertainties. The measurement is in agreement with the latest theory prediction at NNLO pQCD, which yields $\sigma_{\text{tot}}(t\bar{t}) = 252.9^{+13.3}_{-14.5}(\text{scales} \oplus \text{pdf} \oplus \alpha_{\text{s}})$ pb [3].

5 Dilepton and ℓ +jets channel (CMS)

 $t\bar{t}$ cross section in the ℓ +jets decay channel using 2.3 fb⁻¹ of data at \sqrt{s} = 7 TeV [14]. Events are triggered by the single e- or μ -trigger and the offline selection requires an isolated lepton with p_T > 35 GeV. Additionally electrons (muons) are required to have $|\eta| < 2.5 (2.1)$. The $/E_T$ originating from the non-reconstructed neutrinos is required to be larger than 20 GeV. At least one jet with $p_T >$ 35 GeV and $|\eta| < 2.4$ is required and at least one of the jets has to be identified as a b-jet. As an example Figure 6 shows the distribution of the secondary vertex mass for the μ +jets channel. A maximum likelihood fit using the secondary vertex mass distribution in different number of jet and The total *b*-tag bins is performed. $t\bar{t}$ cross section assuming m_t = 172.5GeV is then measured to be $\sigma_{tot}(t\bar{t}) =$ $158.1 \pm 2.1(\text{stat}) \pm 10.2(\text{sys}) \pm 3.5(\text{lumi})$ pb, which is in agreement with the latest theory prediction of $\sigma_{tot}(t\bar{t})$ = $172^{+4.4}_{-5.8}$ (scales) $^{+4.7}_{-4.8}$ (pdf) pb [3]. Table 3 gives a comparison to an ATLAS measurement in the ℓ +jets channel [15] as well as to results in the dilepton channel [16, 17] (these result were not presented at TOP2013).

CMS performed a combined measurement of the heavy flavor contribution and the



Figure 6: The secondary vertex mass distribution for different bins of the number of jets and *b*-tags. The expected $t\bar{t}$ cross section is normalized to 7.45 pb.

Two CMS measurements are presented at the increased energy of $\sqrt{s} = 8$ TeV, one in the ℓ +jets channel [18] and one using events in the dilepton channel (*ee*, $\mu\mu$ and $e\mu$) [19]. In case of the ℓ +jets channel events are required to have an isolated electron or muon with $p_T > 30$ (26) GeV and $|\eta| < 2.5$ (2.1) and at least four jets. The two leading jets are required to have $p_T > 45$ GeV, whereas the next-two leading jets are selected if $p_T > 35$ GeV. All jets are required to be within $|\eta|$ of 2.5 and at least one jet needs to be *b*-tagged. The $t\bar{t}$ cross section is determined from a template fit to the invariant mass distribution of the lepton and the *b* quark $M_{\ell b}$ (see Figure 7 a) and b)). The total $t\bar{t}$ cross section assuming $m_t = 172.5$ GeV is then measured to



Figure 7: The invariant mass distribution $M_{\ell b}$ for a) electrons and b) muons, the expected $t\bar{t}$ cross section is normalized to the measured cross section of 8.27 pb.

be $\sigma_{\text{tot}}(t\bar{t}) = 228.4 \pm 9(\text{stat})^{+29.0}_{-26.0}(\text{sys}) \pm 10(\text{lumi})$ pb. The dominating systematic uncertainties arise from the jet energy scale and the *b*-tagging efficiency measurement. The measurement is



Figure 8: Data are compared to MC for different number of *b*-tags for the a) $e\mu$ channel and for the b) summed *ee* and $\mu\mu$ channel.

in agreement with the latest theory prediction of $\sigma_{tot}(t\bar{t}) = 245.8^{+6.2}_{-8.4}$ (scales) $^{+6.2}_{-6.4}$ (pdf) pb [3]. In addition a CMS measurement in the dilepton channel at 8 TeV is presented. Events are selected by requiring isolated electrons or muons with $p_T > 20$ GeV and $|\eta| < 2.5$ or $|\eta| < 2.4$, respectively. To suppress background from Z+jets contributions an invariant mass window cut

Measurement	\mathscr{L} [fb ⁻¹]	$\sigma_{ m tot}(tar{t})$ [pb]	total rel. unc.
ATLAS 7 TeV $(\ell + jets)$	0.7	$179 \pm 4(\text{stat}) \pm 9(\text{sys}) \pm 7(\text{lumi})$	6.7%
ATLAS 7 TeV $(\ell \ell)$	0.7	$176 \pm 5(\text{stat}) \stackrel{+14}{_{-11}}(\text{sys}) \pm 8(\text{lumi})$	8.9%
CMS 7 TeV $(\ell + jets)$	2.3	$158.1 \pm 2.1(\text{stat}) \pm 10.2(\text{sys}) \pm 3.5(\text{lumi})$	6.9%
CMS 7 TeV $(\ell\ell)$	2.3	$162 \pm 2(\text{stat}) \pm 5(\text{sys}) \pm 4(\text{lumi})$	4.1%
Theory:			
NNLO pQCD	NA	$172.0^{+6.4}_{-7.5}$ (scales \oplus pdf) [3]	4%
ATLAS 8 TeV $(\ell + jets)$	5.8	$241 \pm 2(\text{stat}) \pm 31(\text{sys}) \pm 9(\text{lumi})$	13%
ATLAS 8 TeV $(e\mu)$	20.3	$237.1 \pm 1.7(\text{stat}) \pm 7.4(\text{sys}) \pm 7.4(\text{lumi})$	4.7%
CMS 8 TeV $(\ell + jets)$	2.8	$228.4 \pm 9(\text{stat})^{+29.0}_{-26.0}(\text{sys}) \pm 10(\text{lumi})$	13%
CMS 8 TeV $(\ell\ell)$	2.4	$227 \pm 3(\text{stat}) \pm 11(\text{sys}) \pm 10(\text{lumi})$	7%
Theory:			
NNLO $pQCD$	NA	$252.9^{+13.3}_{-14.5}$ (scales $\oplus \mathrm{pdf} \oplus \alpha_{\mathrm{s}}$) [3]	5.5%

Table 3: Summary of presented and discussed measurements of the total $t\bar{t}$ production cross sections and their uncertainties at the LHC. The ATLAS measurement in the $e\mu$ channel has an additional uncertainty of 4.0 pb originating from the uncertainty on the beam energy.

6 Conclusion

Measurements of the $t\bar{t}$ production cross section in electron and muon final states have been presented. The results from Tevatron and the LHC are in good agreement with theory predictions. More results from the Tevatron using the full data set are expected very soon. The results at the LHC are compatible between ATLAS and CMS and overall have small uncertainties despite the higher pile-up environment at $\sqrt{s} = 8$ TeV compared to $\sqrt{s} = 7$ TeV. The individual LHC measurements are challenging the precision of the theory calculations. The most precise measurement to date at $\sqrt{s} = 8$ TeV uses events in the dilepton decay channel by ATLAS and more high precision results are to come. INCLUSIVE TOP PAIR PRODUCTION AT TEVATRON AND LHC IN ELECTRON/MUON ...

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Measurements of $t\bar{t}\gamma$, $t\bar{t}Z$, and $t\bar{t}W$ production

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Measurements of the production of top quark pairs in association with electroweak vector bosons from the CMS, ATLAS and CDF collaborations are presented. The CDF collaboration measures the cross section of top pair plus photon production and the ratio of this cross section the to inclusive top pair cross section using 6 fb⁻¹ of data at $\sqrt{s} = 1.96$ TeV with the results $\sigma_{t\bar{t}\gamma} = 0.18 \pm 0.07(stat.) \pm 0.04(sys.) \pm 0.01(lumi.)$ pb and $\sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}=0.024\pm0.009}$. The ATLAS collaboration measures the top pair plus photon cross section at $\sqrt{s} = 7$ TeV using 1.04 fb⁻¹ of data with the result $\sigma_{t\bar{t}\gamma} = 2.0 \pm 0.5(stat.) \pm 0.7(sys.) \pm 0.08(lumi.)$. The ATLAS collaboration also sets an upper limit on $\sigma_{t\bar{t}Z}$ of 0.71 pb using 4.0 fb⁻¹ of data at $\sqrt{s} = 7$ TeV. The CMS collaboration measures the $\sigma_{t\bar{t}Z}$ and $\sigma_{t\bar{t}V(V=W,Z)}$ cross sections using 5.0 fb⁻¹ of data at $\sqrt{s} = 7$ TeV with the results $\sigma_{t\bar{t}Z} = 0.28^{+0.14}_{-0.11}(stat.)^{+0.09}_{-0.03}(sys.)$ pb.

1 Introduction

The top quark was first observed by the CDF and D0 experiments in $p\bar{p}$ collisions at the Tevatron collider in 1995 [1, 2]. The dominant production mode for the production of top quarks at hadron colliders is the production of top quark pairs via the strong interaction. Much rarer production modes in which the top quark pair is produced in association with an electroweak boson (γ, Z, W^{\pm}) are now also within reach due to the large datasets recorded at the Tevatron and LHC colliders. Measurements of these processes allow precise tests of the predictive power of the Standard Model (SM) [3]. Due to its large mass the top quark could play a crucial role in electroweak symmetry breaking. These measurements presented in this note have the potential to allow direct access to the electroweak couplings of the top quark. These processes have similar cross sections and are significant backgrounds to the production of top pairs in association with a Higgs boson. Hence these measurement provide valuable constraints which will improve the precision with which the $t\bar{t} + H$ process can be measured. In Beyond the Standard Model (BSM) models such as technicolor and models containing strongly coupled Higgs the top quark exhibits altered couplings. As a result these measurements can place constraints on these classes of BSM physics models.

In this note, a suite of measurements of these processes performed by the CDF, ATLAS and CMS experiments are detailed.

Measurements of $t\bar{t}\gamma$, $t\bar{t}Z$, and $t\bar{t}W$ production

2 CDF measurements

CDF measures both the cross section of top pair production in association with a photon $(\sigma_{t\bar{t}\gamma})$ and the ratio between $\sigma_{t\bar{t}\gamma}$ and the inclusive top pair production cross section $(\sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}})$ [4]. The measurement utilises 6.0fb^{-1} of integrated luminosity from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected using the CDF II detector. The analysis focuses on the semi-leptonic decay channel by requiring an electron (e) or muon (μ) with $E_T^{e,\mu} > 20$ GeV, a photon (γ) with $E_T^{\gamma} > 10$ GeV, a jet identified as originating from a b-quark, missing transverse energy $E_T^{miss} > 20$ GeV, total transverse hadronic energy, (H_T) greater than 200 GeV and three or more jets. In order to suppress the backgrounds from photons or leptons that originate from hadronic decay within jets both the lepton and the photon are required to be isolated from other activity in the calorimeter.

After the application of these criteria, the selected event sample is dominated by $t\bar{t}\gamma$. Inclusive $t\bar{t}$ production is selected by applying nearly the same set of criteria with the omission of the photon requirement. These similar selections ensure that systematic uncertainties largely cancel in the measurement of $\sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}}$. The numbers of background events passing these criteria are estimated using simulation. Using these selected events the following results are obtained: $\sigma_{t\bar{t}\gamma} = 0.18 \pm 0.08$ pb and $\sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}} = 0.024 \pm 0.009$. These results are consistent with the SM prediction.

3 ATLAS measurements

3.1 $\sigma_{t\bar{t}\gamma}$

ATLAS performs a first measurement of the $\sigma_{t\bar{t}\gamma}$ in pp collisions using 1.04 fb⁻¹ of data at $\sqrt{s} = 7$ TeV [5]. This measurement focuses on the single or dilepton decay channels including τ leptons. Electron candidates are defined as energy deposits in the electromagnetic calorimeter with an associated, well measured track. All electron candidates are required to have a transverse momentum (P_T) greater than 25 GeV and $|\eta_c| < 2.47$ where η_c is the pseudorapidity of the electromagnetic cluster associated with the electron. Muon candidates are reconstructed from track segments in the different layers of the muon chambers and are matched with tracks found in the inner detector. In this analysis, muon candidates are required to have $P_T > 25$ GeV and $|\eta| < 2.5$. In order to suppress the backgrounds from hadrons mimicking leptons and the semi-leptomic decays of heavy quarks within jets, the lepton candidates are required to be isolated. Since photons can convert into e^+e^- pairs by interacting with detector material, there are two categories of reconstructed photons. Photons are reconstructed as unconverted photons or are recovered from identified electrons that are more likely to be converted photons. The photon falls into the fiducial region if the $|\eta|$ of its cluster is smaller than 2.37 and not in the transition region between barrel and end-cap calorimeters. The transverse energy of the photon cluster is required to be larger than 15 GeV. Photons must fulfil a set of tight requirements on shower shapes and hadronic leakage. No isolation criterion is applied, since this information is used to estimate the fraction of photon candidates from misidentified hadrons in the final fit.

The event selection requires the presence of exactly one reconstructed μ (e) with $P_T > 20$ (25) GeV, $E_T^{miss} > 20$ GeV and $E_T^{miss} + m_T(W) > 60$ GeV in the muon channel and $E_T^{miss} > 35$ GeV and $E_T^{miss} + m_T(W) > 25$ GeV in the electron channel. In addition the events are required to contain at least four jets, one of which has been identified as originating from a b-quark. In order to select photons the following criteria are applied: the event must contain

one well-identified photon with $E_T > 15$ GeV. In the electron channel the invariant mass of the electron and photon is required to be outside a ± 5 GeV mass window around the Z peak to reject $Z \rightarrow e^+e^-$ events.

The cross section is extracted via a template fit to the distribution of the p_T^{cone20} variable. p_T^{cone20} is defined as the scalar sum of the transverse momenta of all the tracks in the cone with $\Delta \mathbf{R} < 0.2$ around the photon candidate. Signal photons are generally isolated, fake photons arising from hadrons are typically surrounded by other particles from the fragmentation process. The template for signal photons is obtained from $Z \to e^+e^-$ events in data by exploiting the similar p_T^{cone20} distributions of electrons and signal photons. The template for fake photons arising from hadrons is extracted from a data sample using jet triggers. Backgrounds from top pair events with electrons faking photons are estimated by applying a data-derived scale factor to a simulated sample of top pair events. Other backgrounds from top pair events are estimated using data-driven methods.

The largest systematic uncertainty on this measurement arises from the estimation of the efficiency of photon identification. Systematic uncertainties from imperfect Monte Carlo modelling are quantified by comparing alternate $t\bar{t}$ simulations. Uncertainties due to jet energy scale and b-tagging efficiencies are estimated from the methods described in [7, 9]



Figure 1: The post-fit distributions for the single electron channel (left) and single muon channel (right). The predicted signal $t\bar{t}\gamma$ contributions is shown on top of the background contributions.

The fitted $t\bar{t}\gamma$ contribution is converted into the following results for the cross section times branching ration (BR):

$$\sigma_{t\bar{t}\gamma} \cdot BR = 2.0 \pm 0.5 \; (stat.) \; pb \tag{1}$$

which is consistent with the SM prediction.

3.2 $\sigma_{t\bar{t}Z}$

ATLAS performs a search for $t\bar{t}Z$ in production in pp collisions using 4.7 fb⁻¹ of data at $\sqrt{s} = 7$ TeV [6]. The analysis concentrates on final states containing exactly three leptons, in which the Z boson decays to a pair of leptons and one of the W boson from the top decay decays leptonically.

Measurements of $t\bar{t}\gamma$, $t\bar{t}Z$, and $t\bar{t}W$ production

All electron candidates are required be isolated and to have $|\eta_{cluster}| < 2.47$ and $E_T > 25$ GeV. Muon candidates are required to be isolated and to satisfy $P_T > 20$ GeV and $|\eta| < 2.5$. All jets are required to satisfy $P_T > 20$ GeV and $|\eta| < 2.5$. Events are required to have exactly three leptons, four jets with $P_T > 30$ GeV and $E_T^{miss} > 30$ GeV. Additionally, one pair of leptons with opposite-sign charges and same flavour and a dilepton invariant mass consistent with a Z boson is required. In the final signal region, at least of the jets is required to be b-tagged.

There are a number of SM processes which can produce three real isolated leptons. The dominant process for the signal regions is the production of $(t\bar{b}Z + \bar{t}bZ + X)$ along with WZ + jets and ZZ + jets. The contributions of this processes to the signal region are estimated using simulation. The background from events containing fewer than three real leptons but at least one fake leptons is estimated using a data-driven technique known as the *matrix-method* that is described in [6].

Systematic uncertainties arising from the mis-modelling of lepton trigger, reconstruction, identification and isolation efficiencies are estimated from data. The lepton momentum scale and resolution is measured similarly. The jet energy scale and b-tagging efficiencies are measured using techniques described in [8, 10, 11] Systematic uncertainties on individual reconstructed object are propagated to the E_T^{miss} . The effect of variations of the renormalisation and factorisation scales is also included. The effect of mis-modelling of initial and final state radiation (ISR/FSR) is studied by varying the amount of (ISR/FSR) in the $t\bar{t}Z$ simulation. A cross section uncertainty of 50% is applied for the background process WZ + jets. In table 1 the numbers of events expected from simulation and observed in data for the signal region are shown. One event is observed in the data. The expected number of signal events in the signal region is 0.85 ± 0.04 (stat.) ± 0.14 (syst.). The expected number of background events from SM processes with three real leptons, obtained from simulation, is 0.28 ± 0.05 (stat.) ± 0.14 (syst.). The expected fake lepton background is $0.0^{+1.6}_{-0.0}$

	SR
$t\bar{t}Z$	0.85 ± 0.04
WZ+jets	0.06 ± 0.04
ZZ+jets	0.014 ± 0.014
$t\bar{t}W$	0.011 ± 0.008
$(t\bar{b}Z + \bar{t}bZ) + X(= jj, l\nu)$	0.125 ± 0.013
WZbbjj	0.065 ± 0.016
MC Total	1.13 ± 0.06
Fake lepton background	$0.0^{+1.6}_{-0.0}$
Observed	1

Table 1: Number of events observed in data and expected from the $t\bar{t}Z$ signal process and various background for the signal region. The uncertainties shown on the backgrounds estimated using simulation are statistical only.

The results are translated into a 95% credibility upper limit on $\sigma_{t\bar{t}Z}$ using a Bayesian prescription. A flat prior probability distribution is assumed for the number of signal events and a Poisson likelihood is used. The observed upper limit is 0.71 pb with an expectation of 0.74 pb which is consistent with the SM prediction.

4 CMS measurements

CMS performs two complementary analyses to provide the first measurement of the production of a $t\bar{t}$ pair in association with a vector boson [12]. The analyses utilise 5.0 fb⁻¹ of pp collision data at $\sqrt{s} = 7$ TeV. Muons are measured with the combination of the tracker and the muon system, in the pseudorapidity range $|\eta| < 2.4$. Electrons are detected as tracks in the tracker pointing to energy clusters in the electromagnetic calorimeter up to $|\eta| = 2.5$. Both muons and electrons are required to be isolated and to have P_T greater than 20 GeV. Jets are required to have an $|\eta| < 2.4$ and a $P_T > 20$ GeV. Jet are identified as originating from b-quarks by a b-tagging algorithm which provides a efficiency for tagging b-jets of approximately 65% and a misidentification 1%.

4.1 Trilepton analysis

The trilepton analysis aims to select events from the process $pp \to t\bar{t}Z \to (t \to bl^{\pm}\nu)(t \to bjj)(Z \to l^{\pm}l^{\pm})$ (with l = e or μ). The analysis requires two same-flavour, opposite sign charge leptons with $P_T > 20$ GeV, where the dilepton system must have an invariant mass between 81 and 101 GeV and $P_T > 35$ GeV. In addition, a third lepton with $P_T > 10$ GeV and at least three jets two of which have been b-tagged are required. Finally the scalar sum of all the selected jets (H_T) is required to be larger than 120 GeV. Background contributions arise from the Drell-Yan, $t\bar{t}$ and WZ processes. Event samples with looser requirements are used to determine the background contributions from the data. The total systematic uncertainty is evaluated by assessing the relative change in signal efficiency and background yield in the simulation when varying relevant sources of systematic uncertainties in the simulation by $\pm 1 \sigma$. The dominant uncertainty comes from the background estimate. The cross section is extracted simultaneously from all channels with the result:

$$\sigma_{t\bar{t}Z} = 0.28^{+0.14}_{-0.11}(stat.)^{+0.06}_{-0.03}(sys.) \text{ pb}$$
⁽²⁾

This measured cross section is compatible with the NLO prediction of the Standard Model which is $0.137^{+0.012}_{-0.016}$ pb.

4.2 Dilepton analysis

The dilepton analysis aims to select events originating from the processes: $pp \to t\bar{t}W \to (t \to bl^{\pm}\nu)(t \to bjj)(W \to l^{\pm}\nu)$ and $pp \to t\bar{t}Z \to (t \to bl^{\pm}\nu)(t \to bjj)(Z \to l^{\pm}l^{\mp})$ (with l = e or μ). The dilepton analysis requires the presence of two same-sign dileptons, one with $P_T > 55$ GeV and one with $P_T > 30$ GeV with a dilepton invariant mass greater than 8 GeV, at least three jets with $P_T > 20$ GeV one of which is b-tagged and $H_T > 100$ GeV. The main background contributions arise from the non prompt leptons or from mis-reconstruction effects and are estimated using the data. Systematic uncertainties relative to experimental measurements or model uncertainties are evaluated similarly to the trilepton analysis.

In Fig. 2 the event yields separated in lepton flavour channels for the trilepton and dilepton analyses are shown. A total of 16 events are selected in data, compared to an expected background contribution of 9.2 ± 2.6 event. The significance of the observed $t\bar{t}V$ signal is equivalent to 3.0 standard deviations. A combined cross section is measured simultaneously from the three channels with the result:

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$$\sigma_{t\bar{t}V} = 0.43^{+0.17}_{-0.15}(stat.)^{+0.09}_{-0.07}(sys.) \text{ pb}$$
(3)

This result is compatible with the NLO predictions of the standard model which is $0.306^{+0.031}_{-0.053}$



Figure 2: Event yields separated in lepton flavour channels for the trilepton (left) and dilepton channels (right). The expected contributions form signal and background processes are indicated.

5 Conclusions

The following measurements of $t\bar{t} + \gamma$, $t\bar{t} + Z$ and $t\bar{t} + W$ from the CDF, ATLAS and CMS experiments have been presented. The CDF experiment measured both $\sigma_{t\bar{t}\gamma}$ and the cross section ratio $\frac{\sigma_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}}$ at $\sqrt{s} = 1.96$ TeV. The ATLAS experiment measured the $\sigma_{t\bar{t}\gamma}$ cross section and sets upper limits on the $\sigma_{t\bar{t}Z}$ at cross section $\sqrt{s} = 7$ TeV. The CMS experiment measured $\sigma_{t\bar{t}Z}$ and the inclusive cross section $\sigma_{t\bar{t}V}$ where V = W, Z at $\sqrt{s} = 7$ TeV. In all cases the results are consistent with the predictions of the SM.

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Measurement of the jet multiplicity in dileptonic top-quark pair events at $\sqrt{s} = 8$ TeV

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Jet multiplicity distributions in top pair events are measured in pp collisions at $\sqrt{s} = 8$ TeV with the CMS detector using a dataset corresponding to 19.6 fb⁻¹. The normalized differential top-antitop quark cross section is measured in the dileptonic t \bar{t} decay channels as a function of the jet multiplicity for different jet transverse momentum (p_T) thresholds. Furthermore, the distribution of the fraction of events without additional jets above a threshold is measured as functions of the additional jets p_T and of the scalar sum of the transverse momenta of all additional jets. The data are compared to several predictions from perturbative QCD calculations.

1 Introduction

A high fraction of processes that occur in pp collisions at the Large Hadron Collider involve large hadronic activity and hence high jet multiplicities. The fraction of $t\bar{t}$ events with additional jets in the final state contributes to about half of the total number of $t\bar{t}$ events. These events with high jet multiplicities provide a handle to constrain initial and final state radiation, test perturbative QCD, and to tune parton shower models. Furthermore, these events are dominant background for associated Higgs + $t\bar{t}$ production and for several searches for physics beyond the Standard Model. The measurement [1] of jet production in association with top pairs is performed using dileptonic decays of top quarks in proton-proton collisions at $\sqrt{s} = 8$ TeV using data collected with the CMS detector [2] corresponding to a luminosity of 19.6 fb⁻¹.

2 Event selection

The dileptonic decays of the top-quark pair are characterized by a subsequent decay of both W-bosons to a lepton and a neutrino. The final states containing e^+e^- , $\mu^+\mu^-$, and $e^\pm\mu^\mp$ are subject of the presented analysis. Therefore, events are selected with at least two oppositely charged isolated leptons ($p_T > 20$ GeV, $|\eta| < 2.4$) and two jets ($p_T > 30$ GeV, $|\eta| < 2.4$) of which at least one is identified as a b-jet to reduce background from Drell-Yan processes. Heavy-flavor resonance decays are suppressed by removing events with a dilepton invariant mass $M_{ll} < 20$ GeV in all channels. Contributions from Z production in the *ee* and $\mu\mu$ channels are further reduced by requiring M_{ll} to be outside of (91 ± 15) GeV and $E_T > 40$ GeV. A kinematic reconstruction is performed to distinguish between the two b-jets originating from the tt decay and additional jets.

3 Differential cross section as a function of jet multiplicity

The differential cross section as a function of jet multiplicity is defined as

$$\frac{d\sigma_{t\bar{t}}}{dN_i^i} = \frac{N_{data}^i - N_{bkg}^i}{\Delta_x^i \epsilon^i \mathcal{L}} \tag{1}$$

where N_j^i is the jet multiplicity, N_{data}^i is the number of selected events in jet multiplicity bin i, N_{bkg}^i is the number of estimated background events, \mathcal{L} the integrated luminosity, Δ_x^i is the bin width, and ϵ^i the selection efficiency including acceptance effects. Detector effects are corrected using a regularized single-value-decomposition unfolding technique. The differential cross section is normalized to the total cross section measured in the same analysis and the results of all studied top-decay channels are combined. Systematic uncertainties are estimated for each jet multiplicity individually. The dominant contributions arise from the jet energy scale and variations of model parameters. The measurement is restricted to the visible phase space defined in the simulation: all decay products of the top-quark pair (except for the neutrinos) and all additional jets are required to fulfill the acceptance criteria $|\eta^l| < 2.4, p_T^l > 20$ GeV (leptons) and $|\eta^j| < 2.4, p_T^j > 30$ GeV (jets). A jet is rejected if it contains a leading lepton in a cone of $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} = 0.4$.

In Figure 1 the normalized differential cross section for two different jet p_T thresholds is shown. The data are compared to MadGraph and POWHEG, both interfaced to PYTHIA, and MC@NLO interfaced to HERWIG. In all simulations, the top-quark mass is set to 172.5 GeV. Missing higher order QCD contributions to the matrix element calculations are estimated by variations of renormalization (μ_R) and factorization scale (μ_F). The scale ($Q^2 = \mu_R^2 = \mu_F^2$) in MADGRAPH is set to the squared sum of top mass and the p_T of all visible decay products. It is varied by a factor of four up and down. A preference of the data to higher Q^2 in MADGRAPH is observed.

4 Additional jet gap fraction

The gap fraction is defined as the fraction of events that do not contain additional jets above a certain p_T threshold. This observable provides insight into jet activity arising from gluon radiation. Additional generated jets are defined in the visible phase space except for the two highest p_T jets originating from B-hadrons.

In Figure 2 the gap fraction for different pseudorapidity ranges is shown. The predictions from MADGRAPH+PYTHIA and POWHEG+PYTHIA are similar and slightly below the measured values. MC@NLO+HERWIG predicts a higher gap fraction for central η , but agrees well with data for larger pseudorapidities.

The veto on additional jets can be applied to the scalar sum of all additional jet transverse momenta (H_T) . The resulting gap fraction for the full pseudorapidity range is presented in Figure 3. The values obtained with MADGRAPH+PYTHIA and POWHEG+PYTHIA are slightly below the measurements, whereas MC@NLO+HERWIG predicts a slightly higher gap fraction. Predictions using MADGRAPH+PYTHIA with the nominal and a higher choice of Q^2 describe the data better than the ones with lower scale choice.



Figure 1: Measurements of the normalized differential cross section shown as a function of jet multiplicity for jet $p_T > 30$ GeV (top) and jet $p_T > 60$ GeV (bottom). The inner (outer) error bars represent statistical (total) experimental uncertainties. Left: the measurements (closed symbols) are compared to predictions using MADGRAPH+PYTHIA (solid line), POWHEG+PYTHIA (dashed line) and MC@NLO+HERWIG (dash-dotted line). Right: The measurements are compared to MADGRAPH predictions with different choices of the scale in the matrix element (Q^2) and for the parton-shower matching.



Figure 2: Gap fraction as a function of leading additional jet p_T for different η regions. The measurements (closed symbols) are presented with statistical uncertainties (vertical error bars, covered by the size of the symbols) and total uncertainties, represented by a shaded band. For comparison, predictions from MADGRAPH+PYTHIA (dark solid line), POWHEG+PYTHIA (light solid line) and MC@NLO+HERWIG (dashed line) are shown.





Figure 3: Gap fraction as a function of H_T . The measurements (closed symbols) are presented with statistical uncertainties (vertical error bars, covered by the size of the symbols) and total uncertainties, represented by a shaded band. For comparison, predictions from MAD-GRAPH+PYTHIA (dark solid line), POWHEG+PYTHIA (light solid line) and MC@NLO+HERWIG (dashed line) are shown on the left. On the right side, the measurements are compared to MAD-GRAPH predictions with different choices of the scale in the matrix element (Q^2) and for the parton-shower matching.

5 Summary

The normalized top-pair production cross section in pp collisions at $\sqrt{s} = 8$ TeV is measured at the CMS experiment using data based on an integrated luminosity of 19.6 fb⁻¹. The cross section is measured in the dileptonic decay channels and presented as a function of the number of jets in the event. The gap fraction is studied as a function of leading-jet transverse momentum and as a function of the scalar sum of all additional jets. The measurements are compared to QCD predictions obtained using MADGRAPH and POWHEG, interfaced to PYTHIA, and MC@NLO interfaced to HERWIG. Different scale choices for the hard scattering and the parton shower matching are studied.

References

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New physics in single-top production

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In this paper an overview of recent results on the search for physics beyond the Standard Model in the electro-weak top-quark production from the ATLAS, D0, CDF and CMS collaborations is given. This includes searches for W' and b* resonances as well as measurements of *CP* violation, the W helicity fractions and the top-quark polarisation in single-top production. A brief review on the search for flavour-changing neutral currents and cross-section measurements with respect to the CKM matrix element $V_{\rm tb}$ is given.

1 Introduction

The electro-weak production of top-quarks (single-top) provides a unique window for searches of new physics beyond the Standard Model (SM). Effects of new physics can manifest themselves either as new resonances in the production process or alter the structure or strength of the weak coupling of the top-quark. This would result in visible mass peaks in the measurement or in deviations of the observed cross-sections from the SM prediction. Experimentally, such effects are studied best in single-top production for which the cross-section is directly proportional to the weak coupling of the top-quark. This is different for the more dominant tt production process. In top-quark pair production, any modification of the weak coupling would alter only the branching fractions of the top-quark decay which are not measurable at a hadron collider. Another advantage of single-top production is that the scale for new physics, $\Lambda_{\rm NP}$, can be probed at higher energies. The contribution of new physics to single-top production would scale as $(\sqrt{s}/\Lambda_{\rm NP})^n$, while for top-pair production its contribution is only $(m_t/\Lambda_{\rm NP})^n$ with nbeing the dimension in the effective operator framework and \sqrt{s} denoting the centre-of-mass energy of the hard scattering process. The latter can be substantially larger than the mass of the top-quark, m_t , at the Tevatron or the LHC [1, 2].

Modifications of the Wtb vertex by new physics can be described by an effective Lagrangian using so-called anomalous couplings

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu} \left(V_{\rm L}P_{\rm L} + V_{\rm R}P_{\rm R}\right) tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}}{m_{\rm W}}q_{\nu} \left(g_{\rm L}P_{\rm L} + g_{\rm R}P_{\rm R}\right) tW_{\mu}^{-} + \text{h.c.}$$
(1)

with the projection operators $P_{\rm L,R} = \frac{1}{2}(1 \mp \gamma^5)$ and the four-momentum transfer q at the Wtb vertex. The anomalous couplings $V_{\rm L}$, $V_{\rm R}$, $g_{\rm L}$ and $g_{\rm R}$ are all complex and vanish in the SM, except for $V_{\rm L}$ which is real and equal to $V_{\rm tb}$.

In the SM three production channels exist. These are the production in the t and s-channel, and the associated production of a W boson and a top-quark, as shown in Fig. 1. For all three channels cross-section calculations are available at next-to-leading order (NLO) QCD [3, 4, 5].



Figure 1: Feynman diagrams of single-top production at leading-order QCD in the SM. Three production channels exist: the exchange of a W in the *t*-channel (a), *s*-channel production (b) and the associated production of a W boson (c).

Single-top production was first observed at the Tevatron [6, 7] in the t and s-channel and later also at the LHC [8, 9, 10, 11] in the t and Wt channels. All results are consistent with the SM prediction.

2 W' Searches

Charged massive vector gauge bosons, W', are proposed by several extensions of the SM, such as warped extra-dimensions [12, 13, 14], technicolour models [15, 16], right-handed massive W bosons [17] or little higgs theories [18, 19]. As indicated in Fig. 2, the final-state of the W' decay is the same as for the s-channel production in the SM. The motivation to choose the W' \rightarrow tb $\rightarrow \ell \nu$ bb channel is two-fold: many models propose large couplings to the third generation of quarks which also disfavour the all-hadronic searches, and moreover, searches for leptonic decays of the W'



Figure 2: W' production at tree-level. Besides the W' $\rightarrow t\bar{b}$ process shown, the process W' $\rightarrow \bar{t}b$ also exists.

have a lower sensitivity to the lepto-phobic W' models. In order to perform model-independent tests, one defines an effective Lagrangian containing left and right-handed couplings of the W'

$$\mathcal{L} = \frac{V'_{ij}}{2\sqrt{2}} \bar{f}_i \gamma_\mu \left(g'_{\mathrm{R}_{ij}} (1+\gamma^5) + g'_{\mathrm{L}_{ij}} (1-\gamma^5) \right) W'^\mu f_j + h.c.$$
(2)

with the left-handed and right-handed couplings $g'_{\rm L}$, $g'_{\rm R}$ and V' denoting the CKM matrix element in the case of quarks and δ_{ij} for leptons. For right-handed couplings the situation is more complex since the mass of the right-handed neutrino involved in the process is not known. For small masses of the right-handed neutrino, hadronic and leptonic decays are allowed, while for masses larger than the W' mass only hadronic decays are allowed. The left-handed W' (W'_L) can decay leptonically or hadronically, however, for the leptonic decay, the final-state is the same as for SM *s*-channel production causing an interference. A common choice for the couplings are the two pure cases, W'_L with $g_{\rm L} = g_{\rm w}$, $g_{\rm R} = 0$ and the right-handed W' (W'_R) with $g_{\rm L} = 0$, $g_{\rm R} = g_{\rm w}$, and the mixed case with $g_{\rm L} = g_{\rm w}$, $g_{\rm R} = g_{\rm w}$.



Figure 3: The left-hand figure (a) shows the upper limit on the production cross-section for $W'_{\rm R}$ times the branching ratio dependent on the W' mass. The contour plot on the right (b) shows the lower limit of the W' mass dependent on the coupling strengths $a_{\rm L}$ and $a_{\rm R}$. Both figures are taken from [20].



Figure 4: The upper figures show the upper limit on the production cross-section times branching ratio for the W'_L (a) and W'_R (b). The red lines indicate the predictions for the case $m(v_R) > m(W')$. In figures (c) and (d) the exclusion limits for the left and right-handed cases are presented dependent on the coupling strength and the W' mass. All figures are taken from [21].
2.1 W' Search at CMS

The CMS collaboration analysed 19.6 /fb of the 2012 data-set with a centre-of-mass energy of 8 TeV [20]. A cut-based analysis was performed using a typical event selection for the single-top s-channel by requiring one isolated high- p_{\perp} electron or muon, at least two high- p_{\perp} jets, at least one of them b-tagged and a significant amount of missing transverse energy. The top-quark was reconstructed by imposing a W mass constraint. The analysis results are collected in Fig. 3. Upper limits of the W' production cross-section have been determined, dependent on the W' mass, using multiple predictions for the signal in the range of 0.8-3 TeV, as shown in Fig. 3a. The signal was generated for the two scenarios of the right-handed neutrino mass, while neglecting the SM s-channel interference. A comparison of the cross-section limits with the prediction indicated by the red lines yields a lower limit for the mass of the W'_R (and W'_L when ignoring the interference with SM s-channel) of m(W') > 2.03 TeV@95% C.L. In addition, mass limits were determined by varying the coupling strengths $a_{L,R} = g_{L,R}/g_w$ in the range between 0 and 1 resulting in Fig. 3b.

2.2 W' Search at ATLAS

For the W' search at ATLAS an integrated luminosity of 14.3/fb of the 8 TeV data was analysed [21]. Instead of a simple cut-based analysis, boosted decision trees with 14 input variables were used for the signal extraction. Only the scenario with the mass of the right-handed neutrino larger than the W'_R mass was studied. As for the CMS analysis, the interference with the SM s-channel production was neglected in the case of the W'_L. Figure 4 presents the main analysis results. From the upper limits of the production cross-sections lower mass limits for W'_L and W'_R are obtained: $m(W'_L) > 1.74$ TeV and $m(W'_R) > 1.84$ TeV, both at 95% C.L. Exclusion limits of the left and right-handed coupling strengths $g_{L,R}/g_w$ versus the W' mass are also shown. In contrast to the CMS analysis the coupling strengths had been varied separately and their range was extended to values of 2.

3 b^{*} Searches

The ATLAS collaboration has published final results on searches for single b^{*} production using an integrated luminosity of 4.7/fb at $\sqrt{s} = 7 \text{ TeV}$ [22]. In this search the b^{*} resonance decays into a W boson and a single top-quark as described in [23]. These kinds of couplings to the third generation of SM quarks occur in some Randal–Sundrum models [24, 25] or composite Higgs models [26, 27, 28]. As for the W' searches, the b^{*} interaction is described by using effective Lagrangians for the production and decay of the b^{*}. They contain the left and right-handed couplings $\kappa_{\rm L}$, $\kappa_{\rm R}$



Figure 5: Observed and expected upper cross-section limits for the left-handed b^{*} production and decay at ATLAS [22]. The black line indicates the predicted cross-section.

for the b^{*} production, and $g_{\rm L}$, $g_{\rm R}$ for its decay. The analysis was performed for the case of



Figure 6: Contours for several b^* lower mass limits in the two-dimensional plane of the couplings for the production and the decay of the b^* , for the case of left-handed (a), right-handed (b) and vector-like couplings (c). All figures are taken from [22].

both outgoing W bosons decaying leptonically ("di-lepton" channel) and one of them decaying hadronically ("lepton + jets" channel). The signal, which is very similar to the associated Wt production, was discriminated by using the scalar sum of the transverse momenta of all reconstructed objects, H_{\perp} , for the di-lepton case, and using the reconstructed invariant mass m_b^* for lepton + jets final-states. The resulting upper limit on the cross-section depending on the b^{*} mass and the corresponding prediction are presented in Fig. 5. The following lower mass limits are obtained:

pure left-handed	$\kappa_{\mathrm{L}} = g_{\mathrm{L}} = 1$	$m(b_{\rm L}^*) >$	870 GeV@95% C.L.
pure right-handed	$\kappa_{\mathrm{L}} = g_{\mathrm{L}} = 0$	$m(\mathbf{b}_{\mathbf{R}}^{*}) >$	920 GeV @95% C.L.
mixed (vector-like)	$\kappa_{\mathrm{L}} = g_{\mathrm{L}} = 1$	$m(\mathbf{b}_{\mathrm{L R}}^*) > 1$	1030 GeV@95% C.L.

Mass contours in the plane of the left and right-handed couplings for the three cases are given in Fig. 6.

4 CP Violation

The violation of CP invariance is believed to be the reason for the matter-antimatter asymmetry in baryogenesis. However, the observed CPviolation in the systems of neutral kaons and Bmesons can not fully account for the observed asymmetry. The ATLAS collaboration has performed a search for possible CP violation in single-top t-channel production at a centre-ofmass energy of $\sqrt{s} = 7$ TeV using an integrated luminosity of 4.66 /fb [29]. The decay of the top-quark can be described in the most general effective operator framework by an effective Lagrangian which contains left-handed and righthanded vector couplings, $V_{\rm L}$ and $V_{\rm R}$, as well as tensor couplings $g_{\rm L}$ and $g_{\rm R}$ [30, 31]. While in the SM all couplings, except for $V_{\rm L} = V_{\rm th}$, are s



Figure 7: The angle $\theta^{\rm N}$ is defined by the lepton momentum \vec{p}^{ℓ} and the direction \vec{N} normal to the plane defined by the direction of the spectator quark $\vec{s}_{\rm t}$ and the W boson, \vec{q} , in the rest-frame of the top-quark.

the SM all couplings, except for $V_{\rm L} = V_{\rm tb}$, are supposed to be zero, a non-zero imaginary part



Figure 8: The measurement of the forward-backward asymmetry $A_{\rm FB}^{\rm N}$ allows to extract the imaginary part of the anomalous tensor coupling $g_{\rm R}$ for the top-quark decay depending on the polarisation \mathcal{P} of the top-quark (a). The difference of the normal helicity fraction $F_{\rm L}^{\rm N}$ and $F_{\rm R}^{\rm N}$ of the W boson from the top-quark decay is also shown (b). Both figures are taken from [29].

of $g_{\rm R}$ would result in a violation of CP invariance. Since in the case of single-top *t*-channel production the top-quark is highly polarised ($\mathcal{P} \approx 0.9$) along the direction of the spectator quark, the forward-backward asymmetry $A_{\rm FB}^{\rm N}$ of the angle $\theta^{\rm N}$, described in Fig. 7, is very sensitive to $\Im(g_{\rm R})$. While in the SM the value of $A_{\rm FB}^{\rm N}$ is supposed to be zero, in the general case of non-zero anomalous couplings the relation $A_{\rm FB}^{\rm N} = 0.64 \mathcal{P} \cdot \Im(g_{\rm R})$ holds. Here, $V_{\rm tb} = 1$ and $\Re(g_{\rm L}) = 0$ is assumed.

Using a standard single-top t-channel lepton + jets selection and applying an unfolding procedure for the distribution of event counts in bins of $\cos \theta^{\rm N}$ which takes migration effects into account, the ATLAS collaboration obtains $A_{\rm FB}^{\rm N} = 0.031 \pm 0.065({\rm stat.})^{+0.029}_{-0.031}({\rm syst.})$ for the forward-backward asymmetry. The resulting confidence intervals for the imaginary part of $g_{\rm R}$ depending on the degree of polarisation of the top-quark are depicted in Fig. 8a. Within its uncertainty this result is consistent with the SM expectation. The forward-backward asymmetry is also related to the W helicity fractions $F_{\rm L}^{\rm N}$ and $F_{\rm R}^{\rm N}$, which are defined in the same basis as $\theta^{\rm N}$, by $A_{\rm FB}^{\rm N} = {}^{3}\!/4\mathcal{P}\cdot(F_{\rm R}^{\rm N} - F_{\rm L}^{\rm N})$. In the SM the difference between $F_{\rm L}^{\rm N}$ and $F_{\rm R}^{\rm N}$ is zero. Figure 8b shows its confidence intervals for various values of the polarisation.

5 Helicity Fractions

The polarisation of the W boson in top-quark decays is sensitive to non-SM couplings of the Wtb vertex [32]. Since the W can be left-handed, right-handed or longitudinal, its total decay width splits into the corresponding partial widths, $\Gamma(t \to Wtb) = \Gamma_L + \Gamma_R + \Gamma_0$. The helicity fractions are defined as the branching ratios, hence $F_{L,R,0} = \Gamma_{L,R,0}/\Gamma$. Unitarity requires $F_L + F_R + F_0 = 1$. The latest SM predictions at QCD NNLO accuracy yield $F_L = 0.311(5)$, $F_R = 0.0017(1)$ and $F_0 = 0.687(5)$ [33]. In single-top events the helicity fractions can be obtained experimentally from the angular distribution of the angle θ_ℓ^* described in Fig. 7 between the lepton and the W



Figure 9: In (a) the correlation of the measurements for the W helicity fractions $F_{\rm L}$ and F_0 is shown. The obtained value for $F_{\rm R}$ is indicated in (b) in comparison to other recent $F_{\rm R}$ measurements from the LHC and Tevatron experiments. The exclusion limits obtained from the measurement of the helicity fractions for the real part of the tensor couplings $g_{\rm L}$ and $g_{\rm R}$ are shown in (c). From [34].

boson

$$\frac{1}{\Gamma} \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\ell}^{*}} = \frac{3}{8} \left(1 - \cos\theta_{\ell}^{*}\right)^{2} F_{\mathrm{L}} + \frac{3}{8} \left(1 + \cos\theta_{\ell}^{*}\right)^{2} F_{\mathrm{R}} - \frac{3}{4} \sin^{2}\theta_{\ell}^{*} F_{0} \,. \tag{3}$$

The measured helicity fractions can be used to constrain the anomalous couplings $V_{\rm L}$, $V_{\rm R}$, $g_{\rm L}$ and $g_{\rm R}$ at the Wtb decay vertex.

The CMS collaboration has released results on the W helicity fractions in single-top t-channel and s-channel events using an integrated luminosity of 1.14 /fb of the 7 TeV data-set and 4.66 /fb of the 8 TeV data-set in the μ + jets channel [34]. The helicity fractions $F_{\rm L}$ and F_0 have been used as fit parameters in a re-weighting procedure of all simulated events. A binned maximum likelihood fit of the simulated angular distributions to those in real data measured the following values: $F_{\rm L} = 0.293 \pm 0.069(\text{stat.}) \pm 0.030(\text{syst.})$ and $F_0 = 0.713 \pm 0.114(\text{stat.}) \pm 0.023(\text{syst.})$. Figure 9a shows these values together with their correlation. Assuming unitarity, a value of $F_{\rm R} = -0.006 \pm 0.057(\text{stat.}) \pm 0.027(\text{syst.})$ is obtained, which is contained in the overview of recent $F_{\rm R}$ measurements in Fig. 9b. All three measured helicity fractions are consistent with the SM prediction. The results have been used to set exclusion limits on the real parts of the anomalous tensor couplings $g_{\rm L}$ and $g_{\rm R}$ as presented in Fig. 9c. The best fit values are $g_{\rm L} = -0.014$ and $g_{\rm R} = 0.007$.

6 Top-Quark Polarisation in Single-Top Production

In single-top *t*-channel production the top-quarks are highly polarised because of the V-A structure of the Wtb vertices. New physics beyond the SM would alter these couplings and affect the polarisation as shown in [30]. The degree of polarisation of the top-quark, \mathcal{P} , is related to the spin asymmetry by

$$A_{\ell} = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} = \frac{1}{2} \mathcal{P} \cdot \alpha_{\ell} , \qquad (4)$$

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Figure 10: Measured angular distributions of $\cos \theta_{\ell}^*$ for the muon channel (a) and electron channel (b) in single-top *t*-channel production (filled black circles). The results for two different generators are shown for comparison. Both figures are taken from [35].

where α_{ℓ} denotes the spin-analysing power, which is nearly one for charged leptons being used as spin analyser. Since the top-quark spin is preferably aligned along the direction of the recoil jet (spectator), the measurement is best performed by means of the angle θ_{ℓ}^* , which is defined here as the angle between the charged lepton from the top decay and the recoil jet in the rest-frame of the top-quark. The angular distribution of θ_{ℓ}^* in the top-quark decay is directly related to the spin asymmetry and thus to the polarisation

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\ell}^{*}} = \Gamma\left(\frac{1}{2} + A_{\ell}\cos\theta_{\ell}^{*}\right) = \frac{1}{2}\Gamma\left(1 + \mathcal{P}\alpha_{\ell}\cos\theta_{\ell}^{*}\right).$$
(5)

The CMS collaboration has measured the top-quark polarisation in single-top *t*-channel production at $\sqrt{s} = 8$ TeV using an integrated luminosity of 20 /fb [35]. After a common event selection for the lepton + jets channel, the signal was enhanced by using boosted decision trees. By means of a regularised unfolding method based on generalised matrix inversion [36], the angular distributions of the angle θ_{ℓ}^* were obtained for electrons and muons, as shown in Fig.10. The forward-backward asymmetry with respect to the angle θ_{ℓ}^* is a measure for the spin asymmetry A_{ℓ} . The resulting values are:

 $\begin{array}{ll} \mbox{electron channel} & A_{\rm e} = 0.41 \pm 0.07 \; ({\rm stat.}) \pm 0.15 \; ({\rm syst.}) \\ \mbox{muon channel} & A_{\mu} = 0.29 \pm 0.11 \; ({\rm stat.}) \pm 0.28 \; ({\rm syst.}) \\ \mbox{combined} & A_{\ell} = 0.41 \pm 0.06 \; ({\rm stat.}) \pm 0.16 \; ({\rm syst.}) \\ \end{array}$

The combined result is connected to a polarisation of the top-quark in single-top *t*-channel production of $\mathcal{P} = 0.82 \pm 0.12$ (stat.) ± 0.32 (syst.).

7 Cross-Section Measurements

Combined measurements of the different single-top production channels also provide a good way to search for new physics beyond the SM. The D \emptyset collaboration recently reported evidence for single-top production in the s-channel with a significance of 3.7 standard deviations

in proton-antiproton collisions at a centre-of-mass energy of 1.96 TeV using an integrated luminosity of 9.7/fb [38]. The analysis, which was a combination of artificial neural networks, boosted decision trees and matrix elements methods, includes independent measurements of the *t*-channel and *s*-channel cross-sections. The results are shown in Fig. 11 in comparison with the prediction of the SM and those of several other models. The measurements are, however, not yet precise enough to distinguish between the predictions of the different models.

The CKM matrix element $V_{\rm tb}$, which plays a key role in searches for new physics, is directly accessible from single-top cross-section measurements by using the relation $|V_{\rm tb}|^2_{\rm obs} = \frac{\sigma_{\rm obs}}{\sigma_{\rm SM}} \cdot$ $|V_{\rm tb}|^2_{\rm SM}$. In the SM $|V_{\rm tb}|_{\rm SM} \approx 1$ and the following assumptions are used: $|V_{\rm tb}|^2 \gg |V_{\rm ts}|^2 + |V_{\rm td}|^2$ and the Wtb vertex is of V-A type while CP is conserved. Two scenarios are usually looked at: in one scenario anomalous left-handed couplings $f_1^{\rm L}$ are allowed such that values of $|V_{\rm tb} \cdot f_1^{\rm L}| > 1$ are possible, while in the other $|V_{\rm tb}|$ is restricted to the SM region of 0 to 1 with $f_1^{\rm L} = 1$. Recent results for the two scenarios by the Tevatron and LHC experiments are collected in Tab. 1. All values are consistent with the SM.



Figure 11: Single-top cross-section measurements for the t and s-channel by the D \emptyset collaboration [38]. The predictions of the SM and several other models are indicated in the figure.

Experiment	Process	$\int dL [fb]$	$ V_{ m tb} \cdot f_1^{ m L} $	$ V_{\rm tb} $ @95% C.L.	Publishe	ed
CDF	s+t	7.5	0.96 ± 0.10	> 0.78	Apr 12	[39]
DØ	s+t	9.7	$1.12^{+0.09}_{-0.08}$	> 0.92	Jun 13	[38]
CMS	t	5.0	0.96 ± 0.08	> 0.81	Sep 12	[40]
CMS	Wt	12.2	1.03 ± 0.13	> 0.78	Jul 13	[41]
ATLAS	t	5.8	$1.04_{-0.11}^{+0.10}$	> 0.80	Sep 12	[42]

Table 1: Recent results on $V_{\rm tb}$ by single-top measurements from the Tevatron and LHC experiments.

8 Summary

Single-top signatures allow many models of new physics to be tested. Several new results from the LHC and Tevatron experiments are available which are summarised in this paper. Searches for W' and b^{*} resonances conducted by ATLAS and CMS did not reveal any signal. Also, the ATLAS collaboration found no indication for CP violation in the single-top sector. The CMS collaboration measured the W boson helicity fractions and the top-quark polarisation in single-top events for the first time. No evidence for flavour-changing neutral currents was seen by ATLAS and CMS (this topic is discussed in [43] and references therein). All recent cross-section and $V_{\rm tb}$ measurements are consistent with the SM within their uncertainties.

NEW PHYSICS IN SINGLE-TOP PRODUCTION

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Theoretical summary

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This is a summary of theoretical progress presented at TOP2013. I review new results and methods in producing top quarks singly, in pairs or in association with other particles and/or jets, in addition to special aspects of its production like the forward-backward asymmetry. The role of top in certain New Physics models was discussed, as well as the careful definition of its mass. The emergent picture is one of impressive progress on the theoretical front of top quark physics.

1 Introduction

In this meeting many interesting new results in top physics were presented, in both experimental and theoretical talks. Very interestingly, and quite typically for this conference series there was much experimental detail in theoretical presentations, and vice versa.

The top quark long reigned supreme as the most interesting particle to study at highenergy colliders, but in July 2012 it was surpassed by the appearance of the Higgs boson in the ATLAS and CMS detectors. But even here top plays a key role, enabling Higgs boson production through gluon fusion and a top quark loop.

Let us briefly review why the top quark, its production and decay characteristics and its behavior in loops is such an important particle. First, it has many quantum numbers and thus couples to almost all other particles, through various (chiral, vector, scalar) structures, all of which bear scrutiny for deviations. Precise scrutiny is feasible because the large top mass implies, first, that it couples weakly to QCD, but strongly to whatever breaks the electroweak symmetry, and second, that its resulting large width minimizes hadronization effects and allows preservation of spin information.

But the possibility of its accurate study is not sufficient reason for devoting so much energy to this scrutiny. It is especially promising because top is a troublemaker for the Standard Model, contributing significantly to the quadratic divergences of the Higgs self energy. But, in yet another twist, the troublesome top quark is also a life raft for beyond the Standard Model (BSM) theories such as the MSSM, by raising, through its role in loop corrections, the allowed upper limit on the light Higgs mass in that theory.

With the Tevatron having made the first thousands top quarks, leading to its discovery and tests of some of its properties, the LHC, especially in the upcoming 13 TeV run, is a genuine top quark factory and will allow us to study the top quark in great detail, which this conference bears witness to.

THEORETICAL SUMMARY

2 Top production

To study tops, we must make them first and moreover understand very well the production mechanism. Very interesting results were reported in both pair and single top production. Let us briefly recall some basic aspects of fixed order (LO, NLO, NNLO, etc) calculations. LO is defined by the simplest way, with the lowest number of QCD interactions, in which the desired final state can be made. Usually, but not always (cf. Higgs production through gluon fusion) this implies a tree-level amplitude. The LO approximation to the cross section is the amplitude times its complex conjugate, summed (averaged) over final (initial) quantum numbers. NLO then includes both virtual corrections to either the amplitude or its complex conjugate, or the amplitude with one parton more, squared. The NNLO consists of a purely virtual 2-loop or 1-loop squared component, a 1-real plus 1-virtual component, and finally a 2-real component squared. Handling the intermediate infrared and collinear divergences is not easy, especially for NNLO. The benefit of these higher-order corrections is a more accurate estimate (due to the mere fact of including the corrections, as well as the very typical smaller resulting uncertainty due to scale variations), and a better description of the physics by allowing for extra partons. We were reminded by Frederix in this conference that NLO calculations are now fully automatized in the aMC@NLO framework [1], and that the act of calculating now is just a series of steps involving downloading the code, generate a process through python, and after writing the process to disk, start event generation with NLO plus parton shower accuracy.

2.1 Pair production

Let us review the status of, and main ideas behind theoretical calculations for top quark pair production. The inclusive top pair production cross section has always played a role that is both useful and instructive in perturbative QCD, because it only involves QCD couplings, and involves a truly large mass that must be accounted for in the matrix elements and the phase space measure. The NLO corrections were computed in the late 80's [2, 3, 4, 5]. In these first calculations phase space was (partially) integrated over analytically; a fully differential calculation was completed shortly thereafter [6]. The combination of such a fully differential calculation with parton showers, such as MC@NLO [7, 8] and POWHEG [9, 10] is now the state of the art at this order in perturbation theory. These codes combine the virtues of the exclusiveness of an parton shower event generator with the accuracy of a NLO calculation.

A recent major development has been the completion of the full NNLO calculation for the inclusive pair production cross section [11, 12, 13, 14], which was presented at this conference by Czakon. This is veritably a milestone in top quark physics. The result is a hadronic cross section computed with a theoretical accuracy at the percent level. The calculations involving corrections to both the $q\bar{q}$ and the gg channel have been completed, as well as the NLO corrections to the qg channels. For both the $q\bar{q}$ and gg channel, the second order corrections are composed of three classes of contributions, some computed at different times by various authors. These are (i) the two-loop corrections, (ii) the one-loop plus one real emission corrections, and (iii) the double real emission contribution [16, 17, 18]. The one-loop, one real emission contributions are done, since the NLO calculation for $t\bar{t}$ + jet is available [19, 20]. The two-loop virtual corrections have been performed in Refs. [21, 22, 23, 24, 25]. The methods used so far are a combination of analytical and numerical ones. The latter involve solving differential equations in the kinematic invariants, which requires a highly accurate initial condition (chosen to be at high energy), and avoiding singularities in the equations. The double-real emission contribution

was achieved through the use of a method called STRIPPER [16]. The one-loop, one-real emission diagrams could be computed with well-established techniques. The tour-de-force calculation has produced remarkable results, with good perturbative convergence and very small uncertainties. Given these properties and the excellent agreement with measurements, as shown in Fig. 1, a comparison of theory and data for the inclusive cross section can be used to infer useful knowledge about the gluon density. Recently a first study in this direction was done [26], demonstrating the feasibility and desirability of this.

On top of the exactly calculated orders one can add to arbitrarily high orders logarithms that are enhanced near threshold, i.e. threshold resummation. As the latter also underlies recent theoretical estimates of the top quark charge asymmetry, discussed in section 5, as well as various distributions, let us review this method briefly here, in general terms. When the top quark pair is produced near threshold in hadronic collisions, certain logarithms can become numerically large. It is important to note here that the definition of the threshold depends on the observable. Thus, for the inclusive cross section threshold is given by the condition $T_1: s - 4m^2 = 0$. For the transverse momentum distribution we have $T_2: s - 4(m^2 + p_T^2) = 0$, and for the doubly differential distribution in p_T and rapidity we can choose

$$T_3: s - 4(m^2 + p_T^2) \cosh y = 0$$
 or $T_3: s + t + u - 2m^2 = 0.$ (1)

The perturbative series for any of these (differential) cross sections can be in general be expressed as

$$d_{\alpha}\sigma(T_{\alpha}) = \sum_{n} \sum_{k}^{2n} \alpha_{s}^{n} c_{n,k}^{\alpha} \ln^{k}(T_{\alpha}), \qquad (2)$$

plus non-logarithmic terms. Here T_{α} represents any of the threshold conditions, suitably normalized, for the observables enumerated by α . Note that it is allowed to use e.g. T_2 for the inclusive cross section, by first analyzing $d\sigma/dp_T$ and then integrating over p_T , and similarly for T_3 . For any complete fixed order calculation this will give the same answer, but if one only selects the logarithmic terms because the exact answer is unknown, numerical differences will occur. Such kinematic differences can then be classified as a theoretical uncertainty [27].

The threshold logarithms result from integration over phase space regions where the emitted gluons are soft and/or collinear to their on-shell emitter. Resummation concerns itself with carrying out the sum in Eq. (2), and the result takes the generic form

$$d\sigma = \exp\left(Lg_0(\alpha_s L) + g_1(\alpha_s L) + \alpha_s g_2(\alpha_s L) + \ldots\right) \times C(\alpha_s).$$
(3)

Including up to the function g_i in the exponent amounts to NⁱLL resummation, with the coefficient $C(\alpha_s)$ then evaluated to i-1 order. Key benefits of threshold resummation are (i) gaining all-order control of the large, positive terms plague fixed-order perturbation theory, thereby restoring predictive power, and (ii) reduction of scale uncertainty. Regarding the first point, the reason these resummable terms are positive for the top quark pair inclusive cross section is that, while the hadronic cross section is Sudakov suppressed near threshold, the PDF's provide too much suppression, which the partonic cross section must then partially compensate with positive corrections. Regarding the second point, when examining the sources of μ_F dependence, they occur both in the PDF and in the partonic cross section now both *in the exponent*, which improves the cancellation[28].

The state-of-the-art accuracy for threshold resummation for inclusive pair production cross section at present is NNLL [29, 30]. From such all-order results, approximate NNLO results



Figure 1: Left pane: NNLO-NNLL prediction for the LHC as function of the collider c.m. energy. Right pane: progress in reducing scale variation due to increasing perturbative and resummation accuracy. [14]



Figure 2: From left to right the s-channel (1), t-channel (2) processes, and the Wt associated (3) production channel.

were constructed before the completion of the exact calculation. This is of particular interest for thresholds T_1 and T_3 . The latter, being dependent on t and u, then allows estimating threshold resummation corrections to the forward-backward asymmetry. Other approximate NNLO calculations use threshold T_3 , and, as mentioned above, assign the ambiguities due to using pair-invariant mass (PIM) or one-particle inclusive (1PI) kinematics in the precise definition of the threshold to a theoretical error [27, 32, 33].

The state of the art was presented by Czakon, who showed (see Fig. 1) also the impressive progress over time in accuracy of the theoretical description. Each component of the uncertainty is now at the few percent level.

2.2 Single top

Tops are produced singly through the weak interaction, in processes that are usually referred to in relation to Born kinematics, see Fig. 2. A particularly important aspect of single-top production is that both V_{tb} can be directly measured and the chiral structure of the tWb vertex can be tested. This is because top quarks produced in this way through a charged current interaction are highly polarized. Also important, and stressed at this meeting, is the issue of how many active quark flavors to choose. For instance, through the dominant *t*-channel at the LHC, inclusive measurements can be confronted with a 5-flavor NLO calculation, allowing extraction of the *b*-quark density. For situations with a tagged jet, and 4-flavor scheme seems



Figure 3: Doubly resonant diagrams in NLO corrections to Wt production.

more natural. Finally, we note that the different single top production channels are each sensitive to different varieties of New Physics, Thus, the *s*-channel will be sensitive to e.g. W' resonances, the *t*-channel to FCNC's.

The inclusive cross sections at the Tevatron are rather small, their contributions being about 1 pb for the s channel and 2 pb for the t channel, with the Wt channel negligible.

2.2.1 s and t channel

Experimentally, both of these single top production processes turned out to be rather more difficult to separate from backgrounds than expected, as the latter were larger, and similar to shape to the signals. Based on samples of 3.2 fb^{-1} by CDF and 2.3 fb^{-1} by D0, the Tevatron combination[34] of a number of CDF and D0 measurements yielded an inclusive single top production cross section of

$$\sigma = 2.76^{+0.58}_{-0.47} \text{ pb}\,,\tag{4}$$

and a measurement of $|V_{tb}| = 0.88 \pm 0.07$. Based on samples of up to 9.7 fb⁻¹ per experiment, recently CDF and D0 reported the Tevatron combination[35] for s-channel single top production

$$\sigma_s = 1.29^{+0.26}_{-0.24} \text{ pb} \,. \tag{5}$$

Furthermore, a D0 measurement [36] of only the *t*-channel cross section yielded $\sigma_t = 3.07^{+0.54}_{-0.49}$ pb. The measured cross sections agree within errors with the NLO calculations [37, 38, 39, 40, 41, 42, 43, 44], and with MC@NLO [45] and POWHEG [46].

At the LHC at 7 TeV, the inclusive SM production rates of the s-channel, t-channel and Wt channel are approximately 4.6, 65 and 16 pb respectively; at 8 TeV they are 5.6, 88 and 22 pb, respectively. Evidently the t-channel yields by far the dominant contribution. Within errors, the t-channel cross section measurements above agree with the NLO calculations, and the values of V_{tb} which are extracted are compatible with 1.

2.2.2 Wt channel

An interesting and subtle issue arises in the Wt mode of single top production. In the radiative corrections some diagrams contain an intermediate anti-top splitting into a W and anti-down type quark, a process which can become resonant. From another viewpoint, these diagrams can be seen as LO $t\bar{t}$ on-shell' pair production (having an order-of-magnitude larger cross section), with subsequent \bar{t} decay, see Fig. 3. One is therefore faced with the issue to what extent the Wt and $t\bar{t}$ can be defined and/or separated as individual processes, with the main difficult caused by interference between the resonant and non-resonant diagrams. To this end several definitions of the Wt channel have been given in the literature, each with the aim of recovering a well-behaved expansion in α_s for a meaningfully defined observable.

THEORETICAL SUMMARY

In Ref. [48] the interference issue was addressed extensively in the context of event generation, in particular the MC@NLO framework (POWHEG has implemented essentially the same method [49]). Two different procedures for subtracting the doubly-resonant contributions and thereby recovering a perturbatively well-behaved Wt cross section were defined. In "Diagram Removal (DR)" the graphs in Fig. 3 were eliminated from the calculation, while in "Diagram Subtraction (DS)" the doubly resonant contribution was removed via a subtraction term. The DS procedure leads to the following expression for the cross section

$$d\sigma^{(2)} + \sum_{\alpha\beta} \int \frac{dx_1 dx_2}{x_1 x_2 S} \mathcal{L}_{\alpha\beta} \left(\hat{S}_{\alpha\beta} + I_{\alpha\beta} + D_{\alpha\beta} - \tilde{D}_{\alpha\beta} \right) d\phi_3, \tag{6}$$

where $\alpha\beta$ labels the initial state channel in which the doubly-resonant contribution occurs: gg or $q\bar{q}$. \hat{S} is the square of the non-resonant diagrams, I their interference with D, the square of graphs of Fig. 3. The subtraction term \tilde{D} requires careful construction [48]. It was shown that, with suitable cuts, the interference terms are small. From Eq. (6) one sees that the difference of DR and DS is essentially the interference term. A particularly suitable cut is a putting a maximum on the p_T of the second hardest *b*-flavored hadron, a generalization of a proposal made in Ref. [41]. Thus defined, the Wt and $t\bar{t}$ cross sections can be separatedly considered to NLO.

The experimental status of this production mode at the time of writing is as follows. In the 7 TeV run, ATLAS [50] and CMS [51] have measured the Wt-channel cross section, with the results

ATLAS[2.05 fb⁻¹]:
$$\sigma_{Wt} = 16.8 \pm 2.9 \,(\text{stat}) \pm 4.9 (\text{sys}) \,\text{pb}$$
,
CMS [4.9 fb⁻¹]: $\sigma_{Wt} 16^{+5}_{-4} \,\text{pb}$. (7)

Based on a data set of 12.2 fb⁻¹, recently CMS has in fact identified the Wt-channel cross section for the 8 TeV run[52] at the 6.1σ level

$$\sigma_{Wt} = 23.4 \pm 5.4 \,\mathrm{pb}\,. \tag{8}$$

Within errors, the Wt-channel cross section measurements above agree with the NLO calculations[53, 41, 54], and the NLO plus parton showers discussed above [48, 55, 49].

One way to avoid the above difficulties in separating Wt from $\bar{t}t$ is to consider the common final state WWbb (in the 4-flavor scheme) and not ask if there were one or two intermediate top quarks involved in producing this final state – zero intermediate top quarks is also a possibility here. For zero *b*-quark mass, two groups have computed the NLO corrections to this production process [56, 57]. A preliminary result, using aMC@NLO was shown for the case where the *b* quark is taken massive. For the rates and distributions examined there seemed to be only small changes with respect to the massive case.

A completed study was shown investigating off-shell effects in *t*-channel production, in part as a test of the narrow-width approximation. Also confronted with the exact calculation was an effective theory approach [59]. It was shown that the NWA approximation does not always work well, whereas the ET approach does.

3 Top spin

Part of the attractiveness of the top quark is its capacity to self-analyze its spin, through its purely left-handed SM weak decay. This is both a useful aid in signal-background separations,



Figure 4: In *t*-channel single-top production at the Tevatron, a clear correlation of the lepton flight direction with the recoiling light quark jet. The correlation disappears when spin-correlations are turned off in MC@NLO [60].

and itself a property worthy of detailed scrutiny, as certain New Physics models could introduce right-handed couplings. The correlation between top spin and directional emission probability for its decay products is expressed through

$$\frac{d\ln\Gamma_f}{d\cos\chi_f} = \frac{1}{2} \left(1 + \alpha_f \cos\chi_f\right) \tag{9}$$

where $|\alpha_f| \leq 1$, with 1 indicating 100% correlation. For the dominant decay mode

$$t \to b + W^+ (\to l^+ + \nu) \tag{10}$$

at lowest order, we have $\alpha_b = -0.4$, $\alpha_{\nu} = -0.3$, $\alpha_W = 0.4$, $\alpha_l = 1$. QCD corrections to these values are small. The charged lepton direction (or the down-type quark in a hadronic decay of the intermediate W) is indeed 100% correlated with the top quark spin. This is amusingly more than for its parent W boson, a consequence of interference of two amplitudes with different intermediate W polarizations.

In single-top quark production, which occurs via the charged weak interaction, the top is produced left-handed, so a correlation should be a clear feature of the production process and a discriminant from the background. In Fig. 4 this correlation as computed with MC@NLO [60] is shown. A preliminary study from CMS [61] was shown in which the pattern of Fig. 4 was looked for, and was indeed found. From such a constant slope one might infer [62] the inclusive *t*-channel cross section, using only a straight-section piece to extrapolate to all angles.

4 Top, friends and imitators

Among the classic imitators of a top quark signal at hadron colliders is the V+jet final state. The QCD corrections for V+jets are now known up to 5 jets at least, and matched to parton showers. We were reminded of the very impressive progress made in this direction in recent years. In particular also the merging of matrix elements to parton showers is now a wellmastered craft.

THEORETICAL SUMMARY

A very clear overview was given of the tremendous advances made in describing $\bar{t}t$ plus various particles or jets, plotting calculations in 3D using the axes of increasing powers of α_s (NLO, NNLO), of the number of external lines, and of finite width and other effects. Especially noteworthy is that the processes $\bar{t}t$ plus QCD objects such as one or two jets, two extra b quarks or even two extra t quarks (four tops) have been computed to NLO in recent years. Depending on the final state, parton shower effects or narrow/finite width effects are included. But also processes such as $\bar{t}t$ plus a photon, vector boson or a Higgs are available to NLO, sometimes with an additional jet, and in cases with either stable tops, or including its decays. Also for New Physics showing up indirectly through $\bar{t}t$ plus missing E_T for certain modes available at least through NLO [63]. For top pair plus Higgs production, available as an NLO calculation, matched to parton showers, and interfaced to MadSpin [65], an interesting and fairly wellworking approximation involving top fragmentation into top plus Higgs was explained. With the major backgrounds also available to NLO, it seems the main tools for a good extraction of the top Yukawa are available. Backgrounds will be very challenging for $\bar{t}th$, so testing for deviations from the Standard Model will be hard. We were reminded that it might be better to look at single top plus Higgs production [66], where the Standard Model amplitude is strongly suppressed due to interference effects so BSM might come more easily to the fore.

5 Charge asymmetry

Another, complementary test of the top quark production mechanism is the charge asymmetry: the difference in production rates of tops and anti-tops at fixed rapidity

$$A_t(y) = \frac{N_t(y) - N_{\bar{t}}(y)}{N_t(y) + N_{\bar{t}}(y)}.$$
(11)

While electroweak production via a Z-boson could produce a (very small) asymmetry at LO, QCD itself produces it at $\mathcal{O}(\alpha_s^3)$ through a term proportional to the SU(3) d_{abc} symbol [3, 5, 67, 19]. In the $q\bar{q}$ channel this arises from an interference between the Born and the one-loop box diagram. In the matrix elements, the asymmetry reveals itself in terms of the Mandelstam variables t and u as terms that are odd under $t \leftrightarrow u$ interchange. In $t\bar{t}$ plus 1 jet production an asymmetry can already occur at tree level (essentially, this amounts to a different cut of the same amplitude). Measurements [68, 69, 70, 71] by the Tevatron experiments show substantial deviations from the Standard Model prediction for pair production, especially a deviation of more than 3 standard deviations by CDF at large invariant $t\bar{t}$ masses [69]. There is therefore considerable interest in this observable. In recent analyses by D0 [72, 73] the asymmetry is found to be not so large, though a discrepancy persists.

The effect of this interference amounts to the intuitive picture that the incoming quarks (as opposed to anti-quarks) tend to repel the produced top quarks towards larger rapidity, and/or attract the produced anti-top quarks toward slightly smaller rapidities. The net effect, therefore, at the Tevatron, where the top- anti-top pairs are produced in $q\bar{q}$ annihilation, is a shift of the top quark rapidity distribution towards larger rapidity, and of the anti-top distribution towards smaller values. This clearly creates a *y*-dependent asymmetry of the type (11). Because of the asymmetry in the amount of quarks and anti-quarks in the two Tevatron beams, this translates also to a forward-backward asymmetry A_{FB} .

Since the leading contribution to this effect for pair production involves a loop diagram, the asymmetry itself is of leading order accuracy. Clearly, the impact of even higher orders becomes interesting which at this stage can only be assessed from approximate, resummation based calculations to NLL [74, 27] or NNLL [75]. For this only resummations based on threshold T_3 (1) can be used. The higher order corrections so computed are small, so that the computed QCD asymmetry is stable with respect to their inclusion. The higher order asymmetry is then also reasonably insensitive to scale variations. With the methods discussed by Czakon we can look forward to the exact NLO asymmetry

Besides defining the asymmetry in terms of the top quark itself (11), one may define it also in terms of the leptons produced in top and/or anti-top decay, either in the lepton-plus-jets or the di-lepton channel. The A_{FB}^{ll} asymmetry will be in general a little washed out, but leptons are relatively easy to measure. (There is however still a need for unfolding due to limited acceptance.)

At the Tevatron, CDF and D0 have performed a set of measurements for various types of asymmetries. At the constructed top quark level the measured asymmetries exceed the theory prediction by a few standard deviations. Recent A_{FB} measurements in the lepton-plus-jets channels corrected to the parton level are $16.4 \pm 4.7\%$ (CDF) [76] and $19.6 \pm 6.5\%$ (D0) [71], vs. $8.8 \pm 0.6\%$ according to the SM.

In this conference the theoretical status of the charge asymmetry was reviewed quite comprehensively by Westhoff [77], who also discussed a number of New Physics options that would fit the observed enhanced asymmetry, such as axigluons, or a Z' boson.

As noted above, the charge asymmetry is present at leading order in $t\bar{t}$ + jet production. However, here NLO corrections [19, 20] wash out the asymmetry for this reaction. An explanation for this effect was given in [20], based on the following structure of the NLO forwardbackward asymmetry for this reaction

$$A_{\rm FB}(t\bar{t}j) = \alpha_s^3 \frac{C}{\ln(m/p_{T,j})} + \alpha_s^4 D_{\rm hard} \,. \tag{12}$$

The second term, appearing at NLO, cancels the first as they have opposite signs. The inverse logarithm is due to the fact that the denominator in the asymmetry has a higher power of leading soft logarithms. Also for $t\bar{t}jj$ the NLO term seems to reduce the LO contribution to the asymmetry [78].

At the LHC, the net effect of the QCD induced asymmetry is an overall broadening of the top quark rapidity distributions and a slight narrowing of the anti-top rapidity distribution. Because of the symmetry of two proton beams there is no forward-backward asymmetry, but a charge asymmetry that is most pronounced at larger rapidities. Recently proposed new observables [79, 80]. with promising sensitivity for the LHC were also discussed in this meeting by Westhoff.

6 Top and New Physics

Nierste reviewed the status of limits on SUSY signals. For g-2 of the muon, the 3.6 σ discrepancy with the Standard Model prediction would be alleviated by SUSY. He pointed out that certain off-diagonal elements of the squark mass matrix, in particular those involving the third generation, can lead to an enhanced single top production rate.

According to the MSSM, stops are among the most promising new particles to look for, being colored and thus having a large cross section, and being in most reasonable scenarios the lightest among the squarks. Spannowsky reviewed the reasoning behind this, and outlined

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various search strategies, which are generally in good shape. He pointed out that there are however gaps in parameter space, which given how central this search is for the ATLAS and CMS experiments, should be closed, and he discussed a number of strategies to do so.

Weiler reminded us of the attractiveness of the possibility of the Higgs boson being composite, and a pseudo-Goldstone boson of an enhanced symmetry. Drawing further inspiration from pion physics, this idea, if correct, would suggest fermionic symmetry partners of the top quark to be relatively light, below a TeV, and worth looking for.

The top-Higgs Yukawa coupling, discussed earlier in the context of $\bar{t}tH$ production, plays of course a direct role in the direct gluon fusion channel of Higgs production, through a top quark loop. Delaunay addressed the issue of how to extract information about possible New Physics contributions to this loop effect. Clearly, given the measured production rate being in fairly good agreement with the Standard Model, the net deviation is not very large, but this could be due to a cancellation of New Physics vertex and propagators effects. To pry apart this cancellation, one might look at Higgs plus one jet production, the contributions to which include diagrams where the extra gluon is emitted from within the New Physics loops, thereby disturbing the putative balance of NP propagator and vertex effects, and giving a handle on such New Physics.

Godbole pointed out the importance of angular distributions and kinematic distributions to probe for modifications of the top quarks couplings [81, 82]. With the scale of New Physics apparently high, an effective operator approach

$$\mathcal{L}^{\text{eff,BSM}} = \sum_{i} \frac{C_i}{\Lambda^2} O_i$$

seems the appropriate approach, which in turn causes such coupling modifications. Top produced in the decay of stops and sbottoms are polarized, and this may be used both in search strategies, and beyond that in determining the squark interactions [83]. For instance, if a Z'would polarize tops at production, the azimuthal asymmetry

$$A_{\phi} = \frac{\sigma(\cos\phi_l > 0) - \sigma(\cos\phi_l > 0)}{\sigma(\cos\phi_l > 0) + \sigma(\cos\phi_l > 0)},\tag{13}$$

where ϕ_l is the azimuthal angle of the lepton with respect to the beam-top plane, would be sensitive to the amount of left-handed and right-handed coupling, even more so when judicious cuts on the p_T of the top are chosen. Also when a charged Higgs is present, such an asymmetry, would also discriminate [83] among Wt and H^-t production.

7 Top mass

Central to top quark physics is the meaning and value of its mass. The Tevatron experiments [84, 85] have measured the mass with an error of 0.87 GeV/ c^2 , *i.e.* to an accuracy of less than 0.5%; the LHC experiments [86] with an error of 0.95 GeV/ c^2 ,

$$CDF/D0 [8.7 \,\text{fb}^{-1}]: 173.20 \pm 0.51(stat) \pm 0.71(sys) \,\text{GeV}/c^2,$$

ATLAS/CMS [4.9 fb^{-1}]: 173.29 ± 0.23(stat) ± 0.92(sys) GeV/c^2 . (14)

Together with an accurately measured W boson mass, a precisely known top mass severely constrains the mass range of the Higgs boson [87]. Indeed the measured Higgs boson mass seems

quite consistent given present accuracies. Therefore its precise measurement is of considerable importance, and so also its careful definition. Given the measured mass of the Higgs boson, a precise determination of the top quark mass becomes especially interesting in the issue of the (meta)stability of the EW vacuum, as discussed by Shaposhnikov at this meeting.

A natural definition of an elementary particle mass is based on the location of the pole of the full quark propagator, i.e. the pole mass. After summing self-energy corrections the full propagator reads

where Σ contains $1/\epsilon$ UV divergences from loop integrals. Renormalization now amounts to replacing the bare mass m_0 by an expression involving the renormalized mass m

$$m_0 = m \left(1 + \frac{\alpha_s}{\pi} \left[\frac{1}{\epsilon} + z_{finite} \right] \right), \tag{16}$$

after which the UV divergences cancel in (15). The choice of z_{finite} determines the scheme. Choosing it such that

$$\frac{1}{\not\!p - m_0 - \Sigma(p, m_0)} = \frac{c}{\not\!p - m} \tag{17}$$

defines the pole-mass scheme, which amounts to pretending that the particle can be free and long-lived. However, because the top quark, being colored, can never propagate out to infinite times - a requirement for the definition of a particle mass in scattering - such a pole only exists in perturbation theory, and its location is intrinsically ambiguous by $\mathcal{O}(\Lambda_{QCD})$ [88, 89, 90].

Experimentally, the top quark mass is reconstructed by collecting jets and leptons. The decay channels used are the dilepton channel - two isolated leptons with opposite charge and at least two jets[91, 92]; the lepton + jets channel - an isolated lepton and at least four jets[93, 94]; the all-hadronic channel[95, 96]. However, soft particles originating from both within and outside these jets may affect the reconstructed mass.

Although the experiments reconstruct the pole mass (or something close to it), theoretically it would be more desirable to have a short-distance mass, free of $\mathcal{O}(\Lambda_{QCD})$ ambiguities. Such is the $\overline{\text{MS}}$ mass $\bar{m}(\mu)$ evaluated at some scale μ , whose relation to the pole mass is known to three loops in QCD[98]. For μ one often takes the implicit value found when intersecting the $\bar{m}(\mu)$ curve with the $\bar{m}(\mu) = \mu$ axis, yielding $\bar{m}(\bar{m})$.

Theoretical and MC aspects of the top mass were discussed in this meeting by Mangano, the theoretical aspects especially addressing ambiguities.

Numerically, the relation between the pole mass and the the $\overline{\mathrm{MS}}$ mass reads

$$m = \bar{m}(\bar{m}) \times (1 + 0.047 + 0.010 + 0.003)$$

each term corresponding to a loop order. The series shows excellent convergence. The remaining uncertainty is about 500 MeV, when assuming the asymptotic series starts diverging again. (The 4-loop result would be very interesting in order to test this issue.) Note that this still exceeds the non-perturbative ambiguity on the pole pole due to renormalon effects from infrared sensitive regions.

The MS mass $\bar{m}(\mu)$ may be extracted more indirectly, through a proxy observable such as the inclusive cross section expressed in the $\overline{\text{MS}}$ mass [99]. Mangano pointed out that this seems a very safe procedure, in contrast to e^+e^- collisions, as the IR sensitive region only contributes

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about a permille to the inclusive cross section, and that, to good accuracy, it seems safe to interpret the MC mass parameter as the pole mass.

He also proposed a different and interesting mass proxy: (twice) the end-point energy of the electron in a semi-leptonic decay in the top quark restframe. Uncertainties from b-jet reconstruction are greatly suppressed to well below the permille level. The difficulty will be however the reconstruction of the top quark rest frame, or more generally the top quark momentum.

8 Conclusions

Although discovery of the top quark is now nearly 20 years old, in a sense top quark physics as a field is just beginning. A flood of new, higher energy data are in the offing that will also challenge their theoretical description and interpretation. The severe constraints of precise measurement, the entry of the Higgs boson and its strong interaction with the top quark sector, are inspiring not only remarkable increases in theoretical accuracy and the developments of methods thereto, but also novel ideas from New Physics modelling to enhancing data analysis methods. Therefore, in spite of the occasional rain at this conference, the outlook for top quark physics seems very bright indeed.

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Observation of associated production of a single top quark and W boson at 8 TeV

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Electroweak production of single top quarks has been observed by the D0 [1] and CDF [2] experiments at the Tevatron. There are three main processes that can produce a single top quark in the Standard Model: the t-channel exchange of a virtual W boson, the s-channel production and then decay of a virtual W boson, and the associated production of a top quark with a W boson (tW). Associated tW production had a negligible cross-section at the Tevatron and so was not previously accessible. At the Large Hadron Collider (LHC), it has a higher cross-section than the s-channel and as such represents a significant contribution to single top quark production.

Associated tW production is an interesting production mechanism for several reasons: its interference with top quark pair production [3], its sensitivity to new physics [4] and its role as a background to several SUSY and Higgs searches. Evidence for tW associated production has been previously presented by ATLAS [5] and CMS [6], and we present here the first observation of tW production at the CMS experiment in pp collisions at $\sqrt{s} = 8$ TeV.



Figure 1: Feynman diagrams for tW single-top-quark production at next-to-leading order that are removed from the signal definition in the DR scheme, the charge-conjugate modes are implicitly included.

The next-to-leading order (NLO) Feynman diagrams for tW production, shown in Fig. 1, present a conceptual problem due to their mixing with perturbative QCD top quark pair $(t\bar{t})$ production. Two methods have been proposed for describing the tW signal: "Diagram Removal" (DR) [3], where the doubly resonant diagrams are excluded from the signal definition; and "Diagram Subtraction" (DS) [3], in which the differential cross section is modified by a gauge-invariant subtraction term, which locally cancels the contribution of the $t\bar{t}$ diagrams. The DR scheme is chosen for this analysis, but the difference between the two schemes is observed to be consistent within statistical uncertainties and is accounted for as a systematic uncertainty.

The analysis presented here investigates the channels in which both W bosons (from the associated production and the top decay) decay leptonically into a muon or electron and the corresponding neutrino. Tau decays are modelled, but not considered in the signal definition. The leptonic final states of the tW process are characterised by two isolated, oppositely charged leptons, a jet from the hadronisation of the b quark, and a substantial amount of missing transverse energy (E_T^{miss}) due to the neutrinos. The primary source of background is $t\bar{t}$ production, with $Z/\gamma *$ +jets processes also contributing strongly in the *ee* and $\mu\mu$ channels.

The analysis uses fits to a discriminant variable built from kinematic quantities combined using a boosted decision tree (BDT). Two further analyses, intended as cross-checks of the robustness of the multivariate approach, are performed using event counts and kinematic variables as the basis of a fit. For all of the analyses, a sample corresponding to an integrated luminosity of 12.2 fb⁻¹ of pp collisions at $\sqrt{s} = 8$ TeV collected by the CMS detector was used. A full description of the CMS detector can be found in [7].

All objects used for selection are reconstructed using the particle flow (PF) algorithm [8, 9]. Data samples are chosen by requiring two leptons (muons or electrons) in the trigger for the event. All events are required to have at least one well reconstructed primary vertex; fake vertices (where a vertex is reconstructed in a location where no interaction occurred) are suppressed by requiring the vertex to have more than 4 associated tracks, |z| < 24 cm and $\rho < 2.0$ cm.

Exactly two oppositely charged, isolated leptons are required in the event. Muons are required to be reconstructed by both the tracking and muon systems. They are selected if they have a transverse momentum (p_T) greater than 20 GeV and fall within the pseudorapidity (η) range $|\eta| < 2.4$. Additionally, there is a requirement on the relative isolation of the muon, $I_{rel} < 0.2$ where I_{rel} is defined as the sum of the p_T of all neutral and charged particles within a cone of $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} < 0.4$ divided by the p_T of the lepton.

Electrons are reconstructed from energy deposits in the electromagnetic calorimeter and matched to hits in the silicon tracker. They are required to have a $p_T > 20$ GeV and $|\eta| < 2.5$. The electron must have a transverse impact parameter (IP) with respect to the beam spot of less than 0.04 cm. Additionally, electrons are required to have $I_{rel} < 0.15$ within a cone $\Delta R < 0.3$.

The signal region contains exactly two leptons, so events with additional muons or electrons passing a looser selection of $p_T > 10$ GeV are vetoed to suppress background processes. To remove low-mass $Z/\gamma *$ events, the invariant mass of the leptons, m_{ll} , is required to be greater than 20 GeV. In order to further reduce the contribution from $Z/\gamma *$ +jets and other background processes such as WZ and ZZ, events in the *ee* and $\mu\mu$ final states are rejected if m_{ll} is within the Z mass window of 81 to 101 GeV. The *ee* and $\mu\mu$ channels are required to have $E_T^{miss} > 50$ GeV, to further suppress the $Z/\gamma *$ +jets backgrounds.

Events failing the Z mass veto are used to reweight the Drell-Yan background Monte Carlo. Using the distribution of E_T^{miss} in the control region additional scale factors are derived that account for the difference between data and simulation based on the amount of missing energy in the event.

PF jets are reconstructed using the anti- k_T algorithm [10] with a resolution parameter of 0.5. Jets are required to have $p_T > 30$ GeV and $|\eta| < 2.4$. A multivariate b-tagging algorithm is used to determine whether a jet came from a b-quark decay, combining tracking information to determine a discriminant. Loose jets are defined in this analysis as any jet failing the above requirements, but passing a selection of $p_T > 20$ GeV and $|\eta| < 4.9$.

In order to constrain the dominant $t\bar{t}$ background, three regions are defined; one signal region and two $t\bar{t}$ enriched control regions. The signal region is defined as containing exactly one b-tagged jet (1j1t), whilst the control regions contain exactly two jets, with one and two b-tags respectively (2j1t and 2j2t).

After the selection is applied, a multivariate analysis is applied in order to discriminate between the tW signal and dominant $t\bar{t}$ background. A boosted decision tree (BDT) is trained using the "Toolkit for Multivariate Data Analysis" (TMVA) [11]. The training is carried out using simulated events for tW and $t\bar{t}$ passing the 1j1t signal region event selection. The thirteen variables combined in the BDT are chosen on the basis of their separation power between the tW signal and $t\bar{t}$ background, and their consistency between data and simulation is confirmed using the control regions. A fit is then performed to the shape of the BDT discriminant over all regions and channels in order to extract the significance and cross-section of the tW signal.



Figure 2: Distribution of the number of loose jets in an event for signal and control regions. This quantity is one of the 13 used as input to the BDT.

The statistical analysis is based on a binned likelihood fit of the BDT distributions. The expected yield for bin i, λ_i , is given by the sum over all considered background processes and the tW signal, scaled with a signal strength modifier μ which is the signal cross sections in units of the Standard Model prediction,

$$\lambda_i = \mu S_i + \sum_k B_{k,i}$$

where k runs over all considered background processes, B_k is the background template for background k, and S is the signal template, scaled according to luminosity measurements and the cross section predicted by the Standard Model.

Nuisance parameters that affect the expected yield, θ_u , are introduced for every source of uncertainty, labelled as u, that affects the predicted event yield. To quantify an excess of events, we use the test statistic q_0 , defined as:

$$q_0 = rac{\delta}{\delta\mu} \mathcal{L}(\mu=0,\hat{ heta_0}| ext{data})$$

The likelihood is maximised with the signal strength held constant at zero, and the nuisance parameters allowed to float freely, thus finding the maximum likelihood under a backgroundonly hypothesis. The p-value is then defined as the probability to obtain a test statistic value of q_0 as high as, or higher than, the one observed in data under the background-only hypothesis $(\mu = 0)$. The distribution of q_0 is determined by generating pseudo-data sets randomly varying the nuisance parameters θ_0 . The 68% confidence level interval is evaluated using the profile likelihood method [12].



Figure 3: Signal region BDT discriminant for all decay channels, used for fitting.

Systematic uncertainties are treated as nuisance parameters in the fit, and are estimated by their impact on the fitted distributions. A wide range of systematic uncertainties, both theoretical and experimental, are considered. All uncertainties are taken into account by their impact on the shape of the fitted distributions, with the exception of the luminosity, lepton identification and reconstruction efficiencies and $t\bar{t}$ cross section uncertainties which are handled as uncertainties in the production rate.

The effect of each systematic is estimated based on its contribution to the uncertainty on the cross section. The impact of the theory shape uncertainties are estimated by a maximum likelihood fit, setting the nuisance parameters to the $\pm 1\sigma$ levels. For the other uncertainties the cross section is measured with the uncertainty fixed at its central value. The difference in the error on cross-section measurement from the nominal profile likelihood fit is then attributed to that individual uncertainty source.

The main sources of uncertainty are found to be the theoretical uncertainties. The largest uncertainty comes from varying the Matrix Element/Parton Shower (ME/PS) matching thresholds on the $t\bar{t}$ MC samples, giving an uncertainty of 14% on the measured cross section. Choosing different renormalisation/factorisation (Q^2) scales for the tW and $t\bar{t}$ samples leads to an uncertainty on the cross section of 11%. Varying the top-quark mass around the measured values gives an uncertainty on the cross section of 10%.

Two additional analyses were carried out as tests of the robustness of the BDT analysis: the first used a fit directly on the event counts and the second on the transverse momentum of the system (p_T^{syst}) , defined as the vector sum of the transverse momentum of the leptons, b-tagged jet and missing transverse energy of the event. Both analyses use the same event selection as the BDT with additional cuts. First, events with any loose b-jets (loose jets as defined above passing the b-tagging criteria) were vetoed. Secondly, an additional requirement that the scalar

Observation of associated production of a single top quark and $W \dots$

sum of the transverse momentum of the two leptons, jet and $E_T^{miss}(H_T)$ be greater than 160 GeV was applied in the $e\mu$ channel. The fit was performed in the same way as described for the BDT.



Figure 4: Distributions fitted in the cross check analyses. The event counts for all channels and regions (left), and the transverse momentum of the system for all channels in the signal region (right).

For the BDT analysis, an excess of events compared to a background-only hypothesis of 6.0σ is observed, compared to an expected significance, extracted from simulation, of $5.4^{+1.5}_{-1.4}\sigma$. The measured cross section, including both statistical and systematic uncertainties, is found to be $23.4^{+5.5}_{-5.4}$ pb, in agreement with the Standard Model. This compares favourably to the Standard Model cross section value of $22.2 \pm 0.6 \pm 1.4$ pb at $\sqrt{s} = 8$ TeV, assuming a top-quark mass of 172.5 GeV [13].

The event count based analysis observes a signal excess of 3.6σ , with an expected significance of $2.8^{+0.9}_{-0.8}$, and measures a cross section of $33.9^{+8.6}_{-8.6}$ pb. The p_T^{syst} fit analysis observes an excess of 4.0σ against an expected significance of $3.2^{+0.9}_{-0.9}$, and measures a cross section of $24.3^{+8.6}_{-8.8}$ pb. All the results are consistent with each other and the Standard Model.

The production of a single top quark in association with a W boson is observed in the dilepton decay channel in pp collisions at $\sqrt{s} = 8$ TeV in the CMS experiment at the LHC. A multivariate analysis is used to extract the tW signal from the dominant $t\bar{t}$ background, and an excess of events over a background-only hypothesis is observed with a significance of 6.0σ . The cross section is measured to be $23.4^{+5.5}_{-5.4}$ pb, in agreement with the Standard Model.

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Combination of single top-quark cross-section measurements in the t channel at $\sqrt{s} = 8$ TeV with the ATLAS and CMS experiments

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A combination of measurements of the single top-quark production cross-section in the t channel at $\sqrt{s} = 8$ TeV by the ATLAS and CMS experiments at the LHC is presented. The measurements from ATLAS and CMS are based on integrated luminosities of 5.8 fb⁻¹ and 5.0 fb⁻¹, respectively. The best linear unbiased estimator (BLUE) method is applied for the combination, taking into account the individual contributions to systematic uncertainties of the two experiments and their correlations. The combined single top-quark production cross-section in the t channel is $\sigma_{t-ch.} = 85 \pm 4 \text{ (stat.)} \pm 11 \text{ (syst.)} \pm 3 \text{ (lumi.)}$ pb = 85 ± 12 pb, in agreement with the theoretical predictions.

1 Introduction

Single top-quark production in high-energy proton-proton (pp) collisions proceeds dominantly via the t channel in the Standard Model (SM). The next-to-leading order (NLO) QCD prediction, obtained with MCFM [1], of the single top-quark production cross section in the t channel at $\sqrt{s} = 8$ TeV for a top-quark mass of 172.5 GeV is:

$$\sigma_{t-\text{ch.}}^{\text{th}} = 85.8^{+2.6}_{-1.9} \,(\text{scale})^{+0.6}_{-0.7} \,(\text{PDF})\,,\tag{1}$$

where the first uncertainty is due to the scale dependence and the second uncertainty is due to the parton distribution function (PDF) uncertainty. The approximate next-to-NLO (NNLO) QCD prediction [2] is compatible with the NLO QCD prediction within uncertainties:

$$\sigma_{t-\text{ch.}}^{\text{th}} = 87.2_{-0.7}^{+2.1} \,(\text{scale})_{-1.7}^{+1.5} \,(\text{PDF}) \,. \tag{2}$$

The ATLAS and CMS experiments measured the single top-quark *t*-channel production cross section in pp collisions at $\sqrt{s} = 8$ TeV. ATLAS performed a fit to the distribution of a neural-network discriminant constructed to separate signal from background. On a dataset collected in 2012 corresponding to 5.8 fb⁻¹, the following cross-section was measured [3]:

$$\sigma_{t-\text{ch.}} = 95.1 \pm 2.4 \,(\text{stat.}) \pm 18.0 \,(\text{syst.}) \,\text{pb} = 95.1 \pm 18.1 \,\text{pb}. \tag{3}$$

CMS applied kinematic requirements to enhance the signal-to-background ratio and performed a fit to the distribution of the pseudorapidity of the light-quark jet to extract the signal yield.

Shapes for the dominant background processes, top-quark pair production $(t\bar{t})$ and the production of a W boson in association with jets (W+jets), as well as the rate of W+jets events, were determined from control samples in data. The measured cross-section from a data sample collected in 2012 corresponding to an integrated luminosity of 5.0 fb⁻¹ is [4] is:

$$\sigma_{t-ch.} = 80.1 \pm 5.7 \,(\text{stat.}) \pm 11.0 \,(\text{syst.}) \pm 4.0 \,(\text{lumi.}) \,\text{pb} = 80.1 \pm 13.0 \,\text{pb}.$$
 (4)

A sizable fraction of the systematic uncertainties are uncorrelated between the two experiments. Hence, a combination of both measurements allows a reduction of the total uncertainty. The combination of ATLAS and CMS measurements of single-top production in the t channel [5] is presented in the following. The combination is performed using the best linear unbiased estimator (BLUE) method [6, 7]. In the present case, systematic uncertainties are known as relative uncertainties, instead of absolute ones. This deviation from the purely Gaussian assumption, underlying the original BLUE formulation, is known to cause a bias which can be significantly mitigated by applying the method iteratively: for each iteration the individual ATLAS and CMS systematic uncertainties (described in Section 2) are rescaled to the central value obtained from the BLUE combination and the procedure is repeated until the updated central value converges to a stable result. The method converges after just a few iterations. This approach was also adopted in Ref. [8] and [9].

2 Uncertainty categories

The sources of uncertainties determined by ATLAS and CMS are organized in various categories as shown in Table 1, together with the assumed values of correlations between the two experiments. The correlation estimates reflect the present understanding and the limitations due to the different choices made by the experiments when evaluating the individual uncertainty sources. The impact of the assumptions about correlation coefficients is evaluated by performing stability cross-checks described in Section 3.2, in which correlations are changed with respect to the values reported in Table 1. A more complete discussion about uncertainties and their treatment in ATLAS and CMS can be found in [5].

Statistics: Statistical uncertainties due to the size of the available data sample and from the limited size of the simulated samples are uncorrelated between ATLAS and CMS.

Luminosity: The uncertainty due to the determination of the integrated luminosity is separated into a luminosity-calibration contribution, correlated between ATLAS and CMS, and an uncertainty associated with the long-term stability of relative-luminosity measurements, that is entirely detector specific and therefore uncorrelated between the two experiments.

Simulation and modeling: Theoretical uncertainties affect the predicted signal and background rates and the modeling of simulated samples. In some cases, different approaches are adopted in ATLAS and CMS. In particular, ATLAS quotes an uncertainty due to the modeling of initial-state radiation (ISR) and final-state radiation (FSR), while CMS quotes an uncertainty due to the assumed factorization and renormalization scale (Q^2). Those uncertainties, as well as the uncertainties due to PDF and t-channel generator, are assumed to be 100% correlated in the two experiments.

Jets: Uncertainties related to the jet energy scale (JES), jet resolution, and jet reconstruction efficiency could be potentially correlated, due to contributions from theory modeling uncertain-

ties. The uncertainties are anyway assumed to be uncorrelated in the two experiments, and this assumption is varied in the stability studies.

Background normalization: Two sources of uncertainty affect the normalization of the different background components: normalization from theoretical predictions, which is assumed to be 100% correlated, and the extraction of rates and/or shape from data, which is uncorrelated between ATLAS and CMS.

Detector modeling: We consider all sources of uncertainties due to the modeling of detector effects to be uncorrelated, except for the b-tagging efficiency uncertainty for which theoretical modeling uncertainties, although not dominant, are correlated. Since this uncertainty is sizable a conservative correlation factor of 50% is assumed. This value is varied in the stability studies.

Table 1: Categories of sources of uncertainties for the ATLAS and CMS measurements with assumed correlation factors (ρ). The relative cross-section uncertainty corresponding to each source of uncertainty is shown for both measurements. The total uncertainty, shown for each measurement, is the quadratic sum of all individual uncertainties.

Category	ATLAS		CMS		ρ
Statistics	Stat. data	2.4%	Stat. data	7.1%	0
	Stat. sim.	2.9%	Stat. sim.	2.2%	0
Total		$\mathbf{3.8\%}$		7.5%	0
Luminosity	Calibration	3.0%	Calibration	4.1%	1
	Long-term stability	2.0%	Long-term stability	1.6%	0
Total		3.6%		4.4%	0.78
Simulation and modeling	ISR/FSR	9.1%	Q^2 scale	3.1%	1
	PDF	2.8%	PDF	4.6%	1
	t-ch. generator	7.1%	t-ch. generator	5.5%	1
	$t\bar{t}$ generator	3.3%			0
	Parton shower/had.	0.8%			0
Total		12.3%		7.8%	0.83
Jets	JES	7.7%	JES	6.8%	0
	Jet res. & reco.	3.0%	Jet res.	0.7%	0
Total		8.3%		6.8%	0
Backgrounds	Norm. to theory	1.6%	Norm. to theory	2.1%	1
	Multijet (data-driven)	3.1%	Multijet (data-driven)	0.9%	0
			W+jets, $t\bar{t}$ (data-driven)	4.5%	0
Total		3.5%		5.0%	0.19
Detector modeling	b-tagging	8.5%	b-tagging	4.6%	0.5
	$E_{\mathrm{T}}^{\mathrm{miss}}$	2.3%	Unclustered $E_{\rm T}^{\rm miss}$	1.0%	0
	Jet Vertex fraction	1.6%	1		0
			pile up	0.5%	0
	lepton eff.	4.1%			0
			μ trigger + reco.	5.1%	0
	lepton res.	2.2%			0
	lepton scale	2.1%			0
Total		10.3%		6.9%	0.27
Total uncert.		19.2%		16.0%	0.38

Source	Uncertainty (pb)
Statistics	4.1
Luminosity	3.4
Simulation and modeling	7.7
Jets	4.5
Backgrounds	3.2
Detector modeling	5.5
Total systematics (excl. lumi)	11.0
Total systematics (incl. lumi)	11.5
Total uncertainty	12.2

Table 2: Contribution of each uncertainty category to the combined cross-section uncertainty.

3 Result

3.1 Combined single top-quark cross section

The total covariance matrix, determined as the sum of all covariance matrices from the uncertainty categories reported in Table 1, is:

$$\mathbf{C} = \begin{pmatrix} 269 & 84\\ 84 & 182 \end{pmatrix} \mathrm{pb}^2, \tag{5}$$

which has an overall correlation of 0.38. The BLUE weights are determined to be 0.35 for ATLAS and 0.65 for CMS, and the combined result is:

$$\sigma_{t-ch.} = 85.3 \pm 12.2 \,\mathrm{pb}\,.$$
 (6)

The χ^2 of the combination is 0.79, with one degree of freedom.

The contribution of each uncertainty category to the combined cross-section uncertainty is shown in Table 2. The combined result with separate uncertainty contributions from statistics, luminosity, and all other systematics uncertainties is:

$$\sigma_{t-ch.} = 85.3 \pm 4.1 \,(\text{stat.}) \pm 11.0 \,(\text{syst.}) \pm 3.4 \,(\text{lumi.}) \,\text{pb} = 85.3 \pm 12.2 \,\text{pb}. \tag{7}$$

The improvement on the relative uncertainty of the combined result (14.3%) is significant compared to the uncertainties on ATLAS (19.2%) and CMS (16.0%) measurements. The absolute uncertainty on the combined cross section is also slightly improved with respect to the smallest uncertainty on the individual measurements used in the combination.

3.2 Stability tests

The stability of the cross-section combination with respect to the assumed correlations between ATLAS and CMS uncertainties is tested by varying the correlation factors of the following uncertainties: the correlation factors of the uncertainties assumed to be fully correlated are varied, separately, from the default value of $\rho = 1.0$ to 0.5 or 0; the systematic uncertainties treated in this way are those for the luminosity calibration, ISR/FSR, Q^2 scale, PDF, *t*-channel generator, and backgrounds normalized to theory predictions; the correlation factor of the b-tagging uncertainty, assumed to be partially correlated, is varied from $\rho = 0.5$ to 0 or 1; the

correlation factor of the JES uncertainty, assumed to be uncorrelated, is varied from $\rho = 0$ to 0.5 or 1, in order to see the impact of a possible residual correlation. Table 3 summarizes the result of these tests. For each source of uncertainty the correlation factor ρ is varied from its default value to the tested values and the corresponding shifts (in pb) on the combined central value and on the measured uncertainty are reported.

These tests indicate that the result is stable with respect to the assumptions about the systematic uncertainty correlations, and that the combination yields an improvement with respect to the individual measurements. However, a better assessment of the systematic uncertainty correlations across experiments will be the aim of future measurements and combinations.

Table 3: Results of the stability tests performed on the correlation assumptions about the uncertainty categories. For each test the correlation factor ρ is varied from its default value to a test value and the corresponding shifts on the combined central value and on the measured uncertainty are reported.

Source	Default ρ	Test ρ	Shift: central value (pb)	Shift: uncertainty (pb)
Luminosity calibration	1	0.5/0	+0.1/+0.1	-0.1/-0.2
Simulation and modeling	1	0.5/0	+0.4/+0.7	-0.5/-1.1
JES	0	0.5/1	-0.4/-0.8	+0.3/+0.6
b-tagging	0.5	0/1	+0.2/-0.3	-0.2/+0.2

4 Summary

The ATLAS and CMS measurements of single top-quark production cross sections in the t channel are combined using the BLUE method. The combined cross section is determined to be:

$$\sigma_{t-ch.} = 85 \pm 4 \,(\text{stat.}) \pm 11 \,(\text{syst.}) \pm 3 \,(\text{lumi.}) \,\text{pb} = 85 \pm 12 \,\text{pb} \,.$$
 (8)

The result of the combination of ATLAS and CMS measurements is shown together with the individual ATLAS and CMS measurements and compared to theory predictions [1, 2] (see Section 1) in Fig. 1. The result is in agreement with both NLO and approximate NNLO predictions. The systematic uncertainty, dominated by theoretical uncertainties, is the largest contribution to the total uncertainty. The result was found to be stable with respect to the variation of the correlation assumptions of each of the uncertainty category considered.

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Figure 1: Single top-quark production cross-section measurements performed by ATLAS and CMS, and combined result (light-blue band), compared with SM predictions [1, 2] (pink bands). Statistical, systematic, and luminosity uncertainties are represented by blue error bars, ordered from the innermost to the outermost. For theoretical predictions the renormalization/factorization scale uncertainty and PDF uncertainty are represented by red error bars, ordered from the innermost to the outermost.

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New physics in top pair production

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We present the latest results about the searches for a new physics in top quark pair production. The ATLAS and CMS collaborations results are presented using the data collected at LHC in 2012 at the energy of interactions of 8 TeV. The most of such searches look for vector-like quarks. No presence of excess is found and the 95% C.L. lower limits on vector-like quark masses are set between about 600 – 850 GeV depending on quark type and its decay mode. The searches for an excited top quark and a baryon number violation in $t\bar{t}$ process are also presented.

1 Introduction

The Standard Model (SM) of the particle physics is extremely successful in describing the experimental data. However, we know that it is incomplete, e.g. it does not include the gravitational interaction. We want to find a more general theory of which the SM is just a low-energy approximation. Since the top quark is the heaviest elementary particle known, the processes which involve the top quark production are therefore the natural place to look for a manifestation of a new physics.

This article presents the searches which either involve the production of $t\bar{t}$ pair or the final state mimics the $t\bar{t}$ pair signature. Specifically, there are covered searches for the pair production of vector-like quarks, the 4th generation chiral quarks, the sgluons, and the Kaluza-Klein excitations (Sec. 2) followed by the excited top quark search (Sec. 3) and the search for baryon number violation in $t\bar{t}$ process (Sec. 4). The searches for the flavor changing neutral currents and the searches involving the single top final states are presented in the other articles of these proceedings, see [1, 2].

The results from ATLAS [3] and CMS [4] experiments are presented. In all searches, ATLAS used the data collected at CERN Large Hadron Collider (LHC) in 2012 at the energy of interactions of 8 TeV corresponding to 14.3 fb⁻¹ of integrated luminosity while CMS used 19.6 fb⁻¹ (except in the vector-like bottom quark search presented in Sec. 2.2.1 where the luminosity of 19.8 fb⁻¹ was analysed). All the limits mentioned below correspond to either 95% credibility or confidence level (C.L.) depending whether Bayesian (CMS, except for search in Sec. 4) or frequentist (ATLAS) approach was applied.

2 Vector-like quark searches

The discovery of the Higgs particle raised the questions for a mechanism to stabilize its mass since the loop corrections to the mass of a scalar particle diverge. There should be other new particles which cancel these contributions. There are several models (e.g. the little Higgs models, the composite Higgs model, the grand unification models) predicting such heavy quarks which are assumed to have only the vector couplings to the gauge bosons (therefore called the 'vector-like' quark) and the masses independent of their coupling to the Higgs boson thus evading many constraints from the electroweak measurements and from the discovery of the Higgs particle.

The vector-like quarks (VLQ) could be a singlet or a doublet under the electroweak SU(2) x U(1) transformation. It is assumed the dominant decay modes are to the 3rd generation quark and W/Z/H boson, see Fig. 1. It is possible that such vector-like quarks can have also the exotic electric charge of 5/3e or -4/3e.

The mass dependence of the branching ratios (BR) for various scenarios and decay modes is shown in Fig. 2 for both the vector-like top (T, left) and the vector-like bottom quarks (B, right). The branching ratios corresponding to a singlet model in the limit of a large mass are 50%, 25%, 25% for the decay modes $T/B \rightarrow b/t+W$, $T/B \rightarrow t/b + Z$, $T/B \rightarrow t/b + H$, respectively.







Figure 2: The branching fractions mass dependence for the vector-like top (left) and bottom quark (right) in the different scenarios [6].

The analysis strategy for VLQ search from the ATLAS and CMS experiment is different. The ATLAS analyses exploit the topologies of specific decay modes of the VLQ, while still estimating the limits for all possible BR combinations. On the other hand, CMS performs more general searches that attempt to cover all decay modes at once.

Although the 4th chiral quark generation is highly disfavored after the Higgs discovery, the searches for such quarks have been performed as a part of the analyses considering also the other models. When it is the case, such analyses will be also mentioned below.
2.1 ATLAS searches

2.1.1 Search for $T \rightarrow tH$ decays

In this analysis [5], the search for the pair of vector-like top (VLT) quark is performed assuming a significant branching ratio for the subsequent T decay into the top quark and the Higgs boson.

The data are analyzed in the sample where it is required one lepton (electron or muon), the large missing E_T ($E_T^{miss} > 20$ GeV and $E_T^{miss} + m_T > 60$ GeV where m_T is the transverse mass of the lepton and E_T^{miss}) and at least 6 jets where at least two of them are identified as coming from the hadronization of a *b*-quark (*b*-tagged).

The analysis exploits the expected large scalar sum of the p_T of a charged lepton, E_T^{miss} and the p_T of the jets (H_T) and the number of b-tagged jets in the signal events to discriminate against the background, see Fig. 3. There are three sub-channels defined according to the number of b-tags $(2,3,\geq 4)$ in order to optimize the sensitivity.



timize Figure 3: The H_T distribution. The expected signal in the *T* doublet sceits are nario for $M_T = 600$ GeV is shown [5].

There is no signal found and the mass limits are placed in the general 2D plane of $BR(T \rightarrow tH)$ vs.

 $BR(T \rightarrow bW)$ ($BR(T \rightarrow tZ)$ is subsequently determined by the unitary condition), see Fig. 11 where the label 'Ht+X' corresponds to this analysis. The limits on different scenarios (a singlet or a doublet) correspond to the particular points in this plane.

2.1.2 Search for $T/B \rightarrow t/bZ$ decays

ATLAS also searches for the VLQ pair assuming such VLQ to have a significant branching fraction into its corresponding 3rd generation partner and the Z boson which decays leptonically [6].

The events in the sample are required to have at least 2 leptons of the same flavor with the opposite electric charge and at least 2 b-tagged jets. It is expected that in the VLQ decays there will be a quite high activity in the transverse plane and the Z boson will be boosted. Therefore, the high cuts on the scalar sum of p_T of jets, $H_T(jets) > 600$ GeV and $p_T(Z) > 150$ GeV are applied in the final selection.

The discriminant used to separate the signal from the background is the invariant mass of the reconstructed Z boson and the b-tagged jet, see Fig. 4. Since no signal is found, the limits are placed in the general 2D plane of $BR(T \rightarrow tH)$ vs. $BR(T \rightarrow bW)$, see Fig. 11 and Fig. 12 for the 'Zb/t+X' analysis.



Figure 4: The invariant mass of Z boson and the b-tagged jet [6].

2.1.3 Search for $T \rightarrow bW$ decay

Finally, ATLAS searches for the vector-like top quark pair assuming VLT to have a significant decay branching fraction into b quark and W boson [7].

The events in the sample are required to have one lepton, the large missing E_T and at least 4 jets where at least one of them is b-tagged.

The W bosons and b jets from T decays are expected to be highly energetic with large angular separation between them while the decay products from the W bosons have small angular separation. This is taken into account when defining two types of W_{had} candidates depending on whether the decaying quarks are reconstructed as one or two jets.

The reconstructed heavy quark mass m_{reco} built from the W_{had} candidate and one of the two b-jet candidates is used as a discriminant, see Fig. 5. Among all possible combinations, the one with the smallest absolute difference between two reconstructed heavy quark masses is chosen.



Figure 5: The reconstructed invariant mass of the W boson and the b-jet [7].

There is no signal over expected background observed and the lower limits are again placed in the general 2D plane of $BR(T \to tH)$ vs. $BR(T \to bW)$, see Fig. 11 where the label 'Wb+X' corresponds to this analysis.

This analysis also places the lower limit on the mass of the chiral fourth generation top quark partner of 740 GeV while the expected limit is 770 GeV. This result is also applicable to the vector-like quark with the electric charge of -4/3e.

2.1.4 Search for same-sign leptons

The ATLAS experiment also performs a search for a new physics in the events with a samesign dilepton pair, a b-tagged jet, and significant additional jet activity [8]. Such final state signature is predicted in various models, which are considered here: the pair production of 4th chiral generation b' quarks, the pair production of VLQ, the sgluon (color-adjoint scalars) pair production and the model with two universal extra dimensions both leading to four top quark production.

The events in the sample are required to have two leptons (electrons or muons) where the invariant mass of the same flavor leptons is inconsistent with Z boson mass, the large missing $E_T > 40$, the large scalar sum of p_T of leptons and jets $H_T > 550$ GeV and at least 2 jets where at least one of them is b-tagged. The additional criteria on H_T , the number of b-jets and the charge of leptons are optimized for the various models in question.

There is no excess of events over predicted background observed and the observed yields are used to place the limits. The 4th generation chiral b-quark has lower mass limit $m_{b'} > 720$ GeV (assuming $BR(b' \to Wt) = 100\%$). The vector like top (bottom) quark is limited to the mass $m_{T(B)} > 540$ (590) GeV (assuming BR consistent with T/B being a singlet), for the limits in the general BR plane, see Fig. 11 and Fig. 12. The s-gluon lower mass limit is 800 GeV and the lower limit on the Kaluza-Klein mass is 900 GeV.

2.2 CMS searches

2.2.1 Inclusive searches for vector-like top and bottom quark

CMS performs inclusive search for both the VLT and the vector-like bottom (VLB) quark that are pairproduced together with their antiparticles and decay into three different finale states, $T \rightarrow tZ/bW/tH$, $B \rightarrow bZ/tW/bH$ [9, 10]. In the T decays, all decay channels produce the final states with the b quarks and the W bosons where at least one W boson is considered to decay leptonically. In the B decays, exactly one lepton is selected from the W decay where the Wmay come directly from the B quark or from its decay products, such as $t \rightarrow Wb$ or $H \rightarrow WW$.

For the large masses of VLT or VLB, it is expected that their decay products will be highly boosted and could be merged into one single jet. Therefore, the additional jet reconstruction (independent of the standard jet reconstruction using the anti- k_t algorithm) is performed using the Cambridge-Aachen (CA) algorithm with a distance parameter of 0.8. The jets are required to have $p_T > 200$ GeV. In the VLT analysis, the W-jets are identified if their mass is between 60 and 130 GeV and they contain at least two sub-jets. Similarly, the top-jets are identified if the decay prod-



Figure 6: The BR triangle with the observed limits for the T quark mass. Every point in the triangle corresponds to a particular set of branching fraction values subject to the constraint that all three add up to one [9].

ucts of hadronically decaying top quark are merged in one jet and have the mass between 140 and 250 GeV and at least three sub-jets with a minimum pairwise mass above 50 GeV. In the VLB analysis, the V-jets are identified if the mass of two sub-jets is between 50 and 150 GeV and the ratio of the most massive sub-jet mass to the mass of the jet is below 0.4.

The VLT analysis is split into the single-lepton and the multilepton channel. In the single-lepton channel, the boosted decision trees (BDT) are used to separate the signal from the backgrounds while the multilepton analysis simply uses the yields as the discriminant in the limit calculation. The VLB analysis is performed in the single-lepton channel where the data fit is performed to the 2-dimensional distribution of the scalar sum of the jets transverse energies, the lepton p_T and the missing E_T vs. the V-tag multiplicity.

The full BR space is explored and no excess of the signal over the background is found. The lower limits between 687 and 782 GeV are placed for the VLT quark mass for all possible BR combinations, see Fig. 6. For the VLB quark, the lower B mass limits between 582 and 732 GeV are placed depending on the BR, see Fig. 7. The shaded regions in Fig. 7 represent regions with small expected sensitivity, precisely that the ex-



Figure 7: The BR triangle with the B quark mass observed limits [10].

pected limit is less than 500 GeV.

2.2.2



Vector-like bottom $B \rightarrow bZ$ search

Figure 8: The mass exclusion limits on $BR(B \rightarrow bZ)$ [11].

CMS searches for the VLB quarks assuming one of the pair produced VLB decays into $B \rightarrow bZ$ [11]. Only two decay modes of VLB $B \rightarrow bZ$ and $B \rightarrow bZ$ tW are assumed in this analysis.

Two leptons and at least one b-tagged jet are required in the final state. The dilepton invariant mass is required to be consistent with Z boson mass while the transverse momentum criteria on the lepton pair $p_T(\ell \ell) > 150$ GeV is also applied.

The data-driven estimate of Z + b jet background was performed by considering the different regions of the two-dimensional plane of the number of jets and the b-tagging discriminant variables for the signal and the control regions.

The kinematics of B quark is reconstructed from two leptons and the highest- p_T b-jet. The invariant mass of B is used as a discriminant. No

excess of the events is found and the limits on $BR(B \rightarrow bZ)$ from 30% to 100% as a function of VLB mass are determined, see Fig. 8. The observed (expected) lower limit on the mass of the B quark is 700 (680) GeV assuming $BR(B \rightarrow bZ) = 100\%$ which could be compared to the observed (expected) limit of ~ 750 (750) GeV from a similar analysis in ATLAS, see Fig. 12.

$\mathbf{2.3}$ Search for vector-like top quark with charge 5/3e

The CMS experiment searches for the vector-like quarks with the exotic charge of 5/3e assuming their pair production and the decay to the top quark and the W boson of the same-sign charge, see Fig. 9 [12]. As a consequence, two same-sign leptons are possible in the final state which is quite rare signature within the SM processes.

Since both the top quark and the W boson from $T_{5/3}$ decay are expected to be highly boosted, the top/W boosted tagging techniques are used to identify these objects. The jets corresponding to highly boosted top quarks ('CA top jets') are clustered using the CA clustering algorithm with a distance parameter of 0.8. The main conditions applied are the jet $p_T > 200$ GeV, at least three sub-jets and the mass of jet being in between 140 and 250 GeV. The jets corresponding to highly boosted W bosons ('CA W jets') are also clustered using the CA algorithm with a distance parameter of 0.8 and are required to have $p_T > 200$ GeV, exactly two sub-jets



Figure 9: The pair production of $T_{5/3}$ quarks and the decay to same-sign dilepton final state [12].

and the mass of jet in between 60 and 130 GeV. All other jets are identified as anti- k_t jets with radius parameter of R = 0.5 (AK5 jets).

Since lots of final state high- p_T particles are expected to be produced in decays of $T_{5/3}$, two strong cuts are applied as part of the event selection. The very high cut on $H_T > 900$ GeV is applied where H_T is the scalar sum of the p_T of all the jets and leptons in the event. Another cut is applied on the number of constituents N(con) >5 where each AK5 jet and each lepton not used for the same-sign lepton requirement counts as one constituent while 'CA W jet' counts as two and 'CA top jet' as three constituents.

There is no excess of events above the background observed, see Fig. 10. The event yields from all channels $(ee,e\mu,\mu\mu)$ are combined when setting the limits. The lower limit is placed on mass of $T_{5/3}$: m > 770 GeV, while the expected limit is 830 GeV.

2.4 Summary of VLQ searches



Figure 10: The reconstructed mass of $T_{5/3}$ [12].

The ATLAS searches for vector-like quarks are summarized in Fig. 11 and Fig. 12. It can be seen that the full

BR space is excluded up to about 550 (450) GeV for the vector-like T(B) quark while for the specific decay mode, the limit goes up to about 850 GeV (assuming $BR(T \to tH) = 100\%$).



Figure 11: Summary of ATLAS searches for vector-like top quarks [13].

Since the ATLAS and CMS experiments applied different strategies for their searches and CMS used larger statistics, the obtained results mostly reflect this. While CMS has the higher



Figure 12: Summary of ATLAS searches for vector-like bottom quarks [13].

limit for the full BR plane (687 GeV comparing to ~ 500-600 GeV from ATLAS), the limit for the branching ratio being 1.0 for a certain decay mode is sometimes higher for ATLAS, e.g. for $BR(T \rightarrow tH) = 1.0$. The limits for the vector-like *B* quarks are usually stronger for CMS since ATLAS did not yet obtain the result optimized for the $B \rightarrow bH$ decay mode. It should be also noted that the ATLAS limits could be improved in the future by combining all the different analyses.

3 Search for excited top quark

Many theories beyond the SM surmise the top quark may be a composite rather than an elementary particle. An experimental test of such a prediction would be to search for the existence of an excited top quark (t^*) .

CMS performs such search for the pair produced excited top quark assuming a model in which t^* has spin 3/2 and decays 100% of time to the top quark via the emission of a gluon [14]. The analysis is performed in the lepton+jets channel requiring the presence of one lepton (electron or muon) and at least six jets with at least one of them being b-tagged in the final state.

The t^* mass reconstruction is performed by the minimization of the χ^2 where the invariant mass of the top quark and the gluon m_{t+g} is a free param-



Figure 13: The reconstructed mass of the top quark and the gluon, the background fit and the expectation for the signal [14].

eter. The data driven method is used to estimate the background contribution in the signal region by fitting the invariant mass of the top quark and the gluon with a Fermi-like function.

As seen in Fig. 13, no significant excess of the events over the predicted background is observed and the lower observed (expected) limit is placed on the mass of excited top m > 803 (739) GeV.

4 Baryon number violation search

In the SM, the baryon number is conserved while it can be violated in many theories, such as the supersymmetry and the grand unified theories. It was recently suggested that the baryon number violation (BNV) can proceed in the processes involving the top quark where it would undergo the decay of the type $t \rightarrow \bar{b}\bar{c}\mu^+(\bar{t} \rightarrow bc\mu^-)$ and $t \rightarrow \bar{b}\bar{u}e^+(\bar{t} \rightarrow bue^-)$ involving an electron or a muon in final state.

The CMS experiment searches for such violation in the $t\bar{t}$ process where one SM top quark decays hadronically into three jets and one top quark decays through the BNV mode [15]. Such a final state includes an isolated lepton and five jets but no significant missing transverse momentum. Only one relatively loosely btagged jet is required in order to maintain the sensitivity of the search to other possible BNV decays involving only the light-quark jets. This so-called 'basic selection' is used for the normalization of SM $t\bar{t}$ and t + W processes. As a result of the normalization, the impact of the systematic uncertainties is largely reduced.



Figure 14: The missing E_T distribution after the final selection. The signal contribution for $t\bar{t}$ with the baryon number violation decays at the level of 0.5% is also shown [15].

The final ('tight') selection involves two additional cuts to enhance the presence of the signal. The first requirement is on the missing energy $E_T^{miss} < 20$ GeV (Fig. 14). The second requirement is on the compatibility of the event with the kinematics expected in the $t\bar{t}$ event having SM-BNV decays. The compatibility is tested using the χ^2 which includes the terms of the reconstructed masses of the W boson and the hadronically decaying top quark and the top quark with the BNV decay. The best combination for a given event must pass the cut $\chi^2 < 20$.

The branching-ratio for the BNV decay mode is estimated from the likelihood fit to the yield in data for the tight selection where the expected number of the events is a function of the $t\bar{t}$ and tW efficiencies of passing the tight selection which themselves are the function of BR for BNV decay.

There is no excess of events observed and the upper limit of 0.15% is placed on the branching ratio for the baryon number violating decay for the combined electron and muon analysis while the expected upper limit was estimated to be 0.29%.

5 Conclusion

There are plenty of searches for a new physics in $t\bar{t}$ pair production from the ATLAS and CMS experiments performed using the LHC data delivered in 2012 at the energy of the interaction

of 8 TeV.

The significant mass ranges of the top quark partners are excluded for various models. The vector-like quark masses are excluded at 95% C.L. below the range of about 600 - 850 GeV depending on the quark type and its decay mode. The lower limit on the mass of the excited top quark of 790 GeV is set at 95% C.L. The baryon number violation mode of top quark is excluded for the branching ratio above 0.15% at 95% C.L.

Although there are no hints of the new physics yet, there are still many analyses in the preparation.

The next round of LHC running is supposed to start at the beginning of 2015 with the much higher energy of interaction (13 TeV or 14 TeV). We can hope some new physics will be revealed. If that will happen, there is a high chance it will be in the top quark sector.

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Measurement of the top quark mass in dileptonic top quark pair decays with $\sqrt{s} = 7$ TeV ATLAS data

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The top quark mass in dileptonic top quark pair decays is measured using 4.7 fb⁻¹ of proton-proton collision data recorded at the centre of mass energy $\sqrt{s} = 7$ TeV by the ATLAS experiment at the LHC in 2011. The event topology is characterised by the presence of two charged leptons, at least two neutrinos, and several jets, two of which originate from bottom quarks. Using the template method and the m_{\ellb} observable, defined as the average invariant mass of the two lepton plus *b*-jet pairs in each event, the top quark mass is measured to be $173.09 \pm 0.64_{\text{stat}} \pm 1.50_{\text{syst}}$ GeV.

1 Introduction

The mass of the top quark (m_{top}) is a fundamental parameter of the Standard Model of particle physics. The most recent combination of the measurements performed at the LHC [1], based on data luminosities of up to 4.9 fb⁻¹, yields $m_{\text{top}} = 173.29 \pm 0.95$ GeV. The LHC at CERN serves as a top quark factory, and thanks to the large sample of top anti-top quark $(t\bar{t})$ pairs collected by the ATLAS experiment analyses exploiting the $t\bar{t}$ dileptonic final state $t\bar{t} \to W^+ bW^- \bar{b} \to$ $\ell^+ \nu b\ell'^- \bar{\nu'}\bar{b}$ can also provide precision measurements of m_{top} , as presented in the following [2].

2 Event reconstruction, modeling and selection

The data used in this analysis correspond to 4.7 fb⁻¹ of proton-proton (*pp*) collision data at $\sqrt{s} = 7$ TeV recorded by the ATLAS detector [3] during 2011.

The final state considered in this analysis is $t\bar{t} \to W^+ bW^-\bar{b} \to \ell^+ \nu b\ell'^- \bar{\nu'}\bar{b}$, with ℓ being either electron (e) or muon (μ). This results in three different decay channels, which are all considered in this analysis. The decay channels involving tau leptons are not taken into account due to the difficulties in tau lepton reconstruction. To identify jets originating from the hadronisation of b-quarks an algorithm based on a neural-net, relying on topological properties such as the vertex decay length significance, is applied [4]. The chosen working point of this "MV1" algorithm corresponds to a b-tag efficiency of 70% for jets originating from b-quarks in simulated $t\bar{t}$ events and a light quark jet rejection factor of about 130. The selection of events consists of a series of requirements on the general event quality and on the reconstructed objects, that are designed to select events consistent with this topology. It is characterised by the presence of two isolated leptons with relatively high $p_{\rm T}$, missing transverse momentum ($E_{\rm T}^{\rm miss}$) arising from the two neutrinos from the leptonic W-boson decays, and two *b*-jets. Consequently exactly two *b*-tagged jets with $p_{\rm T} > 25$ GeV and exactly two opposite sign leptons with $p_{\rm T,e} > 25$ GeV, $p_{\rm T,\mu} > 20$ GeV are required. In the same flavour channels events have to satisfy $E_{\rm T}^{\rm miss} > 60$ GeV.

Monte Carlo (MC) simulated events are used to model the $t\bar{t}$ signal events and most of the physics background processes, consisting mostly of single top quark production in the Wtchannel and the small contributions from Drell-Yan processes and diboson production with additional jets. Events may also be wrongly reconstructed as dileptonic $t\bar{t}$ decays due to the presence of misidentified, or "fake", leptons together with b-tagged jets and $E_{\rm T}^{\rm miss}$. This contribution is estimated using a data-driven method [5], found to be consistent with zero and, consequently, neglected in the $m_{\rm top}$ measurement. Additional information on the sample production and the samples used for background and systematics evaluation can be found in [2].

The observed numbers of events in data after the event selection, together with the expected numbers of signal and background events corresponding to the integrated luminosity of 4.7 fb⁻¹, are given in Table 1. The relative fractions of events in data for the *ee*, $e\mu$ and $\mu\mu$ channels respectively are 9%, 67% and 24%. Assuming a top quark mass of $m_{top} = 172.5$ GeV, the number of events observed in data is about 16% higher than the prediction, but still consistent within uncertainties. This does not affect the analysis, because the template method implemented here depends on the shape of the distributions only, and does not rely on the normalisation of the signal plus background prediction. In all kinematic distributions the shape of data can be properly accounted for by the sum of signal and background predictions.

	All	chan	nels
$t\bar{t}$ signal	2400	\pm	400
Fake leptons	-4	\pm	7
Single top quark	73	\pm	15
Drell-Yan	3.1	\pm	1.3
Diboson	0.75	\pm	0.29
Total expected	2500	\pm	400
Total observed	2913		

Table 1: The observed and expected numbers of events after the final event selection.

3 The template method

In the template method, simulated distributions are constructed for a chosen quantity sensitive to the parameter under study, known as the "physics parameter", using a number of discrete values of that parameter. These templates are then fitted to functions that interpolate between different input values of the physics parameter, fixing all other parameters of the functions. In the final step a likelihood fit of these functions to the observed data distribution is used to obtain the value for the physics parameter that best describes data. The $m_{\ell b}$ estimator is defined as the average invariant mass of the lepton *b*-jet systems, leading to two possible assignments of the two *b*-jets to the two charged leptons. The assignment corresponding to the



Figure 1: (a) Estimator distribution after applying all selection requirements for data (points), the sum of signal and background (black line) and for background alone (grey histogram). The signal plus background prediction is normalised to the number of events observed in data. The uncertainties shown for data are statistical only. The hatched band indicates the shape uncertainty of the signal and background contributions due to the leading jet uncertainties. The rightmost bin contains the overflow. (b) Dependence of the distribution on $m_{\rm top}$ for signal samples for different input top quark masses and the signal probability density functions.

lowest $m_{\ell b}$ estimator is chosen, which yields the correct matching in 77% of the cases. The $m_{\ell b}$ distribution for data and the prediction for $m_{top} = 172.5$ GeV are shown in Figure 1(a). Figure 1(b) shows the sensitivity of the $m_{\ell b}$ observable to the input value of the top quark mass by the superposition of the signal templates and their fits for three input m_{top} values. The parameters of the fitting functions of $m_{\ell b}$ depend linearly on m_{top} for both the signal and background templates, the latter being introduced by the single top quark contribution. This allows to build signal and background probability density functions for the $m_{\ell b}$ estimator that depend only on m_{top} . These functions are then used in an unbinned likelihood fit to data for all events, $i = 1, \ldots, N$. The likelihood function maximised is:

$$\mathcal{L}(m_{\ell b}|m_{\mathrm{top}},r) = \prod_{i=1}^{N} \left[(1-r) \cdot P_{\mathrm{sig}}(m_{\ell b}|m_{\mathrm{top}}) + r \cdot P_{\mathrm{bkg}}(m_{\ell b}|m_{\mathrm{top}}) \right],$$

where P_{sig} and P_{bkg} are the signal and background probability density functions and r is the relative normalisation of the background contribution. The value of r is small, $r = 0.03 \pm 0.01$, and is fixed to its nominal value in the likelihood fit.

Using pseudo-experiments on large Monte Carlo samples, a good linearity is found between the input top quark mass and the results of the fits. Within their statistical uncertainties, the mean values and widths of the pull distributions are consistent with the expectations of zero and one, respectively. This shows that the method is unbiased and the statistical uncertainty is evaluated correctly. The expected statistical uncertainty on $m_{\rm top}$ obtained from pseudoexperiments for an input top quark mass of $m_{\rm top} = 172.5$ GeV and for a luminosity of 4.7 fb⁻¹ is 0.64 GeV.

Description	Value [GeV]
Measured value	173.09
Statistical uncertainty	0.64
Detector modeling	1.25
MC modeling	0.80
Background	0.14
Method calibration	0.07
Total systematic uncertainty	1.50
Total uncertainty	1.63

Table 2: The measured value of $m_{\rm top}$ and the statistical and systematic uncertainties.

4 Systematic uncertainties

The systematic uncertainties are estimated by varying the respective uncertainty source and determining the impact on the mass measurement via pseudo-experiments. Wherever applicable the uncertainty sources are varied by one standard deviation $(\pm 1\sigma)$ with respect to the default value. The resulting average value of the fitted m_{top} in the pseudo-experiments is compared to the corresponding value without variation and the difference is used to determine the systematic uncertainty. The total uncertainty is calculated as the quadratic sum of the individual contributions, i.e. neglecting possible correlations. The sources and systematic uncertainties investigated are summarised in Table 2 and explained below.

- **Detector modeling:** This category summarises object-related uncertainties, comprising e.g. jet and lepton energy scale, reconstruction efficiency or pile-up. As expected from an analysis without in-situ calibration of the jet energy scale, the dominant systematic uncertainties on $m_{\rm top}$ stem from the imperfect knowledge of the jet and *b*-jet energy calibration, contributing with O(0.8) GeV each.
- **MC modeling:** This category summarises uncertainties related to the signal simulation, such as the choice of the event generator, hadronisation model, choice of proton PDF, modeling of colour reconnection, underlying event or initial and final state radiation. The dominant contributions of O(0.4) GeV come from the hadronisation model and the modeling of the underlying event.
- **Background:** The impact of the uncertainty of the background contribution on the final result is obtained by varying the background normalisation within its uncertainty and reevaluating the top quark mass using the template fit.
- Method calibration: The good linearity found between the input top quark mass used in the simulation and the results of the fit described in Section 3 shows that the method is unbiased at the level of statistical precision of the MC samples. The maximum between the average absolute mass deviation and its statistical uncertainty observed in the $m_{\rm top}$ variation samples is assigned as an uncertainty.

5 Results

The result of the fit to 2011 ATLAS data in the dileptonic $t\bar{t}$ decay channel is

$$m_{\rm top} = 173.09 \pm 0.64_{\rm stat} \pm 1.50_{\rm syst} \text{ GeV}.$$

Figure 2 shows the $m_{\ell b}$ distribution in data together with the corresponding fitted probability density functions for signal plus background and for the background contribution alone. The inset shows the $-2 \ln \mathcal{L}$ profile as a function of the fitted top quark mass. The vertical lines correspond to $\pm 1\sigma$ of the statistical uncertainty. The result has a total uncertainty similar to that of the ATLAS m_{top} measurement obtained in the lepton+jets channel [6].



Figure 2: Fitted $m_{\ell b}$ distribution in data. The fitted probability density functions for the signal plus background and for the background contribution alone are also shown. The inset shows the $-2 \ln \mathcal{L}$ profile as a function of the fitted top quark mass.

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From the LHC to a future lepton collider

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I discuss the complementarity of top quark physics that can be studied at the LHC and at a future lepton collider.

1 Introduction

The goal of this talk is to discuss a synergy between top quark studies at the LHC and at a future lepton collider. I rely here on the results obtained by the Top Quark Working Group [1] in the context of the Snowmass community planning exercise, an important event that occurred in the first half of 2013 in the United States.

I think everybody would agree that a top quark is a "known unknown". Indeed, on one hand, we understand very well how top quarks are embedded into the Standard Model and, as the result, we can precisely describe what to expect in any process that involves top quarks. On the other hand, we believe that top quarks should have unusual features since they appear to couple to the Higgs boson so strongly. As a consequence, it is then logical to assume that top quarks play some role in the resolution of the Naturalness problem and to search for clues to the solutions to this problem in physics of top quarks.

The majority of solutions to the Naturalness problem suggested so far are based on one of three distinct mechanisms that stabilize the Higgs mass or the scale of electroweak symmetry breaking: spin-zero partners of top quarks (e.g. supersymmetric models), spin one-half partners of top quarks (e.g. little Higgs models) and composite models of Higgs bosons and top quarks. When we think about the future of the top quark physics and, in particular, discuss an interplay of lepton and hadron colliders, it is useful to have these three mechanisms in mind.

Top quark studies at hadron colliders (for a review see Refs. [2, 3]) have given us measurements of the top quark mass, the top quark charge, the top quark spin and the top quark couplings to gluons and W-bosons, as well as cross-sections and kinematic distributions in various top quark production channels with reasonable precision. Except for an intriguing problem with the forward-backward asymmetry at the Tevatron [4], results of all existing measurements are consistent with the Standard Model. However, one has to keep in mind that after almost twenty years of top quark discovery, some top quark properties are still poorly known experimentally. A striking example is provided by the top quark couplings to neutral electroweak gauge bosons. As we discuss below, probing these couplings may turn out to be very important; hopefully, first interesting results on $t\bar{t}Z/\gamma$ will be obtained at the LHC and then substantiated at a lepton collider.

It is well-known that hadron and lepton colliders are complimentary. The LHC is a broadband discovery machine with huge rates and large backgrounds where precision measurements

FROM THE LHC TO A FUTURE LEPTON COLLIDER

are difficult but not impossible. Lepton colliders are precision tools with low backgrounds, small event rates and high luminosity. These are great machines for accurate measurements of top quark properties, especially those that involve electroweak interactions. When we talk about lepton colliders it is important to emphasize that we do not talk about a definite machine at the moment. Indeed, energy, layout and the geographic location of a future lepton collider are not yet fixed so that one can consider different scenarios including the Higgs factory with the center-of-mass energy of 250 GeV, as well as 500 and 1000 GeV machines. It is still being discussed if the next collider should be linear such as the ILC [5] or circular, such as TLEP [6]. For the purposes of this talk, I will consider a generic lepton collider where energy is a continuous parameter and the luminosity is not unreasonably high. The important difference between circular and linear colliders is the beam polarization option that is available at a linear collider. As we will see shortly, access to beam polarization makes significant differences in physics reach in some cases.

Similar to other aspects of collider physics, top quark physics involves measurements and searches. It is obviously important to have a balanced combination of the two. To some extent, the desire to have this balance explains why we always talk about hadron and lepton colliders since, almost by design and certainly in the popular culture, hadron colliders are associated with searches and lepton colliders with precision measurements. It is important to understand, however, that times have changed and that there is a great track record of precision measurements at hadron colliders. Quite often, lepton colliders improve on precision obtained at a hadron collider but they can hardly contribute to searches. It is therefore important to understand in which cases added precision provided by a lepton collider relative to what the LHC can do justifies building a new machine, at least from the perspective of the top quark physics. This is a difficult question but it is central for the discussion of the complementarity of hadron and lepton colliders. To illustrate possible answers to this question, I will to discuss 1) the top quark mass measurements; 2) studies of top quark production at threshold at a lepton collider; 3) top quark couplings to electroweak gauge bosons; 4) top quark flavor-violating decays; 5) physics beyond the Standard Model. I conclude in Section 7.

2 The top quark mass

The discussion of the top quark mass provides a great illustration of all issues related to the complementarity of lepton and hadron colliders. It is well-known that the top quark mass can be measured much more precisely at a lepton collider than at a hadron collider. However, it is important to understand why the increased precision in the top quark mass measurements is relevant. We will consider a few examples to illustrate that.

First, recall that intrinsic consistency of the Standard Model can be checked through precision electroweak fits that express, e.g. m_W through m_t , m_Z , etc. The rule of thumb [7] is that a 6 MeV precision on m_W corresponds to 900 MeV precision on m_t . Pushing only one observable to higher precision does not help much with the interpretation of precision electroweak fits. Currently, we know m_W to about 15 MeV and it is expected that both the LHC and the ILC will probably reduce the error on M_W to 6-7 MeV but not much beyond that [7]. Hence, from the point of view of precision electroweak fits, measurement of the top quark mass to 300 - 500 MeV is entirely sufficient, even in the post-LHC era.

Another place where precise knowledge of the top quark mass appears to be necessary is the issue of the vacuum stability in the Standard Model. Given the uncertainty on the top quark

	Ref.[11]		Projection	s
CM Energy	7 TeV		$14 { m TeV}$	
Luminosity	$5fb^{-1}$	$100 f b^{-1}$	$300 f b^{-1}$	$3000 f b^{-1}$
Syst. (GeV)	1.8	1.0	0.7	0.5
Stat. (GeV)	0.90	0.10	0.05	0.02
Total	2.0	1.0	0.7	0.5

Table 1: Projections [1, 10] for the uncertainty in m_t determined using the CMS end-point method [11]. Extrapolations are based on the published CMS analysis.

mass of about 500 MeV, one determines the scale where the Higgs self-coupling turns negative to within a factor of five. This is sufficient to understand if we live in an unstable, stable or metastable Universe, so that unless the precise lifetime of the Universe becomes important, the 500 MeV uncertainty on m_t does not prevent us from drawing physics conclusions.

Taking $\delta m_t = 500$ MeV as a reasonable goal, we should ask whether or not the LHC can achieve it. Interestingly, we are already not too far from it. Indeed, the current uncertainty from combined Tevatron measurements is close to 900 MeV [8], while precision of current measurements at the LHC is close to one GeV [9]. One can expect that precision of traditional methods, such as the matrix element method and the template method, can be pushed further to approximately $\delta m_t \sim 600$ MeV by collecting more data. Unfortunately, improvements in precision do not continue past 300 fb⁻¹ integrated LHC luminosity, due to increased pileup and related difficulties with the top quark reconstruction [10].

While $\delta m_t \sim 600$ MeV is definitely in the right ballpark, the standard criticism of traditional methods is that, due to biases in parton shower event generators, they provide us with a top mass parameter that is neither the pole mass nor the $\overline{\text{MS}}$ mass. Even if we know this parameter to high precision, its deviation from the m_t^{pole} or $m_t^{\overline{\text{MS}}}$ can be much larger than the quoted error, leading to a significant confusion. While this might be a valid concern as a matter of principle, in my opinion, the whole issue is not important at the $\mathcal{O}(500)$ MeV level of precision. For example, there should be little doubt that pole quark masses are used in perturbative parts of event generators such as PYTHIA and HERWIG but, of course, one has to be sure that non-perturbative effects are not large for observables from which the top quark mass is extracted.

The good news is that a number of new techniques for measuring the top quark mass, such as the CMS end-point method [11], were recently suggested. These methods appear to be more clean theoretically because it is easier to understand what mass parameter is measured and why potential contamination of top quark pair production by BSM physics does not affect the extracted value of m_t . The new methods also show better behavior when extrapolated to higher luminosities and pileups. As can be seen from Table 1, a precision of about 500 MeV using the end-point method can be reached at 3000 fb⁻¹. It can be expected that after combining a few of such clean measurements with each other, the precision $\delta m_t \sim 300 - 400$ MeV can be reached – that is better than what is required for precision electroweak fits both during the LHC era and beyond.

The need for additional improvements in m_t measurements may be justified if there are significant breakthroughs in m_W measurements that push its precision to a few MeV range

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or if the "vacuum (in)stability scenario", i.e. no new physics all the way to the Planck scale, becomes a leading paradigm in BSM physics. In the latter case, on can argue that the scale μ_Q where the Higgs quartic coupling turns negative is related to underlying fundamental physics, making precise determination of μ_Q an important task. In the SM, μ_Q depends on m_H and m_t . The Higgs mass can be measured to about 100 MeV at the LHC. The error on the scale where the quartic coupling turns negative is equally shared between δm_t and δm_H [12]. Therefore, from this perspective, measuring m_t to 100 MeV precision is valuable.

Measuring m_t to 100 MeV can only be done at a lepton collider [13], either from the threshold scan or from the measurement of the invariant mass distribution of top quark decay products at higher energies. In case of the threshold mass extraction, the error on m_t is very small, close to 40 MeV, but it gets amplified by almost a factor of two because the transition from the pole mass to the $\overline{\text{MS}}$ mass is not known sufficiently well. This, however, is a theoretical issue which will be definitely worked out if the need arises.

3 Top quark threshold production at a lepton collider

One of the attractive points of a lepton collider is that it can study production of top quarks at threshold, with $E_{\rm CM} \sim 2m_t$. Independent of any utilitarian goal, top quark threshold production gives us an opportunity to a study beautiful and unique physics system of almost free but nevertheless strongly interacting quarks. Indeed, the lifetime of a top quark is short enough to prevent it from hadronizing into t-hadrons, yet it is long enough to allow produced t and \bar{t} to get sufficiently far from each other to experience long-range Coulomb-like QCD interaction. These Coulomb-like interactions are enhanced by the inverse relative velocity of top quarks and, at threshold, require a resummation to all-orders in perturbation theory. The top quark width plays an important conceptual role by screening the non-perturbative effects and providing an opportunity to compute the entire line-shape for threshold top quark production. Let me also note that an accurate approximation for the cross-section has been worked out theoretically [14] and an even better approximation is in the works [15].

What are the interesting measurements that one can do at the top threshold? To understand this, let us imagine that we measure the top production cross-section as a function of the center-of-mass energy, and the top quark momentum distribution in the threshold region. Both of these quantities are affected by a number of things including the top quark mass, the top quark width, the strong coupling constant at relatively low energy scales and even the top-Higgs Yukawa coupling. Going back to measurements of interesting quantities and focusing on threshold line-shape and momentum distributions, it is easy to see that the cross-section at the peak, the position of the peak and the average momentum of produced top quarks are determined by three interesting parameters – the top quark mass, the top quark width and the strong coupling constant [16]

$$\sigma_{\text{peak}} \sim \frac{\alpha_s^3}{m_t \Gamma_t}, \quad E_0 \sim -m_t \alpha_s^2, \quad \langle p_t \rangle \sim m_t \alpha_s.$$
 (1)

Hence, by measuring the three quantities experimentally, we obtain the mass, the width and the strong coupling constant and, as was shown in Ref. [16], this can be done to very high precision. I want to emphasize, in particular, that a few percent precision with which the top quark width can be measured at a lepton collider is about fifty times higher than what one can

do at the LHC. The importance of measuring the width with high precision is discussed at the end of this talk.

4 Couplings of top quarks to electroweak bosons

Couplings of top quarks to W and Z bosons and photons are well-known in the Standard Model, because gauge charges of left-handed and right-handed top quarks are fixed and the Standard Model interactions are restricted to a renormalizable subset. Of course, in a more general case that also includes radiative corrections in the Standard Model, these restrictions do not apply and one can write more general couplings that involve non-renormalizable interactions and arbitrary mixtures of left- and right-handed currents. The simplest extension of the tbWinteraction is an addition of the right-handed current and the dipole dimension-five operator

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu} \left(V_L P_L + V_R P_R\right) t W_{\mu}^{-} - g\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{2m_W} \left[g_L P_L + g_R P_R\right] t W_{\mu}^{-} + \text{h.c.}$$
(2)

The strength of the left-handed current V_L is arbitrary; in the Standard Model, it is related to the CKM matrix element V_{tb} . The strength of the left-handed current is measured in the *t*-channel single top production. Current LHC measurements [17, 18, 19, 20] give $V_L \approx 1.13 \pm$ 0.13, in agreement with the Standard Model at the ten percent level. One can expect that measurements of single top production cross-section at 3000 fb⁻¹ LHC will provide a three percent measurement of V_L .

The Lorentz structure of anomalous tWb coupling can be studied in top quark decays. There, a useful observable is the distribution of a relative angle between electron and W-boson momentum in the top quark rest frame. This distribution reads

$$\frac{\mathrm{d}\Gamma_t}{\Gamma_t \mathrm{d}\cos\theta} = \frac{3}{4}\sin^2\theta F_0 + \frac{3}{8}(1+\cos\theta)^2 F_R + \frac{3}{8}(1-\cos\theta)^2 F_L.$$
(3)

Coefficients F_0 and F_{\pm} correspond to relative probabilities for the top quark to decay to a W-boson with longitudinal, left-handed and right-handed polarizations. Currently, theoretical [21, 22, 23] and experimental [24, 25, 26] results are in agreement, but theory predictions are about one order of magnitude more precise. One can also use these measurements to constrain g_L, g_R and V_R in Eq.(2) to be smaller than 0.1.

We have described how V_L can be obtained from the measurement of a single-top production cross-section. However, one can also measure V_L assuming that the top quark can only decay to the Wb final state and that the CKM matrix is unitary. If so, then the ratio of the number of b-jets and light-quark jets from top decays is fixed in terms of V_{tb} and, if this ratio is measured, V_{tb} can be extracted. In fact, this was recently done by the CMS collaboration [27]. The result is the measurement of V_{tb} with the precision of just two percent. It is interesting to note that if the top quark width at a lepton collider will indeed be measured to two percent precision, it will be immediately possible to put strong limits on invisible decays of top quarks or to check the consistency of the above-mentioned CMS measurement. Indeed, by measuring the top width and assuming that it is saturated by $t \to Wb$ decays, we can turn a 2% width measurement into a 1% measurement of V_{tb} which is very competitive with V_{tb} determinations from singletop production. Furthermore, given the possibility to fully reconstruct top quarks at a lepton collider in a low-background environment, it should be possible to explore anomalous couplings in the tWb vertex from angular distributions of top and W decay products with a much higher

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Collider	LF	IC	ILC/CLIC
CM Energy [TeV]	14	14	0.5
Luminosity $[fb^{-1}]$	300	3000	500
SM Couplings			
photon, F_{1V}^{γ} (0.666)	0.042	0.014	0.002
Z boson, F_{1V}^Z (0.24)	0.50	0.17	0.003
Z boson, F_{1A}^{Z} (0.6)	0.058	_	0.005
Non-SM couplings			
photon, F_{1A}^{γ}	0.05	_	—
photon, $F_{2V}^{\overline{\gamma}}$	0.037	0.025	0.003
photon, F_{2A}^{γ}	0.017	0.011	0.007
Z boson, $\overline{F_{2V}^Z}$	0.25	0.17	0.006
Z boson, ReF_{2A}^Z	0.35	0.25	0.008
Z boson, $Im \tilde{F}_{2A}^{Z}$	0.035	0.025	0.015

Table 2: Table from Ref. [1]. Expected precision of the $t\bar{t}\gamma$ and $t\bar{t}Z$ coupling measurements at the LHC [31, 32] and the linear collider [33]. Expected magnitude of such couplings in the SM is shown in brackets. Note that the "non-standard model" couplings appear in the Standard Model through radiative corrections; their expected magnitude, therefore, is 10^{-2} .

precision than what is achievable at the LHC. This may be particularly important for studying possible CP-violation in top decays.

The situation becomes different if we consider interactions of electrically neutral electroweak gauge bosons with top quarks. The generic interaction vertex of top quarks with photons or Z bosons is parametrized as

$$\Gamma_{\mu} = ie \left\{ -\gamma_{\mu} \left(F_{1V} + F_{2V} + \gamma_5 F_{1A} \right) + \frac{(p - p')_{\mu}}{2m_t} \left(F_{2V} - i\gamma_5 F_{2A} \right) \right\},\tag{4}$$

where form factors F_i are functions of the momentum transfer q^2 . If the mass scale of BSM physics is high, the q^2 -dependence can be neglected. Current experimental knowledge of $t\bar{t}Z$ and $t\bar{t}\gamma$ couplings is poor. There is a measurement of the top quark charge from the sum of charges of jets that originate from top decay [28], and evidence that $t\bar{t}Z$ and $t\bar{t}\gamma$ couplings are non-vanishing since cross-sections for $t\bar{t}Z$ and $t\bar{t}\gamma$ production in proton collisions are different from zero [29, 30].

Cross sections for producing top quarks in association with electroweak gauge bosons increase dramatically once higher energies become available. This leads to higher statistics and to the possibility to measure top quark couplings much more precisely, as can be seen from projections in Table 2. For both the photon and the Z-boson, couplings that do not vanish at tree level in the SM can be measured to 10 - 50 percent. In fact, by measuring these couplings to ten percent we start probing an interesting region of parameter space since there are examples of physics beyond the Standard Model that lead to this level of deviations. In particular, $\mathcal{O}(10\%)$ deviations in $t\bar{t}Z$ are a smoking gun of composite or extra-dimensional models [34], while much smaller changes in $t\bar{t}Z$ vertex are expected in weakly-interacting extensions of the SM, e.g. the supersymmetry.

Collider	LHC		ILC	ILC	CLIC
CM Energy [TeV]	14	14	0.5	1.0	1.4
Luminosity $[fb^{-1}]$	300	3000	1000	1000	1500
Top Yukawa coupling κ_t	(14 - 15)%	(7-10)%	10%	4%	4%

Table 3: Table from Ref.[1]. Expected precision of the top quark Yukawa coupling measurement expected at the LHC and the linear collider [35]. The range for the LHC precision corresponds to an optimistic scenario where systematic uncertainties are scaled by a factor 0.5 and a conservative scenario where systematic uncertainties remain at the 2013 level [36, 37, 38]. The ILC [33, 39] and CLIC [40] projections assume polarized beams and nominal integrated luminosities.

Measurements of $t\bar{t}Z$ and $t\bar{t}\gamma$ couplings at a lepton collider will lead to extremely precise results that may be of interest to either explore deviations observed at the LHC or to search for even smaller indirect evidence for physics beyond the Standard Model. Since the precision of the couplings measurement improves by more than one order of magnitude at a lepton collider relative to what can be achieved at the LHC, the sensitivity to energy scales of BSM physics increases by almost a factor three. It should be also emphasized that new opportunities at a linear collider arise thanks to the beam polarization that allows us to disentangle different (c.f. Eq.(4)) anomalous couplings in $t\bar{t}Z$ and $t\bar{t}\gamma$ vertices.

Measurements of the top-Higgs Yukawa coupling are exceptionally important. This coupling holds clues to the Naturalness problem and it is the main ingredient in the discussion of the vacuum stability. A smaller top Yukawa coupling will ameliorate many concerns related to the above-mentioned problems while a larger Yukawa coupling will amplify them. Knowledge of the top Yukawa coupling allows us to predict the strength of $H\gamma\gamma$ and Hgg interactions in the Standard Model, so that by comparing our expectations to direct measurements of $H\gamma\gamma$ and Hgg rates, we can probe for additional contributions to these interactions.

The Higgs-top Yukawa coupling can be measured at the LHC in the process $pp \to t\bar{t}H$ by considering rare decays of the Higgs boson. In Table 3 we summarize prospects for measuring the top Yukawa coupling at the LHC; it follows from that table that one can probably reach the 10% precision on the top-Higgs Yukawa coupling at the high-luminosity LHC. At a lepton collider, the situation with measuring the top Higgs Yukawa coupling depends on the energy of the machine. This is so, because the primary process for measuring top Yukawa is $e^+e^- \to t\bar{t}H$ and it has a kinematic threshold at $2m_t + m_H \approx 470$ GeV, which is rather high. The maximum of $e^+e^- \to t\bar{t}H$ cross-section occurs at above 500 GeV; if it can be reached, the top Yukawa coupling can be measured to about 4 percent precision.

It is also possible that the top Yukawa coupling is of a more general type than what exists in the Standard Model. The most general $Ht\bar{t}$ coupling is $H\bar{\psi}(a+ib\gamma_5)\psi$. A non-vanishing *b* implies CP-violation. The possibility to study CP violation in top quark interactions with the Higgs boson at the ILC was discussed in Ref. [41] where further details can be found.

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	D II II	Q 1		D (
Process	Br Limit	Search	Dataset	Reference
$t \to Zq$	2.2×10^{-4}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	$300 \text{ fb}^{-1}, 14 \text{ TeV}$	[43]
$t \to Zq$	7×10^{-5}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	$3000 \text{ fb}^{-1}, 14 \text{ TeV}$	[43]
$t \to Zq$	$5(2) \times 10^{-4}$	ILC single top, $\gamma_{\mu} (\sigma_{\mu\nu})$	$500 \text{ fb}^{-1}, 250 \text{ GeV}$	Extrap.
$t \to Zq$	$1.5(1.1) \times 10^{-4(-5)}$	ILC single top, $\gamma_{\mu} (\sigma_{\mu\nu})$	$500 \text{ fb}^{-1}, 500 \text{ GeV}$	[44]
$t \to Zq$	$1.6(1.7) imes 10^{-3}$	ILC $t\bar{t}, \gamma_{\mu} (\sigma_{\mu\nu})$	$500 \text{ fb}^{-1}, 500 \text{ GeV}$	[44]
$t \to \gamma q$	8×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	$300 \text{ fb}^{-1}, 14 \text{ TeV}$	[43]
$t\to \gamma q$	$2.5 imes 10^{-5}$	ATLAS $t\bar{t} \to Wb + \gamma q$	$3000 \text{ fb}^{-1}, 14 \text{ TeV}$	[43]
$t\to \gamma q$	6×10^{-5}	ILC single top	$500 \text{ fb}^{-1}, 250 \text{ GeV}$	Extrap.
$t\to \gamma q$	$6.4 imes 10^{-6}$	ILC single top	$500 \text{ fb}^{-1}, 500 \text{ GeV}$	[44]
$t\to \gamma q$	$1.0 imes 10^{-4}$	ILC $t\bar{t}$	$500 \text{ fb}^{-1}, 500 \text{ GeV}$	[44]
$t \rightarrow gu$	4×10^{-6}	ATLAS $qg \to t \to Wb$	$300 \text{ fb}^{-1}, 14 \text{ TeV}$	Extrap.
$t \to g u$	1×10^{-6}	ATLAS $qg \to t \to Wb$	$3000 \text{ fb}^{-1}, 14 \text{ TeV}$	Extrap.
$t \to gc$	1×10^{-5}	ATLAS $qg \to t \to Wb$	$300 \text{ fb}^{-1}, 14 \text{ TeV}$	Extrap.
$t \to gc$	4×10^{-6}	ATLAS $qg \to t \to Wb$	$3000 \text{ fb}^{-1}, 14 \text{ TeV}$	Extrap.
$t \to hq$	2×10^{-3}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	$300 \text{ fb}^{-1}, 14 \text{ TeV}$	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	$3000 \text{ fb}^{-1}, 14 \text{ TeV}$	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \rightarrow Wb + hq \rightarrow \ell\nu b + \gamma\gamma q$	$300 \text{ fb}^{-1}, 14 \text{ TeV}$	Extrap.
$t \to hq$	2×10^{-4}	LHC $t\bar{t} \rightarrow Wb + hq \rightarrow \ell\nu b + \gamma\gamma q$	$3000 \text{ fb}^{-1}, 14 \text{ TeV}$	Extrap.

Table 4: Projected limits [1, 42] on top FCNC at the LHC and ILC. "Extrap." denotes estimates based on extrapolation as described in the text. For the ILC/CLIC, limits for various tensor couplings are shown in brackets.

5 Flavor changing decays of top quarks

Flavor-changing decays of top quarks $t \to u\gamma$, $t \to cZ$, $t \to Hu$ etc. are allowed in the Standard Model, but have tiny branching fractions thanks to CKM and loop suppression. Given the tiny SM contributions it is natural to expect that if there are other contributions to these decays they may become clearly observable. The branching fractions that can be expected in various extensions of the Standard Model are between 10^{-4} and 10^{-10} ; further details can be found in Refs. [1, 42]. Current experimental measurements are becoming sensitive to top quark flavor-violating branching fractions as small as 10^{-3} , which means that the next step in the exploration of flavor-changing top decays may become very interesting.

Expectations for further improvements in measuring flavor-violating decays of top quarks are shown in Table 4. The entries in that table are collected from various studies, referenced there, or are obtained by extrapolation. It follows from that table that high-luminosity LHC will be able to probe top flavor-changing branching fractions down to the $10^{-4} - 10^{-5}$ level which is a very interesting range. Except for a few cases, the ILC will probably not be able to do significantly better. A truly new element that the ILC will provide is related to the possibility to use polarization information to disentangle decays facilitated either by current operators $q\gamma_{\mu}tZ^{\mu}$ or dipole operators $q\sigma_{\mu\nu}tZ^{\mu\nu}$. Such a separation does not appear possible at the LHC although it will be important for understanding the flavor-changing interactions of top quarks if a signal is discovered. Moreover, it is interesting to point out that one can study top quark flavor-violating processes at a 250 GeV machine by searching for single top production $e^+e^- \rightarrow Z/\gamma \rightarrow t\bar{q}$ that occurs through flavor-violating tqZ and $tq\gamma$ vertices The reach appears

to be quite comparable to what can be expected at the LHC and at a higher-energy lepton collider, see Table 4.

6 Searches for physics beyond the Standard Model

We will now turn to the question of what a lepton collider can do to search for physics beyond the Standard Model related to top quarks. Admittedly, given bounds on such physics that have already been provided by the LHC, one should not expect many BSM discoveries from a lepton collider. Indeed, the existing limits are in the range of 1 TeV for generic stops, fermionic partners of top quarks, resonances that decay to $t\bar{t}$ pairs and so on. Clearly, all these particles are way too heavy to be produced at a lepton collider whose energy is below a TeV.

However, there are cases when generic mass bounds mentioned above do not apply. Such cases are typically connected with complicated mass patterns of BSM particles which significantly change the experimental acceptances assumed for setting direct limits. To give an example, suppose that a dominant decay mode of a stop is $\tilde{t} \to t + \chi_0$ and that masses of tops and stops are close, $m_{\tilde{t}} \approx m_t \gg m_{\chi}$. Then the stop signal is difficult to pick up over the $t\bar{t}$ background since the neutralino in the final state is soft and does not produce additional missing energy. One can use other observables – for example spin correlations – to disentangle tops from stops [45] but these techniques are difficult and not yet fully established. So, it is conceivable that regions where stops are relatively light will remain undiscovered at the LHC. However, a linear collider with sufficient energy can easily discover these particles and perform a detailed analysis of their properties through the threshold scan.

7 Conclusions

According to conventional wisdom, hadron and lepton colliders are complimentary: hadron colliders are designed for discoveries and lepton colliders – for precision measurements. While this premise is correct in general, it may not accurately reflect the actual situation now since the Tevatron and LHC experiments have demonstrated that impressive precision measurements can be performed at hadron colliders. It is expected that such measurements will successfully continue at a higher-energy and higher-luminosity LHC and that, in many cases, they will be probing interesting and important regions of parameter spaces which will further benefit our understanding of the top quark physics.

Significant improvements in precision at a lepton collider are possible in measurements of the top quark mass, the top quark width, the top quark couplings to electroweak gauge bosons and the Higgs boson, and in top quark flavor-violating decays. There are scenarios – in particular models of composite tops and Higgs – where such precision measurements will be crucial for understanding physics beyond the Standard Model. Further discussions of these issues can be found in Ref.[1]. In general, expected improvements in our understanding in top quark physics, Higgs physics and precision electroweak physics leave little doubt that a lepton collider with a reach that includes the top quark threshold and *beyond* is a fantastic tool for future research in particle physics.

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$t\bar{t}$ plus jets measurements

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Jet multiplicity distributions are measured in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS detectors at the LHC. The measurements are performed in the dileptonic and the lepton plus jets channels. Several QCD calculations are compared with the data.

1 Introduction

About half of the total $t\bar{t}$ events produced at the Large Hadron Collider have additional hard jets in the final state. To describe these events correctly, higher order QCD calculations, including contributions from initial and final state radiation, are required. Precise measurements of the jet multiplicity in $t\bar{t}$ +jets events are useful not only to provide a test of perturbative QCD, but also because they are an important background to $t\bar{t}H$ and some SUSY final states. Finally, anomalous production of $t\bar{t}$ + jets could signal physics beyond the Standard Model (SM).

In the SM, top quarks decay most of the times to a W boson and a bottom quark. Depending on the decay mode of the W there are three different $t\bar{t}$ signatures: fully hadronic, lepton plus jets and dileptonic final states. This note includes results obtained in the lepton plus jets and the dileptonic channels with the ATLAS [1] and CMS [2] detectors. CMS uses the complete 2011 and 2012 datasets, which amount to 5 fb⁻¹ and 19.6 fb⁻¹ respectively, whereas ATLAS uses only the 2011 dataset, which amounts to 4.7 fb⁻¹.

2 Theoretical predictions

Data are compared with several predictions from perturbative QCD calculations. Table 1 summarizes the different simulated samples used in the analyses.

3 Dilepton channel

The dilepton channel is particularly suited to the study of $t\bar{t}$ jet multiplicity distributions as, at leading order, only two charged leptons and two *b*-jets are produced in the final state. Thus, any additional jet can be ascribed to higher order QCD effects. Jets are reconstructed differently in ATLAS and CMS. ATLAS forms topological clusters from energy deposits. These clusters are then used as input to the anti-k_T algorithm [3] with a radius parameter of R = 0.4. CMS reconstructs events using a particle-flow technique, in which signals from all subdetectors are combined. Jets are reconstructed by clustering the particle-flow candidates using the anti-k_T algorithm with size parameter R = 0.5.

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Sample	ATLAS	CMS
$t\bar{t}$	Alpgen [4]+Herwig [5]	MadGraph [6]+Pythia [7]
	Alpgen+Pythia	Powheg [8]+Pythia
	Powheg+Pythia	MC@NLO [9]+Herwig
	MC@NLO+HERWIG	
W+jets	Alpgen+Herwig	MadGraph+Pythia
Z+jets	Alpgen+Herwig	MadGraph+Pythia
Diboson	Herwig	MadGraph+Pythia
Single top	ACERMC [10] (t-channel)	Powheg+Pythia
	MC@NLO (all channels)	
$Z/\gamma *$		MadGraph+Pythia

Table 1: Simulated samples used in the jet multiplicity measurements.

ATLAS	CMS
Electrons: $p_T > 25 \text{ GeV } \& \eta < 2.47$	Electrons: $p_T > 20 \text{ GeV } \& \eta < 2.4$
Muons: $p_T > 20 \text{ GeV } \& \eta < 2.5$	Muons: $p_T > 20 \text{ GeV } \& \eta < 2.4$
Jets: $p_T > 25 \text{ GeV } \& \eta < 2.4$	Jets: $p_T > 30 \text{ GeV } \& \eta < 2.4$
Single lepton triggers	Dilepton triggers
Two opposite-sign leptons	At least two opposite-sign leptons
At least two jets	At least two jets
At least two identified <i>b</i> -jets ($\epsilon_{\text{tagging}} \approx 70\%$)	At least one identified <i>b</i> -jet ($\epsilon_{\text{tagging}} \approx 80 - 85\%$)
$E_T^{\text{miss}} > 40 \text{ GeV} (ee, \mu\mu \text{ only})$	$E_T^{\text{miss}} > 30 \ (40) \text{ GeV}$ in the 7 (8) TeV data analysis
$H_T > 130 \text{ GeV} (e\mu \text{ only})$	
Veto Z-boson and vector-meson regions $(ee, \mu\mu)$	Veto Z-boson and vector-meson regions $(ee, \mu\mu)$
	Use kinematic reconstruction to determine
	top-pair properties and identify $2 b$ -jets
	originating from decays of t-quarks

Table 2: ATLAS (7 TeV data analysis) and CMS (both 7 TeV and 8 TeV data analyses) dilepton channel event selection criteria [13–15].

The $t\bar{t}$ pairs are reconstructed requiring two isolated charged leptons, electrons or muons, at least two jets, and at least one (ATLAS) or two (CMS) candidate *b*-jets. Table 2 shows the details of the different event selection criteria applied in the ATLAS [13] and CMS [14, 15] analyses.

The jet multiplicity distributions show good agreement with the theoretical predictions, although the simulation predicts a slightly higher jet multiplicity than observed in 8 TeV data, as can be seen in Fig. 1.

The differential cross-section as a function of the jet multiplicity is measured from the number N_{data}^i of events in data in bin *i*, the number of estimated background events N_{bkg}^i , the integrated luminosity \mathcal{L} , the bin width Δ_x^i and a factor ϵ^i to correct for detector efficiencies and acceptances in each bin of the measurement, according to the expression

$$\frac{d\sigma_{t\bar{t}}}{dN} = \frac{N^i_{data} - N^i_{bkg}}{\Delta^i_x \epsilon^i \mathcal{L}}.$$
(1)



Figure 1: Reconstructed CMS jet multiplicity distribution after event selection for all jets with transverse momenta above 60 GeV (left) and 100 GeV (right) [15].

The normalised differential cross-section is derived by dividing it by the total cross-section measured in the same analysis. The advantage of using normalised cross-sections is that systematic uncertainties correlated across all bins of the measurement cancel out. The migration of events across bin boundaries and the statistical correlations among neighbouring bins caused by trigger and detector efficiencies and resolutions are corrected using a regularised unfolding method [16,17]. Several sources of systematic uncertainty have been considered, originating both from detector effects as well as theoretical uncertainties. The dominant systematic uncertainties arise from the uncertainty of the jet energy scale as well as from model uncertainties. The total systematic uncertainty is about 3% at low jet multiplicities increasing to about 20% in the bin with at least five jets. The latter is dominated by the statistical uncertainty of the modified simulated samples.

Figure 2 shows the normalised differential cross-section as a function of the jet multiplicity for the 8 TeV CMS data sample. In general MADGRAPH and POWHEG generators interfaced with PYTHIA provide a reasonable description of the data, whereas MC@NLO interfaced with HERWIG does not generate sufficiently large jet multiplicities. The choice of larger scales leads to an improved description of the data up to high jet multiplicities. The same behaviour is observed in the 8 TeV data sample.

An alternative way to quantify the jet activity that arises from quark and gluon radiation is to determine the fraction of events that do not contain additional jets above a given threshold. The 'gap fraction' variable is defined as

$$f(Q_0) = \frac{n(Q_0)}{N},$$
 (2)

where N is the number of selected events and $n(Q_0)$ is the subset of those that do not contain any additional jet above a transverse momentum threshold Q_0 in a central rapidity interval. This veto can be extended beyond the leading additional jet using the alternate definition



Figure 2: Normalised CMS differential cross-section as a function of the jet multiplicity for jets with $p_T > 30$ GeV (top row) and $p_T > 100$ GeV (bottom row). The figures on the left show the comparison of the data with different theoretical predictions. The figures on the right show the behaviour of the MADGRAPH generator when varying the Q^2 and matching scales [15].

$$f(Q_{sum}) = \frac{n(Q_{sum})}{N},\tag{3}$$

where $n(Q_{sum})$ is the number of events in which the scalar transverse momentum sum of the additional jets in the rapidity interval is less than Q_{sum} . This definition is sensitive to all hard emissions accompanying the $t\bar{t}$ system.

Using 7 TeV data, ATLAS measures the gap fraction as a function of Q_0 and Q_{sum} , as shown in Figs. 3 and 4, which compare the data with several theoretical predictions in three rapidity regions. Data have been corrected for detector effects to obtain results at the particle level. Reasonable agreement is found in the full rapidity interval, but no simulation agrees in the most forward region, where too much jet activity is predicted. MC@NLO predicts too little activity in the central region as well. The fact that $f(Q_{sum})$ is lower than $f(Q_0)$ probes quark and gluon radiation beyond first emission. Only 2.05 fb⁻¹ of data are used in this measurement.



Figure 3: Measured ATLAS gap fraction as a function of Q_0 compared with several theoretical predictions in different rapidity regions [13]. The measurement is done with 7 TeV data.

CMS performs similar measurements using both 7 and 8 TeV data, and in addition studies the gap fraction for the second additional jet. In general, all generators are found to give a reasonable description of the data. Differences between MC@NLO interfaced with HERWIG and POWHEG or MADGRAPH are similar to the precision of the measurements. Increasing the Q^2 scale improves the agreement of MADGRAPH with data, while varying the matching thresholds increases the difference between data and simulation.

4 Lepton plus jets channel

The $t\bar{t}$ pairs are reconstructed in this channel requiring one isolated charged lepton, electron or muon, at least three jets, and at least one (ATLAS) or two (CMS) candidate *b*-jets. Jets are reconstructed using the same methods presented in Section 3. Table 3 shows the details of the



Figure 4: Measured ATLAS gap fraction as a function of Q_{sum} compared with several theoretical predictions in different rapidity regions [13]. The measurement is done with 7 TeV data.

different event selection criteria applied in the ATLAS [18] and CMS [19] analyses.

This channel suffers from more background than the dilepton one, mainly from W+jetsand QCD multijet processes. The shape of the W+jets background is assumed to be well described by the simulation whereas its overall normalisation is extracted from data, using the ratio between the W^+ and W^- production cross-sections, whose theoretical prediction is known with a precision of few percent. The normalisation is obtained separately for W + 3jet, W + 4 jet and $W+ \geq 5$ jet events. ATLAS evaluates the QCD multijet background from data using a matrix method. CMS exploits the fact that leptons from QCD multijet events are expected to be less isolated than leptons in other processes, and obtains a reasonably pure sample of QCD multijet events by inverting the selection criteria placed on the lepton relative isolation. Contributions from other processes are obtained from simulation. Fig. 5 shows the jet multiplicity distributions for the CMS 7 TeV data sample.

ATLAS corrects the jet multiplicity spectra back to the particle level by accounting for

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ATLAS	CMS
Electrons: $p_T > 25 \text{ GeV } \& \eta < 2.47$	Electrons: $p_T > 30 \text{ GeV } \& \eta < 2.5$
Muons: $p_T > 25 \text{ GeV } \& \eta < 2.5$	Muons: $p_T > 30 \text{ GeV } \& \eta < 2.1$
Jets: $p_T > 25 \text{ GeV } \& \eta < 2.5$	Jets: $p_T > 35 \text{ GeV } \& \eta < 2.4$
Single lepton triggers	Single muon and single electron plus 3 jets triggers
Exactly one isolated lepton matching trigger	Exactly one isolated lepton
Veto events with other leptons with $p_T > 15 \text{ GeV}$	
At least three jets	At least three jets
At least one identified <i>b</i> -jet ($\epsilon_{\text{tagging}} \approx 70\%$)	At least two identified <i>b</i> -jets ($\epsilon_{\text{tagging}} \approx 80 - 85\%$)
$E_T^{\text{miss}} > 30 \text{ GeV}$	
$m_T(W) > 35 \text{ GeV}$	

Table 3: Lepton plus jets channel event selection criteria [18, 19].



Figure 5: Reconstructed CMS jet multiplicity distribution after event selection for all jets in the e+jets (left) and μ +jets (right) channels [19].

detector efficiencies, resolution effects and biases. The data are corrected using the following expression

$$\vec{N}_{part} = \vec{f}_{part!reco} \cdot \mathbf{M}_{part}^{reco} \cdot \vec{f}_{reco!part} \cdot \vec{f}_{accpt} \cdot \left(\vec{N}_{reco} - \vec{f}_{bkg}\right),\tag{4}$$

where f_{accpt} is an acceptance correction for all selection efficiencies except for the jet multiplicity requirement; $f_{recolpart}$ is a correction for events passing the jet multiplicity requirement at reconstruction level but not at particle level; \mathbf{M}_{part}^{reco} is a response matrix provided for the unfolding of the jet multiplicity to correct for the jet resolution and reconstruction effects. Finally, $f_{part!reco}$ corrects for events which fulfill the particle-level jet multiplicity requirement but fail the same at reconstruction level. Fig. 6 shows the fully corrected particle-jet multiplicities for various jet transverse momentum thresholds in the electron channel compared to different theoretical predictions. For the lowest jet transverse momentum threshold, all predictions agree with data in the three- and four-jet bins. MC@NLO underestimates data for events with more than six jets in the lowest jet transverse momentum bin and for lower multiplicities as the

transverse momentum threshold increases.

CMS provides the normalised differential cross-section of $t\bar{t}$ events as a function of the number of additional partons, which are defined as those with transverse momenta larger than 30 GeV and whose distance ΔR to all $t\bar{t}$ decay products is larger than 0.5. Fig. 7 shows this distribution compared with expectations from different generators. The measured fractions of events with zero, one and two or more additional hard partons are in excellent agreement with MADGRAPH and POWHEG generators. Furthermore, already with the 7 TeV dataset, the precision of the measurement is significantly better than the scale variations and can be used to constrain them.

5 Summary

 $t\bar{t}$ jet multiplicity measurements are useful to test theoretical predictions and to look for beyond the Standard Model signals. Both ATLAS and CMS find good agreement between data and simulation except for MC@NLO Monte Carlo, which produces too little jet activity at high jet multiplicities. Furthermore, there is some indication that data prefer a lower α_S value for multi-leg generators. Finally, with the present data sets, the ability to constrain models at large jet multiplicities is limited by the large statistical uncertainty.

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Figure 6: ATLAS particle-jet multiplicities for the electron channel and the jet p_T thresholds (from left to right and top to bottom) 25, 40, 60 and 80 GeV. Data are shown in comparison to several theoretical predictions [18].

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Figure 7: Measured CMS normalised cross-section measurement of $t\bar{t}$ processes with additional partons in the μ +jets channel [19].

Probing QCD parameters with top-quark data

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Results from inclusive and differential measurements of the production cross sections for top quarks in proton-proton collisions at center-of-mass energies of 7 and 8 TeV are compared to predictions at next-to-leading and next-to-next-to-leading order in perturbative Quantum Chromodynamics. From these studies, constraints on the top-quark mass, the strong coupling constant, and on parton distribution functions are determined.

1 Introduction

Quantum Chromodynamics (QCD) is the theory of the strong interaction between quarks and gluons. The only free parameters of the QCD Lagrangian are the quark masses and the strong coupling constant, α_S . The factorization theorem of QCD allows the calculation of cross sections, σ , to be split into hard-scattering matrix elements, $\hat{\sigma}$, on the one hand and parton distribution functions (PDFs) on the other. While $\hat{\sigma}$, describing the short-distance structure of a reaction, is process-dependent but perturbatively calculable, the PDFs, which account for the non-perturbative long-distance structure, are universal but have to be determined from experimental data.

The top quark is by far the heaviest of all quarks. Measurements of the top-quark mass, m_t , have been brought to an impressive precision at the Tevatron, $m_t = 173.20 \pm 0.87$ GeV [1], and at the Large Hadron Collider (LHC), $m_t = 173.20 \pm 0.95$ GeV [2]. However, exact relations between these results and theoretically well-defined mass schemes have not yet been established.

The strong coupling constant has been measured in numerous processes and at different energies. The latest world average, which takes the mass of the Z boson as reference scale, is $\alpha_S(m_Z) = 0.1184 \pm 0.0007$ [3]. This average and its remarkable precision are driven by results obtained at relatively low energies, namely from hadronic decays of τ leptons and from lattice QCD. Cross sections for jet production at the LHC allow α_S to be probed even up to the TeV scale. However, the corresponding jet cross sections have typically been calculated only to next-to-leading order (NLO) QCD so far and they suffer from sizable uncertainties related to choice and variation of the renormalization and factorization scales, μ_R and μ_F , as well as from non-perturbative corrections.

PDF groups have released a large number of different PDF sets. For a given order in perturbation theory, the main differences between these PDF sets arise from the choice of the included data, the treatment of systematic uncertainties in the data and of correlations, the parametrization at the starting scale, the chosen heavy-quark scheme, and the values of the quark masses and of $\alpha_S(m_Z)$. At present, all PDF sets exhibit a significant uncertainty on the gluon density at medium-high parton momentum fractions, x. This uncertainty affects predictions for Higgs-boson, top-quark, and jet production as well as many scenarios for new physics beyond the Standard Model.

In this article, constraints on PDFs, $\alpha_S(m_Z)$, and m_t from LHC top-quark data as well as their interplay are discussed. In general, the evolution of such QCD analyses is as follows: First, identify and potentially maximize the sensitivity of experimental data to the parameters of interest. Then, understand correlations, both between theory parameters and within the data. And, eventually, improve PDFs or determine other parameters by including the new data in QCD fits.

2 Top-quark pair production

2.1 The total cross section

At the LHC, top quarks are produced at relatively high rates, predominantly in pairs of quarks and anti-quarks $(t\bar{t})$ from gluon-gluon fusion. The calculation of the total $t\bar{t}$ cross section, $\sigma_{t\bar{t}}$, to next-to-next-to-leading order (NNLO) plus next-to-next-to-leading-log (NNLL) resummation has recently been completed [4]. The uncertainties related to higher orders, estimated via the variation of μ_R and μ_F , to the PDFs, to $\alpha_S(m_Z)$, and to m_t now amount to roughly 3% each. From the experimental point of view, $\sigma_{t\bar{t}}$ has been measured by the ATLAS and CMS Collaborations at proton-proton center-of-mass energies, \sqrt{s} , of 7 and 8 TeV, using the various $t\bar{t}$ decay channels. The most precise results have been obtained in the dilepton channel [5, 6], both of them yielding a total uncertainty on $\sigma_{t\bar{t}}$ below 5%.

The predicted $\sigma_{t\bar{t}}$ strongly depends on the assumed values of m_t and $\alpha_S(m_Z)$, but also the measured cross section can depend on them. Dependencies of the measured cross section arise from the acceptance corrections, which are derived using simulated $t\bar{t}$ events. Figure 1 compares CMS' most precise single measurement of $\sigma_{t\bar{t}}$ [5], which was obtained at $\sqrt{s} = 7$ TeV, to the NNLO+NNLL prediction with five different NNLO PDF sets. These PDF sets are provided for a series of $\alpha_S(m_Z)$ values, which allows the full correlation between the choice of $\alpha_S(m_Z)$ and the parton densities to be preserved. Relatively small differences are found between four of the five PDF sets, namely between CT10, HERAPDF1.5, MSTW2008, and NNPDF2.3. ABM11, by contrast, does not only have a smaller default value of $\alpha_S(m_Z)$ but also a smaller gluon density, which results in a lower $\sigma_{t\bar{t}}$ prediction compared to the other PDF sets at any given $\alpha_S(m_Z)$ value. While the measured $\sigma_{t\bar{t}}$ has a sizable m_t dependence, only a minor dependence on $\alpha_S(m_Z)$ was found.

CMS used this comparison between measured and predicted $\sigma_{t\bar{t}}$ for extractions of m_t and $\alpha_S(m_Z)$ [7]. The NNLO+NNLL prediction was taken as a Bayesian prior to the cross-section measurement, which enabled the construction of marginalized posteriors in m_t and $\alpha_S(m_Z)$. The measured cross section was parametrized using a Gaussian probability function along $\sigma_{t\bar{t}}$. The PDF uncertainty on the predicted $\sigma_{t\bar{t}}$ was also assumed to be Gaussian and convoluted with a step function that yields equal probabilities for all $\sigma_{t\bar{t}}$ values covered by the μ_R and μ_F variations and vanishes elsewhere. No big changes were found when trying different parametrizations for the scale uncertainty. The marginalized posteriors were then obtained by integrating over $\sigma_{t\bar{t}}$. For given values of $\alpha_S(m_Z)$ or m_t , these posteriors yield the most probable m_t and $\alpha_S(m_Z)$ values, respectively, together with Bayesian confidence intervals that account for the uncertainty on the measured cross section and the PDF and scale uncertainties on the predicted cross section. Additionally, the following uncertainties were taken into account:
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- An uncertainty of 0.65% on the LHC beam energy $(E_{\rm LHC})$ [8], translating into 46 GeV on the nominal \sqrt{s} value of 7 TeV.
- For the m_t determination, the uncertainty of 0.0007 on the $\alpha_S(m_Z)$ world average, which was used as constraint.
- For the m_t determination, an uncertainty of 1 GeV on the equality of top-quark pole mass and the top-quark mass in the Monte Carlo simulation (m_t^{MC}) [9], since the simulation was employed for the acceptance corrections in the $\sigma_{t\bar{t}}$ measurement.
- For the $\alpha_S(m_Z)$ determination, an uncertainty of 1.4 GeV on the Tevatron average for m_t , which was used as constraint. This variation accounts for both the 0.9 GeV uncertainty of the Tevatron average itself and the 1 GeV uncertainty in relating m_t^{MC} , employed also to calibrate these direct mass measurements, to the top-quark pole mass.

Using NNPDF2.3, the results are

$$m_t = 176.7^{+3.1}_{-2.8} (\text{exp.})^{+1.5}_{-1.3} (\text{PDF})^{+0.9}_{-0.9} (\text{scale})^{+0.7}_{-0.7} (\alpha_S)^{+0.9}_{-0.9} (E_{\text{LHC}})^{+0.5}_{-0.4} (m_t^{\text{MC}}) \text{ GeV}$$

= 176.7^{+3.8}_{-3.4} GeV

and, alternatively,

$$\alpha_S(m_Z) = 0.1151^{+0.0025}_{-0.0025}(\text{exp.})^{+0.0013}_{-0.0011}(\text{PDF})^{+0.0009}_{-0.0008}(\text{scale})^{+0.0013}_{-0.0013}(m_t)^{+0.0008}_{-0.0008}(E_{\text{LHC}})$$

= 0.1151^{+0.0033}_{-0.0032}.

The results with all five PDF sets are shown in Figure 2. These are the first extractions of the top-quark pole mass at full NNLO QCD, of $\alpha_S(m_Z)$ from top-quark data, and of $\alpha_S(m_Z)$ at full NNLO QCD from a hadron collider. There are only small differences between the result obtained with CT10, HERAPDF1.5, MSTW2008, and NNPDF2.3, while the smaller gluon density of ABM11 requires either a lower m_t or a higher $\alpha_S(m_Z)$ value to reproduce the $\sigma_{t\bar{t}}$ measured by CMS. Using ABM11 with its default $\alpha_S(m_Z)$ of 0.1134 ± 0.0011 would yield $m_t = 166.3^{+3.3}_{-3.1}$ GeV, which is significantly lower than the results from direct m_t measurements and than the results obtained via $\sigma_{t\bar{t}}$ when using the other PDF sets.

First studies illustrating the impact of the total $\sigma_{t\bar{t}}$ as measured at LHC and Tevatron in particular on the gluon PDF have been released by different authors [10, 11, 12]. However, more work is needed to accurately incorporate all systematic uncertainties and correlations, both between the PDFs, α_S , and m_t and among the experimental data, as well as the experimental m_t dependencies. Ratios of the $t\bar{t}$ cross section measured at different center-of-mass energies (8 to 7 TeV; later: 14 to 8 TeV) also have promising prospects for PDF fits, since the PDF uncertainties on the predicted ratios are significantly larger than the combined μ_R , μ_F , α_S , and m_t uncertainties [11], but such cross-section ratios require a thorough understanding of the correlations between the systematic uncertainties on the measured $\sigma_{t\bar{t}}$ at the different centerof-mass energies.



Figure 1: Predicted $t\bar{t}$ cross section at NNLO+NNLL, as a function of the top-quark mass (left) and of the strong coupling constant (right), using five different NNLO PDF sets, compared to the cross section measured by CMS [7].



Figure 2: Results obtained for the top-quark mass (left) and for the strong coupling constant (right) by comparing the measured $t\bar{t}$ cross section from CMS to the prediction at NNLO+NNLL using five different NNLO PDF sets [7].

2.2 Differential cross sections

ATLAS and CMS have measured a variety of (normalized) differential cross sections for $t\bar{t}$ production [13, 14, 15, 16, 17]. These results can be compared to predictions at NLO or, in some cases (namely the distributions as a function of the transverse momentum and the rapidity of the top-quarks as well as the invariant mass of the $t\bar{t}$ system), to calculations at approximate NNLO.

In general, kinematic regions in which the PDF uncertainty on the predicted cross section is larger than other modeling uncertainties are considered to have the largest potential to improve the accuracy of future PDF fits. The ATLAS Collaboration compared differential $t\bar{t}$ cross sections at $\sqrt{s} = 7$ TeV to predictions at NLO QCD with different NLO PDF sets [18, 17]. The best PDF sensitivity was found in the rapidity and the invariant mass of $t\bar{t}$ system, $y_{t\bar{t}}$ and $m_{t\bar{t}}$. The size of the corresponding theory uncertainties are illustrated in Figure 3. Both $y_{t\bar{t}}$ and $m_{t\bar{t}}$ are directly correlated with the momenta of the incoming partons. Large rapidities require one incoming parton with high x, the other one with small x. Large $m_{t\bar{t}}$ values also probe the high-x regime. However, it has to be kept in mind that electroweak corrections to differential $t\bar{t}$ cross sections are known to be non-negligible, in particular for high transverse momenta and invariant masses but also for the shape of the $y_{t\bar{t}}$ distribution (as discussed, for example, in [19]), and that these corrections are typically not yet included in these comparisons.



Figure 3: Relative uncertainties on the NLO prediction with NNPDF2.3 for the normalized $t\bar{t}$ cross section as a function of the rapidity (left) and the invariant mass (right) of the $t\bar{t}$ system [18].

Using the first 2.1 fb⁻¹ of data at $\sqrt{s} = 7$ TeV, ATLAS quantified the compatibility between measured differential cross sections in the lepton+jets channel and the corresponding NLO predictions with five different NLO PDF sets (ABM11, CT10, HERAPDF1.5, MSTW2008, NNPDF2.3), taking into account all experimental and theoretical uncertainties as well as binto-bin correlations for the data [18]. The best separation strength was found for $y_{t\bar{t}}$, where the χ^2 probabilities range from 21% for CT10 to 83% for NNPDF2.3.

Recently, the ATLAS Collaboration released updated results for differential $t\bar{t}$ cross sections [17], now using the full dataset at 7 TeV, corresponding to 4.6 fb⁻¹. The compatibility between data and NLO prediction is shown in Figure 4 for $y_{t\bar{t}}$, $m_{t\bar{t}}$, and the transverse momentum of the top quarks, $p_{T,t}$. In all three cases, a significant tension in shape between the predictions with the various PDF sets can be seen. As before, the level of agreement between

data and prediction appears to be better with MSTW2008 than with CT10 and better with NNPDF2.3 compared to MSTW2008. However, the new data seems to prefer the prediction with HERAPDF1.5. Again, electroweak corrections are not yet included here but could yield a non-negligible contribution.



Figure 4: Ratios of the NLO predictions with four different NLO PDF sets to the measured normalized $t\bar{t}$ cross section as a function of rapidity (left) and invariant mass (center) of the $t\bar{t}$ system as well as the transverse momentum of the top quarks (right) [17].

3 Production of single top quarks

The production of single top quarks occurs via weak, charged-current interactions. At the LHC, the dominant process is the t-channel exchange of a virtual W boson between a light quark from one of the colliding protons and a bottom quark from the other proton. Since the up-quark density in protons is about twice as high as the down-quark density, the cross section for the production of single top quarks is about twice as high as the cross section for single anti-top quarks. Precise measurements of the ratio $R_t = \frac{\sigma_t}{\sigma_t}$ can provide a handle on the ratio of the u/d densities in the proton. They probe the kinematic regime $0.02 \leq x \leq 0.5$ and are thus complementary to measurements via the charge asymmetry in W-boson production, which probe $0.001 \leq x \leq 0.1$ at the LHC and $0.005 \leq x \leq 0.3$ at the Tevatron.

The ratio R_t has been measured by ATLAS [20] and CMS [21] at $\sqrt{s} = 7$ TeV and 8 TeV, respectively, to be:

$$R_t$$
 (7 TeV) = 1.81 ± 0.10 (stat.) $^{+0.21}_{-0.20}$ (syst.) = 1.81 $^{+0.23}_{-0.22}$, and R_t (8 TeV) = 1.76 ± 0.15 (stat.) ± 0.22 (syst.) = 1.76 ± 0.27.

In both cases, the sign of the top-quark charge was inferred from the reconstructed charge of the final-state lepton that had been associated to the top-quark decay. The observed R_t are compatible with the predictions at NLO QCD. This is shown in Figure 5 using predictions with various PDF sets. The spread of the predictions with different PDF sets is approximately of the same size as the uncertainty on the predictions. Apart from the light-quark PDFs and the renormalization and factorization scales, the predicted cross sections for single top-quark production depend also on the choice of the heavy-flavor scheme (fixed-flavor schemes with four

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or five active flavors versus variable flavor schemes), the bottom-quark density in the proton, and the bottom-quark mass. However, the uncertainty on the measured R_t is currently still roughly more than twice as large as the total uncertainty on the prediction.



Figure 5: Comparisons between the ratio of the production cross sections for single top quarks and single anti-top quarks, measured by ATLAS at $\sqrt{s} = 7$ TeV (left) [20] and by CMS at 8 TeV (right) [21], and the NLO prediction with various PDF sets.

4 Conclusions

The large samples of top-quark data that are being collected at the LHC enable new and ever more precise QCD analyses.

The precisely measured total cross section for $t\bar{t}$ production together with the prediction at NNLO+NNLL QCD allows for extractions of the top-quark pole mass that are significantly more precise than previous determinations of the top-quark mass from cross sections. Alternatively, when constraining m_t to the average of previous measurements, the $t\bar{t}$ cross section enables the first $\alpha_S(m_Z)$ determination at NNLO QCD at a hadron collider. The precision is competitive with other $\alpha_S(m_Z)$ measurements. Furthermore, the inclusive $t\bar{t}$ cross section is currently the only process that directly allows the high-x gluon PDF to be probed at full NNLO QCD. An improved precision on the gluon PDF is crucial not only for future top-quark analyses but also many Higgs-boson analyses and new-physics searches. Differential $t\bar{t}$ cross sections are starting to allow for even more explicit PDF discrimination. The most sensitive distributions are the differential cross sections as a function of the rapidity and the invariant mass of the $t\bar{t}$ system. In any of these QCD analyses using $t\bar{t}$ cross sections, it is imperative to consider the full correlations between m_t , α_S , and the gluon PDF as well as the correlations within the experimental data.

A handle on the ratio of the *u*-quark to *d*-quark PDFs can eventually be obtained from more precise measurements of the charge ratio in t-channel production of single top quarks.

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Measurement of the W-boson helicity in $t\bar{t}$ lepton+jets events

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The top quark decays almost exclusively to a W-boson and a bottom quark and, due to its high mass, its spin information is passed on to the decay products, restricting the possible decay configurations. The top quark decay is entirely described by the weak charged current, characterized by a V-A structure. Within the Wtb interaction, the right-handed helicity state of the W-boson is suppressed, and at leading order (LO) the longitudinal and left-handed states contribute for 70% and 30%, respectively. These helicity fractions are only slightly influenced by higher-order corrections [1].

Experimentally the W-boson helicity fractions can be obtained by measuring the angular distribution of the W-boson's decay products, for which the dependence is given in Equation 1. The considered helicity angle θ^* is defined as the angle between the direction opposite to the top quark and the direction of the down-type fermion, both boosted to the W-boson rest frame.

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}F_L(1-\cos\theta^*)^2 + \frac{3}{4}F_0(\sin\theta^*)^2 + \frac{3}{8}F_R(1+\cos\theta^*)^2 \tag{1}$$

An accurate measurement of the W-boson helicity fractions is of large importance for the validation of the V-A structure of the weak charged current and for probing physics beyond the Standard Model (SM). Current measurements of the W-boson helicity fractions in top-quark decays [2, 3, 4, 5] are in agreement with the SM predictions. Possible deviations from the SM helicity fractions can be interpreted as anomalous Wtb couplings [6] which are described by the most general dimension-six Lagrangian [7]:

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}(V_LP_L + V_RP_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}V_{tb}(g_LP_L + g_RP_R)tW_{\mu}^{-} + h.c., \quad (2)$$

where V_L , V_R , g_L , and g_R are complex constants, $q = p_t - p_b$, where $p_t (p_b)$ is the four-momentum of the top quark (b quark), $P_L (P_R)$ is the left (right) projector operator, and h.c. denotes the Hermitian conjugate. Within the SM V_R , g_L , and g_R are equal to zero, and $V_L = V_{tb} \simeq 1$.

The measurements presented here are based on proton-proton collisions collected by the CMS [8] detector in 2011 at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of 5 fb⁻¹. For this analysis t \bar{t} events for which one of the W-boson decays into a lepton (muon or electron) and corresponding neutrino, and the other one decays into two light jets have been considered. A similar analysis has been performed for data collected in 2012 at 8 TeV, corresponding to 19.6

 ${\rm fb}^{-1}$ integrated luminosity, for which only final states containing a muon have been considered.

The top-quark decay products are reconstructed using the particle-flow algorithm [9]. The events are required to have an isolated lepton, and events with additional muons or electrons are rejected in order to reduce background contributions. The jets are clustered using the anti- k_t algorithm [10] with a distance parameter of 0.5. The full event selection for both the 7 TeV and 8 TeV analysis can be found in Table 1. In the latter analysis additional asymmetric kinematic jet p_T cuts have been applied in order to be consistent with the 8 TeV triggers, requiring the three most energetic jets to have $p_T > 55$, 45, and 30 GeV.

	7 TeV N	Iuon Cl	nannel	7 TeV Ele	ctron C	hannel	8 TeV M	Iuon Ch	annel
> 4 jets	$p_{\rm T}$ > 30 GeV	$ \eta < 2.4$		$p_{\rm T}$ > 30 GeV	$ \eta < 2.4$		$p_{\rm T}$ > 20 GeV	$ \eta < 2.5$	
Lepton	$p_{\rm T}$ > 25 GeV	$ \eta $ < 2.1	$\begin{array}{l} {\rm PFIso} \\ < 0.125 \end{array}$	E_{T} > 30 GeV	$ \eta $ < 2.5	PFIso < 0.1	$p_{\rm T}$ > 26 GeV	$ \eta $ < 2.1	PFIso < 0.12

Table 1. Lychu belecului ioi une i and o iev anaiyo	Table	1:	Event	selection	for	the	7	and	8	TeV	analys	sis
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In order to reduce the QCD multi-jet background, the transverse mass, M_T , of the leptonically decaying W-boson is required to be greater than 30 GeV. Limiting this M_T variable to 200 GeV reduces the contribution of background events originating from dileptonically decaying tt pairs where one lepton escapes detection. In this analysis also a high-efficiency b-tagging algorithm, the Combined Secondary Vertex [11], is required for at least two jets, reducing the QCD background as well as the W-boson production in association with jets (W+jets).

In order to fully reconstruct the top-quark pair topology a kinematic fit [12] is applied which improves significantly the accuracy of the reconstructed tt kinematics. In this analysis the use of the $\cos \theta^*$ variable requires the full reconstruction of the kinematics of the neutrino. Since from measurements only the transverse components of this particle are known, the kinematic fit is also used to obtain the z-component of the neutrino. The obtained distributions can be found in Figures 1 and 2 for the 7 and 8 TeV analyses, respectively. For the hadronic branch of the event only the absolute value of $\cos \theta^*_{hadr}$ is considered since the down-type fermion cannot be identified.

The actual determination of the helicity fractions consists of two distinct steps. First a reweighting procedure, based on MC simulation, is used which produces any new helicity \vec{F} starting from the original ones $(F_{L,0,R}^{SM})$ used in the simulation. Each MC semi-leptonic t \bar{t} event is reweighted using the generated $\cos \theta^*$ value, as shown in Equation 3.

$$W(\cos\theta_{gen}^*;\vec{F}) = \frac{\frac{3}{8}F_L(1-\cos\theta_{gen}^*)^2 + \frac{3}{4}F_0(\sin\theta_{gen}^*)^2 + \frac{3}{8}F_R(1+\cos\theta_{gen}^*)^2}{\frac{3}{8}F_L^{SM}(1-\cos\theta_{gen}^*)^2 + \frac{3}{4}F_0^{SM}(\sin\theta_{gen}^*)^2 + \frac{3}{8}F_R^{SM}(1+\cos\theta_{gen}^*)^2}$$
(3)

Afterwards the helicity fractions are fitted using a binned Poisson likelihood. For each bin of the $\cos \theta^*_{reco}$ distribution the number of expected $N_{MC}(i; \vec{F})$ and observed $N_{data}(i)$ events are compared:

$$\mathcal{L}(\vec{F}) = \prod_{bin \ i} \frac{N_{MC}(i; \vec{F}) N_{data}(i)}{N_{data}(i)!} \exp^{-N_{MC}(i; \vec{F})}.$$
(4)

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Figure 1: Angular distributions for the muon+jets (left) and electron+jets (right) channels using 7 TeV data. At the bottom, the ratio between prediction and data is given.



Figure 2: Angular distributions using 8 TeV data. At the bottom, the ratio between prediction and data is given.

The number of expected events are defined in Equations 5-7. For the top-quark pair events an additional normalization component $\mathcal{F}_{t\bar{t}}$ is introduced which absorbs a large fraction of the experimental and theoretical systematics but doesn't influence the helicity fractions.

$$N_{t\bar{t}}(i,\vec{F}) = \mathcal{F}_{t\bar{t}} \left[\sum_{t\bar{t} \ events} W(\cos\theta_{gen}^*;\vec{F}) \right], \tag{5}$$

$$N_{MC}(i,\vec{F}) = N_{BKG}(i) + N_{t\bar{t}}(i,\vec{F}), \tag{6}$$

$$N_{BKG}(i) = N_{W+jets}(i) + N_{DY+jets}(i) + N_{single-top}(i) + \mathcal{F}_{t\bar{t}} \times N_{t\bar{t}\ non-\ell+jets}(i).$$
(7)

In this analysis two different fits are performed. Since the helicity fractions are constrained by unitarity $(F_0 + F_R + F_L = 1)$, from Equations 5-7 can be seen that only three parameters

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remain free: F_0 , F_L , and $\mathcal{F}_{t\bar{t}}$, resulting in the so-called 3D fit. In case of the 2D fit the number of free parameters is further reduced by constraining the right-handed helicity fraction to the SM prediction ($F_R = 0$).

Several sources of systematic uncertainties are investigated and listed in Table 2. The simulated backgrounds have been scaled with a percentage of $\pm 15\%$, $\pm 40\%$, $\pm 30\%$, and $\pm 100\%$, respectively for the single-top t-channel, single-top tW channel, DY+jets sample, and W+jets sample to obtain their influence on the measurement of the helicity fractions. As can be seen from the table, the dominant sources of background for the 7 TeV analysis are the W+jets background normalization, the signal modelling, and the statistics of the simulated samples. The hadronic branch, using $|\cos^{had} \theta^*|$, has significant larger systematic uncertainties mainly due to the dominant W+jets background and the contribution of JES, JER, and PDF uncertainties, and are not shown in the Table.

For the 8 TeV analysis the dominant backgrounds are rather similar, with the additional studied E_{T}^{miss} distribution being very important. For this dataset, it was observed that the slope of the E_{T}^{miss} distribution obtained in data was not well reproduced in simulation. Therefore a reweighting was done for the simulated events and the difference in obtained helicity fractions was taken as systematic.

	7 TeV systematics		8 TeV systematics		
	3D	fit	2D fit	3D fit	
	$\pm \Delta F_0$	$\pm \Delta F_0$	$\pm \Delta F_0$	$\pm \Delta F_0$	$\pm \Delta F_0$
JES	0.006	0.003	0.001	0.002	< 0.001
JER	0.011	0.007	0.001	0.004	0.003
Lepton eff.	0.001	0.002	0.002	0.001	< 0.001
b-tag eff.	0.001	$< 10^{-3}$	$< 10^{-3}$	0.001	< 0.001
Pileup	0.002	$< 10^{-3}$	0.008	< 0.001	0.001
Single-t bkg.	0.004	0.001	0.003	0.002	< 0.001
W+jets bkg.	0.013	0.004	0.006	0.001	< 0.001
DY+jets bkg.	0.001	$< 10^{-3}$	0.001	0.009	< 0.001
MC statistics	0.016	0.012	0.010	0.003	0.002
Top-quark mass	0.016	0.011	0.019	0.012	0.008
$t\bar{t}$ scales	0.009	0.009	0.011	0.012	0.012
$t\bar{t}$ match. scale	0.011	0.010	0.008	0.012	0.008
PDF	0.002	$< 10^{-3}$	0.003		
$t\bar{t} p_T$ reweig.				0.001	< 0.001
E_{T}^{miss} shape				0.004	0.018

Table 2: Systematics for the combined lepton+jets channel for both the 3D and 2D fit obtained from fitting the leptonic branch of the event.

For the 7 TeV analysis the most precise measurement was obtained using a 3D fit on the leptonic branch of the event. The results combining the muon and electron channel are:

 $\left\{ \begin{array}{l} F_0 = 0.682 \pm 0.030 ~({\rm stat}) \pm 0.033 ~({\rm syst}), \\ F_L = 0.310 \pm 0.022 ~({\rm stat}) \pm 0.022 ~({\rm syst}), \\ F_R = 0.008 \pm 0.012 ~({\rm stat}) \pm 0.014 ~({\rm syst}). \end{array} \right.$

These measured helicity fractions have been used to set limits on the anomalous couplings. For this two specific scenarios have been considered for both of which CP conservation is assumed. For the first scenario $V_L = 1$, $V_R = g_L = 0$ are set and $\operatorname{Re}(g_R)$ is considered as a

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free parameter. The result is shown in Equation 8 and can be translated in terms of effective operators [6], given in Equation 9. Secondly $\operatorname{Re}(g_L)$ and $\operatorname{Re}(g_R)$ are chosen as free parameters of the fit. Figure 3 shows the regions of the $\operatorname{Re}(g_L)$, $\operatorname{Re}(g_R)$ plane allowed at 68% and 95% CL.

$$\operatorname{Re}(g_R) = -0.008 \pm 0.024 \text{ (stat)}^{+0.029}_{-0.030} \text{ (syst)}$$
(8)

$$\frac{1}{\Lambda^2} \operatorname{Re}(C_{uW}^{33}) = -0.088 \pm 0.280 \text{ (stat)}_{-0.352}^{+0.339} \text{ (syst)} \operatorname{TeV}^{-2}$$
(9)



Figure 3: Regions of the $\operatorname{Re}(g_L)$, $\operatorname{Re}(g_R)$ plane allowed at 68% and 95% CL

For the 8 TeV analysis the measurement was only performed using a 3D fit on the leptonic branch of the event, for which the helicity fractions yield:

$$\begin{cases} F_0 = 0.659 \pm 0.015 \text{ (stat)} \pm 0.023 \text{ (syst)}, \\ F_L = 0.350 \pm 0.010 \text{ (stat)} \pm 0.024 \text{ (syst)}, \\ F_R = -0.009 \pm 0.006 \text{ (stat)} \pm 0.020 \text{ (syst)}. \end{cases}$$

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Signal modeling uncertainties in top quark production

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The modeling of top quark production with Monte Carlo generators is discussed. The treatment of systematic uncertainties on the modeling of top quark pairs as well as single top quark production is presented for the four experiments ATLAS, CDF, CMS, and D0.

1 Introduction

The signal modeling with modern Monte Carlo generators is an important ingredient for precise measurements in top quark physics. In proton-proton collisions at the LHC, roughly about 10^7 top quarks have been produced in collision runs between 2010 and end of 2012. Various measurements of top quark quantities have been performed by the ATLAS [1] and CMS [2] collaborations, but also analyses from the Tevatron experiments, CDF [3] and D0 [4], are competitive in their precision. Many of these analyses are limited by the knowledge of the signal process modeled with Monte Carlo event generators. Therefore, the understanding of uncertainties arising from the choice of model parameters in the simulation is a prerequisite for a precise understanding of top quark physics.

The signal modeling of top quark production in hadron collisions comprises several steps. First of all, top quarks can be either produced in pairs via processes of the strong interaction or as single top quarks mediated by the electroweak force. The hard interaction of top quark production is usually simulated with matrix element generators. Matrix element generators evaluate Feynman diagrams for a specific process and randomly generate events according to the transition amplitudes. The matrix element simulation starts from initial state partons (quarks or gluons), includes the production of top quarks, and can include the decay of the top quarks into leptons and light quarks. Depending on the generator, the matrix element calculation includes only leading order (LO) or also next-to-leading order (NLO) diagrams. Additional parton radiation can be included in multi-parton generators.

The remaining low-energetic processes that take place in hadron collisions have to be generated with tools partially based on non-pertubative techniques. This includes the evaluation of parton density functions (PDF) for the initial state partons, showering including initial and final state radiation (ISR/FSR), hadronization, the simulation of the underlying event (UE), and the modeling of pile-up interactions.

All steps of the simulation include free parameters that have to be adjusted properly. Uncertainties on these modeling parameters have to be propagated into final results of top quark measurements.

2 Default tt Monte Carlo Samples

The four experiments follow different approaches on the modeling of top quark pair events. The list of most commonly used generator settings is summarized for the ATLAS experiment in Table 1, for the CMS collaboration in Table 2, for CDF in Table 3, and for D0 in Table 4. In the matrix element generators, the top quark mass has been set to 172.5 GeV in most samples. The choice of which sample is used as default depends on the needs of a particular analysis. Multi-parton generators like MadGraph [5] or Alpgen [6] may be best suited for an analysis relying on the correct modeling of additional jets. NLO generators like MC@NLO [7, 8] or Powheg [9, 10, 11] are expected to give most precise results in analyses depending on the correct description of higher-order effects.

Matrix element	Shower and hadronization	PDF	UE tune
MC@NLO v4.0	Herwig 6.5	cteq66 [13]	AUET1/2 [14]
	+ Jimmy 4.31 [12]	or CT10 [15]	
Powheg-hvq v1.0 $[17]$,	Pythia 6.4 [16]	cteq66 (7 TeV)	Perugia 2011 C [18]
POWHEG-BOX v1.0		CT10 (8 TeV)	
Alpgen 2.13	Herwig $6.5 + \text{Jimmy } 4.31$	cteq6ll [19]	AUET2

Table 1: Default Monte Carlo samples used for top quark pair production at ATLAS.

Matrix element	Shower and hadronization	PDF	UE tune
MadGraph v5	Pythia 6.4	cteq61 [19]	Z2 [20] (7 TeV)
			$Z2^{*}$ [20] (8 TeV)
Powheg-hvq v1.0,	Pythia 6.4	cteq6m [19] (7 TeV)	Z2 (7 TeV)
POWHEG-BOX v1.0		CT10 (8 TeV)	$Z2^{*}$ (8 TeV)
MC@NLO v3.4	Herwig $6 + \text{Jimmy}$	cteq6m	default tune

Table 2: Default Monte Carlo samples used for top quark pair production at CMS.

Matrix element	Shower and hadronization	PDF	UE tune
Pythia 6	Pythia 6	cteq51 [21]	Tune A $[22]$
			Tune A-pro
Powheg-hvq v1.0	Pythia 6	cteq66	Tune A-pro

Table 3: Default Monte Carlo samples used for top quark pair production at CDF.

Matrix element	Shower and hadronization	PDF	UE tune	
Alpgen	Pythia 6	cteq61	Modified Tune A	
MC@NLO	Herwig 6	cteq66	Modified Tune A	

Table 4: Default Monte Carlo samples used for top quark pair production at D0.

3 Modeling uncertainties on top quark pair production

To evaluate systematic uncertainties arising from the variation of different settings in the Monte Carlo event generation, several samples have been generated. In each of these samples, a specific parameter or setting is varied. The impact on the final result of an analysis is usually determined by exchanging the default Monte Carlo sample by the sample with systematically varied settings. In the following subsections, the common systematic uncertainties on top quark pair production modeling taken into account by measurements from the LHC and Tevatron experiments are summarized.

3.1 Matrix element variation

The choice of the matrix element generator used as default is more or less arbitrary because it is often not a priori clear which Monte Carlo event generator describes the specific features of an analysis best. To validate a systematic uncertainty on this choice, the usual approach is to exchange the default matrix element generator by another one and quote the difference on the final result of a measurement as systematic uncertainty. It is preferred to exchange the matrix element generator only and keep hadronization and shower models unaffected. Typical top quark analyses quote for instance the difference between Powheg and Alpgen or MadGraph and Powheg, i. e. the difference between LO and NLO generators.

3.2 Scale uncertainty

The renormalization and factorization scale Q^2 is a free parameter in the Monte Carlo event generation. It defines the scale at which the running coupling of the strong interaction and the PDF is evaluated. A usual choice of the scale parameter is $Q^2 = m_{top}^2$ or $Q^2 = m_{top}^2 + \sum_{partons} p_T^2$ in case additional partons are included in the matrix element. A variation of this scale leads to a change in the amount of additional partons being radiated. As systematic uncertainty, the scale parameter in the matrix element is varied up and down by a factor of two.

In CMS, the scale variation is done simultaneously in both the matrix element and the shower in case of MadGraph and Powheg interfaced to Pythia. With this approach, the uncertainty on the amount of ISR/FSR in the shower is assumed to be correlated with the scale variation in the matrix element. All other experiments quote an independent uncertainty on the amount of ISR/FSR by varying the ISR/FSR tuning parameters. The recent approach by ATLAS is to vary the renormalization scale in the Alpgen matrix element and in the Pythia ISR/FSR simultaneously [23].

3.3 Matching uncertainty

When using multi-parton generators like MadGraph or Alpgen, additional jets can be simulated by either the matrix element or the parton shower. The matrix element is expected to be best suited for the description of hard additional partons, the parton shower performs better in describing soft and collinear radiations. The transition between both approaches is handled with a matching algorithm to avoid a possible overlap. The MLM matching algorithm [24] is most often used in the simulation of hadron collisions. It comprises matching-specific free parameters. In CMS the *qcut*, defing the cut-off momentum scale for additional partons from the shower, is used to evaluate the matching uncertainty in MadGraph samples showered with Pythia. The optimal jet matching parameter is determined by inspecting differential jet rates for various values of qcut in the simulation. The differential jet rate distributions are required to be smooth in the transition region between additional jets generated in the matrix element and simulated with the parton shower. As systematic uncertainty, the value of qcut is varied up and down by a factor of two.

3.4 Hadronization

Similar to the variation of the matrix element, also the hadronization model can be exchanged to quote a systematic uncertainty. In the ATLAS collaboration, the result from Pythia that features the Lund string model is compared to the Herwig cluster model of hadronization. The difference between these samples is quoted as systematic uncertainty.

3.5 Underlying Event

The underlying event comprises multi-parton interactions, hadronization of beam remnants, hadron decays, and also ISR/FSR processes can be treated as part of the UE. The modeling of the UE depends on numerous parameters. The specific setting of these parameters is called tune. There exist various tunes derived from comparisons of collision data from several experiments (also including LEP) to simulations. The systematic impact of the UE tune is validated by comparing Monte-Carlo simulations with different tune settings. At the Tevatron experiments, this is often done in parallel with the hadronization uncertainty. When exchanging Pythia with Herwig, also the UE tune is changed from Tune A to the Jimmy tune. In ATLAS and CMS several comparisons of tunes are performed. For example, the Z2* tune is compared to Perugia 2011 C tune or the Perugia tune is compared to the Perugia 2011 mpiHi parametrization, a dedicated change in the Perugia tune with increased multi-parton interactions.

3.6 Color reconnection

In QCD processes like $t\bar{t}$ production, initial and final state partons of the matrix element simulation are color charged particles. Due to color charge conservation and confinement the hadronization process has to include a color string connection between initial and final state. The UE tunes of Pythia include dedicated settings to handle color reconnection effects. To evaluate systematic uncertainties on this effect, UE tunes with and without the employment of color reconnections are compared.

3.7 Top quark mass

The top quark mass is set to 172.5 GeV in most of the default $t\bar{t}$ simulations. For top quark mass measurements, additional samples with various mass values have been generated. In other analyses than top quark mass measurements, these samples can be used to evaluate the impact of variations in the top quark mass.

3.8 PDF

The uncertainty on the parton-distribution function is the only uncertainty that does not require the simulation of additional Monte Carlo samples. These uncertainties are obtained from re-

weighting default simulations. The re-weighting is done for every generated event according to the probability to observe this event with certain initial state partons at specific momentum fractions x given another PDF set than the default PDF parametrization. Typical PDF sets used as default are cteq6 subsets or CT10. To determine the systematic uncertainty, the default samples are either weighted according to different PDF sets like CT10, NNPDF [25], or MSTW [26] or are re-weighted according to the cteq6 eigenvectors that parametrize the uncertainty of the cteq6 fit. In most analyses, the treatment of the PDF uncertainty follows these recommendations developed by the PDF4LHC working group [27].

3.9 Top quark $p_{\rm T}$

Measurements of differential top quark pair production cross sections at CMS [28, 29] show a discrepancy in the top quark $p_{\rm T}$ distribution between data and simulation. The uncertainty on the modeling of the transverse momentum distribution in t \bar{t} events is only considered by the CMS experiment since no significant difference between data and simulation is observed in the corresponding ATLAS measurement [30]. To account for this difference seen by the CMS experiment, several analyses perform a re-weighting of simulated t \bar{t} events to correct the modeling of the top quark $p_{\rm T}$ distribution. The difference between un-weighted and twice weighted sample with respect to the nominally weighted sample is taken as systematic uncertainty in these analyses.

4 Validation of systematic uncertainties

To justify the variation of Monte Carlo models used to evaluate systematic uncertainties, several validation analyses are carried out. Many systematic variations are connected to changes in the strong coupling constant α_S , like modifications of the Q^2 scale, matching threshold, or the ISR/FSR parameters. Variations of α_S will lead to enhanced or reduced amount of parton radiation. A natural choice to evaluate these variations is the analysis of jet activity. Studies of additional jet activity in pure t \bar{t} events are carried out by the ATLAS [31, 32] and CMS [33] experiments. In these studies, additional jets that can not be assigned to the t \bar{t} system are selected. Beside the multiplicity of additional jets and basic kinematic observables like momentum and rapidity of these jets, the gap fraction of additional jets is measured. The gap fraction f(Q) for leading additional jets is defined as

$$f(Q) = \frac{N(p_{\rm T} < Q)}{N_{total}} \tag{1}$$

where N_{total} is the total number of selected events and $N(p_T < Q)$ the number of events that does not contain any jet (apart from jets assigned to the $t\bar{t}$ system) with transverse momentum p_T larger than the threshold parameter Q. Alternatively, the gap fraction can be defined as

$$f(Q) = \frac{N(H_{\rm T} < Q)}{N_{total}} \tag{2}$$

where $N(H_{\rm T} < Q)$ is the number of events where the summed transverse momentum $H_{\rm T}$ of all additional jets does not exceed Q. Examples of gap fraction distributions compared to different variations of Monte Carlo samples are presented in Figure 1. In the CMS measurement, it can be seen that the variations of Q^2 scale and matching parameters well cover the fluctuation

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Figure 1: Examples of gap fraction measurements of CMS [33] (left) and ATLAS [32] (right) compared to different variations of $t\bar{t}$ simulations.

observed in data. From the gap fraction measurement in ATLAS it has been concluded that the variation of the ISR parameter in the AcerMC [34] simulation overestimates the uncertainty consistent with the observed data.

A validation of the different available UE tunes has been performed in an analysis by ATLAS [35] using jet shape variables. The internal structure of a jet gives rise to the evolution of the parton shower around a hard quark or gluon emission. In this analysis, jet shape variables are analyzed separately for light and b-quark jets in $t\bar{t}$ events. As exemplary variable, the integrated jet shape $\Psi(r)$ in a cone of radius r smaller than the jet radius R around the jet axis is defined as

$$\Psi(r) = \frac{p_{\rm T}(0, r)}{p_{\rm T}(0, R)}$$
(3)

where $p_{\rm T}(r_1, r_2)$ is the scalar sum of the $p_{\rm T}$ of the jet constituents within a slice of radii r_1 and r_2 . The comparison of the integrated jet shape in data to various hadronization and UE models is shown in Figure 2. Most simulations describe the data very well, only the Pythia tune A pro without special treatment of color reconnection effects is found to show some deviations from data.

A similar analysis of the UE has been carried out by CMS [36]. This analysis features the particle flow (PF) algorithm [37] that allows for reconstructing individual particles from the combination of measurements in various detector components. In highly pure $t\bar{t}$ events, the number of charged PF candidates, the total momentum flux in the transverse plane of all charged PF candidates, and their average transverse momentum are measured in different regions with respect to the momentum of the reconstructed $t\bar{t}$ system. Results of this analysis are shown in Figure 3. The difference observed between data and simulation is almost covered by the considered UE tune variations. Especially the tune without color reconnection (labeled No CR) over-estimates the observed variation in data.

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Figure 2: Integrated jet shape measurement [35] for jets with $p_{\rm T}$ between 50 and 70 GeV. A comparison to Monte Carlo simulations with different hadronization models (left) and ratios between measured and simulated integrated jet shapes for different UE tunes (right) are shown.

A second aspect of this analysis is the study of b-quark fragmentation in $t\bar{t}$ events. Events with an additional muon pair inside a b-tagged jet are selected. This is a clear signature for a decay of a b quark into J/ψ with J/ψ further decaying into $\mu^+\mu^-$. The reconstructed J/ψ mass peak is shown in Figure 4. A good agreement between data and $t\bar{t}$ simulation is observed, also for other kinematic properties of the J/ψ meson.

5 Impact of modeling uncertainties on selected results

Many analyses of top quark pair production have reached a relatively high level of precision. First of all, the inclusive t \bar{t} cross section measurements at LHC but also at Tevatron are systematically dominated. For example, the latest inclusive cross section combination of both Tevatron experiments yields $\sigma_{t\bar{t}}(1.96 \text{ TeV}) = 7.65 \pm 0.20(\text{stat.}) \pm 0.29(\text{syst.}) \pm 0.22(\text{lumi})$ pb [38]. The systematic uncertainty on the total measurement includes uncertainties on the signal modeling of 0.22 pb for the CDF measurement and 0.13 pb on the D0 result. Also one of the latest single measurements performed by ATLAS that yields $\sigma_{t\bar{t}}(8 \text{ TeV}) = 237.7 \pm 1.7(\text{stat.}) \pm 7.4(\text{syst.}) \pm 7.4(\text{lumi}) \pm 4.0(\text{beamenergy})$ pb [39] has a dominant uncertainty of 1.52% on the total cross section due to modeling uncertainties on the t \bar{t} signal.

The mass measurements are perhaps the most precise measurements in the top quark sector. An accurate modeling of the t \bar{t} signal process is a crucial ingredient to these measurements. Mass determinations are nearly the only analyses considering all uncertainties on the Monte Carlo modeling described above. The Tevatron combination results in $m_t = 173.20 \pm$ 0.87 GeV [40]. The uncertainty on the measured mass value is dominated by t \bar{t} modeling uncertainties which sum up to $\Delta m_t = 0.52$ GeV. Also the latest mass combination of the LHC experi-





Figure 3: Data to Monte Carlo ratio distributions from the CMS UE measurement [36] for the average number of charged particles (left), total transverse momentum (center), and average particle momentum (right) as function of the $p_{\rm T}$ of the t $\bar{\rm t}$ system in different orientations with respect to the $p_{\rm T}(t\bar{t})$ direction.



Figure 4: Data to simulation comparison of reconstructed J/ψ mass from muon pairs selected in b-tagged jets in $t\bar{t}$ events selected in the lepton+jets channel (left) and the di-lepton channel (right) [36].

ments [41] is dominated by uncertainties on the signal model. Beside the uncertainty on the b-jet energy scale, the total uncertainty on the result of $m_{\rm t} = 173.29 \pm 0.23({\rm stat.}) \pm 0.92({\rm syst.})$ GeV is dominated by uncertainties on color reconnection ($\Delta m_{\rm t} = 0.43$ GeV) and radiation modeling ($\Delta m_{\rm t} = 0.32$ GeV).

Also in several measurements of top quark properties, the modeling of the t \bar{t} signal has often the largest impact on the total systematic uncertainty. As an example, the charge asymmetry measurement by CMS [42] has reached a high precision using the total data sample from the 2012 run. Although the systematic uncertainty on the inclusive charge asymmetry of $A_C = 0.005 \pm 0.007(\text{stat.}) \pm 0.006(\text{syst.})$ is rather small, the uncertainties become larger when measuring the charge asymmetry differentially as function of kinematic observables. In this case, the uncertainty rises to more than $\Delta A_c = 0.02$ in certain bins of the measurement, dominated by uncertainties on hadronization and matrix element generation. Also other properties measurements like the W helicity combination from ATLAS and CMS [43] heavily rely on the correct modeling of differential distributions of the t \bar{t} process in simulation. Approximately half of the systematic uncertainties on the measured helicity fractions $F_0 = 0.6262 \pm 0.034(\text{stat.}) \pm 0.048(\text{syst.})$ and $F_L = 0.3592 \pm 0.021(\text{stat.}) \pm 0.028(\text{syst.})$ are driven by uncertainties on the signal model.

6 Modeling of single top quarks

Beside top quark pair production, top quarks are also being produced as single quarks in electroweak processes. Three processes contribute to single top quark production: t channel, s channel and tW channel. These three processes are generated separately by all collaborations. At the Tevatron, the contribution of the tW channel is negligible. Therefore, only s and t channel processes are simulated. CDF utilizes Powheg [44] interfaced to Pythia 6 for the shower with cteq66 as PDF for both single top quark production modes. D0 simulates single top quark events with the SINGLETOP generator [45] together with Pythia 6 for shower and hadronization and cteq6m as PDF. At the ATLAS experiment, different generators are used for all production modes. The t channel is simulated with AcerMC v3.7 [34] interfaced to Pythia 6 and PDF set cteq6ll. The s and tW channels are either being generated with MC@NLO 4 together with Herwig 6 and Jimmy and cteq66 PDF for samples with 7 TeV center-of-mass energy, or with Powheg [44, 46] interfaced to Pythia 6 and with the CT10 PDF in case of 8 TeV. CMS uses the same combination of Powheg and Pythia for all three single top quark production modes but with cteq6m as default PDF set.

Most systematic uncertainties on the modeling of single top quark production are handled in a similar way as the modeling uncertainties on $t\bar{t}$ production described above. Since no analysis uses multi-parton generators like MadGraph for the simulation of single top quark events no parton matching uncertainty has to be considered. The precision of most single top quark measurements has not yet reached the same level of accuracy as some analyses of top quark pair production. Thus, uncertainties on color reconnection and UE tunes have not yet been considered for the simulations of single top quarks. Although statistical uncertainties are still larger compared to most $t\bar{t}$ studies, the inclusive single top quark t channel cross section measurements are already limited by systematic uncertainties. In a recent ATLAS measurement, a cross section of $\sigma_t = 95 \pm 18$ pb has been determined [47]. The statistical error is almost negligible and the systematic uncertainty is mainly driven by modeling uncertainties on ISR/FSR treatment and matrix element generators. In this particular analysis, the uncertainty on the matrix element generation is estimated by comparing the default AcerMC simulation to higher-order predictions from MCFM [48].

In the tW channel, a special systematic uncertainty on the modeling with Monte Carlo generators has to be considered. The tW process is not unambiguously distinguishable from t \bar{t} at NLO because there are interfering Feynman diagrams from both processes. Two different approaches exist to remove the overlap between tW and t \bar{t} processes, the diagram subtraction (DS) and the diagram removal (DR) methods. Both schemes are available in the MC@NLO and Powheg event generators. Samples for the tW process with both schemes have been generated and the difference between the DS and DR schemes is considered as additional systematic uncertainty. In the analysis of the tW channel by CMS [49] that yields a cross section of $\sigma_{\rm tW} = 23.4^{+5.5}_{-5.4}$ pb, a change on the result of 2% is observed when exchanging the simulations with DS and DR schemes.

7 Conclusion

The modeling of top quark production in hadron collisions with Monte Carlo event generators includes several technical steps that require dedicated tuning of parameters. Optimizing the event generation is a key ingredient for precise measurements in top quark physics. Uncertainties on the modeling of top quark production are limiting many analyses performed by the four experiments ATLAS, CDF, CMS, and D0. The choice of generator parameters and their variation that is done to determine systematic uncertainties are often not well justified. For example, scale and matching parameters are usually varied by an arbitrary factor of two.

Several studies have been performed to reduce the uncertainties on the modeling of $t\bar{t}$ events and to optimize the generator tuning. In jet activity and underlying event analyses, it has been shown that the considered systematic variations cover the observed fluctuations in data but some of these variations show significant discrepancies with respect to measured distributions. Especially variations of ISR and color reconnection effects clearly overestimate the uncertainties consistent with the observed data. In case of the ISR variations, a new treatment of the radiation uncertainty has been developed in the ATLAS collaboration based on the jet gap fraction measurement. Other systematic uncertainties have been validated but an optimization has not been propagated to the event generation yet. This will have to take place in the future to further improve the sensitivity of many analyses in top quark physics.

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V+jets background and systematic uncertainties in top quark analyses

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Vector boson production in association with jets is an important process to test perturbative quantum chromodynamics and also a background process in top quark analyses. Measurements on vector boson production in association with light and heavy flavour jets are presented, performed by the D0 and CDF collaborations at the Tevatron as well as the ATLAS and CMS experiments at LHC. Techniques applied in top quark analyses to estimate the vector boson+jets background are also discussed.

1 Introduction

Besides searching for new physics, one of the main purposes of hadron collider physics is the precision measurement of processes as predicted by the standard model (SM) of particle physics, and the comparison with theory predictions. Important processes are W+jets and Z+jets (in short: V+jets) production. Understanding the V+jets production processes is important for several reasons. First, inclusive and differential - i.e. as a function of one or more variables - cross sections provide a crucial test of perturbative quantum chromodynamics (pQCD) calculations. Secondly, in many searches and measurements, for example in top quark physics, they constitute one of the major background processes. Finally, the comparison of V+jets measurements with predictions using Monte Carlo (MC) generators helps to improve the tuning or choice of appropriate generators for the modelling.

In the following, measurements of V+jets production from the D0 and CDF experiments at the Tevatron proton-antiproton collider at Fermilab and from the ATLAS [1] and CMS [2] experiments at the LHC at CERN are discussed. Furthermore, the methods to model V+jets background processes in top quark analyses are reviewed. The different definitions of algorithms used for the identification of jets are discussed elsewhere [3].

2 V+jets measurements

The various experiments at the Tevatron and the LHC have released several different measurements of cross sections for W+jets and Z+jets production in association with light and heavy

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flavour jets. The measurements are compared to a variety of predictions. These predictions can be classified into different categories:

- MC generators using leading-order (LO) matrix elements (MEs) plus HERWIG [4] or PYTHIA [5] for parton shower and hadronisation. These MC generators include ALP-GEN [6], MADGRAPH [7] and SHERPA [8].
- MC generators using fixed-order next-to-leading-order (NLO) calculations. In particular, these include BlackHat+SHERPA [9], Rocket+MCFM [10, 11] and MCFM.
- MC generators using fixed-order NLO calculations plus a generator (PYTHIA or HER-WIG) for parton showering and hadronisation. This class includes for example POWHEG [12], MC@NLO [13], MENLOPS [14] and MEPS@NLO[15, 16].
- Calculations using wide angle resummations: HEJ (high energy jet) [17].
- Approximate next-to-next-to-leading-order (NNLO) calculations: LOOPSIM+MCFM [18].
- NLO QCD calculations including NLO electroweak contributions.

For most measurements, several of these predictions are directly compared to the shapes of the differential distributions after correcting for resolution effects, enabling to draw conclusions of the validity of the models for different variables. In the following, an overview of recent W+jets and Z+jets measurements from Tevatron and LHC are given. Details of the event selection and methods for unfolding are omitted in the following and can be found in the respective references of the analyses.

2.1 W+jets measurements

Various measurements of the W+jets process were performed at Tevatron and LHC, with different numbers of jets considered. In all measurements, the W boson is required to decay into a charged lepton (usually electron or muon) and the associated neutrino. Using 320 pb^{-1} of data, CDF performed measurements of the total and differential W+jets cross section, where 1 to > 4 jets are considered [19]. Recently, the D0 collaboration released a measurement of the inclusive and differential W+jets cross section, using events where the W boson decays into an electron and the associated neutrino. With 3.7 fb^{-1} of data, the differential cross section as function of about 40 different variables has been studied [20]. These variables include jet and lepton energy and angular variables, dijet rapidity separations and opening angles, dijet azimuthal angular separations and the W boson transverse momentum. Additionally, the number of jets is measured as function of the scalar sum of the transverse energies of the W boson and the jets and as function of rapidity separations between the jets. The predictions of various calculations, compared to the measured distributions, vary more than the experimental uncertainty, enabling the usage of the measurements for improved modelling of W+jets. The ATLAS and CMS collaborations also performed measurements of W+jets, using 36 pb⁻¹ of 7 TeV LHC data [21, 22], showing in general good agreement between prediction and measurement.

Besides W+jets processes with jets not distinguished according to their flavour, it is crucial to measure W+heavy flavour jet cross sections. These processes contribute an important background in several searches and measurements, in particular analyses where b-jet identification is applied.

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Measurements of $W+b(b)^{-1}$ are interesting to test pQCD predictions in the presence of heavy quarks. A measurement of W+b(b) from 1.9 fb⁻¹ of data by the CDF collaboration has been performed, using at least one identified b-jet [23]. The total cross section has been measured about three standard deviations higher than the NLO prediction. A recent analysis of W+b(b) by the D0 collaboration, using 6.1 fb⁻¹ of data, has shown good agreement between the measured fiducial cross sections and predictions from SHERPA, MCFM and MADGRAPH [24]. In this analysis, a lifetime based multivariate analysis technique has been used to distinguish the flavour contents of the W+jets samples. The ATLAS collaboration has studied W+b(b)events with one identified b-jet on the full 7 TeV data sample of 4.6 fb⁻¹ [25]. The flavour discrimination is done by a template fit of the neural network output distribution that is based on b-jet lifetime information. The fiducial cross section for one and two jets has been measured and compared to pQCD predictions, which show a good agreement for events with two jets, while for events with one jet the compatibility of measurement and prediction are only to the level of 1.5 standard deviations. In this analysis, also differential cross section measurements have been performed, for example as function of the b-jet transverse momentum (p_T) . In this variable, the MCFM and ALPGEN predictions show a slight underestimation of the cross section for large b-jet p_T . Also using the full 7 TeV data sample of 5 fb⁻¹, the CMS collaboration has studied the W+b(b) process with the W boson decaying into a muon and associated neutrino [26]. For this analysis, two identified b-jets are required. In order to distinguish events from $W+c\bar{c}$ and W+bb, the sum of the invariant mass of the secondary vertex within each jet is used. The fiducial cross section shows good agreement with NLO predictions from MCFM. The studied kinematic distributions show also good agreement with MC predictions.



Figure 1: Measured cross sections $\sigma(W^{\pm}D^{\mp}) + \sigma(W^{\pm}D^{*\mp})$ [27] (left) and measured cross section ratio $\sigma(W^{+} + \bar{c})/\sigma(W^{-} + c)$ [28] (right) compared to different PDF predictions.

The study of the W+c(c) process is interesting for various reasons. In particular, the process W+c can be used to probe the strange quark content of the proton and therefore its measurement is useful to distinguish different parton distribution functions (PDFs). Both the ATLAS and the CMS collaboration have performed W+c(c) cross section measurements. The signature of these events is an opposite sign of the W boson and a D meson. At ATLAS, a

¹In the following, V + b(b) refers to V + b, $V + \overline{b}$, and $V + b\overline{b}$. The same applies for V + c(c).

measurement on 4.6 fb⁻¹ of 7 TeV data has been performed, where the *D*-meson is reconstructed from track information [27]. In this measurement, the cross section ratios $\sigma(W^{\pm}D^{\mp})/\sigma(W^{\pm})$ are measured inclusively and also differentially as function of the transverse momentum of the *D*-meson and the pseudorapidity of the lepton from the *W* boson decay. In general, the results show good agreement with predictions, but it can also be observed that some of the PDF sets show a tension with the measurements. Figure 1 (left) shows the measured cross section sum $\sigma(W^{\pm}D^{\mp}) + \sigma(W^{\pm}D^{*\mp})$ compared to different PDF sets. PDF sets where the *s*-quark sea is suppressed relative to the *d*-quark show worse agreement with the measurement than PDFs where this suppression is not included. Using 5.0 fb⁻¹ of 7 TeV data, CMS performed measurements of the total cross section of W+c and cross section ratios as well as measurements differentially as function of the pseudorapidity of the lepton from the *W* boson decay [28]. In this analysis, *c*-jet candidates are identified using secondary vertex information. Figure 1 (right) shows the ratio $\sigma(W^+ + \bar{c})/\sigma(W^- + c)$, compared to different predictions. A good agreement with predictions can be seen.

2.2 Z+jets measurements

The experiments at Tevatron and LHC have also performed measurements of the Z+jets production², where the Z boson is required to decay into a pair of oppositely charged leptons (usually electrons or muons). Using 1.0 fb⁻¹ of data, the D0 collaboration measured the Z+jets total cross section and differential cross section as function of the transverse momenta of the three leading jets [29]. Comparison of the measurements with LO and NLO pQCD predictions and different event generators shows good agreement. The CDF collaboration performed a Z+jetsanalysis using the full Tevatron Run II data sample of 9.64 fb^{-1} [30], where the absolute and differential cross sections are measured, the latter as function of different variables. In general, good agreement between measurement and pQCD predictions could be observed. In a recent analysis by ATLAS, using the full 7 TeV data sample of 4.6 fb^{-1} , inclusive and differential Z+jets cross section measurements with up to seven jets have been performed [31]. The differential studies are done as function of jet multiplicities, jet transverse momenta, and angular distributions. In addition, distributions are studied after a modified selection optimised for vector boson fusion processes. Here, NLO pQCD predictions show a good description of the data, as do matrix element plus parton shower generators, while MC@NLO+HERWIG badly models the distribution as function of the number of jets and underestimates the cross section for large jet p_T . Figure 2 (left) shows the measured Z+jets cross section as function of the number of jets (N_{iet}) . The CMS collaboration has measured azimuthal correlations and event shapes for Z+jets processes, as well as Z+1 jet rapidity distributions in 5.0 fb⁻¹ of 7 TeV data [32]. These comparisons show good agreement between predictions and measurement, except for predictions from PYTHIA. Figure 2 (right) shows the distribution of the azimuthal angle $\Delta \phi(Z, J_1)$ between the transverse momentum vectors of the Z boson and the first leading p_T jet for events with at least one, two or three selected jets.

With the same reasoning as for studies of the W+jets heavy flavour cross section, it is also important to measure Z+jets cross sections with heavy flavour jets. The D0 collaboration recently released a measurement of the ratio $\sigma(Z + b)/\sigma(Z + \text{jets})$ based on 9.7 fb⁻¹ of data [33]. The measurement was done inclusively and differentially as function of the jet transverse momentum, jet pseudorapidity, Z boson transverse momentum, and the azimuthal angle between

 $^{^{2}}Z$ +jets refers here to Z/γ^{*} +jets



Figure 2: Measured cross section for Z+jets as a function of the inclusive jet multiplicity [31] (left), and measured distributions of $\Delta \phi(Z, J_1)$ for different jet multiplicities [32] (right).

the Z boson and the closest jet for events with at least one identified b jet. The inclusive measurement shows good agreement with NLO predictions, while none of the predictions can fully describe all studied variables. Based on 9.1 fb⁻¹ of data, the CDF collaboration measured the inclusive and differential Z+b cross section, where the differential cross section is studied as function of jet p_T and rapidity [34]. The total cross section is found to be larger by about a factor of 1.6 compared to the prediction from ALPGEN, while good agreement with the NLO prediction from MCFM was observed. At the LHC, the ATLAS collaboration has measured the cross section for b-jet production in association with a Z boson in 36 pb⁻¹ of 7 TeV data [35], showing good agreement with NLO pQCD predictions. More recently, the CMS collaboration explored 5.0 fb⁻¹ of 7 TeV data, extracting the total Z + b(b) cross section as well as the ratio of the cross section of a Z boson produced in association with any number of b-jets relative to those containing any number of jets. In addition, kinematic properties are compared to MC predictions using MADGRAPH, showing some deviations between prediction and data.

The first measurement of the cross section ratios $\sigma(Z+c)/\sigma(Z+jets)$ and $\sigma(Z+c)/\sigma(Z+b)$ has recently been performed on 9.7 fb⁻¹ of Tevatron data by the D0 collaboration [36]. The cross section ratios are measured inclusively and differentially as function of jet and Z boson transverse momenta. The inclusive measurements are not in agreement with pQCD predictions and predictions from different event generators. Furthermore, none of the predictions can fully describe the dependencies on all studied variables. It was found that an improved description of the distributions could be found by enhancing the $g \to c\bar{c}$ fraction in PYTHIA by an empirical factor of 1.7.

2.3 Summary of V+jets measurements

Both the Tevatron and the LHC experiments have performed a variety of V+jets measurements. These are in general in good agreement with NLO pQCD predictions and predictions

from multi-leg generators, but also several variables have been identified that are not well modeled by current event generators. These studies are important input for future improvement of the choice and tuning of MC generators and to constrain PDF sets, as is possible with the W+c jet measurement. The inclusive cross section measurements at LHC are in general limited by systematic uncertainties, in particular by uncertainties on the jet energy scale, while for differential measurements, especially for some parts of phase space, the results are still limited by the statistics of the data sample. Currently, the experiments work on further V+jets measurements, in particular on exploring the 8 TeV LHC data sample.

3 V+jets background modelling in top quark analyses

V+jets events are among the major background processes in measurements involving top quarks. W boson production in association with heavy flavour jets can result in final states identical to those originating from the decay of a top-antitop quark pair in the lepton+jets channel as well as (t-channel) single top quark production. Z boson + heavy flavour jets production together with $\not\!\!E_T$ due to mismeasured objects leads to signatures similar to dileptonic top-antitop quark pair decays.

Both LHC and Tevatron experiments use LO matrix element (ME) generators (ALPGEN or MADGRAPH) for the modelling of V+jets background processes, interfaced to PYTHIA or HERWIG as parton shower (PS) MC. As heavy flavour jets can originate from both the ME and the PS, generating V+light jets and V+heavy flavour jets events separately can give rise to the same heavy flavour final states in the multiple samples. Techniques to remove this heavy flavour overlap need to be applied, based for instance on the opening angles between jets.

Only few analyses use theoretical calculations to obtain the normalisation of V+jets background events. Uncertainties on the theoretical cross section predictions increase with increasing jet multiplicity, resulting in large uncertainties in jet multiplicity bins relevant for top quark analyses. Thus, the normalisation of V+jets background events is usually directly measured in the data while the shapes of V+jets distributions are typically taken from MC simulation. V+jets measurement results as presented in Section 2 are, however, not directly used for this purpose so far as these cover phase space regions different from the ones used in top quark analyses. Top quark analyses hence apply their own dedicated techniques to measure the normalisation and, in many cases, the heavy flavour composition of V+jets background events. These techniques are discussed in Sections 3.1 and 3.2.

3.1 W+jets background determination using data

Due to its signature W+jets events are most relevant as background process to lepton+jets $t\bar{t}$ and single top events. W+jets production together with a so-called fake lepton - originating from misidentified jets or leptons from semileptonic c/b hadron decays - are among the background processes of dileptonic $t\bar{t}$ decays. Such fake lepton backgrounds are typically modelled using the so-called matrix method together with leptons fulfilling different categories of isolation criteria. A description on the determination of the fake lepton background can be found in [37]. In the following a selection of data-driven techniques applied by the two Tevatron and LHC experiments is summarised - with focus on the determination of the W+jets background normalisation and heavy flavour composition in lepton+jets $t\bar{t}$ analyses.

To estimate the W+jets normalisation as well as its heavy flavour composition, the W

charge asymmetry technique is widely used in ATLAS. The W charge asymmetry method [38] makes use of the larger number of u valence quarks w.r.t. d valence quarks in protons, resulting in an asymmetric production rate of W^+ +jets and W^- +jets events in proton-proton collisions. The total number of W+jets events can be measured in data according to

$$N_{W^+} + N_{W^-} = \left(\frac{r_{MC} + 1}{r_{MC} - 1}\right) (D^+ - D^-),\tag{1}$$

where N_{W^+} (N_{W^-}) is the number of W^+ +jets $(W^-$ +jets) events, D^+ (D^-) is the number of events containing a positively (negatively) charged lepton after subtraction of non W+jets contributions and $r_{MC} = N(pp \rightarrow W^+ + \text{jets})/N(pp \rightarrow W^- + \text{jets})$, evaluated from MC. As the W charge asymmetry is also sensitive to the heavy flavour composition of W+jets events, the relative fraction of $W+b\bar{b}+\text{jets}$, $W+c\bar{c}+\text{jets}$, W+c+jets and W+light jets events is extracted simultaneously with the overall normalisation in the W+jets dominated 2-jet bin and is then extrapolated to the bins with more than two jets. As an alternative approach [39] measures the W+jets normalisation simultaneously with the $t\bar{t}$ lepton+jets cross section by means of likelihood discriminants, constructed from variables chosen for their signal vs. background discriminating power, see Figure 3 (left).

Similarly to the ATLAS lepton+jets $t\bar{t}$ cross section analysis, the W+jets normalisation and the $t\bar{t}$ cross section are extracted simultaneously in CMS [40]. For this extraction a profile likelihood fit to the distribution of invariant masses of particles belonging to identified displaced vertices (secondary vertex mass, SVM) is performed as a function of jet and b-tag multiplicity. Due to the discriminating power of the SVM between heavy and light flavour jets, the normalisation is evaluated for each of the W+b, W+c, and W+light-flavour sub-samples, as shown in Figure 3 (right). Not only the W+jets yields but also the shapes of W+jets distributions are extracted from the data in the CMS single top t-channel cross section measurement [41]. This is done using a sideband region outside the top quark invariant mass window.

In the D0 lepton+jets $t\bar{t}$ cross section measurement [42] the overall W+jets normalisation is extracted by subtracting all non W+jets events from the data, separately for each jet multiplicity bin. The relative contribution of W+heavy flavour jets (comprising W+b\bar{b}+jets and W+c\bar{c}+jets events), W+c+jets and W+light flavour jets events are determined using NLO calculations and is verified in data using events with exactly one and two jets, split into subsamples with and without b-tagged jets. The W+jets normalisation is also measured simultaneously with the $t\bar{t}$ cross section, using a binned maximum likelihood fit for the predicted number of events in different jet and b-tag multiplicity bins.

In the CDF lepton+jets $t\bar{t}$ cross section measurement [43] the overall W+jets normalisation in pretag events is obtained by subtracting all non W+jets contributions from the data. The contribution of W+heavy flavour jets events to the $t\bar{t}$ signal region with at least one b-tagged jet is extracted using the overall W+jets normalisation in pretag events as well as MC simulation based predictions on the W+heavy flavour fractions together with the tagging efficiency of jets. The fraction of W+heavy flavour jets is evaluated separately for W+b\bar{b}+jets, W+c\bar{c}+jets and W+c+jets events. Additonal correction factors to the MC based heavy flavour fractions are derived using a neural network fit to variables sensitive to jets matched to heavy and light flavour in dedicated control regions. Together with the mis-tag probability for light flavour jets - parameterised as a function of different jet variables - the flavour composition of W+jets events in the signal region can be determined. The heavy flavour contribution is also extracted together with the $t\bar{t}$ cross section via a simultaneous fit to a jet flavour discriminant across nine samples, defined by the number of jets and b-tags [44].



V+jets background and systematic uncertainties in top quark analyses

Figure 3: Results of the combined fit to data in the ATLAS lepton+jets $t\bar{t}$ cross section measurement [39]: The distribution of the likelihood discriminant for data is shown, superimposed on expectations for signal and backgrounds, scaled to the results of the fit (left). Results of the combined fit for the muon+jets channel for single *b*-tag and $\geq 2b$ -tag events in the CMS lepton+jets $t\bar{t}$ cross section measurement [40] (right).

3.2 Z+jets background determination using data

Z+jets background processes in top quark analyses are most relevant to the dileptonic $t\bar{t}$ decay channel. To mimic the dileptonic $t\bar{t}$ final state, Z+jets events are required to have additional \not{E}_T from mismeasured objects. As such mismeasuring effects are difficult to model in MC simulation, the normalisation of Z+jets events is usually extracted from dedicated Z+jets enriched control regions in the data. These control regions are most commonly defined via the dilepton invariant mass m_{ll} , where the control region usually comprises events fulfilling a Z-mass window cut of $|m_{ll} - m_Z| < 10$ GeV, see Figure 4. The Z+jets normalisation within the control region is determined in data and is extrapolated to the $t\bar{t}$ signal region ($|m_{ll} - m_Z| > 10$ GeV) by means of scaling factors extracted from MC simulation [37, 45]. The CMS dilepton $t\bar{t}$ cross section measurement [47] uses additional control regions to evaluate corrections to the MC based scaling factors using data. The ATLAS top polarisation measurement [48] derives correction factors to the MC Z+jets normalisation as a function of \not{E}_T , allowing to account for possible mismodelling of the \not{E}_T distribution in MC simulation.



Figure 4: Dilepton invariant mass distribution of the sum of the e^+e^- and $\mu^+\mu^-$ channels in the CMS dilepton $t\bar{t}$ cross section measurement [46]. The gap in the m_{ll} distribution reflects the requirement that removes dileptons from Z decays. This gap defines the control region used for the estimate of the Z+jets background normalisation.

3.3 *V*+jets background and systematic uncertainties

Thanks to the data-driven techniques, systematic uncertainties on the V+jets background normalisation are usually small. As an example, the W charge asymmetry technique, as applied by the ATLAS collaboration, results in correction factors to the W+jets normalisation of 0.83 ± 0.14 and $0.94^{+0.16}_{-0.14}$ in the electron and muon+jets $t\bar{t}$ channel, respectively. The numbers refer to events passing all signal selection criteria as outlined in [38], including the presence of b-tagged jets. Uncertainties on the MC modelling are usually accounted for by variations of the renormalisation and factorisation scales and, in some cases, additional variations of generator internal cuts.

4 Conclusion

A variety of V+jets measurements has been performed by the D0 and CDF experiments at Tevatron and the ATLAS and CMS experiments at LHC. These measurements are an important input for the future improvement of MC generators. Most top quark analyses at both the Tevatron and LHC experiments use MC generators to model the shapes of the V+jets background distributions while different data-driven techniques are applied to obtain the normalisation as well as the heavy flavour composition in V+jets events. Thanks to these techniques the uncertainties on the V+jets background modelling are usually small in top quark analyses. Further improvement on the V+jets background modelling may be achieved when using the V+jets measurement results directly in top quark analyses, which, due to the different phase space regions covered by V+jets and top quark analyses, is currently not the case.

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Combinations of inclusive $t\bar{t}$ production cross sections at the Tevatron and the LHC

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The results of combining inclusive $t\bar{t}$ production cross-section measurements from D0 and CDF at the Tevatron and from ATLAS and CMS at the LHC are presented.

1 Introduction

Calculations of inclusive $t\bar{t}$ production cross-sections are now available with next-to-next-toleading order (NNLO) and next-to-next-to-leading logarithmic (NNLL) soft gluon resummation [1], for $p\bar{p}$ and pp production processes. It is worth noting that the dominant production mechanism in $p\bar{p}$ collisions at the Tevatron centre-of-mass energy (\sqrt{s}) 1.96 TeV is quark-antiquark annihilation, while in pp collisions at LHC energies ($\sqrt{s}=7$ and 8 TeV) it is mainly gluon-gluon scattering. Precise measurements of these cross sections provide a significant test of the standard model (SM) and of PDFs. Combining measurements from different channels and experiments is central to achieve the best possible precision.

The experimental cross sections are extracted by measuring events in final states expected to have large contributions from $t\bar{t}$ pairs. The SM top-quark decays almost 100% of the time to W + b-quark. Final states are separated according to the W decay into either $e\nu_e, \mu\nu_\mu, \tau\nu_\tau, qq'$ from each top-quark. What is really measured in each final state is the cross section multiplied by the branching ratios of t and \bar{t} , and it is implicitly assumed that these are given by the W branching ratios.

Each experiment combines measurements from different final states to obtain a combined measurement. In turn, the combined measurements from each experiment are combined to give a final result at a given \sqrt{s} . The main issue in combining different measurements is how to handle correlations of systematic uncertainties. In all $\sigma_{t\bar{t}}$ measurements at the Tevatron and even more so at the LHC, the dominant sources of uncertainty are systematic. Two methods are used to combine measurements:

- 1. A best linear unbiased estimator (BLUE). This method requires the construction of a covariance matrix (including statistical and systematic uncertainties) with all correlations determined externally. A weight for each result is obtained by inverting the matrix. The results are then combined using these weights to obtain the best estimate. This method is used by CDF and to combine results from different experiments.
- 2. Construct a combined likelihood taking the product of likelihoods in each channel multiplied by a Gaussian term for each nuisance parameter (i.e. systematic uncertainty source)

centred at zero with width of the variance expected for each parameter. Correlated uncertainties are entered in terms of common parameters. Maximizing the likelihood automatically takes care of the correlations. This method is used to combine the measurements of each individual experiment by DØ, ATLAS and CMS.

2 Tevatron measurements

CDF combines four measurements using the BLUE method: two separate ones from single lepton $(\ell = e \text{ or } \mu)$ +jets channels, one from dilepton $(\ell \ell')$ channels and one from the all jets channel.

- 1. $\ell\ell'$ channel(DIL) [2]: *ee*, $\mu\mu$ and $e\mu$ events are counted when they have at least one *b*-jet in a data sample of 9.1 fb⁻¹ of integrated luminosity ($\int Ldt$).
- 2. ℓ +jets without any *b*-jet requirement (LJ-ANN) [3]: use a neural network (NN) based on 7 kinematic variables to separate signal and background, $\int Ldt = 4.6 \text{ fb}^{-1}$.
- 3. ℓ+jets requiring b-tag (LJ-SVX) [3]: extract signal by a maximum likelihood fit to events with a b-tag.
- 4. all jets channel(HAD) [4]: fit a reconstructed top mass from events with 6-8 jets,> 1 *b*-jet selected with a 13 variable NN, $\int Ldt = 2.9$ fb⁻¹.

The cross-section measurements, their combination and all their uncertainties are given in Table 1. It is worth noting that the measured integrated luminosity, which is a significant source of uncertainty in the $\ell\ell'$ and all hadronic channels measurements, is derived in the ℓ +jets channel using the expected $Z/\gamma *$ cross section rather than from inclusive $p\bar{p}$ measurements. Using the $Z/\gamma *$ measurements results in a luminosity uncertainty that is 2.5 times smaller. The dominant contribution to the CDF combination is the LJ-ANN measurement; adding the other measurements reduces the uncertainty by 10%. Combining the CDF measurements results in $\sigma_{t\bar{t}} = 7.63 \pm 0.50$ (statistical+systematic).

DØ combines two measurements:

- 1. ℓ +jets [5]: two methods were combined to extract the number of $t\bar{t}$ events from orthogonal data sets:
 - (a) a 7 (3) kinematic variable multi-variate discriminant random-forest to separate signal and background in events with 0 (1) *b*-jets and 3 or > 3 jets;
 - (b) a maximum likelihood fit in events with > 1 *b*-jets and 3 or > 3 jets.
- 2. $\ell\ell'$ [6]: fit 4 b-tagging NN discriminant distributions to signal and background templates, $e\mu+1$ jet and ee, $\mu\mu$ and $e\mu+>1$ jet.

The combination was carried out using a modified likelihood with nuisance parameters to take into account systematic uncertainties. The correlations are taken into account by using the same parameters for common systematics:

$$\mathcal{L} = \prod_{i} \prod_{j} P[n_{ij} | \mu_{ij}(\sigma_{t\bar{t}}, \nu_k)] \prod_{k} \mathcal{G}(\nu_k; 0, SD)$$
(1)

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	DIL	LJ-ANN	LJ-SVX	HAD	CDF combined
Central value of $\sigma_{t\bar{t}}$	7.09	7.82	7.32	7.21	7.63
Sources of uncertainty					
Statistical	0.49	0.38	0.36	0.50	0.31
Detector model	039	0.11	0.34	0.41	0.17
Signal model	0.23	0.23	0.23	0.44	0.21
Jets model	0.23	0.23	0.29	0.71	0.21
Method to extract $\sigma_{t\bar{t}}$	0.00	0.01	0.01	0.08	0.01
Background model (theory)	0.01	0.13	0.29	0.00	0.10
Background model (data)	0.15	0.07	0.11	0.59	0.08
Normalization of $Z/\gamma *$ prediction	-	0.16	0.15	-	0.13
Luminosity inelastic $\sigma_{p\bar{p}}$	0.28	0.00	0.00	0.29	0.05
Luminosity detector	0.30	0.02	0.02	0.30	0.06
Total systematic uncertainty	0.67	0.41	0.61	1.18	0.39
Total uncertainty	0.83	0.56	0.71	1.28	0.50

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Table 1: CDF measurements of $\sigma_{t\bar{t}}$ from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with absolute uncertainty components in pb and results of the channel combination.

where i refers to the channels, j to the bins of the NN distribution and k refers to the nuisance parameters. $P(n,\mu)$ is the probability of observing *n* events while expecting μ while $\mathcal{G}(\nu; 0, SD)$ is the Gaussian probability density with mean at zero and width one standard deviation (SD) of the systematic uncertainty ν . This formulation extracts the cross section and handles correlations of systematic uncertainties between channels automatically by maximizing the likelihood with $\sigma_{t\bar{t}}$ and ν_k as free parameters. Table 2 shows the statistical and systematic uncertainties for the dilepton channel and for the combination of dilepton with lepton+jets channel. The cross section measured with $\ell\ell'$ events is $7.36^{+0.90}_{-0.79}$ pb, the one with ℓ +jets events is $7.78^{+0.77}_{-0.64}$ pb and the combined result is $7.56^{+0.63}_{-0.56}$ pb. Combining the measurement from both channels improves the precision by 24% over the best single measurement (single-lepton channel).

The combined CDF and DØ measurements were in turn combined using the BLUE method, to obtain the best $\sigma_{t\bar{t}}$ value for the Tevatron [7]. CDF and DØ have weights of 60% and 40% respectively, while the correlation between them is 17%. The uncertainties for each experiment and their combination are given in Table 3. Quantities known to be correlated are assumed to be 100% correlated, which leads to an overestimate (and thus conservative estimate) of the overall uncertainty. The CDF measurement has a larger weight, due mainly to reducing the luminosity uncertainty in the ℓ +jets channel by using the $Z/\gamma*$ predicted cross section to calculate $\int Ldt$. The CDF, DØ and combined measurements are displayed in Fig 2. The Tevatron combination, $\sigma_{t\bar{t}} = 7.61 \pm 0.41$ pb, improves the precision by 20% over the CDF combined measurement. The combination is in very good agreement with the NNLO+NNLL SM prediction $7.34^{+0.23}_{-0.27}$ pb [1] for a top-quark mass of 172.5 GeV.

	$\ell\ell'$		$\ell\ell' + \ell j$	
Source				
Statistical	+0.50	-0.48	+0.20	-0.20
Muon identification	+0.11	-0.11	+0.07	-0.06
Electron identification and smearing	+0.24	-0.23	+0.13	-0.13
Signal model	+0.34	-0.33	+0.16	-0.06
Triggers	+0.19	-0.19	+0.05	-0.05
Jet energy scale	+0.13	-0.12	+0.04	-0.04
Jet reconstruction and identification	+0.21	-0.20	+0.12	-0.09
b-tagging	+0.06	-0.06	+0.16	-0.14
Background normalization	+0.29	-0.27	+0.11	-0.10
W+HF fraction	-	-	+0.12	-0.04
Luminosity	+0.57	-0.51	+0.48	-0.43
Other	+0.10	-0.10	+0.06	-0.06
Template statistics	+0.08	-0.08	+0.04	-0.04

Table 2: The DØ breakdown of uncertainties (in pb) in the $\ell\ell'$ channel and the combined $\ell\ell'$ and ℓj measurement using the nuisance parameter technique. The uncertainties show the change in the measured cross section when shifting the nuisance parameter by ± 1 standard deviation from its fitted mean.

	CDF	D0		Tevatron
Central value of $\sigma_{t\bar{t}}$ (pb)	7.63	7.56		7.60
Sources of uncertainty			Correlation	
Statistical	0.31	0.20	0	0.20
Detector model	017	0.22	0	0.13
Signal model	0.21	0.13	1	0.18
Jets model	0.21	0.11	0	0.13
Method to extract $\sigma_{t\bar{t}}$	0.01	0.07	0	0.03
Background model (theory)	0.10	0.08	1	0.10
Background model (data)	0.08	0.06	0	0.05
Normalization of $Z/\gamma *$ prediction	0.13	-	0	0.08
Luminosity inelastic $\sigma_{p\bar{p}}$	0.05	0.30	1	0.15
Luminosity detector	0.06	0.35	0	0.36
Total systematic uncertainty	0.39	0.56		0.36
Total uncertainty	0.50	0.59		0.41

Table 3: CDF and D0 measurements of $\sigma_{t\bar{t}}$ from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with absolute uncertainty components in pb and results of their combination. Systematic uncertainties known to be correlated are assumed to be 100% correlated.

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3 LHC measurements

ATLAS combines six $\sqrt{s} = 7$ TeV measurements [8]:

- 1. three $\ell\ell'$ measurements [9]: $ee, \mu\mu, e\mu$ by counting events with ≥ 2 jets (with and without *b*-jets separately) in a data sample of $\int Ldt = 0.7$ fb⁻¹.
- 2. two ℓ +jets measurements [10]: e+jets, μ +jets using a 4 kinematic variable likelihood discriminant and no b-jet requirement ($\int Ldt = 0.7 \text{ fb}^{-1}$).
- 3. all jets [11]: extract signal by fitting a reconstructed top-quark mass with signal and background templates ($\int Ldt = 1.02 \text{ fb}^{-1}$).

$$\mathcal{L} = \mathcal{L}_{\ell+jets}(\sigma_{t\bar{t}}, L, \vec{\nu}) \prod_{i \in ee, \mu\mu, e\mu} P[n_i | \mu_i(\vec{\nu})] \prod_{j \in \text{all-hadbins}} P[n_j | s_j(\vec{\nu}) + b_j(\vec{\nu})] \prod_{k \notin \ell+jets} \mathcal{G}(\nu_k; 0, SD)$$
(2)

where L is luminosity, μ expected number of events, s_j (b_j) expected number of signal (background) events and $\vec{\nu}$ are nuisance parameters. The main difference with respect to equation (1) is that the ℓ +jets likelihood is approximated by a multivariate Gaussian likelihood ($\mathcal{L}_{\ell+jets}$). Figure 1 shows the negative log likelihood for each channel and the combination as function of $\sigma_{t\bar{t}}/\sigma_{SM}$, with and without including systematic uncertainties. It shows that for the ℓ +jets channel the multivariate Gaussian is a very good approximation to the exact likelihood. The total number of parameters is 89 (including $\sigma_{t\bar{t}}$), 26 are shared between $\ell\ell'$ and ℓ +jets, and 12 are common to all channels. The value of $\sigma_{t\bar{t}}$ obtained from the combination is 177 ± 11 pb, an improvement in precision of 10% over the measurement from ℓ +jets alone, 179 ± 12 pb.

CMS combines seven $\sqrt{s} = 7$ TeV measurements [12]:

- 1. $\ell\ell'$ [13]: *ee*, $\mu\mu$ and $e\mu$ based on counting events with at least one identified *b*-jet ($\int Ldt = 1.14 \text{ fb}^{-1}$).
- 2. ℓ +jets [14]: e+jets, μ +jets ($\int Ldt = 0.8 \text{ fb}^{-1}$, 1.09 fb⁻¹). The number of $t\bar{t}$ events in data samples were extracted by maximizing a binned likelihood of secondary vertex mass distributions. Event samples were split by number of jets and identified *b*-jets.
- 3. all jets [15]: extract the number $t\bar{t}$ events in events with 6-8 jets and two identified *b*-jets by fitting a reconstructed top mass with signal and background templates ($\int Ldt = 1.09 \text{ fb}^{-1}$).
- 4. $\mu + \tau$ [16]: count events with at least one identified *b*-jet after background subtraction and reducing the background by applying a series of cuts ($\int Ldt = 1.09 \text{ fb}^{-1}$).

CMS obtains a cross section combining the above measurements using a binned maximum likelihood fit applied to a combined likelihood function similar to that used by DØ (Eq. 1), a product of the Poisson likelihood of observing a certain number of events given an expected number for each bin considered, multiplied by Gaussian distributions for the nuisance parameters. Counting experiments (*ee*, $\mu\mu$, $e\mu$ and $\mu\tau$) are entered as single bins. The hadronic analysis is based on an unbinned fit to the reconstructed top-quark mass distribution and is not binned. Instead, the results are parametrized so they can be input into the combined likelihood as a single bin. The CMS combined value of $\sigma_{t\bar{t}}$ at $\sqrt{s} = 7$ TeV is 166±13.7 pb, an improvement



Figure 1: ATLAS -log(likelihood) for single lepton (systematic uncertainties do not include parameters common with dilepton and all-hadronic channels), dilepton combined, all-hadronic and all channels combined as function $\sigma_{t\bar{t}}/\sigma_{SM}$ [8].

	ATLAS	CMS		LHC
Central value of $\sigma_{t\bar{t}}$ (pb)	177.0	165.8		173.3
Sources of uncertainty			Correlation	
Statistical	3.2	2.2	0	2.3
Detector model	5.3	8.8	0	4.6
Jet energy scale	2.7	3.5	0	0.13
Signal model				
Monte Carlo	4.2	1.1	1	3.1
Parton shower	1.3	2.2	1	1.6
Radiation	0.8	4.1	1	1.9
PDF	1.9	4.1	1	2.6
Method to extract $\sigma_{t\bar{t}}$	2.4	n/e	0	1.6
Bacgkround model (theory)	1.6	1.6	1	1.6
Background model (data)	1.5	3.4	0	1.6
W leptonic branching ratio	1.0	1.0	1	0.08
Luminosity				
Bunch current	5.3	5.1	1	5.3
Luminosity measurement	4.3	5.9	0	3.4
Total systematic uncertainty	10.8	14.2		9.8
Total uncertainty	11.3	14.4		10.1

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Table 4: ATLAS and CMS measurements of $\sigma_{t\bar{t}}$ from pp collisions at $\sqrt{s} = 7$ TeV with absolute uncertainty components in pb and results of their combination. Systematic uncertainties known to be correlated are assumed to be 100% correlated.

in precision of 3.7% over the ℓ +jets cross section, 164 ± 14.2 pb. The combined $\sigma_{t\bar{t}}$ from ATLAS and CMS were in turn combined using the BLUE method as the different treatment of systematic uncertainties makes the likelihood approach difficult to implement [19]. Table 4 shows a detailed composition of the uncertainties and their correlations used in the combination. Note that whenever a systematic uncertainty is known to be correlated, the correlation is set to 100% (as it was for the CDF-DØ combination in Section 2). The largest uncertainty components are the beam-bunch current (5.3 pb) and the sum of all terms that depend on Monte Carlo simulation (5.0 pb). Both of these are correlated between experiments, together they contribute 7.3 pb uncertainty to the result 173.3 ± 10.1 pb. Combining ATLAS and CMS reduces the uncertainty over the best combined measurement from a single experiment, 177.0 ± 11.3 pb, by 10%. Figure 2 displays the cross-section measurements of each experiment that are used in the combinations and the results of combining the measurements. The best LHC value at $\sqrt{s} = 7$ TeV, 173.3 ± 10.1 pb is in very good agreement with the SM prediction of $172.0^{+6.4}_{-7.5}$ pb[1]. It should be noted that since the combination, CMS has published cross-section measurements in $\ell \ell'$ [17] and ℓ +jets [18] channels using 2.3 fb⁻¹ of data with improved precision.

The LHC measurements of $\sigma_{t\bar{t}}$ at $\sqrt{s} = 8$ TeV have not been combined yet. There is an ATLAS measurement in the $e\mu$ channel using all the data collected in 2012 ($\int Ldt = 20.3$ fb⁻¹) requiring at least one identified *b*-jet, 238 ± 11 pb [20], and a CMS measurement using all three $\ell\ell'$ channels with identified *b*-jets but only a subset of the 2012 data ($\int Ldt = 2.4$ fb⁻¹),

 227 ± 15 [21]. It is worth noting that the largest single source of uncertainty in these LHC measurements is the integrated luminosity. These measurements are in very good agreement with the SM prediction of $245.8^{+8.8}_{-10.6}$ pb [1]. There are also measurements by ATLAS and CMS using the ℓ +jets channels, 241 ± 32 [22] and 228 ± 32 [23], which are in good agreement with $\ell\ell'$ measurements. These measurements do not have an impact on a combined result due to their larger systematic uncertainties.

4 Conclusions

All the various measurements of $\sigma_{t\bar{t}}$ at the Tevatron and LHC are consistent with each other and are in good agreement with SM expectations. By combining the measurements from different channels and experiments the value of $\sigma_{t\bar{t}}$ has been determined with a precision of 5-6% in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [7] and in pp collisions at $\sqrt{s} = 7$ TeV [19] of 7.60 \pm 0.41 pb and 173.3 \pm 10.1 pb respectively. Similar precision has been achieved using just the $e\mu$ channel at $\sqrt{s} = 8$ TeV [20], 238 \pm 11 pb. These measurements are approaching the precision of the NNLO+NNLL theoretical predictions, $7.34^{+0.23}_{-0.27}$ pb, $172.0^{+6.4}_{-7.5}$ pb and 245.8^{+8.8}_{-10.6} pb, and are in excellent agreement with them.

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Figure 2: $\sigma_{t\bar{t}}$ measurements in the channels used for combinations and the combined results. Left CDF and DØ [7], right ATLAS and CMS [19]. The theory band corresponds to the value predicted by NLO calculations, not the more precise NNLO+NNLL calculations referred to in the text.

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Measurement of the charge asymmetry in top quark pair production at CMS

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The $t\bar{t}$ charge asymmetry is measured in the lepton+jets decay channel using a dataset of $19.7 {\rm fb}^{-1}$ collected with the CMS detector at the LHC. We present an inclusive measurement as well as three differential measurements as functions of rapidity, transverse momentum, and invariant mass of the $t\bar{t}$ system. The measured inclusive $t\bar{t}$ charge asymmetry is 0.005 ± 0.007 (stat.) ± 0.006 (syst.); both this result and the differential measurements are consistent with the predictions of the Standard Model.

1 Introduction

One interesting feature of pairwise top quark production is the difference in the angular distributions of top quarks and top antiquarks. In the pp collisions of the LHC this effect is called $t\bar{t}$ charge asymmetry, and calculations within the Standard Model (SM) predict an effect on the order of one percent.

Measurements of the related forward-backward asymmetry in $p\bar{p}$ collisions presented by the CDF and D0 collaborations [1, 2] show deviations of up to 3σ compared to SM calculations, motivating further investigation by other experiments.

The charge asymmetry occurs only in quark-antiquark initial states. Since at the LHC the quarks in the initial state are mainly valence quarks while the antiquarks are sea quarks, the antiquarks have a lower average momentum fraction; in the case of a positive charge asymmetry this leads to an excess of top quarks produced in the forward directions. The sensitive variable $\Delta |y| = |y_t| - |y_{\bar{t}}|$ is used to measure this effect by defining the charge asymmetry A_C as

$$A_C = \frac{N^+ - N^-}{N^+ + N^-} , \qquad (1)$$

where N^+ and N^- represent the numbers of events with positive and negative values in the sensitive variable, respectively.

In this analysis we measure the charge asymmetry as a function of the rapidity, the transverse momentum and the invariant mass of the $t\bar{t}$ system. Each of these differentiating variables v_d is motivated differently: The rapidity $|y_{t\bar{t}}|$ allows a suppression of the symmetric production processes, while the transverse momentum $p_T^{t\bar{t}}$ allows to discriminate between the positive and negative SM contributions to the asymmetry. The invariant mass $m_{t\bar{t}}$, finally, yields the highest sensitivity to possible new physics contributions.

2 Event selection and background estimation

We analyse data collected with the CMS detector in proton-proton collisions at a centre-of-mass energy of 8 TeV, corresponding to an integrated luminosity of $19.7 \, \text{fb}^{-1}$. The analysis focuses on t events where one of the W bosons from the decay of a top quark pair subsequently decays into a muon or electron and the corresponding neutrino, while the other W boson decays into a pair of jets. We therefore select events containing exactly one electron or muon and four or more jets, at least one of which is identified as originating from the hadronization of a b quark. The particle-flow (PF) algorithm [3] is used for the reconstruction of the events.

Electron candidates are required to be isolated, to have a transverse energy larger than 30 GeV and to be within $|\eta| < 2.5$. Muon candidates also must be isolated, and they are required to have a transverse momentum larger than 26 GeV/c and a pseudorapidity of $|\eta| < 2.1$. Jets, finally, have to lie within $|\eta| < 2.5$ and are required to have $p_{\rm T} > 30 \text{ GeV}/c$.

For the estimation of the background contributions we make use of the discriminating power of the transverse mass of the W boson m_{W}^{T} , and of M3, the invariant mass of that combination of three jets that corresponds to the largest vectorially summed transverse momentum.

Background contributions are estimated in both channels separately by means of binned maximum-likelihood fits to the two discriminating distributions. The $m_{\rm W}^{\rm T}$ distribution discriminates between events with and without real W bosons. We separate the data sample into events with $m_{\rm W}^{\rm T} < 50 \,{\rm GeV}/c^2$ and $m_{\rm W}^{\rm T} > 50 \,{\rm GeV}/c^2$, and simultaneously fit the $m_{\rm W}^{\rm T}$ distribution for the low- $m_{\rm W}^{\rm T}$ sample and the M3 distribution for the high- $m_{\rm W}^{\rm T}$ sample. Single-top-quark and Z+jets production are well understood theoretically and their expected contributions are modest, so their normalizations are constrained to the simulation predictions.

With the exception of QCD multijet production all processes are modelled using simulated events. QCD multijet events instead are modelled using a sideband region in data defined by an inversion of the isolation criterion of the charged lepton.

3 Measurement of the $t\bar{t}$ charge asymmetry

The measurement of the t \bar{t} charge asymmetry is based on the fully reconstructed four-momenta of t and \bar{t} in each event. We reconstruct the leptonically decaying W boson from the measured charged lepton and the missing transverse energy $E_{\rm T}^{\rm miss}$, and associate the measured jets in the event with quarks in the t \bar{t} decay chain using a likelihood-based approach to find the right association. For a detailed description of the reconstruction procedure see Ref. [4].

With the resulting measured distribution of the sensitive variable the asymmetry can be calculated using Eq. 1. To be able to compare the asymmetry with predictions from theory at generator level, the reconstructed distributions have to be corrected for several effects. These have their origin in background contributions, reconstruction imperfections and selection efficiencies. After a background subtraction has been performed the distributions are translated from the reconstruction level to the particle level after event selection, and from there to the particle level before event selection. These corrections are achieved by applying a regularized unfolding procedure to data [5] through a generalized matrix-inversion method. In this method, the disturbing effects are described by a smearing matrix S that translates the true spectrum \vec{x} into the measured spectrum $\vec{w} = S\vec{x}$. Technical details of this unfolding procedure can be found in Ref. [4].



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Figure 1: Selection efficiency (left) and migration matrix (right) for the measurement differential in $m_{t\bar{t}}$.

The number of bins and especially the bin ranges used for $\Delta |y|$ and the differentiating variables v_d have to be chosen with care. To stabilize the unfolding procedure it is desirable that the number of entries in each bin of the reconstructed distributions is approximately equal. Similarly, the spectra of generator values after the selection are flattened to give comparable statistics and thus uncertainties to all bins involved in the migration.

We use separate smearing matrices for the inclusive measurement and the three differential measurements, obtained from simulated $t\bar{t}$ events. As an example Figure 1 shows the selection efficiency and migration matrix making up the smearing matrix for the differential measurement in $m_{t\bar{t}}$. In the inclusive measurement the migration matrix simply describes the migration from true values to reconstructed values of $\Delta |y|$; for the migration matrices of the differential measurements migration between bins of the differentiating variable has to be taken into account as well.

The consistency and performance of the unfolding procedure have been verified in a suite of pseudo experiments, each of which tests the unfolding on a sample distribution generated randomly from the templates used in the background estimation.

4 Estimation of systematic uncertainties

Each source of systematic uncertainty is evaluated by repeating the measurement on data using modified simulated samples; the systematic uncertainty for each source is taken to be the maximal observed shift in the values of the unfolded asymmetry. An explanation of the specific methods used to determine the more important uncertainties follows below.

To estimate the uncertainty resulting from possible mismodelling of the $t\bar{t}$ signal we compare samples of simulated $t\bar{t}$ events produced with MC@NLO to samples produced with POWHEG, where both are interfaced to HERWIG for the modelling of the parton shower. In a similar way the impact of a possible mismodelling of the parton shower is studied by comparing samples using two different hadronization models, namely the one implemented in PYTHIA and the one implemented in HERWIG. Finally, the impact of variations in the renormalization and factorization scale (Q^2) in the simulated $t\bar{t}$ events is determined using dedicated samples generated at scales shifted systematically by factors of 2.

Systematic uncertainty	shift in inclusive A_C	range of shifts in differential A_C
JES	0.001	0.001 - 0.005
JER	0.001	0.001 - 0.005
Pileup	0.001	0.000 - 0.003
b tagging	0.000	0.001 - 0.003
Lepton ID/sel. efficiency	0.002	0.001 - 0.003
Generator	0.003	0.001 - 0.015
Hadronization	0.000	0.000 - 0.016
$p_{\rm T}$ weighting	0.001	0.000 - 0.003
Q^2 scale	0.003	0.000 - 0.009
W+jets	0.002	0.001 - 0.007
Multijet	0.001	0.002 - 0.009
PDF	0.001	0.001 - 0.003
Unfolding	0.002	0.001 - 0.004
Total	0.006	0.007 - 0.022

Table 1: Systematic uncertainties for the inclusive measurement of A_C and ranges of systematic uncertainties for the individual bins of the differential measurements.

In order to estimate the influence of possible mismodelling of the W+jets background the measurement is repeated using a W+jets template from a sideband region in data, defined by an inversion of the b-tag requirement.

We perform a conservative estimation of the uncertainty of the data-driven QCD multijet background by taking the maximum deviation out of three scenarios: Replacing the multijet template with the $t\bar{t}$ signal template, replacing it with the simulated W+jets template, or inverting the asymmetry of the multijet template itself.

In contrast to the other systematic effects, the uncertainty due to the unfolding method is estimated by performing pseudo experiments. The simulated $t\bar{t}$ events are reweighted to reproduce the asymmetries observed in the differential measurements on data. The uncertainty of each measurement is estimated as the maximum deviation produced by the unfolding in the three reweighting scenarios corresponding to the three differentiating variables v_d .

5 Results

The result of the inclusive asymmetry measurement is

 0.005 ± 0.007 (stat.) ± 0.006 (syst.),

which can be compared to SM theory predictions of 0.0102 ± 0.0005 [6, 7] and 0.0111 ± 0.0004 [8, 9]. The results of the three differential measurements can be found in Fig. 2, where the measured values are compared to predictions from SM calculations [6, 7, 8, 9] and to predictions from an effective field theory [10, 11, 12]. The latter theory is capable of explaining the CDF results for the forward-backward asymmetry at a new physics scale of about $\Lambda = 1.3$ TeV by introducing an anomalous effective axial-vector coupling to the gluon at the one-loop level.

All measured values are consistent with the predictions of the Standard Model and no hints for deviations due to new physics contributions have been observed. Furthermore, the charge



Figure 2: Corrected asymmetry as a function of $|y_{t\bar{t}}|$, $p_{T,t\bar{t}}$, and $m_{t\bar{t}}$. The measured values are compared to NLO calculations for the SM (1: [6, 7], 2: [8, 9]) and to the predictions of a model featuring an effective axial-vector coupling of the gluon (EAG) [10, 11, 12].

asymmetry in the high-mass region is about 1.5 standard deviations below the predictions from the previously mentioned effective field theory with a new physics scale of $\Lambda = 1.5 \text{ TeV}$ and about 3.5 standard deviations below the predictions for $\Lambda = 1.0 \text{ TeV}$.

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Measurement of top quark polarization in dileptonic top-antitop quark events using the ATLAS detector

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1 Introduction

The top quark polarization is an interesting quantity to probe the Standard Model (SM) of particle physics. Due to its large mass of 173.2 ± 0.9 GeV [1], the top quark's lifetime is an order of magnitude smaller than the hadronization time scale [2], that means it decays before hadronization takes place and offers the opportunity to study a bare quark. This allows us to measure the top quark polarization since the top quark's spin information is transported to the decay products of the W boson. In the SM, top quark pairs are mainly produced unpolarized due to parity conservation in QCD. A small contribution from electroweak effects gives rise to a polarization of 0.003 [3]. New physics models involving anomalous couplings could lead to a significant polarization, in particular models also describing the forward-backward asymmetry (A_{fb}) measured at the Tevatron [4, 5] often include a nonzero polarization that could be observable at the LHC. A first study of the polarization has already been performed at the Tevatron [4] and is compatible with the SM expectation. Polarization affects the angular distribution of the final state

particle. For the polar angle θ of any final state particle (labelled by the index i) with respect to a certain quantization axis, the distribution is described by

$$W(\cos\theta_i) = \frac{1}{2}(1 + \alpha_i P \cos\theta_i), \qquad (1)$$

where P is the polarization and α_i is the spin analyzing power of the corresponding particle i (charged leptons in this analysis) [6]. It describes the correlation between the spin direction of the top quark and the momentum direction of the final state particle and varies depending on the particle type between 0 and 1 with the latter being the maximum. For charged leptons, the spin analyzing power is 1 at leading order [6]. To analyze both top quarks in the event, the measurement is performed in the dilepton final state where both W bosons decay leptonically. This final state gives us three independent channels to



Figure 1: Sketch of the construction of the angle θ between the top and lepton 1.

define that depend on the lepton type, namely ee, $e\mu$ and $\mu\mu$.

In the absence of polarization, the distribution according to Eqn. 1 will be flat, whereas polarization introduces an additional term linear in terms of $\cos \theta$. As a quantization axis, the helicity axis of the parent top quark is taken. The angle θ is then defined by the polar angle of the momentum direction of the lepton in the top rest frame and the momentum direction of the top in the top-antitop rest frame (see Fig. 1).

2 Selection and background modelling

The measurement [7] is performed using 4.7 fb⁻¹ of proton-proton collision data taken at a center of mass energy of 7 TeV at the LHC with the ATLAS detector [8]. Our estimates for the top-antitop signal and background containing two prompt leptons (Z+jets, single top and diboson production) are taken from Monte Carlo. As generator for the signal, MC@NLO [9] is used. Backgrounds containing non-prompt leptons or non-leptonic particles passing the lepton selection (called fakes) are measured via a data-driven approach, the so-called matrix method. [10]

In order to enhance the signal events and suppress background contributions, kinematic cuts are applied to events fulfilling the trigger condition. We require exactly two oppositely charged electrons or muons with one of them matching the object that fired the trigger. At least two jets have to be reconstructed in each event. The dilepton invariant mass m_{ll} in the *ee* and $\mu\mu$ has to be higher than 15 GeV and additionally it has to be more than 10 GeV away from the Z boson mass. This cut on m_{ll} suppresses the large background coming from Z boson production and $q\bar{q}$ resonances. These two channels also have a cut on the $E_T^{miss 1}$, which has to be higher than 60 GeV and accounts for

Source	ee	$e\mu$	$\mu\mu$
$t\bar{t}$	570	4400	1660
Bkgd.	110	700	320
Total	690	5000	1980
Uncert.	± 80	± 500	± 180
Data	740	5328	2057

Table 1: Event yields of signal, background (both rounded) and data after applying the selection along with their total uncertainty. [7]

the two neutrinos from the W bosons from the top pair. For the $e\mu$ channel, the sum of leptons' and jets' E_T has to be larger than 130 GeV. After applying the selection, around 8000 dilepton events remain to study the top quark polarization. Table 1 shows the event yields of signal, background and data for the different channels. One should note that in the *ee* and $\mu\mu$ channels, the shape for the $Z \to ee$ and $Z \to \mu\mu$ background in the corresponding channel are taken from Monte Carlo, but a scale factor is derived from data and applied to the background [7].

3 Event reconstruction

In order to measure the angle θ it is mandatory to reconstruct the $t\bar{t}$ system, which requires the information of all the final state particles. However, the two neutrinos from the W boson decays are only weakly interacting and leave undetected. This leads to an underconstrained system for the reconstruction with 18 kinematic variables from the momentum vectors of the

 $^{{}^{1}}E_{T}^{miss}$ is the magnitude of the negative vectorial sum of the transverse components of all calorimeter cells, corrected for the reconstructed muon momenta.

final state particles, of which only 12 are known. By fixing the top quark and W boson masses to the PDG [11] values we get four additional constraints. With the measured E_T^{miss} information, one could then solve the kinematic equations, but would end up with some ambiguity in the assignment of the leptons and jets to the corresponding top quark when reconstructing it. This ambiguity even increases for every additional reconstructed jet. To circumvent a random choice in the lepton-jet assignment, this analysis uses the so called Neutrino Weighting Tool [12] to reconstruct the top quarks and therefore the whole $t\bar{t}$ system. Instead of using the E_T^{miss} directly for the kinematic equations, it makes a hypothesis on the pseudorapidity η for each neutrino, calculates their longitudinal momenta (up to two solutions due to a quadratic equation) and constructs a weight w by comparing the measured E_T^{miss} with the calculated transverse momentum components $p_{x,y}$ of the two neutrinos ν_1 and ν_2 :

$$w = \prod_{i=x,y} exp\left(-\frac{(E_i^{miss} - p_{i,\nu 1} - p_{i,\nu 2})^2}{2\sigma_{E_T^{miss}}^2}\right).$$
 (2)

The E_T^{miss} resolution $\sigma_{E_T^{miss}}$ is a function of E_T^{miss} and the same within uncertainties for Monte Carlo and data [13]. The more compatible the E_T^{miss} information is with the neutrino p_T derived from the given neutrino η , the higher the weight w.

The η -hypothesis is based on the generated η distribution of the neutrinos, which is described in $t\bar{t}$ MC by a Gaussian distribution of mean 0 and unit width. For each event, 100 assumptions on both η_{ν_1} and η_{ν_2} are made according to this distribution and the weight w is computed for each lepton-jet combination. Additionally, all the jet energies are smeared 50 times to take into account a nominal jet resolution of approximately 3 % and the weights get recomputed each time. The solution with the highest weight is eventually taken as best guess for the reconstruction of the $t\bar{t}$ system. Figure 2(a) shows the data-expectation comparison of the neutrino pseudorapidity after reconstruction and is well described over the whole range. Looking



(a) Neutrino pseudorapidity

(b) $\cos \theta$ for positive and negative leptons

Figure 2: Comparison of predicted signal+background and data events after reconstructing the event with the Neutrino Weighting for all channels combined. [7]

at the cos θ distribution (see Fig. 2(b)) for positive and negative leptons and all channels

combined, we can see the same good agreement for the shape of the distribution. The shape is distorted due to detector acceptance and kinematic cuts on the events.

Since the kinematic equations for the longitudinal component of the neutrino momentum can give non-real solutions, it is not always possible to reconstruct the system. The efficiency of obtaining at least one physical solution for each event is 85% in $t\bar{t}$ MC.

4 Templates and fitting

After selecting and reconstructing our events to get the $\cos \theta$ value of each lepton-top pair, a value for αP is extracted from the $\cos \theta$ distribution, which is done by performing a binned likelihood template fit. The necessary templates with non-zero top quark polarization are obtained by reweighting each event with a weight w_{rew} based on the double-differential cross section for $t\bar{t}$ production [14]

$$w_{rew} = \frac{1 + B_1 \cos \theta_1 + B_2 \cos \theta_2 - C \cos \theta_1 \cos \theta_2}{1 - C \cos \theta_1 \cos \theta_2},$$
(3)

where B_i is equal to $\alpha_i P$, θ_i is the true polar angle between lepton i and its parent top quark and C is the so called anti-correlation factor, which is determined from the MC signal sample by fitting the two-dimensional distribution of both cosines. The denominator takes into account the already existing spin correlation in the signal Monte Carlo, while the numerator introduces the desired polarization of the top quark pairs. The polarization in the templates is constrained to a value of ± 0.3 for αP to avoid getting negative values for the cross section. It has been checked that the reweighting does not introduce a bias to the η -hypothesis of the reconstruction. Two different scenarios are considered for the production mechanism of the top-antitop pairs when introducing the polarization, one CP conserving (CPC) and one CP violating (CPV). For the CPC case, both quarks are polarized in the same way by choosing the same sign for B_1 and B_2 , whereas in the CP violating case, the quarks will have opposite polarization. The likelihood fit is then applied by extracting the fraction f of positive polarization in our distribution and simultaneously the $t\bar{t}$ cross section to reduce normalization uncertainties (see Fig. 3). It is done by calculating the predicted number of events in each bin and channel and comparing it to the number of observed events. The maximized likelihood is the Poisson probability and is multiplied for each bin in the distribution and channel in the analysis. Systematics are considered by creating templates with $\pm 1\sigma$ variations for each source of systematic uncertainties. Correlations between systematics are considered by performing the fit simultaneously for one group of correlated systematics. 1000 pseudo experiments based on the templates are performed to reduce statistical effects on systematic uncertainties. Dominant sources of systematics are uncertainties from Jet Energy Scale, background normalization and signal modelling.



Figure 3: Fit of the $\cos \theta$ distributions of positive and negative leptons for the two different production mechanisms CPC and CPV [7].

5 Results

The fit values for f have to be translated to αP first via $\alpha P = 0.3(2f - 1)$ [7]. For the result of the polarization measurement we get:

$$\begin{aligned} \alpha_l P_{CPC} &= -0.04 \pm 0.03 (\text{stat}) \pm 0.05 (\text{syst}) \\ \alpha_l P_{CPV} &= 0.01 \pm 0.03 (\text{stat}) \pm 0.04 (\text{syst}). \end{aligned}$$

Figure 4 shows the results for each channel and the combination separately.



Figure 4: Results of the fit of $\alpha_l P$ for each channel and the combination for CPC and CPV production mechanisms [7]. All results are in agreement with the SM (dashed line).

The first measurement of the top quark polarization in dileptonic top-antitop quark events has been performed and is consistent with the Standard Model for both models considered. It was furthermore combined with the measurement in the single-lepton channel [7, 15].

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Measurement of the top-quark mass in all-jets $t\bar{t}$ events in pp collisions at 7 TeV

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1 Introduction

These proceedings are an update of the analysis presented at the TOP2012 [1]. A first topquark mass (m_t) measurement is presented in all-jets final states with the CMS detector [2]. This final state yields the largest signal, however, it is dominated by multijet background. The detailed descriptions of this analysis can be found in Ref. [3]. The event selection is very similar to the one from the CMS tt cross section measurement in the same final state [4]. The analysis employs a kinematic fit of the tt final state and likelihood functions for each event ("ideograms") that depend on m_t and jet energy scale (JES).

2 Data samples and event selection

The analysis uses two multijet triggers which collected 3.54 fb^{-1} of the 2011 data sample. Simulation has been used to develop and evaluate the method, while the multijet background is estimated from data employing an event mixing method.

Jets are clustered with the anti- k_t algorithm (R = 0.5) [5, 6] from particles reconstructed by a particle flow algorithm [7]. Events are selected with at least four (five, six) central jets with a transverse momentum of $p_T > 60$ (50, 40) GeV. Additional central jets are considered with $p_T > 30$ GeV. At least two jets originating from bottom quarks are required, being tagged with an algorithm that combines reconstructed secondary vertices and track-based lifetime information [8].

For the final selection, a kinematic least-squares fit [9] is applied, exploiting the characteristic topology: two W bosons reconstructed from untagged jets with an invariant mass of 80.4 GeV [10] and two top quarks of equal mass reconstructed from the W bosons and b-tagged jets.

The fit procedure is repeated for every experimentally distinguishable jet permutation using all jets that pass the selection criteria. Per event, the permutation with the smallest χ^2 is chosen and accepted if the goodness-of-fit probability $P_{\rm gof} = P(\chi^2, n = 3)$ is larger than 0.09. To further reduce the multijet background from $b\bar{b}$ production, an additional criterion on the distance of the two bottom quark candidates, $\Delta R_{\rm b\bar{b}} = \sqrt{\Delta \phi_{\rm b\bar{b}}^2 + \Delta \eta_{\rm b\bar{b}}^2} > 1.5$, is imposed.

3 Background modeling

The multijet background is estimated by an event mixing technique. All events after the b-tagging selection are taken as input and the jets are mixed between the different events such that in every newly generated event all jets are originating from different events, keeping at least two b-tagged jets in the new event.

The simulated $t\bar{t}$ sample and modeled background are normalized to data with the expected signal fraction (f_{sig}) from simulation, which depends on the cross section [11, 12, 13] and the selection efficiency for $t\bar{t}$ events.

4 Ideogram method

A likelihood function is constructed that allows the simultaneous determination of JES and m_t . Based on this likelihood function, two different estimates of m_t are performed: with a fixed JES ("1D analysis") or simultaneously with the JES ("2D analysis").

The observable used for measuring m_t is the top-quark mass from the kinematic fit (m_t^{fit}) . The average reconstructed W-boson mass before they are constrained by the kinematic fit (m_W^{reco}) is taken as an estimator for measuring a global JES. Figure 1 compares data, expectation from simulation, and modeled background for m_t^{fit} and m_W^{reco} .

For the likelihood determination the $t\bar{t}$ events are classified into three categories based on the jet-parton associations in simulation: correct permutations ($f_{cp} = 27.9\%$), wrong permutations ($f_{wp} = 22.6\%$) where at least one jet is not associated to the correct parton, and unmatched permutations ($f_{un} = 49.4\%$), with at least one quark from the $t\bar{t}$ decay not matched unambiguously to a jet.

A likelihood (\mathcal{L}) to estimate $m_{\rm t}$ and JES given the observed data sample can be defined as:

$$\mathcal{L}(m_{\rm t}, {\rm JES}|{\rm sample}) \propto P({\rm sample}|m_{\rm t}, {\rm JES}) = \prod_{\rm events} P(m_{\rm t}^{\rm fit}, m_{\rm W}^{\rm reco}|m_{\rm t}, {\rm JES})^{P_{\rm gof}}$$

There is no correlation between $m_{\rm t}^{\rm fit}$ and $m_{\rm W}^{\rm reco}$, hence, the probability $P\left(m_{\rm t}^{\rm fit}, m_{\rm W}^{\rm reco} | m_{\rm t}, {\rm JES}\right)$ factorizes into

$$P\left(m_{\rm t}^{\rm fit}, m_{\rm W}^{\rm reco} | m_{\rm t}, {\rm JES}\right) = f_{\rm sig} \cdot \sum_{j} f_{j} P_{j}\left(m_{\rm t}^{\rm fit} | m_{\rm t}, {\rm JES}\right) \cdot P_{j}\left(m_{\rm W}^{\rm reco} | m_{\rm t}, {\rm JES}\right) + (1 - f_{\rm sig}) \cdot P_{\rm bkg}\left(m_{\rm t}^{\rm fit}\right) \cdot P_{\rm bkg}\left(m_{\rm W}^{\rm reco}\right),$$

where f_j and P_j with $j \in \{cp, wp, un\}$ are the relative fraction and the probability density functions for signal of the three different permutation cases, which are determined from simulated $t\bar{t}$ events with different generated top-quark masses $(m_{t,gen})$ and different JES. The m_t^{fit} distributions are fitted with a Breit-Wigner function convoluted with Gaussian resolution for the cp case and with the sum of a Landau function and a Gaussian function with common means for the wp and un cases for different $m_{t,gen}$ and JES. The m_W^{reco} distributions are fitted with asymmetric Gaussian functions. The parameters of all fitted signal functions are parametrized linearly in terms of $m_{t,gen}$, JES, and the product of the two. As the background is modeled from data, its probability density distributions do not depend on m_t nor JES.

In the 1D analysis, m_t is estimated from $-2 \ln \{\mathcal{L}(m_t, \text{JES} = 1 | \text{sample})\}$. In the 2D analysis, the most likely m_t and JES are obtained by minimizing $-2 \ln \{\mathcal{L}(m_t, \text{JES} | \text{sample})\}$.



Figure 1: Distance $\Delta R_{b\bar{b}}$ between the two bottom-quark candidates (top left), probability of the kinematic fit (top right), reconstructed top-quark mass from the kinematic fit (bottom right), and average reconstructed W-boson mass before being constrained by the kinematic fit (bottom left). The simulated t \bar{t} signal ($m_{t,gen} = 172.5 \text{ GeV}$) and background from event mixing are normalized to data with an uncertainty band from the signal fraction f_{sig} .

	1D analysis	2D analy	ysis
	$\delta_{m_{\rm t}} ({\rm GeV})$	$\delta_{m_{\rm t}} \ ({\rm GeV})$	$\delta_{ m JES}$
Fit calibration	0.13	0.14	0.001
Jet energy scale	0.97	0.10	0.002
b-JES	0.49	0.52	0.001
Jet energy resolution	0.15	0.13	0.003
b tagging	0.06	0.10	0.001
Trigger	0.24	0.26	0.006
Pileup	0.06	0.10	0.001
Parton distribution functions	0.06	0.10	0.001
Q^2 scale	0.22	0.34	0.005
ME-PS matching threshold	0.24	0.34	0.003
Underlying event	0.20	0.42	0.004
Color reconnection effects	0.15	0.58	0.006
Non-t \bar{t} background	0.13	0.60	0.006
Total	1.21	1.23	0.013

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Table 1: Overview of systematic uncertainties. The total is defined by adding in quadrature the contributions from all sources.

For each combination of m_t and JES 10 000 pseudo-experiments are conducted using simulated $t\bar{t}$ events and modeled background events from event mixing to calibrate the measurement and its statistical uncertainty.

5 Systematic uncertainties

An overview of the different sources of systematic uncertainties is shown in Table 1.

As expected, the main systematic uncertainty in the 1D measurement stems from the uncertainty in JES and the 2D measurement reduces this uncertainty to a small $p_{\rm T}$ - and η -dependent JES uncertainty. However, the 2D approach leads to increased uncertainties for color reconnection effects, underlying event, and the modeling of the non-tt background.

Overall, the 1D measurement offers a better precision on the top-quark mass measurement than the 2D approach.

6 Results

Out of 3.54 fb^{-1} of 2011 data, 2418 events are selected and with a fixed JES=1 result in:

 $m_{\rm t} = 173.49 \pm 0.69 \; ({\rm stat.}) \pm 1.21 \; ({\rm syst.}) \; {\rm GeV}$

The overall uncertainty of the presented 1D analysis is 1.39 GeV.

A simultaneous fit of m_t and JES to the same data yields:

$$m_{\rm t} = 174.28 \pm 1.00 \text{ (stat.+JES)} \pm 1.23 \text{ (syst.) GeV}$$

JES = 0.991 ± 0.008 (stat.) ± 0.013 (syst.)

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The measured JES confirms the JES in data measured in events with Z bosons and photons [14]. The overall uncertainty in the top-quark mass of the presented 2D analysis is 1.58 GeV.

The measured top-quark masses in both analyses are in agreement, with the 1D analysis yielding a higher precision than the 2D analysis. A combination with the three previously published CMS measurements [15, 16, 17] yields a mass of $m_{\rm t} = 173.54 \pm 0.33$ (stat.) ± 0.96 (syst.) GeV = 173.54 ± 1.02 GeV.

7 Summary

A measurement of the top-quark mass is presented using events with all-jets final states, collected by CMS in pp collisions at $\sqrt{s} = 7$ TeV in 2011. A constrained fit reconstructs the complete kinematics of each event. For each selected event a likelihood is calculated as a function of assumed top-quark mass. Using a data sample with an integrated luminosity of 3.54 fb^{-1} , 2418 candidate events are observed and the mass of the top-quark is measured to be $m_{\rm t} = 173.5 \pm 0.7$ (stat.) ± 1.2 (syst.) GeV. To date, this measurement constitutes the most precise determination of the top-quark mass in all-jets final states. A combination with the three previously published CMS measurements [15, 16, 17] yields a mass of $m_{\rm t} = 173.54 \pm 0.33$ (stat.) ± 0.96 (syst.) GeV = 173.54 ± 1.02 GeV.

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The top quark and the SM stability

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I will discuss the significance of precise knowledge of the top quark and Higgs boson masses for physics beyond the Standard Model and cosmology.

1 Introduction

After the discovery of the Higgs boson at the LHC by ATLAS [1] and CMS [2], the last missing particle of the Standard Model (SM) has been found. At present, the message from the LHC can be formulated as follows: the SM is a self-consistent, weakly coupled effective field theory all the way up to the Planck scale. First, no significant deviations from the SM predictions are seen and no convincing signal in favour of existence of new physics beyond the SM is observed. Second, the mass of the Higgs boson M_H is smaller than $M_H^{\text{max}} = 175$ GeV. If this were not the case, the Landau pole in the Higgs scalar self-coupling would be below the Planck quantum gravity scale $M_P = 2.44 \times 10^{18}$ GeV (see, e.g. [3]), calling for an extension of the SM at some energies between Fermi and Planck scales. Finally, the mass of the Higgs is sufficiently large, $M_H > 111$ GeV, meaning that our vacuum is stable or metastable with a lifetime greatly exceeding the Universe age [4]. The schematic behaviour of the Higgs boson self-coupling λ as the function of energy and the lifetime of the Universe as a function of the Higgs boson and top quark masses are shown in Fig. 1.

At the same time, the mass of the Higgs boson, found experimentally, $(M_H = 125.5 \pm 0.2_{stat} \stackrel{+0.5}{-0.6_{syst}}$ GeV, ATLAS [1] $M_H = 125.7 \pm 0.3_{stat} \pm 0.3_{syst}$ GeV, CMS [2]) is very close to the "critical Higgs mass" M_{crit} , which appeared in the literature well before the Higgs discovery in different contexts. The value of M_{crit} is the stability bound on the Higgs mass $M_H > M_{crit}$, see Fig. 2 (the "multiple point principle", put forward in [5], leads to prediction $M_H = M_{crit}$), to the lower bound on the Higgs mass coming from requirement of the Higgs inflation [6, 7], and to the prediction of the Higgs mass coming from asymptotic safety scenario for the SM [8]. The value of M_{crit} depends strongly on the mass of the top quark, calling for its precise measurement.

In this talk, based on the paper we written together with Fedor Bezrukov, Mikhail Kalmykov and Bernd A. Kniehl [9] and on the contribution to Proceedings of the European Physical Society Conference on High Energy Physics (2013) [10], I will discuss the significance of the top quark and Higgs boson masses for physics beyond the Standard Model and cosmology. The paper is organised as follows. In Section 2 we will discuss the absolute stability bound on the Higgs mass, Section 3 provides a short overview of the asymptotic safety scenario for the Standard Model, in Section 4 we will discuss the amazing relationship between the Planck



Figure 1: Left panel: Different patterns of the behaviour of the Higgs self coupling with energy. For $M_H > M_H^{\text{max}}$ the Landau pole appears at energies below the Planck scale. If $M_H < M_{\text{crit}}$ the scalar constant becomes negative at energies below the Planck mass, and electroweak vacuum becomes metastable. Right panel (courtesy of F. Bezrukov): The lifetime of the electroweak vacuum as a function of top quark and Higgs boson masses. Ellipses correspond to 1 and 2 σ contours in M_H and m_t , t_U is the age of the Universe. Along the straight lines the lifetime of the vacuum is given by the number in the plot. The light green region in the upper left corner corresponds to the stable vacuum.



Figure 2: The form of the effective potential for the Higgs field ϕ which corresponds to the stable (left), critical (middle) and metastable (right) electroweak vacuum. The form of the effective potential is tightly related to the energy dependence of the Higgs self-coupling constant $\lambda(\mu)$: the potential is negative almost in the same domain where $\lambda(\phi) < 0$.

and Fermi scales, in Section 5 we discuss a lower bound on the Higgs mass coming from Higgs inflation, and in Section 6 we conclude.

2 Top and Higgs: absolute stability bound

To find the numerical value of $M_{\rm crit}$, one should compute the effective potential for the Higgs field $V(\phi)$ and determine the parameters at which it has two degenerate minima:

$$V(\phi_{SM}) = V(\phi_1), \quad V'(\phi_{SM}) = V'(\phi_1) = 0,$$
 (1)

The renormalisation group improved potential has the form

$$V(\phi) \propto \lambda(\phi)\phi^4 \left[1 + O\left(\frac{\alpha}{4\pi}\log(M_i/M_j)\right)\right],$$
 (2)

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Figure 3: A very small change in the top quark mass converts the monotonic behaviour of the effective potential for the Higgs field to that with an extra minimum at large values of the Higgs field. Horizontal axis: ϕ in GeV; vertical axis : $V(\phi)$ in GeV⁴

where α is the common name for the SM coupling constants, and M_i are the masses of different particles in the background of the Higgs field. So, instead of computing the effective potential, one can solve the "criticality equations":

$$\lambda(\mu_0) = 0, \qquad \beta_\lambda^{\rm SM}(\mu_0) = 0 \ . \tag{3}$$

This simplified procedure works with accuracy $\simeq 0.15 \,\text{GeV}$ for the masses of the Higgs and of the top.

The contribution of the top quark to the effective potential is very important, as it has the largest Yukawa coupling to the Higgs boson. Moreover, it comes with the minus sign and is responsible for appearance of the extra minimum of the effective potential at large values of the Higgs field, see Fig. 3.

The most recent result for $M_{\rm crit}$ is convenient to write in the form¹

$$M_{\rm crit} = \left[129.3 + \frac{y_t(\mu_t) - 0.9361}{0.0058} \times 2.0 - \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \times 0.5\right] \,\text{GeV} \ . \tag{4}$$

Here $y_t(\mu_t)$ is the top Yukawa coupling in the $\overline{\text{MS}}$ renormalisation scheme taken at $\mu_t = 173.2$ GeV, and $\alpha_s(M_Z)$ is the QCD coupling at the Z-boson mass. The computation consists of matching of $\overline{\text{MS}}$ parameters of the SM to the physical parameters such as the masses of different particles and the renormalisation group running of coupling constants to high energy scale,

¹Note that this form is different from the original works, as well as the uniform estimates of the theoretical errors, which are the sole responsibility of the speaker.

supplemented by the computation of the effective potential for the Higgs field. All recent works [9, 11, 12] used 3-loop running of the coupling constants found in [13]-[18]; Ref. [9] accounted for $\mathcal{O}(\alpha \alpha_s)$ corrections to the matching procedure, getting 129.4 GeV for the central value of $M_{\rm crit}$ with the theoretical error 1.0 GeV, Ref. [11] got 129.6 GeV with smaller error 0.7 GeV, accounting for $\mathcal{O}(\alpha \alpha_s, y_t^2 \alpha_s, \lambda^2, \lambda \alpha_s)$ terms in the matching, while the complete analysis of 2-loop corrections in [12] gives 129.3 GeV for the central value with very small theoretical error 0.07 GeV.

At present, we do not know whether our vacuum is stable or metastable. Fig. 4 shows the behaviour of the scalar self-coupling within experimental and theoretical uncertainties, together with confronting the value of $M_{\rm crit}$ from Eq. (4) with the data. For making these plots, the pole top mass was taken from the Tevatron [19], $m_t = 173.2 \pm 0.51_{stat} \pm 0.71_{sys}$ GeV (the combined ATLAS and CMS value is $m_t = 173.4 \pm 0.4 \pm 0.9$ GeV [20]), and the value of $\alpha_s(M_Z) = 0.1184 \pm 0.0007$ [21].

To determine the relation between $M_{\rm crit}$ and M_H , the precision measurements of m_H, y_t and α_s are needed. The main uncertainty is in the value of the top Yukawa coupling, y_t . In general, an x GeV experimental error in m_t leads to $\simeq 2 \times x$ GeV error in $M_{\rm crit}$. The difficulties in extraction of y_t from experiments at the LHC or Tevatron are discussed in [22]. Here we just mention that the non-perturbative QCD effects, $\delta m_t \simeq \pm \Lambda_{QCD} \simeq \pm 300$ MeV lead to $\delta M_{\rm crit} \simeq \pm 0.6$ GeV. The similar in amplitude effect comes from (unknown) $\mathcal{O}(\alpha_s^4)$ corrections to the relation between the pole and $\overline{\rm MS}$ top quark masses. According to [23], this correction can be as large as $\delta y_t/y_t \simeq -750(\alpha_s/\pi)^4 \simeq -0.0015$, leading to $\delta M_{\rm crit} \simeq -0.5$ GeV.

What do the (meta) stability of our vacuum and the agreement of the Standard Model with the LHC experiments mean for cosmology? We can consider two different possibilities.

(i) The Higgs mass is smaller than $M_{\rm crit}$, so that the scalar self coupling crosses zero at energy scale $M_{\lambda} \ll M_P$, where M_{λ} can be as "small" as 10⁸ GeV, within the experimental and theoretical error-bars, see Fig. 4.

(ii) The Higgs mass is larger or equal to $M_{\rm crit}$, and the Higgs self coupling never crosses zero (or does so close to the Planck scale, where gravity effects must be taken into account), see Fig. 4.

If (i) is realised, there are at least two ways to deal with the metastability of our vacuum. The first one is cosmological: it is sufficient that the Universe after inflation finds itself in our vacuum with reheating temperature below M_{λ} . Then this guarantees that we will stay in it for a very long time. This happens, for example, in R^2 inflation [24]. The other possibility is related to possible existence of new physics at M_{λ} scale, which makes our vacuum unique (see, e.g. [25]).

If (ii) is realised, then no new physics is needed between the Fermi and Planck scales.

It is very interesting that the values of M_t and M_H are amazingly close to the critical values, determined from (3). Though this could be a pure coincidence, the discussion below indicates that this may be a very important message about the structure of high energy theory.

3 Top and Higgs: asymptotically safe SM+gravity

The asymptotic safety of the SM [8], associated with the asymptotic safety of gravity [26], is strongly related to the value of the Higgs boson and top quark masses. Though General Relativity is non-renormalizable by perturbative methods, it may exist as a field theory non-perturbatively, exhibiting a non-trivial ultraviolet fixed point (for a review see [27]). If true, all

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Figure 4: Both panels: The shaded regions account for 1 and 2 σ experimental uncertainties in α_s and the pole top quark mass m_t , and theoretical errors in extraction of y_t from experiment. Left panel: Running of the scalar self coupling constant with energy. Dashed and dotted lines correspond to varying in addition the mass of the Higgs boson within 1 and 2 σ experimental errors. Right panel: The blue line gives the relation between α_s and the pole top mass following from Eq. (4) if M_H is identified with $M_{\rm crit}$. The shaded regions around it correspond to 1 and 2 σ experimental errors in the Higgs mass. Red ellipses correspond to the accuracy achievable at e^+e^- collider [22].

other couplings of the SM (including the Higgs self-interaction) should exhibit an asymptotically safe behavior with the gravity contribution to the renormalisation group running included.

The prediction of the Higgs boson mass from the requirement of asymptotic safety of the SM is found as follows [8]. Consider the SM running of the coupling constants and add to the β -functions extra terms coming from gravity, deriving their structure from dimensional analysis:

$$\beta_h^{\text{grav}} = \frac{a_h}{8\pi} \frac{\mu^2}{M_P^2(\mu)} h,\tag{5}$$

where a_1 , a_2 , a_3 , a_y , and a_λ are some constants (anomalous dimensions) corresponding to the gauge couplings of the SM g, g', g_s , the top Yukawa coupling y_t , and the Higgs self-coupling λ . In addition,

$$M_P^2(\mu) \simeq M_P^2 + 2\xi_0 \mu^2$$
 (6)

is the running Planck mass with $\xi_0 \approx 0.024$ following from numerical solutions of functional RG equations [28, 29, 30]. Now, require that the solution for all coupling constants is finite for all μ and that λ is always positive. The SM can only be asymptotically safe if a_1, a_2, a_3, a_y are all negative, leading to asymptotically safe behavior of the gauge and Yukawa couplings. For $a_{\lambda} < 0$ we are getting the interval of admissible Higgs boson masses, $M_{\min}^{\text{safety}} < M_H < M_{\max}^{\text{safety}} \simeq 175$ GeV. However, if $a_{\lambda} > 0$, as follows from computations of [29, 30], only one value of the Higgs boson mass $M_H = M_{\min}^{\text{safety}}$ leads to asymptotically safe behavior of λ . As is explained in [8], this behavior is only possible provided $\lambda(M_P) \approx 0$ and $\beta_{\lambda}(\lambda(M_P)) \approx 0$. And, due to miraculous coincidence of μ_0 and M_P , the difference $\Delta m^{\text{safety}} \equiv M_{\min}^{\text{safety}} - M_{\min}$ is extremely small, of the order 0.1 GeV. The evolution of the Higgs self-coupling for the case of $a_h < 0$ is shown in Fig. 5, and for the case $a_h > 0$ in Fig. 6.

In fact, in the discussion of the asymptotic safety of the SM one can consider a more general situation, replacing the Planck mass in Eq. (6) by some cutoff scale $\Lambda = \kappa M_P$. Indeed, if the Higgs field has non-minimal coupling with gravity (see below), the behavior of the SM coupling may start to change at energies smaller than M_P by a factor $1/\xi$, leading to an expectation for



Figure 5: Schematic depiction of the behavior of the scalar self-coupling if $a_h < 0$ for $M_{\min}^{\text{safety}} < M_H < M_{\max}^{\text{safety}}$ (left) and $M_H < M_{\min}^{\text{safety}}$ (right). In both cases gravity leads to asymptotically free behavior of the scalar self-coupling. Negative λ lead to instability and are thus excluded.

the range of κ as $1/\xi \lesssim \kappa \lesssim 1$. Still, the difference between M_{\min} and M_{\min}^{safety} remains small even for $\kappa \sim 10^{-4}$, where $M_{\min}^{\text{safety}} \simeq 128.4 \,\text{GeV}$, making the prediction $M_H \simeq M_{\min}$ sufficiently stable against specific details of Planck physics within the asymptotic safety scenario.



Figure 6: Schematic depiction of the behavior of the scalar self-coupling if $a_h > 0$ for $M_H > M_{\min}^{\text{safety}}$, leading to Landau-pole behavior (left), $M_H < M_{\min}^{\text{safety}}$, leading to instability (right) and $M_H = M_{\min}^{\text{safety}}$, asymptotically safe behavior (middle). Only this choice is admissible.

4 New physics between the Fermi and Planck scales?

If we fix mass of the top quark, then Eq. 3 determines also the value of the scale μ_0 at which the scalar self-coupling and its β -function vanish simultaneously. The central value for μ_0 is 2.9×10^{18} GeV and is quite stable if m_t and α_s are varied in their confidence intervals (see Fig. 7). One can see that there is a remarkable coincidence between μ_0 and the (reduced) Planck scale $M_P = 2.44 \times 10^{18}$ GeV. The physics input in the computation of μ_0 includes the parameters of the SM only, while the result gives the gravity scale. A possible explanation may

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be related to the asymptotic safety of the SM, as discussed above.

It remains to be seen if this is just the random play of the numbers or a profound indication that the electroweak symmetry breaking is related to Planck physics. If real, this coincidence indicates that there should be no new energy scales between the Planck and Fermi scales, as they would remove the equality of μ_0 and M_P unless some conspiracy is taking place.



Figure 7: The scale μ_0 depending on the top mass M_t . The dashed lines correspond to 1σ uncertainty in α_s . The yellow shaded region corresponds to adding the α_s experimental error and the theoretical uncertainty in the matching of the top Yukawa y_t and top pole mass.

5 Top and Higgs: cosmological inflation

It is well known that for inflation we better have some bosonic field, which drives it (for a review see e.g. [31]). At last, the Higgs boson has been discovered. Can it make the Universe flat, homogeneous, and isotropic, and produce the necessary spectrum of fluctuations for structure formation? The answer to this question is affirmative [32].

The main idea of Higgs inflation is related to a non-minimal coupling of the Higgs field to gravity, described by the action

$$S_G = \int d^4x \sqrt{-g} \left\{ -\frac{M_P^2}{2}R - \frac{\xi |\phi|^2}{2}R \right\} \,. \tag{7}$$

Here R is the scalar curvature, the first term is the standard Hilbert-Einstein action, ϕ is the Higgs field, and ξ is a new coupling constant, fixing the strength of "non-minimal" interaction. This constant cannot be fixed by a theoretical computation, but its presence is actually required for consistency of the SM in curved space-time (see, e.g. [33]).

Consider now large Higgs fields, typical for chaotic inflation [34]. Then the gravity strength, given by the effective Planck mass in the Higgs background, is changed as $M_P^{\text{eff}} = \sqrt{M_P^2 + \xi |\phi|^2} \propto |\phi|$. In addition, all particle masses are also proportional to the Higgs field. This means that for $|\phi| \gg \frac{M_P}{\sqrt{\xi}}$ the physics does not depend on the value of the Higgs field, as all dimensionless



Figure 8: Schematic depiction of the effective potential V for the Higgs field in the Higgsinflationary theory in the Einstein frame for $M_H > M_{crit}$ (left) and $M_H < M_{crit}$ (right). In the second case successful inflation cannot take place.

ratios are $|\phi|$ independent. This leads to an existence of the flat direction for a canonically normalized scalar field χ , related to the Higgs field by conformal transformation. After inflation with $N \simeq 58$ e-foldings the energy of the Higgs field is transferred to other particles of the SM, reheating the Universe up to the temperature $T_{reh} \sim 10^{13-14}$ GeV [35, 36].

For the Higgs inflation to work, the scalar self-coupling constant λ must be positive up to the scale of inflation $\mu_{infl} = M_P/\sqrt{\xi}$. Numerically, this leads to the constraint $M_H > M_{\rm crit}$ with extra theoretical uncertainty of $\delta M_H \sim 1$ GeV [37], see Fig. 8. Though the theory in the electroweak vacuum enters into strong coupling regime at energies smaller than the Planck scale by a factor ξ [38, 39], the analysis of higher dimensional operators and radiative corrections at large Higgs background, necessary for inflation, shows that the Higgs inflation occurs in the weak coupling regime and is self-consistent [37].

The cosmological predictions of the Higgs inflation can be compared with observations performed by the Planck satellite. The Higgs-inflaton potential depends on one unknown parameter, ξ . It can be fixed by the amplitude of the CMB temperature fluctuations $\delta T/T$ at the WMAP normalization scale ~ 500 Mpc, with the use of precise knowledge of the top quark and Higgs masses, and α_s . In general, $\xi > 600$ [6]. Since the Higgs mass lies near $M_{\rm crit}$, the actual value of ξ may be close to the lower bound.

Also, the value of spectral index n_s of scalar density perturbations

$$\left\langle \frac{\delta T(x)}{T} \frac{\delta T(y)}{T} \right\rangle \propto \int \frac{d^3k}{k^3} e^{ik(x-y)} k^{n_s-1}$$
 (8)

and the amplitude of tensor perturbations $r = \frac{\delta \rho_s}{\delta \rho_t}$ can be determined. The predictions, together with the Planck results, are presented in Fig. 9, and are well inside the 1 sigma experimental contour. Moreover, as for any single field inflationary model, the perturbations are Gaussian, in complete agreement with Planck [40].

6 Conclusions

For experimental values of Higgs boson and top quark masses there is no necessity for a new energy scale between the Fermi and Planck scales. The EW theory remains in a weakly coupled

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Figure 9: Left panel: The predictions of Higgs inflation versus observations. Right panel: Predictions of different inflationary models contrasted with the Planck results (from Ref. [40]).

region all the way up to M_P , whereas the SM vacuum state lives longer than the age of the Universe. If the Higgs and top masses would satisfy the "criticality equation" (4), this would put a strong argument in favor of the *absence* of such a scale and indicate that the electroweak symmetry breaking may be associated with the physics at the Planck scale.

The experimental precision in the Higgs boson mass measurements at the LHC can eventually reach 200 MeV. So, the largest uncertainty will remain in the measurement of the mass of the top quark. It does not look likely that the LHC will substantially reduce the error in the top quark mass determination. Therefore, to clarify the relation between the Fermi and Planck scales a construction of an electron-positron or muon collider with a center-of-mass energy of $\sim 200 + 200 \text{ GeV}$ (Higgs and t-quark factory) would be needed. This would be decisive for setting up the question about the necessity for a new energy scale besides the two ones already known—the Fermi and the Planck scales. In addition, this will allow to study in detail the properties of the two heaviest particles of the Standard Model, potentially most sensitive to any types on new physics.

Surely, even if the SM is a valid effective field theory all the way up the the Planck scale, it cannot be complete as it contradicts a number of observations. In fact, all the confirmed observational signals in favor of physics beyond the Standard Model which were not discussed in this talk (neutrino masses and oscillations, dark matter and baryon asymmetry of the Universe) can be associated with new physics *below* the electroweak scale, for reviews see [41, 42] and references therein. The minimal model explaining all these phenomena, ν MSM, contains, in addition to the SM particles, three relatively light singlet Majorana fermions. The ν MSM predicts that the LHC will continue to confirm the Standard Model and see no deviations from it. At the same time, new experiments at the high-intensity frontier, discussed in [43], may be needed to uncover the new physics below the Fermi scale. In addition, new observations in astrophysics, discussed in [42], may shed light on the nature of Dark Matter.

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Experimental status of top charge asymmetry measurements

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The latest measurements of the asymmetry in the angular distributions of the $t\bar{t}$ events are reviewed. The measurements of the forward-backward asymmetry A_{FB} in the $p\bar{p}$ 1.98 TeV collisions at the Tevatron show some tension with the Standard Model calculation, while results of the measurements of the charge asymmetry A_C in pp collisions at 7 TeV and 8 TeV at the LHC are compatible with Standard Model predictions.

1 Introduction

The measurement of the asymmetry in the angular distributions of $t\bar{t}$ events is a powerful test of the Standard Model (SM) predictions, and allows to probe for physics beyond the SM. Different asymmetries are considered at the Tevatron and LHC. At the Tevatron, the $t\bar{t}$ pairs are produced in the $p\bar{p}$ collisions, so we can define the forward-backward asymmetry as

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)},$$

where $\Delta y = y_t - y_{\bar{t}}$ is a difference in rapidity of top and antitop quarks, N(...) is a corresponding number of $t\bar{t}$ events. At the LHC, the pp collisions are forward-backward symmetric, so the charge asymmetry is considered:

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

where $\Delta |y| = |y_t| - |y_{\bar{t}}|$ is a difference in absolute rapidity of top and antitop quarks. The latest SM calculations for those quantities yield $(8.7^{+0.6}_{-0.5})\%$ for the Tevatron, $(1.23 \pm 0.05)\%$ for the LHC 7 TeV and $(1.11 \pm 0.05)\%$ for the LHC 8 TeV [1]. See [2] for the discussion about details of theoretical predictions and possible contributions from the non-SM processes.

The analysis of experimental data includes several steps. After event selection the top and antitop quarks' kinematic parameters need to be reconstructed using measured parameters of leptons, jets and missing transverse energy. Two final states are usually considered for the asymmetry measurement: ℓ +jets and dileptons. In ℓ +jets final state the $t\bar{t}$ pair is decaying to $t\bar{t} \to W^+W^- b\bar{b} \to \ell\nu q\bar{q'} b\bar{b}$, where direction and transverse momentum (p_T) for lepton ℓ and four quark jets are sufficient for reconstruction of the top and antitop parameters. Usually, more or less sophisticated kinematic reconstruction methods are used to account for the ambiguity in attributing jets to partons. These methods usually use constraints on two-jets and
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three-jets invariant masses which correspond to the W-boson and to the top quark masses and improve the uncertainty on the measured jets energies. In the dilepton final state, the $t\bar{t}$ pair decays to the final state with two non-detected neutrinos, $t\bar{t} \to W^+W^- b\bar{b} \to \ell^+\ell^- \nu\bar{\nu} b\bar{b}$. The reconstruction in this final state requires a "scan" of the phase space constrained by the experimental measured parameters of leptons and jets. Parameters of the top quark and antiquark are calculated as a weighted sum of reconstructed parameters in all scan points. The last step in the asymmetry measurements is an unfolding of the reconstructed distributions to the parton level. Strictly speaking, such unfolding is not required if we restrict the measurement to the inclusive asymmetry only. Usually, it is not the case, because it is also interesting to measure the asymmetry dependence from the invariant mass of $t\bar{t}$ pair $(m_{t\bar{t}})$, Δy or other parameters. Such differential measurement is more sensitive to the possible new physics contribution, since it is expected to contribute more in some region or phase space, e.g. at high $m_{t\bar{t}}$.

The procedures of reconstruction and unfolding of top quark parameters complicate quite a lot the asymmetry analyses and require a careful calibration. The alternative approach has been developed for the asymmetry measurements. Instead of measuring the quark asymmetry, we can measure asymmetry in the distributions of leptons. Since direction of leptons is measured with a good precision, no top quark reconstruction or unfolding is needed. The drawback of this approach is that the leptonic asymmetry isn't as powerful as the top quark asymmetry, because the direction of leptons is not fully correlated with the direction of top quark. For example, at the Tevatron, the leptonic asymmetry is defined as

$$A_{\ell} = \frac{N(q \cdot y_{\ell} > 0) - N(q \cdot y_{\ell} < 0)}{N(q \cdot y_{\ell} > 0) + N(q \cdot y_{\ell} < 0)},$$

where y_{ℓ} and q is a lepton rapidity and charge. A_{ℓ} is predicted to be $(3.8 \pm 0.6\%)$ [1]. More interestingly, it was found, that the measurement of the angular distribution of leptons is complementary to the $t\bar{t}$ asymmetry measurement. This is related to the fact, that the angular distribution of leptons is affected not only by the angular distribution of top quark but also by its polarization. In the SM the top quark polarization is zero, but could be significantly different for the non-SM contribution, e.g. in the $t\bar{t}$ production via axigluon mechanism [3]. In the dilepton final state, we also can measure the two-lepton asymmetry, constructed analogously to the $t\bar{t}$ asymmetry. It is defined at the Tevatron as:

$$A_{FB}^{ll} = \frac{N(\Delta y_{\ell} > 0) - N(\Delta y_{\ell} < 0)}{N(\Delta y_{\ell} > 0) + N(\Delta y_{\ell} < 0)},$$

and at the LHC:

$$A_C^{ll} = \frac{N(\Delta|y_\ell| > 0) - N(\Delta|y_\ell| < 0)}{N(\Delta|y_\ell| > 0) + N(\Delta|y_\ell| < 0)},$$

where difference in leptons rapidities is $\Delta y_{\ell} = y_{\ell^+} - y_{\ell^-}$ and $\Delta |y_{\ell}| = |y_{\ell^+}| - |y_{\ell^-}|$.

2 LHC results

The results of the A_C measurement by ATLAS at 7 TeV [4, 5] as well as measurements by CMS at 7 TeV [6, 7] and 8 TeV [8] are shown in the Table 1. The measured values are all compatible with each other and with SM predictions. Measurements of the leptonic asymmetry $A_C^{\ell\ell}$, Table 2, also don't show any deviation from the SM expectation. The enormous statistics

Measurement				Measured Value, $\%$	Theoretical Expectation[1],%
ATLAS	ℓ +jets 7 TeV		$4.7 \ fb^{-1}$	0.6 ± 1.0	1.23 ± 0.05
	dileptons			$5.7 \pm 2.4(stat.) \pm 1.5(syst.)$	
	$\ell + jets$		$5 f b^{-1}$	$0.4 \pm 1.0(stat.) \pm 1.1(syst.)$	
CMS	dileptons			$5.0 \pm 4.3(stat.) \stackrel{+1.0}{_{-3.9}}(syst.)$	
	ℓ +jets	8 TeV	$19.7 \ fb^{-1}$	$0.5 \pm 0.7(stat.) \pm 0.6(syst.)$	1.11 ± 0.04

Table 1: A_C measurements at the LHC [4, 5, 6, 8], unfolded to the parton level.

Measurement				Measured Value, %	Theoretical Expectation[1],%		
ATLAS	dileptons	$7 \ TeV$	$4.7 \ fb^{-1}$	$2.3 \pm 1.2(stat.) \pm 0.8(syst.)$	0.55 ± 0.02		
CMS			$5 \ f b^{-1}$	$1.0 \pm 1.5(stat.) \pm 0.6(syst.)$			

Table 2: $A_C^{\ell\ell}$ measurements at the LHC [5, 7].

accumulated at the LHC allows to investigate the restricted phase space regions, e.g. high velocity and high $m_{t\bar{t}}$ mass regions. In both cases the expectation for the SM asymmetry is larger than for the inclusive asymmetry and the possible contribution from the non SM physics are also expected to be enhanced, see e.g. [9]. Both experiments have looked at the asymmetry differential distributions, but no deviation from SM has been found. For illustration, see two selected distributions in Fig. 1,2.

3 Tevatron results

For quite some time, measurements at the Tevatron were puzzling because of the observed 2–3 standard deviations (SD) between the measured and expected A_{FB} asymmetries. Table 3 shows that the difference between the most recent theoretical prediction and the current measurements of the CDF and D0 experiments [10, 11] are less than 2 SD. In the same time, asymmetry measured at the high $m_{t\bar{t}}$ shows a moderate deviation from the expectation. In particular, CDF results on the measured slope of the A_{FB} asymmetry as a function of $m_{t\bar{t}}$ (Fig. 3) show a 2.4 SD deviation between measured slope and the expected one. In the same measurement $|\Delta y|$ dependence shows even large deviation at the level of 2.8 SD, Fig. 3. The $|\Delta y|$ differential distribution of asymmetry has been also measured in a different way in the CDF experiment. The shape of the unfolded $\cos(\theta)$ distribution has been fitted with the Legendre polynomial series and it was found that the contribution to the asymmetry of the first coefficient in series is different from the SM expectation, see [12] for the detailed description.

The leptonic asymmetry A_{ℓ} is measured by both experiments with full available statistics and demonstrates an agreement at the level of 2 SD with the SM expectation (Table 4), even if the CDF measurement is slightly higher than the expectation. It exists some difficulty in the interpretation of the obtained results. It is related to the fact, that leptonic asymmetries are measured in the phase space limited by the acceptance |y| cut and then extrapolated to the full phase space. These acceptance cuts are different in different measurements, e.g. CDF





Figure 1: Charge asymmetry distribution as a function of $m_{t\bar{t}}$ for the events with $t\bar{t}$ velocity > 0.6 as measured by the Atlas experiment [4].

Figure 2: Charge asymmetry distribution as a function of $m_{t\bar{t}}$ as measured by the CMS experiment [6].

Measurement		Measured Value, $\%$	Theoretical Expectation $[1], \%$		
CDF	$9.4 \ fb^{-1}$	16.4 ± 4.7	8.8 ± 0.6		
D0	$5.4 \ fb^{-1}$	19.6 ± 6.5			

Table 3: A_{FB} measurements in the ℓ +jets final state at the Tevatron [10, 11], unfolded to the parton level.

 ℓ +jets measurement uses |y| < 1.25, D0 ℓ +jets measurement uses |y| < 1.5 and asymmetry in the D0 dilepton channel is measured within the acceptance cut of |y| < 2.0. The extrapolation procedure is model dependent and done in a different way in different measurements. Currently both experiments are working on the combination of measurements and defining the most appropriate extrapolation procedure.

The dilepton final state gives an unique possibility to make a measurement of the $A_{FB}^{\ell\ell}$ asymmetry. The D0 analysis measured it to be equal $12.3 \pm 5.4(stat.) \pm 1.5(syst.)$ [15, 16] which is in agreement with the theoretical prediction 4.8 ± 0.4 [1]. In addition, in this analysis the correlation between $A_{FB}^{\ell\ell}$ and A_{ℓ} measurements has been studied, see Fig 4, and the ratio of these two asymmetries has been found to be $R = A_{\ell}/A_{FB}^{\ell\ell} = 0.36 \pm 0.20$ which is 2 SD away from the expectation, which could be estimated using the predicted values of $A_{FB}^{\ell\ell}$ and A_{ℓ} in [1]: $R_{th} = 3.8/4.8 \sim 0.8$. For further discussion about this measurement see [16].

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	Measurement		Measured Value, %	Theoretical Expectation [1], %
CDF	$\ell + jets$	$9.4 \ fb^{-1}$	$9.4^{+3.2}_{-2.9}$	3.8 ± 0.6
D0	ℓ +jets ($ \eta < 1.5$)	$9.7 \ fb^{-1}$	$4.7 \pm 2.3(stat.) \stackrel{+1.1}{_{-1.4}}(syst.)$	
D0	dileptons	$9.7 \ fb^{-1}$	$4.4 \pm 3.7(stat.) \pm 1.1(syst.)$	

Table 4: A_{ℓ} measurements at the Tevatron [13, 14, 15]. CDF ℓ +jets and D0 dileptons measurements are extrapolated to the full phase space, but D0 ℓ +jets measurement is limited to the acceptance $|\eta| < 1.5$.



Figure 3: A_{FB} asymmetry distribution as a function of $m_{t\bar{t}}$ and $|\Delta y|$ as measured by the CDF experiment in the ℓ +jets final state [10].



Figure 4: A_{ℓ} vs $A_{FB}^{\ell\ell}$ asymmetry as measured by the D0 experiment in the dilepton final state [15, 16].

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Figure 5: Summary of the asymmetry measurements at the Tevatron and LHC.

4 Conclusion

During the last several years Tevatron measurements of the asymmetry show an intriguing deviation from the SM calculation. The current measurements of the inclusive $t\bar{t}$ asymmetry from the CDF and from the D0 experiments don't show any strong deviation from the recent SM calculations, but the asymmetry measurements as a function of $m_{t\bar{t}}$ or $|\Delta y|$ show a significant deviation from the SM at the level more than 2 standard deviations. In the same time D0 didn't yet analyze the full available statistics and hence the final conclusion about the $t\bar{t}$ asymmetry from the Tevatron is still to come. The leptonic asymmetry measurements at the Tevatron deviate less than 2 SD from the SM model predictions, but results still need to be combined to have a more precise conclusion about the level of agreement with the expectation.

Measurements at the LHC don't show any deviation from the SM prediction, but the expected asymmetry is very low and the current precision of the measurements is about 1%, comparable with the expected asymmetry. At the LHC the most interesting direction of study is a measurement of the differential asymmetry as a function of the velocity or invariant $t\bar{t}$ mass. The large statistics accumulated at the LHC make possible the precise measurements in regions of the phase space where both SM and non-SM asymmetries are expected to be large. For the moment, no deviation from the expectations were found. Fig. 5 summarizes current measurements of the inclusive asymmetries both at the Tevatron and LHC and compares them with the expected SM values.

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Separating single top quark signal from background using distribution mixture model

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A very common situation in experimental high energy physics is signal which cannot be separated from background by use of any cut. Application of the distribution mixtures, a modified iterative Expectation-Maximization algorithm for weighted data, and taking advantage of Bayesian statistics represents promising multivariate technique in this area. The paper presents statistical theory, computational aspects of the algorithm, and working results of signal from background separation obtained by application of the proposed method to a single top analysis with the full DØ Run II dataset of 9.7 fb⁻¹ of integrated luminosity with corresponding signal and background Monte Carlo.

1 Distribution mixtures

A distribution mixture model, also known as the Model Based Clustering method (MBC), is an analysis technique that separates data into groups by creating a statistical model. We focused on the Gaussian Mixture Model (GMM), whose parameters can be obtained by an iterative Expectation-Maximization (EM) algorithm which has been modified for weighted events. The MBC allows us to classify given set without training in the separable cases. Since we used this method in single top channels, where the distribution of signal and background is almost the same, we took the advantage of the available Monte Carlo (MC) samples and applied the Bayes rule to compute the *a posteriori* probability of membership of the event to each data class.

Let $\mathcal{S} = (\omega_1, \ldots, \omega_K)$ denote a finite set of disjoint classes with $P(\bigcup_{k=1}^K \omega_k) = 1$, where $P(\omega_k) > 0$ is the *a priori* probability of the *k*-th class. One class represents signal and the others different backgrounds. We focused on estimation of the parameters of class signal and class of all backgrounds together. Assume that $\mathbf{x} = (x_1, \ldots, x_D)$ is the observation of a *D*-dimensional absolutely continuous random variable \mathbf{X} . We want to find out the *a priori* probabilities $P(\omega_k)$ and the shape of distributions $p(\mathbf{x} | \omega_k)$ for each class.

Let $\boldsymbol{x} \in \mathbb{R}^{D \times N}$ represent a set of data of dimension D with N independent and identically distributed (i.i.d.) observations. Let $p_1(\boldsymbol{x} | \theta_1), \ldots, p_M(\boldsymbol{x} | \theta_M)$ be parametric probability density functions of the same type, $\theta_l \in \Theta$, $l \in \{1, \ldots, M\}$, where M denotes the number of mixture components, $M \in \mathbb{N}$, $M \leq N$, and where $\Theta \subset \mathbb{R}^s$ is a parameter space, $s \in \mathbb{N}$.

Then the distribution mixture (see [1]) is any convex combination in the form of

$$p(\boldsymbol{x}|\boldsymbol{\theta}) = \sum_{l=1}^{M} \alpha_l p_l(\boldsymbol{x}|\boldsymbol{\theta}_l), \quad \sum_{l=1}^{M} \alpha_l = 1, \quad \alpha_l \ge 0,$$
(1)

where α_l denotes the *weight* of the *l*-th component. Instead of maximizing log-likelihood function (classic maximum likelihood estimate, MLE), we will maximize the conditional expected value ([2]) of the so-called *complete set* $\boldsymbol{z} = (\boldsymbol{x}^T, \boldsymbol{y}^T)^T$ which consists of the observable data, \boldsymbol{x} , and the missing data, \boldsymbol{y} , denoting membership of the data \boldsymbol{x} to the *l*-th component, i.e.

$$(y_i)_l = \begin{cases} 1, & \text{if } x_i \text{ belongs to the } l\text{-th component,} \\ 0, & \text{otherwise,} \end{cases}$$
(2)

where $i \in \{1, ..., N\}$, $l \in \{1, ..., M\}$, $\boldsymbol{y} \in \mathbb{R}^{M \times N}$, $\boldsymbol{x} \in \mathbb{R}^{D \times N}$, and the complete log-likelihood function is defined as the logarithm of the probability of the complete set:

$$l_c(\theta | \boldsymbol{z}) = \ln p(\boldsymbol{z} | \theta), \quad \theta = (\alpha_1, \dots, \alpha_M, \theta_1, \dots, \theta_M) \subset \mathbb{R}^M \times \mathbb{R}^{s \times M}.$$
(3)

1.1 EM algorithm for weighted Gaussian Mixture Model

The auxiliary function $Q(\theta, \vartheta)$ as the conditional expected value of the complete data is given by

$$Q(\theta, \vartheta) = \mathbf{E}[l_c(\theta \,|\, \boldsymbol{z}) \,|\, \boldsymbol{x}, \vartheta], \tag{4}$$

where θ denotes a new (unknown) value of the distribution mixture parameter and ϑ denotes an old (known) parameter. This function is maximized using the EM algorithm, whose k-th iteration ($k \in \mathbb{N}_0$) consists of two steps ([3, 4]):

1. **E-step**: Calculate the auxiliary function $Q(\theta, \theta^k)$

$$Q(\theta, \theta^{k}) = \sum_{l=1}^{M} \sum_{i=1}^{N} \ln [\alpha_{l}] p(l | x_{i}, \theta^{k}) \gamma(x_{i}) + \sum_{l=1}^{M} \sum_{i=1}^{N} \ln [p_{l}(x_{i} | \theta_{l})] p(l | x_{i}, \theta^{k}) \gamma(x_{i}),$$
(5a)

$$p(l|x_i, \theta^k) = \left(p_l(x_i|\theta_l^k)\alpha_l^k\right) \left(\sum_{l=1}^M p_l(x_i|\theta_l^k)\alpha_l^k\right)^{-1},\tag{5b}$$

where $p_l(x_i | \theta_l^k)$ denotes the probability that observation $x_i \in \mathbb{R}^{D \times 1}$ belongs to the *l*-th component, i.e. the Gaussian probability density function.

2. M-step: Find $\theta^{k+1} = (\alpha^{k+1}, \mu^{k+1}, \mathbb{C}^{k+1}) \in \Theta$ maximizing $Q(\theta, \theta^k)$

$$\alpha_{l}^{k+1} = \left(\sum_{i=1}^{N} p(l \mid x_{i}, \theta^{k}) \gamma(x_{i})\right) \left(\sum_{i=1}^{N} \gamma(x_{i})\right)^{-1}, \quad \mu_{l}^{k+1} = \frac{\sum_{i=1}^{N} p(l \mid x_{i}, \theta^{k}) \gamma(x_{i}) x_{i}}{\sum_{i=1}^{N} p(l \mid x_{i}, \theta^{k}) \gamma(x_{i})}, \tag{6a}$$

$$\mathbb{C}_{l}^{k+1} = \left(\sum_{i=1}^{N} p(l \,|\, x_{i}, \theta^{k}) \gamma(x_{i})(x_{i} - \mu_{l}^{k+1})(x_{i} - \mu_{l}^{k+1})^{T}\right) \left(\sum_{i=1}^{N} p(l \,|\, x_{i}, \theta^{k}) \gamma(x_{i})\right)^{-1}.$$
 (6b)

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Eventually, we can express the posterior probability of the k-th class, i.e. the probability that observation x belongs to the k-th class, using Bayes theorem as

$$P(\text{signal} | \boldsymbol{x}) = \frac{p(\boldsymbol{x} | \text{signal}) P(\text{signal})}{p(\boldsymbol{x} | \text{signal}) P(\text{signal}) + p(\boldsymbol{x} | \text{background}) P(\text{background})}.$$
 (7)

1.2 Computational aspects of the EM algorithm

The classification of the training set is more successful with higher number of components, but it is not trivial to find the optimal number of components because of the potential problems with overfitting (overtraining). Figure 1 shows dependence of the success of the classification on the number of components.

It is crucial to choose appropriate initialization parameters. Convergence of the EM algorithm to a local optimum may produce different results for multiple runs. Thus, we usually set the initial weight of each components to $\alpha_l^0 = \frac{1}{M}$, the initial expected values μ_l^0 are set to the sample means, and the initial covariance matrices \mathbb{C}_l^0 are diagonal matrices containing the sample variance on the diagonal. This modification gives algorithm more variability, therefore, it is subsequently more probable that algorithm converges to a higher local maximum.



Figure 1: ROC curves and histograms of component weights for signal tb vs. all background in 2-Tag 2-Jets with two different settings of the number of components.

2 Analysis of single top MC from the DØ experiment

The MBC method was tested on single top (see [5, 6]) Monte Carlo, corresponding to the full DØ Run II data of 9.7 fb⁻¹ of integrated luminosity. We trained the model on the so-called *small training sample* (STS), tested on the so-called *testing sample* (TS), and finally verified the *a posteriori* distribution of the so-called *yield sample* (YS) and the real *data* from the DØ detector. For details about MC, data, and official DØ analysis using Bayesian Neural Networks

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(BNN), Boosted Decision Trees (BDT), and the Matrix Element (ME) method see [7, 8]. Overall 12 sub-tasks $\{tb, tqb, tb+tqb\} \times \{1\text{-}Tag, 2\text{-}Tag\} \times \{2\text{-}Jets, 3\text{-}Jets\}$ were computed using up to 39 variables. The area under the ROC curve (AUC) varied between 0.62 and 0.8 depending on the analysis channel and the testing set, see Table 1. Results of separation using ME, BNN, BDT, MBC, and Generalized Linear Models (GLM) with probit link function are compared in Figure 2.

NcS	NcB	AUC_{ROC-TS}	$AUC_{ROC-STS}$	AUC_{ROC-YS}	$Err_{\rm TS}$	$Err_{\rm STS}$	$Err_{\rm YS}$	Err_{S-TS}	Err_{S-STS}	Err_{S-YS}
1	350	61.622	67.355	58.788	5.539	5.398	6.934	99.876	99.877	99.893
350	350	70.589	80.319	66.596	19.420	14.359	23.709	59.872	50.340	59.146
450	200	70.838	78.166	67.179	20.441	17.338	25.915	57.040	49.179	54.261
20	110	65.946	68.895	62.498	8.844	8.228	10.758	89.829	89.218	89.598
290	110	71.384	76.938	67.086	25.166	22.675	30.199	47.783	41.123	47.231
350	110	71.339	78.143	67.412	27.462	25.075	32.946	44.185	34.771	42.952
20	80	62.563	63.998	59.420	5.710	5.734	7.178	99.592	99.654	99.666
290	80	71.065	76.800	67.083	29.017	26.652	34.336	42.577	35.555	41.885
170	20	69.699	73.134	65.759	43.201	42.165	49.338	26.716	22.829	26.256
1	1	70.694	70.984	66.917	11.902	11.774	14.503	80.507	80.683	80.207

Table 1: Results of the separation: signal tb vs. all background in 2-Tag 2-Jets. NcS – the number of signal components, NcB – the number of background components, Err_{S-*} – the error on the signal set, Err_* – the error on the whole set.



Figure 2: Comparison of the ROC curves for separating signal from background in the yield sample (with the AUC in the brackets).

3 Discussion

Working results show that MBC can serve as a good alternative method for the separation of signal from background in high energy physics applications. We generally doubled the signal to background ratio for all sub-tasks. In particular, using 290 signal and 110 background components of the distribution mixture, we obtained the best AUC value on the testing sample of 71.384, thereby we improved the signal tb to background ratio in 2-Tag 2-Jets from 1:18 to 1:8 with the *a posteriori* probability threshold $P_t(\text{signal} | \mathbf{x}) = 0.5$ in (7). The MBC method has better results for samples where signal and background correspond to different distributions. Unfortunately, in single top channels the patterns of signal and background are nearly the same. In addition, the implementation of cuts during the preparation of samples removes events from the margins and change the distributions. In order to improve the quality of separation, we will implement the transformation of input variables via combination of ϕ -divergences (see [9]) with particle component analysis and further, more runs of the algorithm with different initial settings have to be performed to find the optimal number of components in each channel.

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Unfolding in particle physics: a window on solving inverse problems

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A pedagogical exposition of unfolding techniques in particle physics is presented. Building on example analyses about top quark physics, the origin, the main building blocks and the crucial challenges of inverse, ill-posed problems in particle physics are discussed.

1 Unfolding foundations

In particle physics unfolding is the ensemble of statistical techniques used to solve what is defined as the *inverse problem*: infer an unknown distribution f(y) for a variable y from the measured distribution g(s) by using knowledge and/or assumptions on the probability distribution that links the observation to the "true" value.

The mathematical foundations of unfolding are intimately related to the description of the inverse problem provided by the Fredholm integral equation of the first type $g(\mathbf{s}) = \int_{\Omega} K(\mathbf{s}, \mathbf{y}) f(\mathbf{y}) d\mathbf{y}$, where the true $f(\mathbf{y})$ distribution of the variable $\mathbf{y} = (y_1, ..., y_J)$ is related to the measured or observed distribution $g(\mathbf{s})$ of the *L*-dimensional variable $\mathbf{s} = (s_1, ..., s_L)$ by the convolution with the *kernel* function $K(\mathbf{s}, \mathbf{y})$ over the subspace Ω of the *J*-dimensional space where \mathbf{y} is defined. An illustrative example, shown in the cartoon of Figure 1, is the inversion of the measuring process for the invariant mass of the pair of top-antitop quarks $(t\bar{t}, m_{t\bar{t}})$ produced in proton-proton (pp) collisions at a center-of-mass energy (\sqrt{s}) of 7 TeV at the Large Hadron Collider (LHC) and reconstructed by the ATLAS detector.

In the very common one-dimensional case, the measured and the true distributions are approximated by histograms representing the values ν_i or μ_i , the expected number of counts in a given interval of real variables s or y respectively, according to the definitions $\nu_i = \int_{s_{i-1}}^{s_i} g(s) ds$ and $\mu_j = \int_{y_{j-1}}^{y_j} f(y) dy$, where the intervals of definition for s and y are divided in N and M sub-intervals respectively by a set of (s_1, \dots, s_N) and (y_1, \dots, y_M) values. The integral kernel K(s, y) form is approximated by a response matrix R(i, j) representing the probability that an event with a value of the y variable in bin j is observed as an event with a value of the s variable in bin i. The extended discretized one-dimensional form of the Fredholm equation is then written [5] as $E[n_i] = \nu_i = \sum_{j=1}^M R_{i,j}\mu_j + \beta_i$, whose vectorial compact form is $E[\mathbf{n}] = \mathbf{v} = R\mathbf{\mu} + \mathbf{\beta}$, where the response matrix R(i, j) also includes the estimate of the reconstruction efficiency and $\mathbf{\beta}$ is the vector of the number of expected background events ¹.

¹Events that pass the selection requirements, but have different origin from the ones of interest.



UNFOLDING IN PARTICLE PHYSICS: A WINDOW ON SOLVING INVERSE PROBLEMS

Figure 1: Scheme of evolution of the measurement of $m_{t\bar{t}}$. The predicted $m_{t\bar{t}}$ distribution [1] (left) for $t\bar{t}$ events produced in $\sqrt{s} = 7$ TeV pp collisions at the LHC is reconstructed [2] (right) after the top quark decay products are measured by the ATLAS detector [3] (middle). A Feynman diagram [4] shows the final state partons from the $t\bar{t}$ decay at leading order.

2 The art of matrix inversion: max. likelihood solution

The formal solution to $\boldsymbol{\nu} = R\boldsymbol{\mu} + \boldsymbol{\beta}$ is written as $\boldsymbol{\mu}_{est} = R^{-1}(\boldsymbol{\nu} - \boldsymbol{\beta})$, where R^{-1} is the inverse of R. This estimate for $\boldsymbol{\mu}$ can also be derived from the principle of maximum likelihood (ML). If one assumes (fairly generally) that the data are independent Poisson observations in each histogram bin, the corresponding likelihood is $\mathcal{L} = \nu_i^{n_i} \frac{e^{-\nu_i}}{n_i!}$ where $\boldsymbol{\nu} = \boldsymbol{\nu}(\boldsymbol{\mu})$ according to the discretized unfolding equation and n_i is the observed number of events in bin *i*. Consequently the maximum likelihood estimator for $\boldsymbol{\nu}$ obtained by imposing $\partial \log \mathcal{L}(\mu_i) / \partial \mu_i = 0 \forall i$ is given by $\boldsymbol{\nu}_{ML} = \mathbf{n}$ and consequently the estimate of $\boldsymbol{\mu}$ is obtained as $\boldsymbol{\mu}_{ML} = R^{-1}(\boldsymbol{\nu}_{ML} - \boldsymbol{\beta}) = R^{-1}(\mathbf{n} - \boldsymbol{\beta}) = \boldsymbol{\mu}_{est}$.

Is this solution always working? An example shown in Ref. [5] reports a double-peaked true distribution for which the resulting ML estimate shows a multi-peaked shape with extremely large variances and very large anti-correlation between neighbouring bins: the estimate turns out to be very different from the known input. The response matrix R for this example is known to have sizable non-diagonal elements and the bin size of the histogram to be "inverted" is smaller than the detector resolution encoded in the model for event migrations. Figure 2 shows the generated "true" histogram μ and the unfolded estimator μ_{est} . What is happening? The application of R^{-1} aims at restoring the original histogram. If the migrations are properly modelled, the inversion returns the correct values if the input data are the expectation vector $\boldsymbol{\nu}$ of the reconstructed bin contents. However the matrix inversion is applied to one instance vector of the data, n, it is not applied to its expectation value ν . As a consequence, in a suggestively descriptive way, R "assumes" that the fluctuations in \mathbf{n} are the residual of a real original structure diluted by the detection effects (and not of statistical origin) and uses the given input and the available model for migrations to reconstruct μ , i.e. it magnifies the fluctuations back into the result. Independently of the large fluctuations induced by the application of the matrix inversion the ML solution provides the unbiased estimator with the smallest variance [5].



Figure 2: Examples of "true" distribution (left) (μ), the resulting estimate for μ_{est} using the ML solution for a given assumption on resolution and efficiency (right, see text) [5]. The vectors μ , ν , **n** and μ_{est} are defined in the text.

3 From inside ill-posed problems to regularization

A detailed two-steps analysis of the discretized unfolding equation is outlined in Section 1.5 of Ref [6] and illustrates the link between fluctuations and instability of the ML solution by exposing the origin of instability in a quantitative manner. A synthetic description is reported here. The likelihood representing the unfolding problem takes the form $\mathcal{L} \propto e^{-\frac{1}{2}\chi^2(\boldsymbol{\mu},\mathbf{d})}$ and the ML solution coincides with a least squares estimate [6]. As a first step a transformation of variables that diagonalizes the generally non-diagonal $\chi^2(\boldsymbol{\mu}, \mathbf{d})$ in the form $\frac{1}{2}\chi^2(\boldsymbol{\mu}, \mathbf{d}) =$ $(R'\boldsymbol{\mu} - \mathbf{d}')^T(R'\boldsymbol{\mu} - \mathbf{d}')$ provides a new vector \mathbf{d}' and a new R' matrix that are written in terms of significances i.e. variables normalized to their uncertainties [6]. In the second step the resulting ML solution is written in terms of significances and parameters that are sensitive to fluctuations by using a singular value decomposition (SVD) of the R' matrix as follows: $\boldsymbol{\mu}_{est} = \sum_{i=1}^{\min(N,M)} \frac{1}{\sigma_i} (\mathbf{u}_i^T \mathbf{d}') \mathbf{v}_i, \text{ where } U = (\mathbf{u}_1,..,\mathbf{u}_N) \text{ and } V = (\mathbf{v}_1,..,\mathbf{v}_M) \text{ are unitary matrices}$ written in terms of their column vectors and $\Sigma = U^T R' V$ is a diagonal matrix of (generally) dimensions $M \times N$ such that $\Sigma_{i,j} = \sigma_i$ for i = j, otherwise $\Sigma_{i,j} = 0$. The diagonal σ_i values are called singular values of the matrix R', they are not negative and can always be arranged in non-increasing order. The sensitivity to fluctuations associated with the ML solution can be quantified by the maximum ratio of the relative precision of the estimated solution μ_{est} to the relative precision of the measured input vector $\mathbf{d} = \mathbf{n} - \boldsymbol{\beta}$, defined as $c = \max_{\mathbf{d}, \delta \mathbf{d}} \left(\frac{\delta \boldsymbol{\mu}_{est} / \boldsymbol{\mu}_{est}}{\delta \mathbf{d} / \mathbf{d}} \right)$ A large value for c implies instability due to small fluctuations in the input i.e. sensitivity to "noise" in the measurement. The quantity c = c(R) is called the *condition* of the R matrix associated to the unfolding. It can be shown that $c(R) = \sigma_{max}/\sigma_{min}$ [6], so the condition of the matrix R can be read off from its SVD. Once the problem is described in terms of uncertainty normalized variables, the large sensitivity of the ML estimator to small, high-frequency-like fluctuations can be detected in the high condition number c(R). In order to pose the problem more properly, it is then necessary to reduce the impact of the low significance, highly oscillating input components while preserving the information available in the remaining high significance, more stable components. The problem is then said to have been "regularized". As the ML estimator is unbiased, regularization inevitably leads to accepting a certain level of bias in exchange for a reduced variance. The bias is defined as the difference between the expected

value of the unfolded result and the true unmeasured expected value. It should be noted that, despite its large variances, the ML solution is fit for use in testing a model against a measurement, as long as the full corresponding covariance matrix is used.

The likelihood formulation of the unfolding problem quantifies the distance between the data vector **n** and the expectation vector $\boldsymbol{\nu}$. In order to filter out a certain amount of the high frequency components of the input and alleviate the sensitivity to large fluctuations (i.e." regularize" the solution), constraints on the initial likelihood can be imposed by adding Lagrange multipliers and describing the regularization as a maximization procedure for a new log-likelihood ϕ written as $\phi = \log \mathcal{L}(\boldsymbol{\mu}) + \tau S(\boldsymbol{\mu})$, where $\mathcal{L}(\boldsymbol{\mu})$ is the initial likelihood, $S(\boldsymbol{\mu})$ is called regularization function, τ is the regularization parameter to tune the strength of the constraints. In this explicit formalism the ingredients for the regularization of a given likelihood $\mathcal{L}(\boldsymbol{\mu})$ are the regularization function $S(\boldsymbol{\mu})$ and a prescription for τ .

A large number of different regularization schemes is available [6]. Examples of schemes used in particle physics include:

- Tikhonov schemes whose constraining function is the mean square of the k^{th} derivative of f(y): $S[f(y)] = \int (\frac{d^k f(y)}{dy^k})^2 dy$. In most applications k = 2 is chosen, setting a constraint on the curvature of the one dimensional distribution being unfolded.
- Iterative schemes using steps where an improved estimate at step n for the distribution to be unfolded is obtained by convolving the estimate at step n 1 with an updating function that depends on the response matrix, the observed distribution and the estimate (n 1) itself.
- Maximum-entropy schemes whose constraining function is the expected amount of information gained in passing from the the initial ansatz to the best estimate i.e. $S(\boldsymbol{\mu}) = H(\boldsymbol{\mu}) = \sum_{i}^{M} \mu_{i} \log \frac{\mu_{i}}{\epsilon_{i}}$, where $\boldsymbol{\mu}$ is the estimator vector for the unknown probability distribution, the index *i* goes from 1 to M, the number of bins of the distribution, and $\boldsymbol{\epsilon}$ is the best initial knowledge about the true, unknown distribution, assumed to be non-negative.
- Non-iterative Bayes-inspired schemes where the full unfolded spectrum is considered a variable to be obtained by a convolution integral of the probability for the migration model and the observed spectrum.
- Iterative unbinned schemes, using event-by-event weights based on the ratio of expected to observed local densities to derive a new estimate of the distribution to be unfolded at each step. A test function based on a Tikhonov-like distance or with the same analytic form as an electric potential (of the new estimate with respect to the old one) is used to quantify the agreement between the estimate at step n and the one at step n-1.

All these schemes provide estimators that result in a reduced statistical variance with respect to the ML solution and inherently add a certain level of bias to the unfolded distribution. The heart of unfolding problems lies in achieving a balance between bias and overall uncertainty.

4 Applied unfolding: the balance of bias and uncertainty

The unprecedentedly large production of top quarks at the LHC allows to use (and explore) unfolding schemes to measure cross sections differentially or to extract parameters from unfolded distributions. These two general classes of analyses provide interesting unfolding examples.

jets channel. The Tikhonov unfold-

ing scheme with k = 2 is tested by

reweighting simulated $t\bar{t}$ events to en-

hance the number of events in a sin-

gle bin (see the cartoon in Figure 4).



Figure 3: Distribution of reconstructed $m_{t\bar{t}}$ with data compared to predictions (left) and associated migration matrix (right) in the electron plus jets channel. Details of figures are reported in Ref. [7].

The response to this "delta-like" pulse is reduced i.e. biased at least by 30% even for the mildest regularized solution, while it maintains a linearity within 1% for the ML unregularized solution. The increase in statistical uncertainty in the final ML-unfolded result (reported in Figure 4) is tolerable as the systematic component is still dominant and under control with respect to the regularized biased result.

In the second class of analyses, a regularized scheme is used to measure the distribution of the difference between the absolute rapidities $(\Delta|y_t|)$ of the reconstructed top quark and antitop quark in a sample enhanced in $t\bar{t}$ events obtained by LHC pp collisions at $\sqrt{s} = 7$ TeV [2]. A Bayesianinspired iterative technique is used to unfold the distribution of $\Delta|y_t|$, shown in Figure 5 together with the corresponding migration matrix for selected events in the muon plus jets channel.



Figure 4: Scheme of "stress" test described in the text (left) and final $1/\sigma_{t\bar{t}} \,\mathrm{d}\sigma_{t\bar{t}}/\mathrm{d}m_{t\bar{t}}$ from Ref. [7] (right).



Figure 5: Distribution of reconstructed $\Delta |y_t|$ with data compared to predictions (left) and associated migration matrix (right) in the muon plus jets channel. Details of figures are reported in Ref. [2]. 260

The number of iterations is tuned to get the expected variation of the value for the asymmetry to be stable within 0.1%in simulated $t\bar{t}$ events. Simulated $t\bar{t}$ events are re-weighted to produce samples with different true asymmetry. The analysis is performed on each sample and the input asymmetries are plotted versus the resulting measured asymmetries after unfolding to check the linearity of the unfolding procedure (as illustrated in the cartoon of Figure 6). The small biases observed in the recon-

structed distributions and the extracted asymmetry are quantified by the largest relative deviation over all the bins and the mean uncertainty-normalized relative difference between true and unfolded values from the pull distributions, respectively. Such values are used to assign additional systematic uncertainties to the unfolded distributions (for which an example is shown in Figure 6) and the final asymmetry.



Figure 6: Scheme of the linearity test described in the text (left) and final unfolded distribution of $\Delta |y_t|$ in the muon plus jets channel from Ref. [2] (right).

5 Optimization and good practices

The ideal (infinite-simulation, infinite-manpower, infinite -time) general procedure for unfolding optimization can be generally described as the variation of the parameters of the unfolding scheme and the binning to scan the values of the figures of merit on which the performance is judged. Ideally one should do this for more than one unfolding scheme, then the method that is expected to perform best should be chosen. All the studies should be performed on simulated events. One can either scan a multi-parameter space i.e. have a function that accommodates requirements in one or more regions of phase space or summarize the requirement for the unfolding in one figure of merit that is a function of the parameters describing the different phase space regions. The figures of merit vary depending on the goal to be achieved and they are functions of bias, statistical and systematic uncertainties of the measurements and additional assessment criteria determined by the analyzers.

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Leptons: e, μ , τ + systematic uncertainties

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An overview of the charged lepton performance in the ATLAS and CMS experiments at the LHC and in the CDF and D0 experiments at the Tevatron is given, in the specific context of physics analyses requiring the selection of leptons from top-quark decays. The trigger and reconstruction algorithms are presented, as well as the identification and isolation criteria, pointing out the specificities of top-quark analysis selections. The impact of the lepton-related experimental systematic uncertainties are discussed.

1 Introduction

The top quark decays mostly into a W boson and a b quark, and in roughly one third of the cases, the W decays into a neutrino and a charged lepton. Hence, the reconstruction of electrons, muons and taus plays a key role in the ability of the top-quark factories to select collision data samples enriched in top-quark events. The four general purpose hadron collider experiments - CDF [1] and D0 [2] at the Tevatron, ATLAS [3] and CMS [4] at the LHC - have developed similar strategies to select these prompt leptons produced in top-quark decays.

For prompt electron or muon triggering, reconstruction and identification, the experiments take advantage of the structure of the detectors, which include a tracker, calorimeters and muon spectrometers. Unlike leptonic taus - which are not distinguished from prompt electrons and muons in the reconstruction - the hadronic taus are also reconstructed, thanks to dedicated algorithms.

The experimental systematic uncertainties related to leptons arise mainly from the efficiency measurements which are necessary for modelling the detector acceptance, the lepton energy scale and resolution, and from the estimation of misidentified lepton background yields.

2 Trigger

The trigger systems of the four experiments share common features: they are divided in an hardware-based first level (L1) using coarse information, and in one or two software-based high level trigger (HLT) levels, which perform a finer reconstruction using the full granularity of the detectors. Top-quark analyses in the four experiments rely mainly on single-lepton trigger menus, with transverse energy (E_T) thresholds sufficient to cope with the high luminosity. Due to higher event rates, the thresholds are higher at the LHC, typically 24 GeV compared to

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18 GeV at the Tevatron, for unprescaled triggers. However, in some cases multi-object triggers such as di-lepton or lepton plus jets are used, in order to increase the sensitivity.

2.1 Electrons

Electron trigger menus are seeded by L1 energy deposits in electromagnetic calorimeters above certain energy thresholds. In order to keep sustainable rates, requirements on the energy deposits in hadronic calorimeters can be applied to reject hadronic backgrounds. Then, the HLT algorithms perform a full reconstruction and apply identification and isolation criteria similar to those used offline. Figure 1 show the trigger efficiency as a function of the offline reconstructed electron transverse energy in ATLAS and CMS. The typical plateau efficiency is 95% for the identification criteria used in top-quark related analyses.



Figure 1: Trigger efficiency for a single electron menu with a 24 GeV threshold in ATLAS [5] (left) and with a 33 GeV threshold in CMS [6] (right).

2.2 Muons

The muon L1 trigger is mostly based on the muon spectrometer system, using fast muon chambers dedicated to the trigger. The HLT performs a full reconstruction combining both the muon chambers and the inner tracker, applying several quality cuts. Figure 2 shows the trigger efficiency with respect to the reconstructed muon transverse momentum in ATLAS and CMS. The typical plateau efficiency values span from 93 % to 98%, depending on the required quality criteria.

2.3 Taus

The tau trigger menus rely on calorimeter deposits with isolation criteria at L1, refined with several additional criteria to reject jet backgrounds at HLT using either the isolation, the track multiplicity or the shower shapes, similarly to the offline identification procedures later described. At LHC, the tau trigger energy thresholds span between 20 and above 100 GeV at



Figure 2: Trigger efficiency for a single muon menu with a 24 GeV threshold in ATLAS [7] (left) and with a 40 GeV threshold in CMS [6] (right).

HLT for the 2012 run. Figure 3 shows the trigger efficiency versus the tau candidate transverse momentum, for a 20 GeV single tau trigger chain in ATLAS. Its plateau efficiency is of the order of 80 %. The advantage of using dedicated tau triggers in D0 is also illustrated in Figure 3, in which the efficiency curve for single-jet and single-tau menus is compared.



Figure 3: Trigger efficiency as a function of the transverse momentum for a single hadronic tau chain with a threshold of 20 GeV in ATLAS [8], measured on data using $Z \to \tau \tau$ events (left). Trigger efficiency as a function of the reconstructed tau transverse energy for a single hadronic tau L1 menu with a threshold of 15 GeV compared with a single jet L1 menu with a threshold of 20 GeV in D0 [9], measured on data using $Z \to \tau \tau$ events (right).

3 Reconstruction and identification

3.1 Electrons

Both the inner trackers and the electromagnetic calorimeters are used to perform offline electron reconstruction. Electron objects are reconstructed by the angular association of an electromagnetic calorimeter cluster and a charged track. The use of tracking algorithms which take into account the bremsstrahlung radiation energy losses allows to improve this association, and hence the reconstruction efficiency. Figure 4 shows the electron reconstruction efficiency in ATLAS as a function of the electron transverse energy, with (in 2012) and without (in 2011) using this improved tracking. The typical efficiency is about 98 % above 30 GeV, in both CMS (not shown) and ATLAS.

Identification criteria are further applied to reject experimental backgrounds, such as hadrons and converted photons. They make use of calorimeter shower shapes, energy leakage in the hadronic calorimeter, and track quality, and can be combined using multivariate techniques such as in CMS, or using E_{T} - and η -dependent rectangular cuts such as in ATLAS for topquark analyses. Categories are defined depending on the strictness of the criteria, with different efficiency and background rejection factors. Figure 4 shows the identification efficiency in CMS as a function of the electron transverse energy in the pseudo-rapidity range $0 < |\eta| < 0.8$, for a category optimised to give an efficiency greater than 85 % in this central region.



Figure 4: Electron reconstruction efficiency in ATLAS as a function of the transverse energy [10] (left) measured on 2011 and 2012 data. Electron identification efficiency as a function of the transverse momentum in CMS, for a typical identification category [11] (right).

In addition to the identification requirements described above, isolation cuts are applied in order to reject the non-prompt leptons from heavy flavour jets and to reduce the sensitivity to pile-up. For top-quark analyses, CMS uses particle-based relative isolation while ATLAS considers calorimeter and tracker absolute isolation, both in fixed-size cones.

3.2 Muons

Muons may be reconstructed with track fitting algorithms separately by muons chambers and from the inner tracker. Depending on the used sub-detectors, the reconstructed objects are divided in different categories. In most top-quark analyses, the selected muons are reconstructed by combining both systems. Additional requirements may be applied, such as track quality cuts in order to reject punch-through, criteria on angular or timing properties to remove cosmic muons in di-muon events, or on the quality of the trajectory fit to cope with hadron in-flight decays. Figure 5 shows the reconstruction efficiency for muons using both the tracker and the muon chambers as a function of the transverse momentum in ATLAS, and the identification criteria as a function of the pseudo-rapidity in CMS. The combined efficiency after application of such requirements is typically better than 95 %.



Figure 5: Muon reconstruction efficiency in ATLAS [12] (left) as a function of the transverse momentum, and muon identification efficiency as a function of the pseudo-rapidity in CMS [13] (right), for two typical object categories.

As for the electron case, isolation cuts are applied in order to improve the purity. The use of relative isolation with a decreasing cone size for increasing muon transverse momenta allows to cope with efficiency losses in boosted topologies in ATLAS.

3.3 Taus

The decay products of two thirds of the hadronically decaying taus consist predominantly of one or three charged pions, in addition to a neutrino and possibly neutral pions. The reconstruction and the identification of these hadronic taus rely on topological properties of calorimeter deposits. In ATLAS, jets with one or three associated tracks are selected, while CMS uses particle flow techniques to reconstruct the charged hadrons and the photons arising from the neutral pion decays. Both LHC experiments use isolation-based discriminants to remove jet and electron fakes. In addition, both the CDF and the D0 experiments have demonstrated their capability to explicitly reconstruct the neutral pion of the tau decays. Figure 6 shows the

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Figure 6: Number of reconstructed tau candidates for the three main decay modes in CMS [14], on 2010 data and for simulated events.

distribution of the reconstructed tau candidates on 2010 collision data in CMS with respect to their decay mode, compared to the predictions for $Z \rightarrow \tau \tau$ signal and for the backgrounds.

Finally, multivariate techniques are used to identify tau candidates. Figure 7 show the identification efficiency as a function of the transverse momentum in ATLAS and CMS, for three categories of multivariate criteria. The typical efficiency for the requirements used in top-quark analyses ranges from 40 to 50%.



Figure 7: Tau identification efficiency as a function of the transverse momentum in ATLAS [15] (left) and in CMS [14] (right), for three multivariate identification criteria.

4 Energy scale and resolution

Energy scale and resolution are estimated on data in a similar way for electrons, muons and taus. The techniques use "standard candles", such as the Z boson or the J/ψ and Υ meson resonances in the di-lepton invariant mass spectrum, or the distribution of the energy measured



Figure 8: Electron energy scale in ATLAS as a function of the average number of interactions per bunch crossing [10] (left). Electron energy resolution in CMS as a function of the energy [11] (right).

by the calorimeters divided by the momentum measured by the inner tracker of $W \to e\nu$ candidate events.

Figure 8 shows electron energy scale measurements in ATLAS and electron energy resolution measurements as a function of the transverse energy in CMS. Figure 9 shows the di-muon mass resolution in ATLAS as a function of the muon pseudorapidity and the muon transverse momentum resolution as a function of the pseudorapidity in CMS.

The typical uncertainty on the tau energy scale is 3 %, as shown for ATLAS on figure 10. Its effect on the reconstructed tau mass is shown for CMS, on the same figure. Similarly, the energy resolution in these experiments has an uncertainty of a few percent.

5 Impact of lepton systematics on top-quark studies

In the analyses, the impact of the uncertainties on trigger, reconstruction and identification efficiencies on the detector acceptance is most of the time estimated by applying event by event scale-factors on yield and shape predictions based on simulation. These scale-factors are calculated by comparing the efficiencies measured on collision data mainly with "tag-and-probe" techniques to the efficiencies measured with the same techniques on simulated data. Their total uncertainties are propagated to the variables used in each analysis. The impact of these effects is sub-dominant in the case of electrons and muons, especially for top-quark mass measurements where these uncertainties are below 1 %, both at Tevatron or at LHC experiments.



Figure 9: Di-muon mass resolution in ATLAS as a function of the pseudo-rapidity [12] (left). Muon transverse momentum resolution in CMS as a function of the pseudo-rapidity [16] (right).



Figure 10: Tau energy scale uncertainty measured on 2012 data and on simulation in ATLAS as a function of transverse momentum, for tau candidates with one track [17] (left). Reconstructed invariant mass of taus decaying into one charged and one neutral pion in CMS, measured on 2010 data and compared with simulation, with nominal or with 3 % shifted tau energy scale [14] (right).

The systematic uncertainty related to the energy scale is measured by varying the energy correction factors by their uncertainties. In a similar way, the uncertainty due to the energy resolution is assessed by varying the resolution by its uncertainty, when smearing the energy on simulation. The propagation of these two effects in top-quark analyses is at most of the order of 1 %.

Aside these detector modelling effects, the measurement of the contribution of reconstructed objects faking prompt leptons gives rise to normalisation and shape uncertainties. Electron and muon fake estimates are described elsewhere. The major source of fake taus are multi-jet and W+jets events. Figure 11 shows the tau fake rates in ATLAS, CMS and CDF as a function of the transverse energy. The typical fake rate value lies between 1 and 3 %, depending on the used identification requirements.



Figure 11: Tau fake efficiency measured on 2012 data in ATLAS as a function of the transverse momentum for a $t\bar{t} \rightarrow \tau + jets$ selection [15] (top left). Tau fake efficiency measured on 2010 data in CMS as a function of the transverse momentum for a $Z \rightarrow \tau \tau$ selection [14] (top right). Tau fake efficiency measured on simulation in CDF as a function of the transverse energy for jets passing a 50 GeV trigger requirement [18] (bottom).

6 Conclusions

The selection of top-quark events in the semi-leptonic decay modes - where all possible objects are present in the final state - is performed using all subsystems of the general-purpose detectors in the ATLAS, CDF, CMS and D0 experiments. For such events, the trigger relies mainly on single-lepton menus, but multi-object triggering strategies are used in some cases, and may be widely used in the 13 TeV run at the LHC in order to cope with higher rates. Using the full detector granularity allows to reconstruct prompt leptons with high efficiencies, and to reject backgrounds thanks to various identification criteria. The systematic uncertainties related to leptons in top-quark related analyses are rarely greater than a few percent, except when selecting hadronic taus where they can rise up to 8 %, especially in the case of cross-section measurements.

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Top charge asymmetry – theory status fall 2013

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I review the current status of the charge asymmetry in hadronic top-quark pair production from a theory perspective. The standard-model predictions for the observables at the Tevatron and LHC are being discussed, as well as possible explanations of the Tevatron excess in terms of new physics. I give an outlook for future investigations of the top-quark charge asymmetry, focussing on novel observables at the LHC.

1 Introduction

The charge asymmetry in top-antitop production provides us with a test of Quantum Chromodynamics (QCD) beyond leading-order (LO) interactions. It manifests itself in differing angular distributions of top and antitop quarks,

$$A_C = \frac{\sigma_A}{\sigma_S}, \qquad \sigma_{S,A} = \int_0^1 \mathrm{d}\cos\theta \left(\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}\cos\theta} \pm \frac{\mathrm{d}\sigma_{\bar{t}t}}{\mathrm{d}\cos\theta}\right),\tag{1}$$

where θ is the scattering angle of the top quark $(\sigma_{t\bar{t}})$ or antitop quark $(\sigma_{\bar{t}t})$ off of the incident quark in the parton center-of-mass frame. Experimentally, the charge asymmetry is measured in terms of top-antitop rapidity differences,

$$A_C^{\exp} = \frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)}.$$
(2)

In proton-antiproton collisions, the total charge asymmetry is closely related to a top-quark forward-backward asymmetry in the laboratory system, which is measured through the rapidity difference $\Delta y = y_t - y_{\bar{t}}$ (yielding $A_C^{\exp} = A_C^y = A_C$). In proton-proton collisions, the charge asymmetry induces a forward-central asymmetry, which is measured through the difference of absolute rapidities $\Delta y = |y_t| - |y_{\bar{t}}|$ (yielding $A_C^{\exp} = A_C^{|y|} \ll A_C$). The sensitivity of $A_C^{|y|}$ to the partonic charge asymmetry is reduced due to $|y_t| - |y_{\bar{t}}|$ not being invariant under boosts along the beam axis. At the LHC, $A_C^{|y|}$ is further suppressed by a large background from symmetric gluon-gluon initial states.

The results of asymmetry measurements at the Tevatron and LHC experiments are summarized in Figure 1 [1] and discussed in detail in the contribution of Viatcheslav Sharyy in these proceedings. Here it shall suffice to mention the observation of an excess in A_C^y at the Tevatron, while measurements of $A_C^{[y]}$ at the LHC are consistent with their standard-model (SM) prediction (and with zero) within uncertainties.

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Figure 1: Charge asymmetry measurements at the Tevatron (left panel) and the LHC (right panel). Shown are the inclusive $t\bar{t}$ asymmetries A_C^y and $A_C^{|y|}$ in lepton+jets and dilepton final states, as well as the lepton asymmetries A_C^{ℓ} ($q\eta$, Tevatron) and $A_C^{\ell\ell}$ ($d\eta$), defined in Eqs. 8 and 9. SM predictions including scale uncertainties are displayed in gray.

This article covers the current theoretical status of the SM prediction for the charge asymmetry (Section 2), as well as potential contributions of new physics (Section 3). I discuss the limitations to observe $A_C^{[y]}$ at the LHC and suggest new observables involving an additional hard jet as an alternative way of measuring the charge asymmetry in proton-proton collisions (Section 4). I conclude in Section 5 with an outlook and comments on related observables that allow a more complete picture of the charge asymmetry.

2 Charge asymmetry in the standard model

In QCD, the charge asymmetry is generated at next-to-leading order (NLO) by additional virtual and real gluon radiation [2], as illustrated in Figure 2. Normalized to the symmetric cross section, the perturbative expansion of the charge asymmetry reads

$$A_C^{\text{QCD}} = \frac{\alpha_s^3 \,\sigma_A^{(1)} + \alpha_s^4 \,\sigma_A^{(2)} + \dots}{\alpha_s^2 \,\sigma_S^{(0)} + \alpha_s^3 \,\sigma_S^{(1)} + \alpha_s^4 \,\sigma_S^{(2)} + \dots} \,. \tag{3}$$

Currently, the charge-asymmetric piece is known at NLO QCD $(\sigma_A^{(1)})$, whereas the symmetric cross section has recently been calculated up to NNLO $(\sigma_S^{(2)})$ [3]. The strong remnant dependence on the factorization and renormalization scales has been significantly reduced by the resummation of large logarithms close to the partonic threshold [4, 5, 6]. The leading contribution to A_C^{QCD} is dominated by the lowest-order expansion of the threshold-resummed cross section, and the asymmetry proves stable under higher-order threshold corrections. The



Figure 2: Charge asymmetry in QCD from quark-antiquark annihilation (left) and quark excitation (right). Shown are representative diagrams for inclusive $t\bar{t}$ production (dashed and dotted cuts, qg contribution negligible) and $t\bar{t} + j$ production (dotted cuts).

numerical impact of fixed-order NNLO contributions $(\sigma_A^{(2)})$ on the asymmetry is not known to date, but is an important ingredient for a precise prediction of A_C^{QCD} .

Electroweak (EW) contributions to the charge asymmetry turn out to be significant. Fixedorder EW corrections increase the Tevatron asymmetry A_C^y by about 23% [7]. Their effect on the LHC asymmetry $A_C^{[y]}$ is smaller due to the different parton distributions in the initial state. The resummation of EW Sudakov logarithms yields an additional enhancement of 5% (apart from a minor double-counting with fixed-order corrections) [8].¹ Including the leading QCD and EW fixed-order contributions, the SM predictions for the asymmetries at the Tevatron and the LHC are given by [9]

$$A_C^y(1.96 \,\text{TeV}) = 8.75 \,{}^{+0.58}_{-0.48} \,\%, \qquad \qquad A_C^{|y|}(7 \,\text{TeV}) = 1.23 \pm 0.05 \,\%, \tag{4}$$

where the errors are scale uncertainties. Notice that A_C decreases if higher-order QCD corrections to σ_S are included. This approach presumably underestimates the charge asymmetry, due to an incomplete cancellation of higher-order effects affecting both σ_S and σ_A .

Since the results of charge asymmetry measurements are compared to predictions from Monte Carlo event generators, a precise understanding of their features is crucial for a correct interpretation. State-of-the-art Monte Carlo generators such as SHERPA and HERWIG++ with NLO matching to parton showers reproduce the qualitative features of the charge asymmetry in QCD: a decline with increasing $t\bar{t}$ transverse momentum $p_T^{t\bar{t}}$, as well as an increase with $M_{t\bar{t}}$ and Δy [10, 11]. However, the substantial dependence of Monte Carlo predictions on the functional scale in the hard process indicates that the observed excess of the asymmetry at high $M_{t\bar{t}}$ and Δy may be due to higher-order QCD and EW corrections not taken into account by Monte Carlo generators.

3 Potential contributions from new physics

Beyond the SM, a charge asymmetry can be generated at tree level by the interference of a new $q\bar{q} \rightarrow t\bar{t}$ process with the QCD amplitude, as illustrated in Figure 3. Light new particles can generate an asymmetry as well through self-interference if their quantum numbers prohibit an interference with the SM amplitude. Possible contributions can be classified into three kinematic categories: a massive color octet with axial-vector couplings to quarks in the s-channel, a vector boson with flavor-changing couplings in the t-channel, or a new scalar in the u-channel. Such

¹Notice that EW Sudakov logarithms significantly reduce the invariant mass spectrum in $t\bar{t}$ production, $d\sigma_{t\bar{t}}/dM_{t\bar{t}}$, which affects constraints on potential new-physics contributions to A_C .

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Figure 3: New-physics contributions to the charge asymmetry at tree level.

new particles and their embedding into specific models have been studied in great detail and found to be strongly constrained by correlated effects on charge-symmetric observables. In particular, the asymmetry excess at the Tevatron has stimulated a large effort to test possible new contributions at the LHC, with beneficial effects on general new-physics searches.

Among color octets with axial-vector couplings to quarks, dubbed "axigluons", two species yield a positive contribution to A_C : light axigluons $(M_G \leq 2m_t)$ with flavor-universal couplings, $g_A^q \cdot g_A^t > 0$ [12], or heavy axigluons $(M_G \gtrsim 2m_t)$ with opposite-sign couplings, $g_A^q \cdot g_A^t < 0$. Axigluons are predicted by a variety of models, such as chiral color featuring an extended strong gauge group [13] or as Kaluza-Klein excitations in the framework of extra dimensions [14]. Apart from model-inherent constraints, axigluons are mostly constrained by the invariant mass spectra of $t\bar{t}$ and dijet production, by the LHC asymmetry $A_C^{[y]}$, as well as electroweak precision observables [15, 16]. Light axigluons are thus required to be broad in order to hide in the $t\bar{t}$ and dijet distributions measured at Tevatron and LHC. They can still account for the Tevatron excess in a mass window 200 GeV $< M_G < 450$ GeV, which may be closed by examining the tail of angular distributions in dijet production at the LHC. Heavy axigluons are highly challenged by a recent model-independent measurement by the CMS collaboration, which confines new-physics effects in the high-energy tail of the cross section, $\sigma_{t\bar{t}}(M_{t\bar{t}} > 1 \text{ TeV})$, to less than 20% [17].

Contributions of scalars in the u-channel are a priori phenomenologically disfavored, since they lead to a strong Rutherford enhancement of the $t\bar{t}$ invariant mass spectrum. They are excluded by measurements of atomic parity violation [18].

Further asymmetry candidates are new vector bosons with masses around 300 GeV and flavor-changing neutral couplings in the t-channel, often referred to as Z' bosons [19]. Strong constraints from flavor observables require a highly non-trivial flavor structure of their couplings, confined to right-handed up and top quarks. Such structures can be arranged for by means of flavor symmetries [20], which also protect the new bosons from inducing undesired same-sign top production. Additional strong constraints on Z' candidates arise, as for the u-channel contributions, from the $t\bar{t}$ and dijet invariant mass distributions and from atomic parity violation. At the LHC, a kinematic angular asymmetry in associated Z't production reconciles t-channel bosons with the measured charge asymmetry $A_C^{[y]}$ [21]. Searches for the corresponding Z't resonances with $Z' \rightarrow \bar{t}u$, however, rule out an explanation of the Tevatron excess unless alternative Z' decay channels dominate [22]. Since many of these constraints are model-dependent, t-channel explanations of the asymmetry are not conclusively ruled out yet. However, the search for Z' bosons in top-like final states at the LHC has a high exclusion potential. Along the lines described in [23] for a W' model, t-channel explanations of the Tevatron excess may be completely ruled out by scanning existing LHC event samples from top-quark analyses for Z' effects.

4 Charge asymmetry observables at the LHC

Due to the smallness of $A_C^{|y|}$, achieving a high significance for a measurement of the charge asymmetry in inclusive $t\bar{t}$ production at the LHC is difficult. With more luminosity during the 14 TeV run, the ultimate sensitivity to the asymmetry will be limited by systematic uncertainties. A dedicated study [24] shows that a significance of 95% may eventually be achieved, if at least 50% of the systematic errors scale with the luminosity. Given these limitations, it is advisable and maybe indispensable to consider alternative strategies to measure the top charge asymmetry at the LHC.

An interesting route to be pursued is top-antitop production in association with a hard jet in the final state. In this process, the charge asymmetry is generated already at tree level by real gluon exchange (see Figure 2). As a first approach, the charge asymmetry can be defined analogously to $A_C^{[y]}$ in inclusive $t\bar{t}$ production. In QCD, this observable has been calculated up to NLO [25, 26]. The resulting asymmetry at the LHC at 7 TeV is extremely small, $A_C^{[y]} = 0.51 \pm 0.09 \%$ [27]. An observation of $A_C^{[y]}$ in $t\bar{t} + j$ production at the LHC thus seems to struggle with even greater difficulties than inclusive $t\bar{t}$ production, with additional experimental challenges due to the extra jet.

However, the definition of the charge asymmetry can be improved by taking the jet kinematics into account [28]. Two observables of a charge asymmetry turn out to be complementary in final-state kinematics and in their sensitivity to initial parton states: The *incline asymmetry* probes the charge asymmetry from quark-antiquark annihilation, whereas the *energy asymmetry* is sensitive to the asymmetry from quark excitation.

The incline asymmetry is defined in terms of the inclination angle φ between the planes spanned by the initial- and final-state quarks and the jet, as illustrated in Figure 4. The differential incline asymmetry

$$\frac{\mathrm{d}\sigma_A^{\varphi}}{\mathrm{d}\theta_j} = \frac{\mathrm{d}\sigma(\cos\varphi > 0)}{\mathrm{d}\theta_j} - \frac{\mathrm{d}\sigma(\cos\varphi < 0)}{\mathrm{d}\theta_j} \quad (5)$$

is largely independent of the jet scattering angle θ_j and therefore maximally sensitive to the top and antitop quarks' angular distributions. To make the incline asymmetry a viable observable for proton-proton collisions, the direction of the incoming quark needs to be determined by focussing on boosted events with large rapidities $y_{t\bar{t}j}$ of the $t\bar{t} + j$ final state. The resulting incline asymmetry for the LHC then reads



Figure 4: Kinematics for the charge asymmetry in $t\bar{t}+j$ production. Definition of the inclination angle φ between the planes (q, \bar{q}, j) and (t, \bar{t}, j) .

$$A_C^{\varphi} = \frac{\sigma_A^{\varphi}(y_{t\bar{t}j} > 0) - \sigma_A^{\varphi}(y_{t\bar{t}j} < 0)}{\sigma_S} \,. \tag{6}$$

With appropriate kinematic cuts, the incline asymmetry reaches up to $A_C^{\varphi} = -4\%$ at the LHC with 14 TeV collision energy.

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The energy asymmetry is defined through the difference $\Delta E = E_t - E_{\bar{t}}$ of top and antitop energies in the parton center-of-mass frame,

$$A_C^E = \frac{\sigma(\Delta E > 0) - \sigma(\Delta E < 0)}{\sigma(\Delta E > 0) + \sigma(\Delta E < 0)}.$$
(7)

It probes the charge asymmetry in the partonic quark-gluon channel and is equivalent to the forward-backward asymmetry of the quark-jet in the top-antitop rest frame. The energy asymmetry is well adapted to the LHC environment. It benefits from the high quark-gluon parton luminosity in proton-proton collisions and can be measured without reconstructing the direction of the incident quark. At the 14 TeV LHC, the energy asymmetry reaches values of up to $A_C^E = -12\%$ in suitable regions of phase space. This new observable thus holds the potential of first observing the top-quark charge asymmetry at the LHC in $t\bar{t} + j$ production. As a caveat, one needs to add that the predictions for A_C^{φ} and A_C^E quoted here might be significantly changed by NLO corrections. Investigations of these contributions are underway [29].

Another alternative measurement of the top asymmetry at the LHC has been suggested for the LHCb experiment [30]. The good coverage of the forward region by the LHCb detector may allow to measure top-antitop rapidity differences in the region of large rapidities, where the charge asymmetry is maximal.

5 Outlook and related observables

The origin of the asymmetry excess at the Tevatron remains a puzzle. While the measurement of a charge asymmetry at the LHC is valuable on its own, the comparison with the Tevatron asymmetry will always be limited due to the different experimental conditions. To shed light on the Tevatron anomaly and to gain further insight into various models in connection with the charge asymmetry, several related observables have been proposed and in some cases been measured.

The charge asymmetry in $t\bar{t}$ production can be measured via the angular distributions of leptons from the top decays without reconstructing the top quarks [31, 32]. Two observables have been probed by experiments, the single-lepton asymmetry

$$A_C^{\ell} = \frac{\sigma(q \cdot \eta_{\ell} > 0) - \sigma(q \cdot \eta_{\ell} < 0)}{\sigma(q \cdot \eta_{\ell} > 0) + \sigma(q \cdot \eta_{\ell} < 0)},$$
(8)

where q and η_{ℓ} are the lepton's charge and pseudo-rapidity, and the dilepton asymmetry

$$A_C^{\ell\ell} = \frac{\sigma(\Delta\eta > 0) - \sigma(\Delta\eta < 0)}{\sigma(\Delta\eta > 0) + \sigma(\Delta\eta < 0)},\tag{9}$$

in terms of the rapidity difference $\Delta \eta = \eta_{\ell^+} - \eta_{\ell^-}$ between leptons from the top and antitop decays. The experimental results for these asymmetries are shown in Figure 1. The relation between the lepton asymmetry and the top-antitop asymmetry is model-dependent. Lepton asymmetries thus prove particularly useful in distinguishing between models with chiral top-quark couplings [33].

Another proposal considers a measurement of the forward-backward asymmetry of bottom quarks at the Tevatron [34]. Above the Z pole, the observable asymmetry is dominated by QCD contributions. Beyond the SM, the bottom charge asymmetry allows to probe the flavor structure of new-physics contributions to the top asymmetry.

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Measurement of jet multiplicity distributions in semi-leptonic top quark pair events

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The normalized differential cross section of $t\bar{t}$ events in the semileptonic decay channel in jet multiplicity bins is presented, measured in proton-proton collisions using $5.0 \,\mathrm{fb}^{-1}$ of data collected at $\sqrt{s} = 7 \,\mathrm{TeV}$. Additionally, the normalized differential cross section of top quark pair production in bins of the number of radiated additional hard partons is measured. These measurements are sensitive to additional radiation at the top quark scale. Comparisons of data with predictions from different Monte Carlo generators or using different scale values for the predictions are provided. Good agreement is observed between data and the prediction from MADGRAPH + PYTHIA.

The inclusive $t\bar{t}$ production cross section at a center of mass energy of 7 TeV has been measured by the ATLAS [1, 2] and CMS [3, 4] collaborations. The large amount of data recorded by the CMS detector [5] in 2011 enables an exclusive measurement of the jet multiplicity in $t\bar{t}$ production. Providing a test of perturbative QCD on the energy scale of top quark production is an important feature of this measurement. Furthermore, top quark pair production events including additional jets are an important background for many Higgs analyses and Beyond the Standard Model searches. Anomalous production of additional jets in $t\bar{t}$ events could be a sign of physics Beyond the Standard Model [6].

Two separate measurements of normalized differential cross sections accounting for the number of jets in top quark pair production events are presented [7]. The determination of the differential $t\bar{t}$ cross section as a function of the jet multiplicity has been performed in the semileptonic electron + jets and muon + jets channels. The measurement of the differential cross section with respect to the number of jets produced in addition to the top quark pairs is shown for the semileptonic muon + jets channel.

Top pair production events feature a top quark and a top anti-quark which, according to the Standard Model (SM), decay into a bottom quark and a W boson at almost 100%. The produced W bosons can either decay leptonically into a charged lepton and a neutrino or hadronically into two light quarks. The semileptonic decay channel of the top quark pair features one leptonically decaying W boson and one hadronically decaying W boson. The corresponding signature contains an energetic charged lepton, missing transverse energy associated with a neutrino, and at least four jets, two originating from b quarks.

The full 2011 CMS data sample has been analyzed, corresponding to an integrated luminosity of 5.0 fb⁻¹. The triggers used for this analysis demand a single electron ($p_T > 25 \text{ GeV}$) and three jets ($p_T > 30 \text{ GeV}$) in the electron + jets channel and a single isolated muon ($p_T > 24 \text{ GeV}$) in the muon + jets channel. The signal process and smaller background processes rely on the prediction by MC simulation while the main backgrounds are estimated using data-driven methods. The $t\bar{t}$ signal events, the W + jets, and the Z + jets background events have been generated with the MADGRAPH v5.1.1 matrix element generator [8] interfaced to PYTHIA 6.424 for parton showering [9]. For the simulation of the single top background events a combination of POWHEG v1.0 and PYTHIA has been used [10]. The diboson background events have been generated with PYTHIA. All generated samples are passed to a full detector simulation using GEANT4 [11] which incorporates the generation of pileup events with a multiplicity matching the one observed in data.

The recorded and simulated events are reconstructed using the particle flow (PF) algorithm [12]. It identifies and reconstructs muons, electrons, photons, charged hadrons, and neutral hadrons produced by the proton-proton collisions including the requirement for charged particles to originate from the primary collision vertex. The reconstructed objects are clustered into jets by applying the anti- k_T algorithm with a distance parameter of 0.5 [13, 14]. Jet energy corrections are applied in order to maintain a relative uniform response of the calorimeter and a calibrated absolute response. The event selection applied matches the signature of the semileptonic decay channel demanding one isolated lepton (electron/muon) with $p_T > 30$ GeV and $|\eta| < 2.5/2.1$. Further at least three reconstructed jets with $p_T > 35$ GeV and $|\eta| < 2.4$ are required for the jet multiplicity measurement while the differential cross section measurement with respect to the number of additional jets requires at least four reconstructed jets with $p_T > 30$ GeV and $|\eta| < 2.4$. Two or more of the selected jets have to be tagged as originating from a bottom quark by the Combined Secondary Vertex (CSV) tagger, which combines reconstructed secondary vertices and track-based lifetime information, at a medium working point (1% misidentification rate) [15].

The prediction for QCD multijet events is extracted from data based on the fact that QCD objects reconstructed as leptons are less isolated. Applying a modified event selection with an inverted lepton isolation cut provides a pure sample of QCD multijet events. The proper normalization of this sample is acquired by performing a maximum likelihood fit in a sideband region where fewer than two b jets are identified. The normalization factor resulting from the fit is used to scale the QCD multijet sample extracted from data with at least two b tagged jets.

The normalization of the W + jets background is modified using information from data. First its normalization is estimated making use of the charge asymmetry of this process at the LHC [16]. The valence quark composition of the colliding protons featuring two up quarks and one down quark favors the production of positively charged W bosons. The contributions of other processes to the charge asymmetry are negligible, therefore the difference in the number of events with positively charged leptons (N^+) and negatively charged leptons (N^-) is proportional to the number of W + jets events.

Besides the normalization, a correction is applied improving the modeling of the heavy flavor fraction in W + jets events. This correction includes a reweighting of W + bX events with a factor 2 ± 1 and W + cX events with factor $1^{+1}_{-0.5}$ [17]. A subsequent renormalization step cancels any event yield changes caused by these last corrections.

The evaluation of systematic uncertainties on the measurement is performed by varying the process samples according to the respective uncertainties. The subsequent treatment differs for the two differential cross-section measurements. For the measurement concerning the jet multiplicity the cross-section calculation is repeated for all systematic variations. The measurement of the production of additional jets makes use of pseudo experiments, randomly generating pseudo data sets from the varied samples. The following sources of systematic uncertainties are considered for this analysis:
Jet Energy Variation of the jet energy scale (JES) and of the jet energy resolution (JER) by their uncertainties.

Background

- W + jets Variation of the W + jets corrections by the uncertainties of the heavy flavor correction and the normalization method.
- **QCD** Variation of the estimated QCD multijet sample due to the choice of the lepton isolation cut and the remaining contamination.
- **Other backgrounds** Variation of sample normalization by a conservative estimation of the uncertainty on the prediction $(\pm 30\%)$.
- \mathbf{Q}^2 Scale Independent variation of the renormalization and factorization scale in MADGRAPH generation of $t\bar{t}$ and W + jets events.
- ME/PS Matching Independent variation of the matrix-element/parton-showering jet-matching threshold in MADGRAPH generation of $t\bar{t}$ and W + jets events.
- **Parton Distribution Function (PDF)** Reweighting of the default MADGRAPH $t\bar{t}$ sample according to the 44 CTEQ66 error PDF sets.
- **Remaining Systematic Uncertainties** Uncertainties from the integrated luminosity estimation, from the trigger efficiency in MC, of the lepton identification and isolation, of the b-tagging efficiency, and of pileup according to the 2011 data scenario are considered.

The differential cross section with respect to the jet multiplicity is defined as

$$\frac{d\sigma_{t\bar{t}}^{\text{measured}}}{dN_{\text{jets}}} = \frac{N_{\text{data}}^i - N_{\text{bkg}}^i}{\epsilon^i \cdot \mathcal{L}} \,. \tag{1}$$

 N_{data}^i (N_{bkg}^i) is the number of data (background) events containing *i* jets and fulfilling the full event selection. The factor $\epsilon^i = \frac{N_{\text{rec}}^i}{N_{\text{gen}}^i}$ corrects for bin-to-bin migration effects between the generator jets and the reconstructed jets. Generator jets are obtained by clustering stable particles applying the anti- k_T algorithm with a distance parameter of 0.5. N_{rec}^i is the number of $t\bar{t}$ signal events with *i* reconstructed jets and passing the full event selection while N_{gen}^i represents the number of $t\bar{t}$ signal events with *i* generator jets with $p_T > 35 \text{ GeV}$ and $|\eta| < 2.4$. Dividing the differential cross section value for each jet multiplicity *i* by the measured inclusive cross section provides the normalized differential cross section

$$\frac{d\sigma}{\sigma_{t\bar{t}} \cdot dN_{\text{jets}}} = \frac{1}{\sigma_{t\bar{t}}^{\text{measured}}} \times \frac{d\sigma_{t\bar{t}}^{\text{measured}}}{dN_{\text{jets}}} \qquad \text{with} \ \sigma_{t\bar{t}}^{\text{measured}} = \sum_{i} \frac{d\sigma_{t\bar{t}}^{\text{measured}}}{dN_{\text{jets}}} \,. \tag{2}$$

The normalization of the differential cross section cancels out the systematic uncertainties correlated over all jet multiplicities. The differential cross section values for each jet multiplicity are calculated for both lepton channels and combined with the BLUE (Best Linear Unbiased Estimator) method [18]. All systematic uncertainties except for the ones concerning the lepton are assumed to be 100% correlated for the combination. Figure 1 shows the results of this measurement compared to the prediction of different MC generator combinations



Figure 1: Measured normalized differential cross section of the $t\bar{t}$ production process as a function of the number of generator jets compared to MC expectations from different generators (left) and generator parameter variations (right).

(MADGRAPH+PYTHIA, POWHEG+PYTHIA, and MC@NLO+HERWIG) and different parameter variations of the nominal generator (Q^2 scale and ME/PS matching).

The measurement of jets produced in addition to top quark pairs is an alternative method to extract information about additional radiation. The determination of the $t\bar{t}$ production cross section differential in the number of additional jets is performed for the μ +jets channel. It starts by classifying the simulated $t\bar{t}$ events depending on the number of additional jets using MC truth information. Additional jets are defined by the absence of a top decay parton within the angular distance of $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.5$ of the respective generator jet fulfilling the jet selection criteria ($p_T > 30 \text{ GeV}$, $|\eta| < 2.4$). The matching of the top decay partons to generator jets enables the identification of hard additional radiation while low angle final state radiation is assigned to the original parton. The simulated $t\bar{t}$ sample is divided into three categories, $t\bar{t} + 0$, 1, and ≥ 2 additional jets, according to the number of generator jets in the event matching the additional jet definition. The corresponding cross sections are extracted by performing a maximum likelihood fit of the signal and the background templates to data. The fit variable

$$\chi = \sqrt{\left(\frac{m_{W^{\text{had}}}^{\text{rec}} - m_{W^{\text{had}}}^{\text{true}}}{\sigma_{W^{\text{had}}}}\right)^2 + \left(\frac{m_{t^{\text{had}}}^{\text{rec}} - m_{t^{\text{had}}}^{\text{true}}}{\sigma_{t^{\text{had}}}}\right)^2 + \left(\frac{m_{t^{\text{lep}}}^{\text{rec}} - m_{t^{\text{lep}}}^{\text{true}}}{\sigma_{t^{\text{lep}}}}\right)^2} \tag{3}$$

is based on the full reconstruction of the $t\bar{t}$ system. The reconstructed masses of the hadronic W boson and both top quarks are calculated for every possible combination of assigning jets to top decay partons with the restriction of always matching b-tagged jets to the bottom quarks. Subsequently the hypothesis with the lowest χ value is kept for each event. The true masses m^{true} and the widths σ_{thad} , σ_{tlep} and σ_{Whad} are determined from the $t\bar{t}$ MC simulation. Due to the sensitivity of the event reconstruction to the relation between the number of reconstructed jets and the number of additional jets, the variable χ provides good discrimination power between the $t\bar{t} + 0$, 1, and ≥ 2 additional jets events containing the same number of reconstructed jets. Therefore performing a simultaneous fit in three exclusive jet

multiplicity bins with events with 4, 5, and ≥ 6 reconstructed jets increases the sensitivity of this measurement. The normalizations of the $t\bar{t} + 0$, 1, and ≥ 2 additional jets signal samples are free parameters in the fit while Gaussian constraints corresponding to the uncertainties of the prediction are applied to the normalizations of the backgrounds.



Figure 2: Result of cross section extraction fit simultaneous in three reconstructed jet multiplicity bins. All templates are scaled by the resulting fit parameters.

The outcome of the maximum likelihood fit is shown in Figure 2. The extracted cross sections including a comparison with the prediction of different MC generators and different parameter variations of the nominal generator are displayed in Figure 3.



Figure 3: Measured normalized cross section of $t\bar{t}$ production processes with additional jets in the μ +jets channel compared with MC expectations from different generators (left) and generator parameter variations (right).

The comparison of the two differential cross section measurements shows a similar behavior of the results. Good agreement between the measured values and the predictions of the MC simulations can be found for the lower jet multiplicities. A slight discrepancy between the measurement and the predictions from MC@NLO+HERWIG and the down variation of Q^2 and matching parameters in MADGRAPH+PYTHIA is observed for high jet multiplicities. Specific modeling configurations cannot be excluded due to the large uncertainties, with main contributions coming from the jet energy scale uncertainty, MC generator parameters (Q^2 scale & ME/PS matching), and the PDF used for the signal simulation.

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Flavor changing neutral currents in top quark production and decay

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Top quark flavor changing neutral current (FCNC) interactions are highly suppressed in the Standard Model. Therefore, any large signal of FCNCs will indicate the existence of new interactions. In this paper, searches for FCNC interactions in top quark production and decay at the Tevatron and LHC are presented. FCNC searches in $t \to qZ$ and $t \to Hq$ decays, and in top quark production in $pp \to t + j$, $pp \to t + Z$ are summarized. The effect of top quark FCNCs on single top quark cross-section, and the searches for samesign top quark pair production through FCNCs are also described. None of the searches yielded positive results and exclusion limits on branching ratios, coupling strengths and cross-sections are obtained. Future prospects of FCNC searches are also briefly discussed.

1 Introduction

Flavor Changing Neutral Currents (FCNCs) are transitions that change the flavor of a fermion without changing its charge. FCNCs are forbidden at the tree level in the standard model (SM) and are suppressed at higher orders due to the GIM mechanism [1]. FCNC interactions occur only at the level of quantum loop corrections with branching ratios, $\mathcal{B}(t \to Xq) \sim 10^{-17} - 10^{-12}$, where $X = H, \gamma, Z$ or g. In models beyond SM, branching ratios up to 10^{-3} are predicted [2]. Therefore, any evidence of an FCNC process will indicate the existence of new physics. Searches for FCNCs might be done using specific models (e.g. two Higgs doublet model) or in a modelindependent way. In this proceeding, the analyses summarized depend on model-independent methods using effective field theory approach. Assuming that the new physics involves particles with a mass scale larger than the top quark mass, the most general effective Lagrangian with terms up to dimension 5 is [2]

$$-\mathcal{L}_{eff} = \frac{g}{2c_W} X_{qt} \overline{q} \gamma_\mu (x_{qt}^L P_L + x_{qt}^R P_R) t Z^\mu + \frac{g}{2c_W} X_{qt} \kappa_{qt} \overline{q} (\kappa_{qt}^v + \kappa_{qt}^a \gamma_5) \frac{i\sigma_{\mu\nu}q^\nu}{m_t} t Z_\mu$$
(1)
+ $e\lambda_{qt} \overline{q} (\lambda_{qt}^v + \lambda_{qt}^a \gamma_5) \frac{i\sigma_{\mu\nu}q^\nu}{m_t} t A^\mu + g_s \zeta_{qt} \overline{q} (\zeta_{tq}^v + \zeta_{qt}^a \gamma_5) \frac{i\sigma_{\mu\nu}q^\nu}{m_t} T^a q G^{a\mu}$
+ $\frac{g}{2\sqrt{2}} g_{qt} \overline{q} (g_{qt}^v + g_{qt}^a \gamma_5) t H + h.c.$

where $q^{\nu} = (p_t - p_q)^{\nu}$ with p_t and p_q representing four-momentum of the top quark and b quark, respectively. The symbols \overline{q} and t represent the quark fields. The coupling constants are normalized as $|x_{qt}|^2 + |x_{qt}^R|^2 = 1$, $|\kappa_{qt}^{\nu}|^2 + |\kappa_{qt}^a|^2 = 1$, etc., with X_{qt} , κ_{qt} , λ_{qt} , ζ_{qt} , and $g_{qt} \in \mathbb{R}^+$

and h.c. represents Hermitian conjugate. For more details, see [2]. Implementation of each term may be different for some of the measurements presented here, and therefore exclusion limits are not directly comparable without the necessary replacements for different representations. The limits on the couplings in this paper are given with the notation in their corresponding publications.

2 FCNCs in top quark decays in $t\bar{t}$ events

2.1 $t \rightarrow Zq$ decays

The exclusion limits obtained from searches for FCNCs processes in top quark decays in $t\bar{t}$ events are summarized in Table 1. Note that there is no published $t \to \gamma q$ result at the LHC yet. The most precise exclusion limit on the $t \to Zq$ branching ratio is obtained by CMS using 19.7 fb⁻¹ proton-proton collision data at a center-of-mass energy (\sqrt{s}) of 8 TeV [3]. The CMS analysis is made in the $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$ final state. Three lepton events are selected with the additional requirements of large missing transverse energy, at least two jets among which exactly one is required to be b-tagged. For signal a MadGraph [5]+Pythia [6] sample is used and backgrounds are estimated using a data-driven approach. The selected Z boson and the jet as well as W boson and b-tagged jet are paired to reconstruct the top quarks. After all selections, the signal region is defined by a 35 GeV Wb and 25 GeV Zj mass window around the top quark mass. The signal, background and data distributions are shown in Fig. 1. The signal region contains one event while the expected SM background is 3.1 ± 5.1 events. Therefore, there is no excess of events over the SM background. The process under investigation can be represented by the first term of the effective Lagrangian in Eq. 1. A branching ratio, $\mathcal{B}(t \to Zq) > 0.07\%$ is excluded at the 95% confidence level (CL). The expected 95% CL upper limit is 0.11%. Combined with the search at 7 TeV [4], the limit is $\mathcal{B}(t \to Zq) > 0.05\%$. The dominant systematic uncertainties in this measurement are factorization and renormalization scales, parton distribution functions (PDFs) and the $t\bar{t}$ cross-section.



Figure 1: Comparison between data and MC distributions of the m_{Zj} (left plot), m_{Wb} (middle plot) and the data points on the m_{Zj} vs m_{Wb} plane (right plot). For the 2D scatter plot the data points are shown before the top quark mass selection requirements. Top quark mass requirements are shown as dotted vertical lines in the left and the middle plots and as a dotted box on the right plot. The expected signal distributions are normalized so that $\mathcal{B}(t \to Zq) = 0.1\%$.

\sqrt{s}	Detector	Channel	$\mathcal{B}(t \to Zq)$	$\mathcal{B}(t \to \gamma q)$	Reference
(TeV)	(integrated luminosity)		(%)	(%)	
1.8	CDF ($\sim 110 \text{ pb}^{-1}$)	dilepton	33	3.2	[7]
1.96	$CDF (1.9 \text{ fb}^{-1})$	dilepton	3.7	-	[8]
1.96	D0 (4.1 fb ^{-1})	trilepton	3.2	-	[9]
7	ATLAS (2.1 fb^{-1})	trilepton	0.73	-	[10]
7	CMS (5 fb^{-1})	trilepton	0.21	-	[11]
7 + 8	CMS $(5.0 + 19.7 \text{ fb}^{-1})$	trilepton	0.05	-	[3]

Table 1: Observed branching ratio exclusion limits for $t \to Zq$ and $t \to \gamma q$ decays in $t\bar{t}$ events at 95% C.L.

2.2 $t \rightarrow Hq$ decays

The discovery of the Higgs boson by the ATLAS [12] and CMS [13] collaborations allows us to search for FCNC interactions occurring through the mediation of the Higgs boson. The ATLAS collaboration conducted a search for FCNC in the $t \to cH$ decays with $H \to \gamma\gamma$ using 4.7 fb⁻¹ and 20.3 fb⁻¹ data collected at $\sqrt{s} = 7$ and 8 TeV, respectively [14]. The search is made using $t\bar{t}$ events for which one of the top quarks decays to cH and the other to bW. Both hadronic and leptonic decays of the W bosons are considered. Backgrounds for non-resonant $\gamma\gamma$ final state are found to be small after $t\bar{t}$ event selection.

found to be small The signal signature is two high E_T well identified and isolated photons. The hadronic channel is selected by requiring at least four jets with at least 1 b-tagged jet and the nonexistence of leptons in the event. The leptonic channel is defined by exactly one lepton and high transverse mass defined by the lepton and E_T^{miss} . In addition, the events are required to fall in certain $m_{\gamma\gamma i}$ and m_{iji} mass windows. The backgrounds include SM Higgs boson backgrounds from gluon fusion, vector boson fusion (qqH), Higgs-strahlung associated production (WH, and ZH), associated Higgs boson production with a $t\bar{t}$ pair $(t\bar{t}H)$, and tH production. Moreover, non-resonant two-photon production with up to three partons is also considered in the backgrounds. A



Figure 2: The diphoton mass spectrum using the selected events in the hadronic channel.

maximum likelihood fit performed on the selected data (50 events in the hadronic channel and 1 event in the leptonic channel) yielded a total of $3.7^{+4.4}_{-3.7}$ signal events. The diphoton mass spectrum using the selected events in the hadronic channel is shown in Figure 2. Assuming $M_H = 126.8$ GeV, the observed limit on the branching ratio is 0.83% at the 95% C.L. and the upper bound on the λ_{tcH} coupling is 0.17.

Craig et al. [15] obtained a branching ratio limit of 2.7% at 95% C.L. for $M_H = 125$ GeV re-interpreting a CMS anomalous multi-lepton search conducted at $\sqrt{s} = 7$ TeV [16]. At $\sqrt{s} = 8$ TeV, CMS searched for $t \to cH$ decays from the $H \to WW^* \to \ell\nu\ell\nu$, $H \to \tau\tau$, $H \to ZZ^* \to jj\ell\ell, \nu\nu\ell\ell, \ell\ell\ell\ell$ processes in $t\bar{t}$ production [17]. The searches have been made

\sqrt{s}	Detector	Decay mode	$\mathcal{B}(t \to cH)$	Ref.
(TeV)	(integrated luminosity)		(%)	
7+8	ATLAS $(4.7+20.3 \text{ fb}^{-1})$	$H \to \gamma \gamma$	0.83	[14]
8	CMS (19.5 fb^{-1})	$H \to WW$	1.58	[17]
8	CMS (19.5 fb^{-1})	$H \to \tau \tau$	7.01	[17]
8	CMS (19.5 fb^{-1})	$H \rightarrow ZZ$	5.31	[17]
8	CMS (19.5 fb^{-1})	$H \to WW + \tau \tau + ZZ$	1.28	[17]

Table 2: Observed branching ratio limits at 95% C.L. for FCNC process in $t \to cH$ decays in $t\bar{t}$ events.

in exclusive multi-lepton channels defined by lepton charge flavor combinations, E_T^{miss} , jet activity, consistency of the invariant mass of opposite-sign lepton pairs with a Z boson, and the presence of b-jets and taus. It is found that the most sensitive signal regions are defined by three leptons, at least one b-tagged jet, no hadronic τ particles, and either no opposite-sign same-flavor pair or an opposite-sign same-flavor pair off the Z boson mass peak. No excess is observed over the SM backgrounds. The limits on the branching ratios are displayed in Table 2 for each decay channel. For the CMS branching ratio limits the assumed Higgs boson mass is $M_H = 125.5$ GeV. The combined branching fraction limit at 95% C.L. obtained by CMS is 1.28% (also shown in Table 2). Note that the exclusion limits were revised after *TOP*2013 conference. The limit obtained by CMS is complementary to the ATLAS search in the $H \to \gamma \gamma$ decay channel.

3 FCNCs in top quark production in single top events

It is difficult to distinguish the $t \to gq$ final state from the QCD multi-jets background. Instead, a much higher sensitivity can be achieved in the searches for the anomalous single top production via the $qg \to t$ process. In the final state, a quark, a gluon, or a Z boson can accompany the top quark. In the following, we summarize the searches made for anomalous top quark production in $pp \to t$, $pp \to t + q/g$, and $pp \to t + Z$ processes. The branching ratio exclusion limits obtained from these searches are summarized in Table 3.

\sqrt{s}	Detector	$\mathcal{B}(t \to gu)$	$\mathcal{B}(t \to gc)$	$\mathcal{B}(t \to Zu)$	$\mathcal{B}(t \to Zc)$	Ref.
(TeV)	(integrated luminosity)	(%)	(%)	(%)	(%)	
1.96	CDF (2.2 fb^{-1})	0.039	0.57	-	-	[18]
1.96	D0 (2.3 fb ⁻¹)	0.02	0.39	-	-	[19]
7	ATLAS (2.1 fb^{-1})	0.0057	0.027	-	-	[20]
7	CMS (4.9 fb^{-1})	0.56	7.12	0.51	11.40	[21]
8	ATLAS (14.2 fb^{-1})	0.0031	0.016	-	-	[22]

Table 3: Observed branching ratio limits for FCNC process in single top production.

3.1 $pp \rightarrow t$

The main differences of $qg \to t$ from the SM processes are that the top quark is produced with almost zero p_T and therefore W and the b-jet are almost back-to-back; the p_T of the W boson

is larger than that of V+jets and diboson and therefore the decay products of the W boson have small opening angles. Another difference is the different charge asymmetry in the two cases. $A = \frac{1}{2} \frac{1}$

ATLAS and CDF collaborations made searches for this process [18, 20, 22]. The signal simulation is made using PROTOS [23] and TOPREX [24] for the ATLAS (\sqrt{s} =7 TeV) and CDF analysis respectively. For the measurement at $\sqrt{s} = 8$ TeV, ATLAS used a new generator, ME_{TOP} [25]. This event generator provides the calculation for the FCNC process at approximate next-to-leading order level. Both collaborations used Bayesian Neural Networks (BNN) to discriminate signal and backgrounds which are dominated by W + jets and QCD multijets. Binned maximum likelihood fits to the BNN output distributions are performed. BNN output distributions normalized to the binned maximum likelihood fit results and with the signal scaled to 20 pb obtained from the ATLAS analysis are shown in Figure 3. The process that is being searched is represented by the fourth term of Eq. 1. The best branching ratio exclusion limits are $B(t \rightarrow u + q) < 3.1 \times 10^{-5}$ and $B(t \rightarrow c + g) < 1.6 \times 10^{-4}$, obtained by ATLAS using 14.2 fb⁻¹ of $\sqrt{s} = 8$ TeV data [22]. From this analysis, the 95% C.L. upper limit on the production



Figure 3: Output distribution of the neural network in the signal region. The signal distribution, scaled to a cross-section of 20 pb, is stacked on top of the backgrounds.

cross-section is determined to be 2.5 pb and the upper limits on the coupling constants are $\kappa_{ugt}/\Lambda < 5.1 \times 10^{-3} \text{ TeV}^{-1}$ (assuming $\kappa_{cgt}/\Lambda = 0$) and $\kappa_{cgt}/\Lambda < 1.1 \times 10^{-2} \text{ TeV}^{-1}$ (assuming $\kappa_{ugt}/\Lambda = 0$). For these exclusion limits, the dominant systematic uncertainties are the jet energy scale and resolution, b-jet tagging efficiency and parton distribution functions (PDFs).

3.2 $pp \rightarrow t + q/g$

The D0 experiment made a search for the production of a top quark with an additional jet using 2.3 fb^{-1} of data [19]. The final state is similar to the t-channel SM single top quark production. The dominant background for this process is W + jets. The signal and background separation is obtained by BNNs. The signal and single top quark backgrounds are simulated by SINGLETOP MC [26, 27]. For BNN, 54 variables are adopted from a subset of the single-top measurement variables and variables from a previous FCNC analysis [28]. Discriminating variables are individual object and event kinematics, top quark reconstruction, jet width, and angular correlations. Fig. 4 displays the background distributions (normalized to their observed limits) and data for the combined BNN discriminants. No FCNC signal is observed and branching ratio limits



Figure 4: Background distributions and data for the FCNC BNN output at the high discriminant region.

of 2.0×10^{-4} for tgu and 3.9×10^{-3} for tgc vertices are obtained. The process is represented by the fourth term of Eq. 1. Upper limits on couplings are $\kappa_{tgu}/\Lambda < 0.013 \text{ TeV}^{-1}$ and $\kappa_{tgc}/\Lambda < 0.057 \text{ TeV}^{-1}$ and the upper limits on the cross-sections are 0.20 and 0.27 pb for the tgu and tgc vertices. Dominant systematic uncertainties are jet energy scale and b-jet tagging modeling.

3.3 $pp \rightarrow t + Z$

CMS performed a search for the FCNC process in single top quark production in association with a Z boson using a 5 fb⁻¹ data sample at $\sqrt{s} = 7$ TeV. In the analysis both gqt and Zqt vertices are probed simultaneously unlike the standard single top quark FCNC searches. The model described in [29] is used and the probed vertices are described by the second and fourth terms of Eq. 1. The Zqt vertex is also probed by the searches in top quark decays as described in the previous sections. The signal signature is three isolated leptons and a b-tagged jet. The signal simulation is made using MadGraph+Pythia. The signal is extracted using kinematic variables and b-jet tagging information combined using a Boosted Decision Tree (BDT). The main backgrounds are fake leptons from the Z + jets process. Other backgrounds are ZZ + jets, $t\bar{t}$, and tZq. The BDT shapes are taken from data for Z + jets, inverting the third lepton isolation and low E_T^{miss} , and other shapes are taken from simulation. Figure 5 displays the BDT output distribution for the gut coupling, summed for the four tri-lepton channels. No FCNC signal is observed and upper limits are derived. The limits on the branching ratios are listed in Table 3. The observed upper limits on the coupling strengths are $\kappa_{gut}/\Lambda < 0.10$ TeV⁻¹, $\kappa_{qct}/\Lambda < 0.35$ TeV⁻¹, $\kappa_{zut}/\Lambda < 0.45$ TeV⁻¹, and $\kappa_{Zct}/\Lambda < 2.27$ TeV⁻¹.



Figure 5: BDT output distribution for the gut coupling (left plot) and Zut (right plot), summed for the four tri-lepton channels. Total uncertainty is shown as hatched areas. The FCNC signal is normalized to a cross-section of 0.1 pb.

3.4 Single Top Quark t-channel cross-section

FCNC modifies the t-channel production rate [30]. Figure 6 shows the s- and tchannel cross-section measurement displaying the equal probability contours for the discriminant with one, two, and three standard deviations [31]. The figure also shows the prediction from SM and from different specific new physics models that can modify the s- or t-channel cross-section. One of the models shown is an FCNC model that assumes a coupling of $k_{tug}/\lambda =$ 0.036 [30, 28] modifying the SM t-channel cross-section. The D0 measurement is consistent with the SM, however to exclude the FCNC model with the assumed parameters more data is needed. The dominant systematic uncertainties are multijet normalization, W/Z + jets heavy flavor correction, ISR/FSR, $t\bar{t}$ cross-section, and b-jet tagging.



Figure 6: Single top production cross-section in the s- vs. t-channel plane. The sensitivity to different models is also shown.

4 Same-sign top quark pair production

The existence of same-sign top quark pair production may indicate the existence of a new heavy resonance. The search for samesign top quark pair production is motivated by the fact that the models to explain the $t\bar{t}$ forward-backward asymmetry (A_{FB}) observed at the Tevatron [32, 33, 34, 35, 36, 37, 38, 39, 40] usually involve FCNCs mediated by a new massive Z' boson. The searches for top quark pair production are made looking for same-sign dilepton events by CDF [41], CMS [42], and ATLAS [43, 44] experiments. As shown in Figure 7 by CMS and ATLAS collaborations, the non-existence of same-sign top quark production indicates that the FCNC interpretation of the Tevatron



Figure 7: Diagrams for $t\bar{t}$ (top) $t\bar{t}j$ (bottom) production mediated by a Z'.

 A_{FB} is disfavored. The most stringent limit is obtained by the ATLAS collaboration using 14.3 fb⁻¹ of $\sqrt{s} = 8$ TeV pp collision data [44]. The signal signature is same-sign dilepton events accompanied by jets in which at least one of them is a b-jet. Moreover, a missing transverse energy of 40 GeV, and an H_T of 550 GeV are required. The signal simulation is made using the PROTOS event generator. The dominant backgrounds are misidentified leptons, charge



Figure 8: Excluded region shown as the shaded area in the Z' mass vs right handed couplings (f_R) frame. One and two standard deviations of the region of parameter space consistent with the A_{FB} measurements at the Tevatron using the leading-order $t\bar{t}$ cross-section calculated by MadGraph are also shown (left plot). Regions consistent with the new physics contributions to the inclusive A_{FB} at the Tevatron, and the $t\bar{t}$ cross-section at LHC (right plot). Limits from the ATLAS analysis at $\sqrt{s} = 7$ TeV are shown by the solid horizontal lines. CDF and D0 A_{FB} measurements are displayed as vertical lines with the associated uncertainty bands (right plot).

misidentifications, and ttW + jets. None of the searches by the different experiments yielded positive results. The 95% C.L. exclusion limits on the cross-section and couplings are obtained by the ATLAS collaboration are shown in Table 4 for different chirality configurations.

Chirality configuration	$\sigma(pp \to tt) \; [pb]$	$ C /\Lambda^2 [{\rm TeV}^{-2}]$
Left-left	0.19	0.092
Left-right	0.20	0.271
Right-right	0.21	0.099

Table 4: Observed limits on the positively-charged tt production.

5 Summary and Prospects

The results of the searches conducted by ATLAS, CDF, CMS, and D0 collaborations are presented. No signs of FCNCs in the decays of $t\bar{t}$, single top quark or same-sign top quark processes have been observed. The exclusion limits are getting closer to the predictions from specific new physics models. First limits on the $t \to cH$ process, presented in this proceeding, are almost at the level of 2HDM predictions. In the $\sqrt{s} = 14$ TeV LHC run, ATLAS and CMS experiments expect the limits to be an order of magnitude smaller, as shown in Figure 9 in the $\mathcal{B}(t \to q\gamma)$ vs $\mathcal{B}(t \to qZ)$ plane. Using 300 fb⁻¹ of 14 TeV data, ATLAS collaboration expects to exclude $\mathcal{B}(t \to qZ) > 2 \times 10^{-4}$ [45] and the CMS experiment expects to exclude $\mathcal{B}(t \to qZ) > 10^{-5}$ [46].



Figure 9: The observed 95% CL limits on the $\mathcal{B}(t \to q\gamma)$ vs. $(\mathcal{B}(t \to qZ))$ plane shown with solid lines for the LEP, ZEUS, H1, D0, CDF, ATLAS and CMS collaborations as of August 10, 2012. The expected sensitivities for ATLAS measurements at 14 TeV with different integrated luminosities are shown with the dashed lines.

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