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

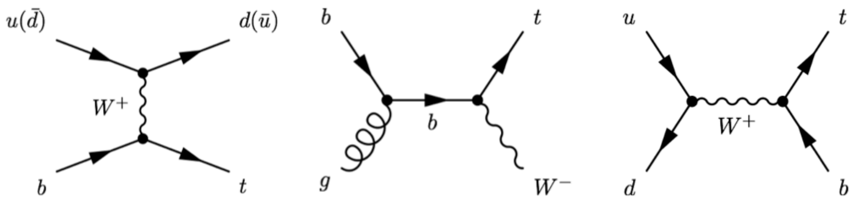

Figure 1: Leading order (LO) diagrams for single top production: t-channel (Left), tW associated production (Center), and s-channel (Right).

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 $1.04 fb^{-1}$ 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 $1.17 fb^{-1}$ in the μ final state and $1.56 fb^{-1}$ 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 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 $m_{j_1 j_2}$. 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

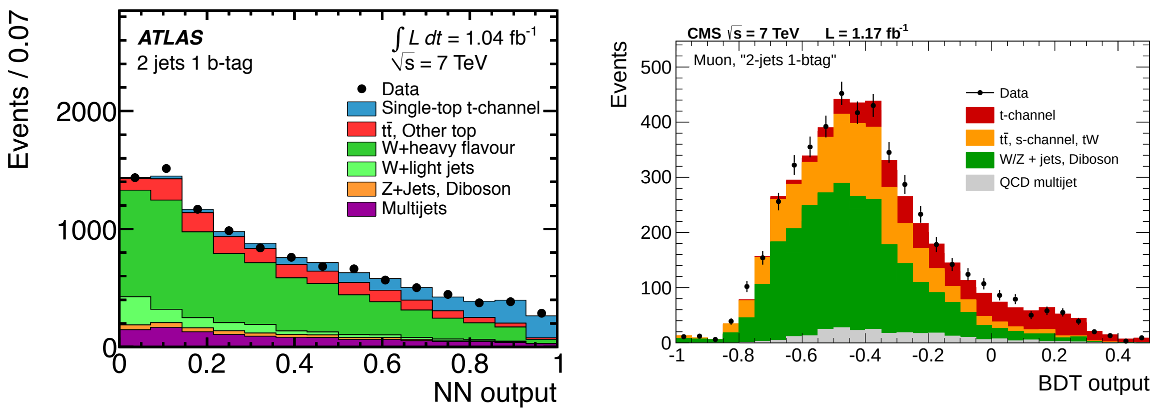

Figure 2: Distributions of the NN output for the 2-jet b-tagged sample in ATLAS (Left), and BDT discriminator output in the muon channel for the '2-jets 1-btag' region in CMS (Right).

inclusive cross-section of:

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

CMS has results in each analysis that are combined into:

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

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

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

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 ($|V_{tb}| \leq 1$), 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^+ 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.

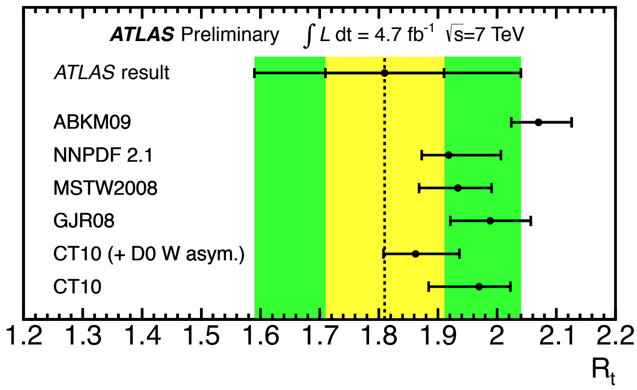

Figure 3: Calculated charge ratio values for different NLO PDF sets.

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 cross-section. ATLAS performs a NN analysis using 5.8 fb^{-1} of integrated luminosity [5]. CMS uses the shape of the $|\eta_{j'}|$ 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

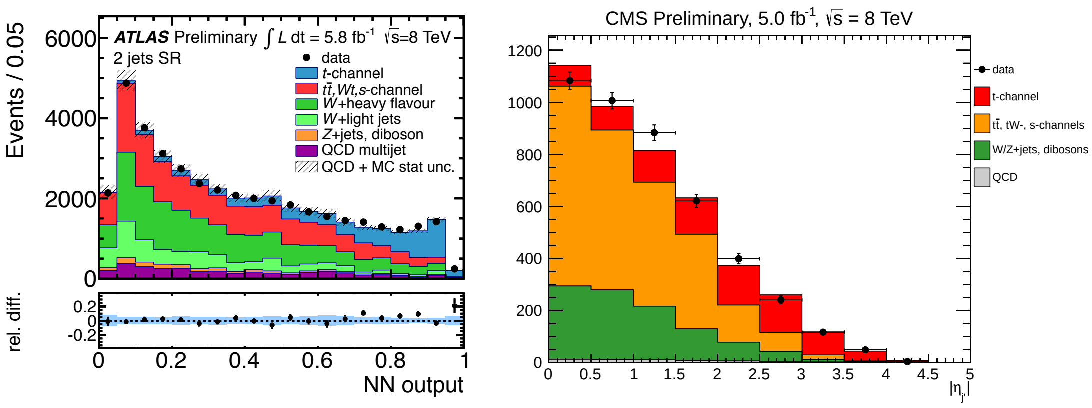

Figure 4: Distributions of the NN output for the 2-jet b-tagged sample in ATLAS (Left), and $|\eta_{j'}|$ in the signal region in CMS (Right).

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:

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

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:

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

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

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

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 $12.2 fb^{-1}$ 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 $2.05 fb^{-1}$ [9], while CMS uses $4.9 fb^{-1}$ [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, eμ and $\mu\mu$. ATLAS and CMS

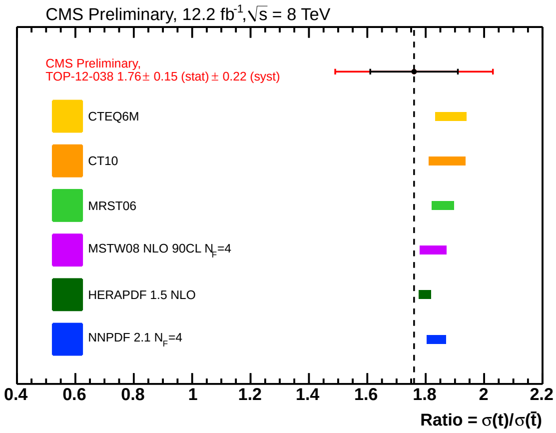

Figure 5: Comparison of the measured charge ratio in the t-channel single top production with the prediction obtained using different PDF sets.

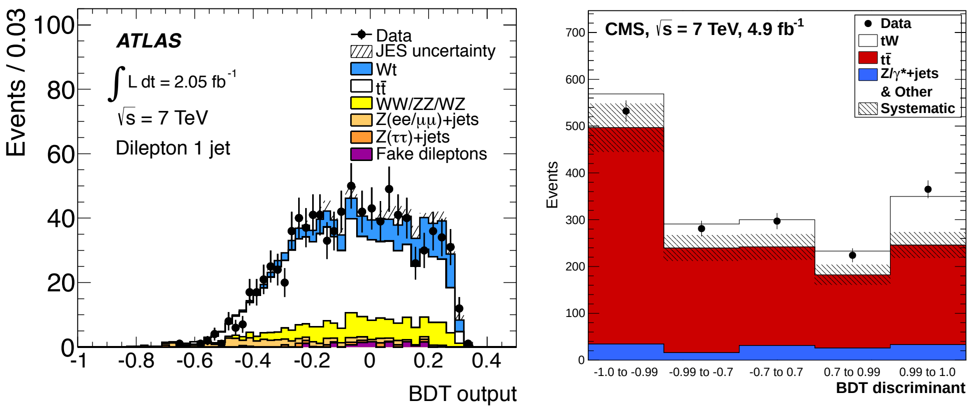

Figure 6: Distributions of the BDT output in ATLAS (Left), and CMS (Right).

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 $Z \to \tau\tau$). 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 $12.2 fb^{-1}$ 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 ($5.4^{+1.5}_{-1.4}\sigma$ 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 $e\mu$

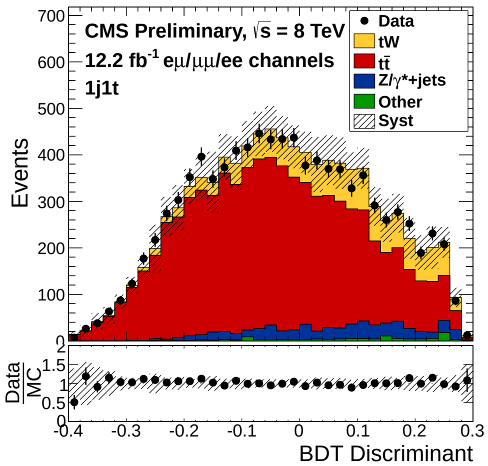

Figure 7: Distribution of the BDT output in the 1jet 1tag region for all the final states together in CMS.

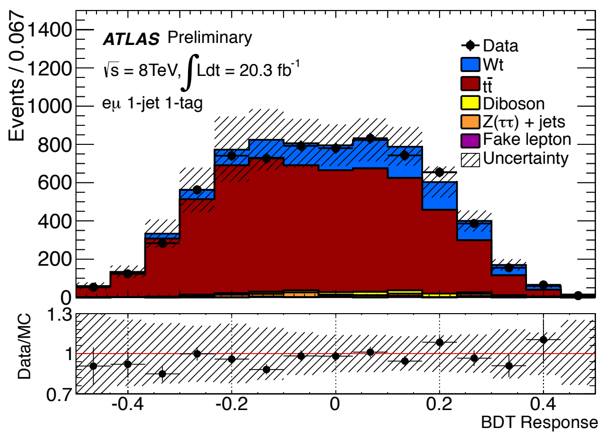

Figure 8: Distribution of the BDT output in events with 1 jet in ATLAS.

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:

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

with a significance of 4.2σ (4.0σ 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 $0.70 fb^{-1}$ 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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