The Latest Results of the ATLAS Experiment on Heavy Quark Physics

Stano Tokar on behalf of the ATLAS Collaboration

Comenius University, FMPI, Mlynska dolina F1, 94248 Bratislava, Slovakia

The latest experimental results obtained by the ATLAS Collaboration using the data produced in pp collisions at $\sqrt{s} = 7$ and 8 TeV are shown. The data were collected by the ATLAS detector in 2011 (7 TeV) and 2012 (8 TeV) with the integrated luminosity of 4.9 fb^{-1} and 21 fb^{-1}, respectively. The main emphasis is on the top and bottom quark physics but the Higgs boson physics and searches of physics beyond the Standard Model are also reported. A lot of new results on the top quark and bottom quark physics are shown and new confirmation are given that the new boson seen at 125 GeV is compatible with the Standard Model Higgs boson at confidence level better than 7σ. No signs of physics beyond the Standard Model found.

1 Introduction

The Large Hadron Collider (LHC) experiments have started a new era of particle physics. The high collision energy available at LHC (7-14) GeV together with the high luminosity allow progress to be made in investigation of the main challenges of particle physics such as the status of the Higgs boson, precision tests of the Standard Model (SM), searches for new physics.

In the pre-LHC era there was a very good agreement between the experimental results and the SM predictions – see the pulls of Quantum Chromodynamics (QCD) and Electroweak (EW) observables in Ref. [1]. All the expected fundamental fermions in three generations and the expected gauge bosons have been experimentally confirmed. The only missing particle was the Higgs boson. Existence of the Higgs boson is critical for the SM as particles acquire mass by interacting with Higgs field which has non-zero vacuum expectation value. This mechanism, called usually Higgs mechanism, is responsible for electroweak symmetry breaking (EWSB). The discovery of a new boson with properties compatible with the SM Higgs boson announced by ATLAS and CMS in July 2012 has filled the last missing piece of the SM.

The SM, despite its success, is widely believed to be only an effective theory valid at the presently accessible energies. It has no appropriate answer to the global questions like the dark matter, baryon asymmetry and dark energy, it does not include the gravitational force, and it does not explain the pattern of fermion masses and the number of generations. The theory has no expplanation for the naturalness (or hierarchy) problem of the Higgs mass. Higgs mass corrections ($\triangle m_{\mathrm{H}}^2$) coming from the heaviest particles (mainly the top quark) are quadratically divergent: $\triangle m_{\mathrm{H}}^2 \sim \Lambda_{\mathrm{UV}}^2$, where Λ_{UV} is the ultraviolet cutoff for loop momentum integration. Among the suggestions to solve this problem the most attractive are approaches presented by Supersymmetry (SUSY) and extra dimensional (ED) models (see Sec. 4).

In the search for a manifestation of a BSM physics, a special role is played by processes with top quarks and b-quarks. Many BSM physics scenarios, if occur, could change significantly these processes. BSM physics could significantly modify the forward - backward asymmetry in $t\bar{t}$ and $b\bar{b}$ production, the spin correlation in $t\bar{t}$ production, the size of the top quark decay width, the polarization of W bosons from the top quark decays, etc. Processes with b-quarks are important especially for a better understanding of CP violation phenomena and rare decays which, being suppressed in the SM, can be sensitive to BSM physics, e.g. the decay $B^0_{d(s)} \to \mu^+\mu^-$. The results of the ATLAS studies of processes with top quarks and b-quarks are main goal of this contribution.

2 The ATLAS Detector

The ATLAS detector [2] is a multipurpose particle physics apparatus operating at one of the beam interaction points of the LHC. It covers almost the entire solid angle around the collision point. ATLAS uses a right-handed coordinate system with its origin in the centre of the detector (the nominal interaction point) and the z-axis along the beam pipe. The x-axis points from the coordinate system origin to the centre of the LHC ring, and the y-axis points upward.

The innermost part of this detector is an inner tracking detector (ID) comprised of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID covers the pseudo-rapidity[1] range $|\ \eta\ |< 2.5$ and is surrounded by a thin superconducting solenoid providing a 2 T magnetic field, and by liquid-argon electromagnetic sampling calorimeters with high granularity (LAr). An iron-scintillator tile calorimeter provides hadronic energy measurements in the central pseudorapidity range ($|\ \eta\ |< 1.7$). The end-cap and forward regions are instrumented with LAr calorimetry for both electromagnetic (EM) and hadronic energy measurements up to $|\ \eta\ |= 4.9$. The calorimeter system is surrounded by a muon spectrometer incorporating three superconducting toroid magnet assemblies, with bending power between 2.0 and 7.5 Tm and the pseudorapidity coverage is: $|\ \eta\ |< 2.7$.

3 Higgs boson search

The most significant results on the Higgs (H) boson search are obtained for the H boson decay to two photons ($H \to \gamma\gamma$) and its decay to four leptons ($H \to ZZ^* \to 4l$). In the analyses the proton-proton (pp) collision datasets corresponding to integrated luminosities of 4.8 fb^{-1} collected at $\sqrt{s} =$ 7 TeV and 20.7 fb^{-1} collected at $\sqrt{s} = 8$ TeV have been used. Figure 1 shows the two-photon invariant mass, $m_{\gamma\gamma}$, for the combination of $\sqrt{s} = 7$ and 8 TeV data with the new boson clearly seen. The largest local significance of the effect for the data sample combination is 7.4σ at the H boson mass M_{H} =126.5 GeV [3]. Combining the H boson decay channels the $H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to 4l$ channels the local significance exceeds 8σ and the combined mass is measured to be $M_{\mathrm{H}} = 125.5 \pm 0.2$(stat) $\pm$ 0.6(syst) GeV. For comparison the combined M_{H} measured by CMS experiment is $M_{\mathrm{H}} = 125.7 \pm 0.3$(stat.) $\pm$ 0.3(syst.) GeV. To confirm that the observed new boson is the H boson predicted by the SM, the global signal strength parameter, μ, as well as the strength parameters, μ_{i}, for the individual channels and a fixed mass M_{H} have been measured. The signal strength is defined as a ratio of the measured cross section for a given channel characterized by production and decay modes to that expected for the SM. Its value measured by ATLAS,

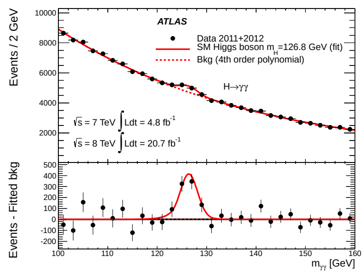

Figure 1: Two photon $m_{\gamma\gamma}$ spectrum.

[1]The pseudorapidity is defined in terms of the polar angle θ as $\eta = -ln(tan(\theta/2))$

combining the individual channel strength parameters, is $\mu = 1.30 \pm 0.20$, a good compatibility with the SM (μ =1). An important test of the status of the new boson is the parity-spin determination. For the SM H boson this quantity is: $J^{\mathrm{P}} = 0^{+}$. The ATLAS and CMS experiments strongly favor $J^{\mathrm{P}} = 0^{+}$ for the new observed boson. The alternatives $J^{\mathrm{P}} = 0^{-}$, 1^{-}, 1^{+}, 2^{+} are excluded at the 95 % confidence level (C.L.). Details of the H boson studies carried out by ATLAS and CMS can be found on their public results web pages [4, 5].

Though the experiments clearly favor the SM hypothesis, questions on the nature of H boson are still relevant. Is the H boson a fundamental boson or is it a composite boson with a new underlying dynamics? For a better understanding of these issues the planned increase in collision energy to 13-14 GeV and integrated luminosity to 300 fb^{-1} is vital.

4 Search of physics beyond the Standard model

The search for physics beyond the SM is a most important task of the ATLAS experiment. Searches are carried out in many directions, among the most promising are the searches within the SUSY and ED approaches.

Search for SUSY particles. The SUSY models [6, 7] are very attractive as they offer a recipe for the naturalness and have a candidate for solution of the dark matter problem. In the former case the large corrections to M_{H} from the top quark loops are compensated by the loop contributions from the SUSY top quark partner - top squark, provided that its mass is not far from the top quark mass. SUSY (R-parity conservation models) predicts pair production of SUSY particles and as a consequence of the lightest SUSY particle (LSP) being stable and serving as a candidate for the dark matter particle. In the minimal SUSY extension of the SM (MSSM) [8] such a particle is neutralino $\tilde{\chi}_1^0$.

The search for the top squark has been carried out by ATLAS in many final states. The superpartners of the left- and right-handed top quarks, $\tilde{t}_{\mathrm{L}}$ and $\tilde{t}_{\mathrm{R}}$, mix to form the two mass eigenstates $\tilde{t}_1$ and $\tilde{t}_2$, where $\tilde{t}_1$ is the lighter one. The pair produced top squarks, $\tilde{t}_1$, are assumed to decay to a top quark and a neutralino ($\tilde{t}_1 \to t + \tilde{\chi}_1^0$) or to a bottom quark and a chargino ($\tilde{t}_1 \to b + \tilde{\chi}_1^{\pm}$). An example of such a search, carried out by ATLAS at pp collision energy of 8 TeV on 20.7 fb^{-1} of data, is shown in Figure 2 where the mass limits on the top squark are presented. Assuming both the top squarks decay to a top quark and an LSP, the top squark masses between 200 and 610 GeV are excluded at 95% C.L. for massless LSPs, and the masses below 500 GeV are excluded for the LSP masses up to 250 GeV. Assuming both the top squarks decay to a bottom quark and the lightest chargino, the top squark masses are excluded up to 410 GeV for massless LSPs and an assumed chargino mass of 150 GeV.

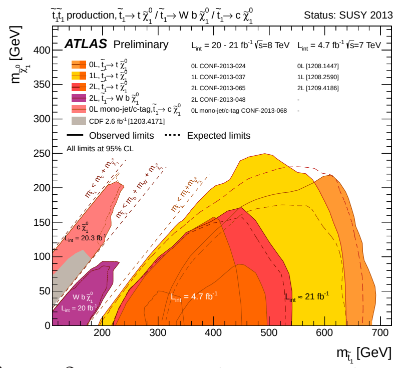

Figure 2: Limits on the top squark mass.

Search for non-SUSY new physics. The hierarchy problem can be solved within the theories with extra dimensions. In the ADD model [9] this problem is solved by lowering the fundamental scale of quantum gravity, M_{D}, to a few TeV instead of $M_{\mathrm{P}} = 10^{19}$ TeV. If M_{D} is of the order of 1 TeV, evaporating fast microscopic black holes (μBH) are predicted to be produced at LHC. The μBH are produced when the impact parameter of the two colliding partons is smaller than the Schwarchild radius of μBH ($R_{\mathrm{S}} = 2G_{\mathrm{N}}M_{\mathrm{BH}}/c^2$, G_{N} is gravitational constant, M_{BH} is the μBH mass). An example of a search for μBH in ATLAS is the analysis carried out in a like-sign dimuon final state [10]. The search for μBH has been carried out using the data sample of 20.3 fb^{-1} at 8 TeV. No excess of events over the SM expectations has been observed. Assuming $M_{\mathrm{D}} = 1.5$ GeV a limit on the μBH mass is found to be 5 TeV.

An example of an ATLAS search for a new physics predicted by Technicolor [11], is the search for a resonant production of two high transverse momentum jets in association with a SM W or Z boson decaying leptonically. In this model a spin 1 particle called technirho (ρ_{T}) decays into a lighter technimeson (technipion π_{T}) and a SM W or Z boson, if the ρ_{T} mass is larger than the sum of the π_{T} and gauge boson masses. In the ATLAS search for resonant dijet production in $Wjj \to l\nu jj$ and $Zjj \to lljj$ ($l = e, \mu$) events [12], a data-set of 20.3 fb^{-1} at 8 TeV has been analysed, but no significant deviation from the SM background prediction is observed in the m_{jj} spectra. The upper limit (95% C.L.) for the technipion is 180 GeV for the Wjj channel and 170 GeV for the Zjj one under the assumption of $m_{\rho_{\mathrm{T}}} = 3/2 \times m_{\pi_{\mathrm{T}}} + 55$ GeV.

From the ATLAS and CMS searches at energies 7 and 8 TeV for the new physics phenomena, can be concluded that no hints of a physics beyond the SM are seen. Details can be found on the public results web-sides of the ATLAS and CMS experiments [4, 5].

5 Top quark physics studies

Top quark physics is one of the most important subjects presently studied at LHC. The top quark properties are still not known properly and the top quark is in many respects an extraordinary particle:

- The mass of top quark (m_{top}) is very big - it is close to the EWSB scale. Its Yukawa coupling, $\lambda_{\mathrm{t}} = \sqrt{2} m_{\mathrm{top}}/\eta \approx 1$.
- The top quark is an excellent perturbative object for testing QCD as it is produced at small distances ($\sim 1/m_{\mathrm{top}}$) characterized by low value of coupling constant $\alpha_{\mathrm{S}} \approx 0.1$.
- It decays before hadronization: the production time ($1/m_{\mathrm{top}}$) $<$ lifetime ($1/\Gamma_{\mathrm{top}}$) $<$ hadronization time ($1/\Lambda_{\mathrm{QCD}}$). It permits study of spin characteristics of the top quark as it is not diluted by hadronization (test of the top production mechanisms) or measurement of W boson helicity (test of the EW V-A structure).
- the $t\bar{t}$ production cross section is sensitive to new physics, e.g. resonant production of $t\bar{t}$ pairs would be a hint of existence of a new boson (KK-gravitons, etc.) or the decay $t \to H^+ b$ would indicate presence of a charged Higgs boson.

In addition, the top quark processes are a very important background for the Higgs processes. It can be concluded that the top quark physics can provide stringent tests of the SM as well as it is an excellent platform for searches for new physics.

The top quark decays rapidly (the decay width is $\Gamma(t \to Wb) = 1.42$ GeV [15]) without forming hadrons and almost exclusively through the mode $t \to Wb$, where the b-quark hadronizes producing shower of particles called b-jet and the W boson decays leptonically or hadronically. From the experimental point of view the $t\bar{t}$ events are classified according to the W bosons decays dividing them into three channels: the dilepton channel (D-L) – both W decay leptonically, the lepton+jets channel (L+J) – one W decays leptonically and the other one hadronically, and the all-hadronic channel (A-H) – both W decay hadronically.

Top quark pair production cross section. The top quark is produced via strong interactions mediated through gluon (production of $t\bar{t}$ pair) and in the electroweak ones (single top quark production). In the former case the main production mechanisms are : the quark annihilation ($q\bar{q} \to t\bar{t}$) and gluon fusion($gg \to t\bar{t}$). In the latter case the production is mediated by W boson (e.g. $u\bar{d} \to W^+ \to t\bar{b}$). The top quark production cross section is calculated using the so-called factorization theorem:

$$\sigma = \sum_{i,j} \int dx_1 dx_2 F_i^{(1)}(x_1, \mu_F) F_j^{(2)}(x_2, \mu_F) \hat{\sigma}_{ij}(s; \mu_F, \mu_R), \tag{1}$$

where $F_i^{(\lambda)}(x_1, \mu_F)$ is the probability density to observe a parton i with longitudinal momentum fraction x_λ in incoming hadron λ, when probed at a scale μ_F, μ_F is the factorization scale (a free parameter) - it determines the proton structure if probed (by virtual photon or gluon) with $q^2 = -\mu_F^2$, μ_R is the renormalization scale defining size of the strong coupling constant and $\hat{\sigma}_{ij}(s)$ is the partonic cross section.

Cross section	2 TeV	7 TeV	8 TeV	14 TeV
$t\bar{t}$ [nb]	7.2	172.0	245.8	953.6
single top [nb]	3.0	84.9	115.7	320.0

Table 1: Top quark production cross section for the energies: 2 TeV (Tevatron) and 7, 8 and 14 TeV (LHC), for the $t\bar{t}$ production and for the single top quark one (single top).

Eq. 1 connects the experimentally measured cross section with the theoretical one and the proton structure functions. The theoretical $t\bar{t}$ partonic cross section is now calculated at the next-to-next-to-leading order (NNLO) with the next-to-next-to-leading logarithmic approximation (NNLL) [13]. The predicted $t\bar{t}$ production cross sections and the single top quark ones [14] are summarized in Table 1. The uncertainty of the theoretical calculations is 4% in the $t\bar{t}$ case and 3-4% in the single top one. The $t\bar{t}$ cross section analysis is carried out in all three above mentioned channels (the L+J, D-L and A-H channels). The most precise results are obtained for the L+J channel. The analysis is based on single lepton high transverse momentum (high p_{T}) trigger. The following reconstructed objects are required [16]: one high-p_{T} lepton, at least four high-p_{T} jets, one or two of them b-tagged, and high missing transverse energy $E_{\mathrm{T}}{}^{\mathrm{miss}}$. Electrons were required to have transverse energy $p_{\mathrm{T}} > 40$ GeV and pseudorapidity in the range $|\ \eta\ | < 2.47$ excluding the region $1.37 < |\ \eta\ | < 1.52$. Muons were reconstructed using information from the muon spectrometer and the inner detector. They were required to have transverse momentum $p_{\mathrm{T}} > 40$ GeV and pseudorapidity $|\ \eta\ | < 2.5$. The main background processes at this study are W boson + jets, Z boson + jets, diboson, single top quark and multi-jet production. The background processes are studied using MC dedicated samples and using a data driven technique [17].

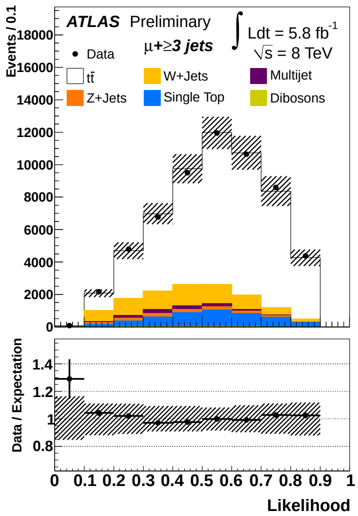

Figure 3: Likelihood discriminant distributions in data in μ+jets channel used for the $t\bar{t}$ cross section determination. The hatched bands display the combined statistical and systematic uncertainty.

The measured cross section, $\sigma_{t\bar{t}}$, is determined using the likelihood discriminant to separate signal events from the background ones and then a procedure is used based on the relation:

$$\sigma_{t\bar{t}} = \frac{N_{\mathrm{obs}} - N_{\mathrm{bkg}}}{A \cdot \epsilon \cdot \int L.dt}, \tag{2}$$

where N_{obs} (N_{bkg}) is the number of the observed candidate (expected background) events, A is the acceptance, ϵ is the trigger efficiency and $\int Ldt$ is the integrated luminosity.

The analysis was carried out using the data sample of 5.8 fb^{-1} at the pp collision energy of 8 TeV. Figure 3 shows the likelihood discriminant distribution in data fitted to the sum of the signal and background templates for the μ+jets channel. The cross section is found to be

$$\sigma_{t\bar{t}} = 241 \pm 2(\text{stat.}) \pm 31(\text{syst.}) \pm 9(\text{lumi}) \text{ pb}.$$

This result is in excellent agreement with the theoretical prediction [13]: $\sigma_{t\bar{t}}^{\text{theo}} = 245.8^{+6.2}_{-8.4}$ (stat.) $^{+6.2}_{-8.4}$ (pdf) pb as well as with the CMS results obtained in L+J (2.8 fb^{-1}) [18] and D-L (2.4 fb^{-1}) [19] channels: $\sigma_{t\bar{t}} = 228 \pm 9(\text{stat.}) \pm 29(\text{syst.}) \pm 10(\text{lumi.})$ pb and $\sigma_{t\bar{t}} = 227 \pm 3(\text{stat.}) \pm 11(\text{syst.}) \pm 10(\text{lumi.})$ pb, respectively.

The $t\bar{t}$ cross section measurements were carried out also at the collision energy of 7 TeV for different channels [20]. The measured $t\bar{t}$ cross sections at 7 and 8 TeV are summarized in Figure 4, where they are compared to the exact NNLO QCD calculation complemented with NNLL resummation [21]. The differential $t\bar{t}$ production cross section was also measured giving good agreement with the SM expectations, details are in Ref. [22].

Measurement of top quark mass. The top quark mass, m_{top}, is one of the SM parameters and is important also for the consistency tests of the SM (indirect determination of the Higgs boson mass). It is reconstructed from the invariant mass of the top quark decay products.

The top quark mass can be reconstructed in all $t\bar{t}$ topologies (L+J, D-L, A-H). The best results are usually obtained in L+J topology. The most common methods used to reconstruct m_{top} are template methods and matrix element methods. In the former case, the method is based on distributions of an observable sensitive to m_{top} (signal templates) for different m_{top} values. Data distribution of this sensitive observable is compared to a combination of the signal and background templates and the best agreements defines the mass (see further for an example). In the latter case, a dependence of the top pair production cross section on top quark mass is used to extract m_{top}. In addition, any variable correlated with top quark mass can be used for determination of m_{top}, e.g. mean lepton p_{T}. An interesting example of an application of the template method is the ATLAS measurement of m_{top} carried out for the $t\bar{t}$ lepton+jets channel using the data sample of 4.7 fb^{-1} at 7 TeV.

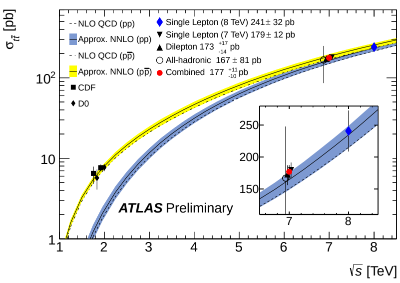

Figure 4: Summary of ATLAS measurements of the $t\bar{t}$ production cross-section at 7 and 8 TeV compared to an approximate NNLO QCD calculations as a function of $\sqrt{s}$.

It is so-called 3-D template method using an approach based on observables $m_{\text{top}}^{\text{reco}}$, $m_{\text{W}}^{\text{reco}}$ and $R_{\text{lb}}^{\text{reco}}$ [23]. The reconstructed top quark mass is found to be

$$m_{\text{top}} = 172.31 \pm 0.75 \text{ (stat+JSF)} \pm 1.35 \text{ (syst) GeV}$$

The first uncertainty corresponds to a combined uncertainty of the statistics, jet energy scale and b-jet energy scale. In ATLAS the analyses on the top quark mass determination are carried out not only in the L+J channel but also in the D-L and A-H channels (see in Ref. [4]). The results of the ATLAS measurements are compared with the CMS and Tevatron results in Figure 5.

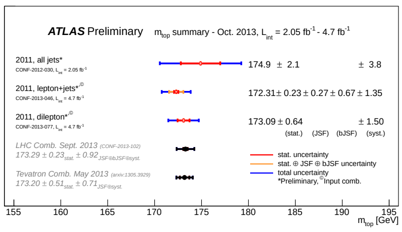

Figure 5: Summary of the ATLAS top quark mass measurements compared with the LHC and Tevatron averages.

5.1 Single top quark results

The single top-quark production occurs via EW interaction. There are three sub-processes contributing to this production: the exchange of a virtual W boson in the t-channel, or in the s-channel, and the associated production of a top quark and an on-shell W boson. The process with the highest expected cross section at the LHC is the t-channel mode.

Among the virtues of the single top quark production are: (1) its cross section is proportional to $\mid V_{tb} \mid^2$, where V_{tb} is an element of the Cabbibo-Kobayashi-Maskawa (CKM) matrix [24] so it enables a direct measurement of this CKM matrix element, (2) charge asymmetry in production of t with respect to $\bar{t}$ is sensitive to the proton u- and d-quark PDFs, and (3) is sensitive to many models of new physics [25]. In addition, the single top quark processes are an important background for Higgs boson studies.

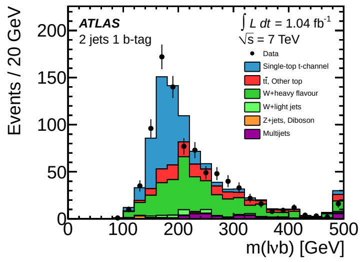

Figure 6: The invariant mass $m(\ell\nu b)$ distribution for the 2-jet b-tagged sample - the signal and different backgrounds are compared.

An example of the ATLAS single top quark studies is the analysis of the t-channel process [26] using 1.04 fb^{-1} of pp collision data at $\sqrt{s}$ = 7 TeV and using 5.8 fb^{-1} at $\sqrt{s}$ = 8 TeV [27]. The study is based on event selection requiring one charged lepton candidate, e or μ, two or three hadronic high-p_{T} jets; and missing transverse momentum $E_{\mathrm{T}}{}^{\mathrm{miss}}$. The measurement of the cross section, σ_t, is based on a fit to a multivariate discriminant constructed with a neural network (NN) to separate signal from background. The most significant background comes from from W-boson production in association with jets .

Energy	σ_t [pb]	$\mid V_{tb} \mid$
7 TeV	83.0 $\pm$ 4(stat) $^{+20}_{-19}$(syst)	$1.13^{+0.14}_{-0.13}$(exp) $\pm$ 4(syst)
8 TeV	95.1 $\pm$ 2.4(stat.) $\pm$18(syst.)	$1.04^{+0.10}_{-0.11}$(exp.)

Table 2: Single top quark production cross sections (σ_t) measured by ATLAS at 7 and 8 TeV and the extracted CKM element $\mid V_{tb} \mid$.

Other significant backgrounds comes from multijet events and $t\bar{t}$ production. Figure 6 shows the invariant mass of the b-tagged jet, the charged lepton, and the neutrino, $m(\ell\nu b)$, for the 2-jet b-tagged sample at 7 TeV. Table 2 shows the t-channel cross sections at $\sqrt{s}$ = 7 and 8 TeV inferred from simultaneous measurements in the 2-jet and 3-jet channels applying a NN-based analysis. Even at 7 TeV the significance of the observed signal corresponds to 7.2σ. The lower limit of $\mid V_{tb} \mid$at 95% C.L. is 0.75 at 7 TeV and $\mid V_{tb} \mid >$ 0.80 at 95% C.L. at 8 TeV.

Measurement of the separate t and $\bar{t}$-quark cross sections, $\sigma_t(t)$ and $\sigma_t(\bar{t})$, was carried out by ATLAS using the data sample of 4.7 fb^{-1} at 7 TeV [28]. The separate cross sections are sensitive to the u- and d-quark PDFs an the SM expectations are $\sigma_t(t) = 41.9^{+1.8}_{-0.8}$ pb and $\sigma_t(\bar{t}) = 22.7^{+0.9}_{-1.0}$ pb. The multivariate technique combining several kinematic variables into one neural network discriminant was used. The obtained cross sections $\sigma_t(t)$ and $\sigma_t(\bar{t})$ are:

$$\sigma_t(t) = 53.2 \pm 1.7(\text{stat.}) \pm 10.7(\text{syst.})\ \text{pb}, \quad \sigma_t(\bar{t}) = 29.5 \pm 1.5(\text{stat.}) \pm 7.3(\text{syst.})\ \text{pb}.$$

The cross sections are, within uncertainties, compatible with the SM expected ones and give the ratio $R_t = \sigma_t(t)/\sigma_t(\bar{t})$ =1.81 $\pm$ 0.10(stat.) $^{+0.14}_{-0.13}$(syst.).

5.2 Top quark properties

Study of the top quark properties enables a test of the SM predictions and search for new physics which can modify the top quark production mechanisms, the Wtb coupling, the top quark decays, etc.

W boson helicity fractions. In the SM (NNLO) the W boson helicity fractions are predicted to be [29]:

$$F_0 = 0.687 \pm 0.005,\ F_{\rm L} = 0.311 \pm 0.005 \text{ and } F_{\rm R} = 0.0017 \pm 0.0001.$$

The fractions F_0, $F_{\rm L}$ and $F_{\rm R}$ are extracted from angular distributions of top quark decay products:

$$\frac{1}{\sigma}\frac{d\sigma}{d\theta^\star} = \frac{3}{4}\left(1 - cos^2\theta^\star\right) F_0 + \frac{3}{8}\left(1 - cos\theta^\star\right)^2 F_{\rm L} + \frac{3}{8}\left(1 + cos\theta^\star\right)^2 F_{\rm R}, \tag{3}$$

where $\theta^\star$ is the angle between the lepton and b-quark reversed momentum in the W boson rest frame. The ATLAS measurement of the W helicity fractions carried out using the data of 1.04 fb^{-1} at 7 TeV and taking into account L+J and D-L events [30] resulted in

$F_0 = 0.67 \pm 0.03 \pm 0.06$, $F_{\rm L} = 0.32 \pm 0.02 \pm 0.02$,
$F_{\rm R} = 0.01 \pm 0.01 \pm 0.04$ ($\pm$stat $\pm$ syst).

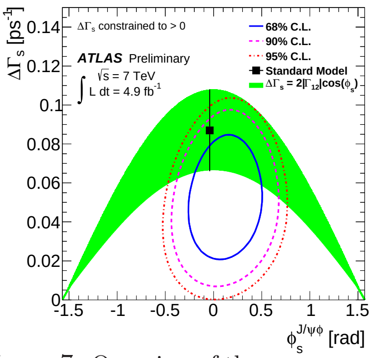

Figure 7: Overview of the measurements included in the combination as well as the results of the combination (see text).

The ATLAS W boson helicity result is compared with other results (CMS, ATLAS dilepton and LHC combination [31]) in Figure 7 giving good agreement of the LHC data with the SM.

Anomalous Wtb couplings. Any deviation of F_0. $F_{\rm L}$ and $F_{\rm R}$ from their SM values is a sign of a new physics. In general the new physics contributing to the Wtb coupling can be generally expressed through an effective lagrangian:

$$L_{Wtb} = \frac{g}{\sqrt{(2)}}\bar{b}\gamma^\mu \left(V_{\rm L}P_{\rm L} + V_{\rm R}P_{\rm R}\right) t \cdot W_\mu^- + \frac{g}{\sqrt{(2)}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}\left(g_{\rm L}P_{\rm L} + g_{\rm R}P_{\rm R}\right) t \cdot W_\mu^+ + h.c.,$$

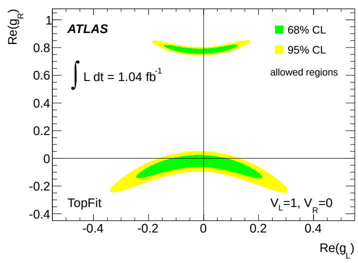

Figure 8: Allowed regions at 68% and at 95% C.L. for the couplings $g_{\rm R}$ and $g_{\rm L}$.

In the SM at tree level $V_{\rm L} = V_{tb} \approx 1$ and $V_{\rm R} = g_{\rm L} = g_{\rm R} = 0$. The limits on the anomalous coupling are inferred from measurement of the helicity fractions using their dependence on the couplings. The ATLAS limits on the anomalous couplings obtained using the data sample of 1.04 fb^{-1} recorded at 7 TeV [30] are shown in Figure 8.

Spin correlation in $t\bar{t}$ events. While the polarization of the t and $\bar{t}$ quarks in $t\bar{t}$ production is predicted to be very small, their spins are predicted be correlated [32]. The analysis carried out by ATLAS [33] uses a data sample of 2.1fb^{-1} collected at 7 TeV. The search was performed in the dilepton topology ($t\bar{t} \to \ell^+\nu\ell^-\bar{\nu}b\bar{b}$) with large $E_{\rm T}^{\rm miss}$ and at least two jets. The observable studied was the azimuthal angle between two leptons, $\Delta\phi$. The measured degree of correlation is found in the helicity and the maximal bases (see details in Ref. [33]):

$$A_{\rm helicity} = 0.40 \pm 0.04({\rm stat.})^{+0.08}_{-0.07},\ \text{the SM expected: } A^{\rm SM}_{\rm helicity} = 0.31$$
$$A_{\rm maximal} = 0.57 \pm 0.06({\rm stat.})^{+0.12}_{-0.10},\ \text{the SM expected: } A^{\rm SM}_{\rm maximal} = 0.44$$

The measured values are compatible within uncertainties with the SM expectations.

Top quark charge. The main issue in the top quark charge study is determination between the SM scenario with decaying top quark having the electric charge of 2/3 (in units of the electron charge magnitude), $t \to W^+ b$, and the exotic one with an exotic quark having the charge of -4/3, $t_X \to W^- \bar{b}$. The study carried out by ATLAS, using the data of 2.05 fb^{-1} at $\sqrt{s}$ = 7 TeV [34], is based on exploiting of the charges of the top quark decay products (W boson and b-quark). The charge of the W boson is determined through charge of the lepton from its leptonic decay ($W^\pm \to \ell^\pm \nu_\ell$). The b-quark charge cannot be determined directly, but it should be correlated with an effective charge of b-jet found using a charge weighting procedure. Within this procedure the charges of tracks belonging to a b-jet cone are weighted using their momentum projection into the b-jet axis giving finally an effective b-jet charge. The observable which is used to distinguish between the SM top quark and the exotic one is $Q_{\text{comb}} = Q_\ell \times Q_{b-\text{jet}}$, where Q_ℓ and $Q_{b-\text{jet}}$ are the charge of lepton and effective charge of b-jet. The lepton and b-jet should come from the same decaying quark, what is provided by fulfilling a lepton b-jet pairing condition based on the lepton–b-jet invariant mass ($m(\ell, b-$jet) which should be (within resolution) less than m_{top}, if lepton and b-jet are top quark decay products. The analysis was performed in the L+J channel and the experimentally observed value is $Q^{\text{obs}}_{\text{comb}}$ = -0.077 ± 0.005, which is in excellent agreement with the SM expected value: $Q^{\text{SM}}_{\text{comb}}$ = -0.075 ± 0.004. For the exotic model a positive value is expected: $Q^{\text{XM}}_{\text{comb}}$ = +0.069 ± 0.004. Taking into account all statistical and systematic uncertainties, the statistical analysis excluded the exotic model with more than 8σ C.L.

From the value of $Q^{\text{obs}}_{\text{comb}}$ assuming the b-quark charge of -1/3, the value of the top quark charge was inferred: Q_{top} = 0.64 ± 0.02 (stat.) ± 0.08 (syst.)

6 Study of b-quark results

Study of B-physics is interesting from many respects but the most attractive are processes connected with the violation of CP symmetry and with the physics beyond the SM.

Dimuon decay of B^0_{S} meson. The decay $B^0_{\text{S}} \to \mu^+\mu^-$ is highly suppressed in the SM and its branching ratio $BR(B^0_{\text{S}} \to \mu^+\mu^-) = (3.5\pm\ 0.3)\times 10^{-9}$. To observe a deviation from the SM branching would mean a manifestation of a new physics. The ATLAS analysis of this decay is based on a dimuon trigger using a data sample of 4.9 fb^{-1} at 7 TeV [35]. The branching $BR(B^0_{\text{S}} \to \mu^+\mu^-)$ is measured with respect to the well-known reference decay $B^\pm \to J/\psi K^\pm$.

The main background comes from $b\bar{b} \to \mu^+\mu^- X$ and from b-hadron decay with one or two hadrons misidentified as muons. Multivariate technique using a Boosted Decision Tree (BDT) was applied to select candidate events. The discriminating variable used by the BDT takes into account that the decay vertex of $B^0_{\text{S}} \to \mu^+\mu^-$ is separated from event primary vertex and that it is two body decay. Using the full data sample at 7 TeV the extracted limits are:

$$BR(B^0_{\text{S}} \to \mu^+\mu^-) < 1.5\ \times 10^{-8} \text{ at 95\% C.L.}$$

After inclusion of the data sample of 21 fb^{-1} at 8 TeV a comparable result with those obtained by LHCb [36] and CMS [37], i.e. to see a value of the branching not only a limit, is expected.

Cross section of b-hadron production. The b-hadron cross section was measured by ATLAS using the data sample of 3.3 pb^{-1} collected at collision energy of 7 TeV. The events were selected using the single muon trigger with a p_{T} threshold of 6 GeV [38]. The analysis is based on partially reconstructed b-hadron decay final state $D^{*+}\mu^- X$ with $D^{*+} \to \pi^+ D^0\ (\to K^-\pi^+)$. The measured integrated b-hadron cross section for $p_{\text{T}}(H_b) > 9$ GeV and $\mid \eta(H_b) \mid < 2.5$ is

$$\sigma(pp \to H_b X) = 32.7 \pm 0.8(\text{stat.})$$
$$\pm\, 3.1(\text{syst.})\ {}^{+2.1}_{-5.6}(\alpha) \pm 2.3(\text{BR}) \pm 1.1(\text{lumi.})\ \mu\text{b},$$

where in addition to the statistical and systematic uncertainties are explicitly shown the uncertainties connected with the decay acceptance (α), the branching ratio (BR) and the luminosity (lumi.).

Comparison with the theoretical calculation shows good agreement as is demonstrated in figure 9. The measured cross section is slightly higher than that of the theoretical model, but still within the uncertainties (for details see ref. [38]).

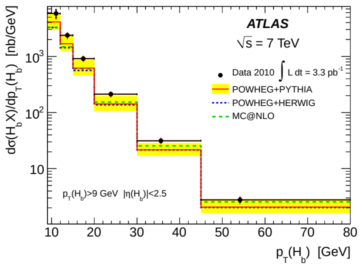

Figure 9: Differential b-hadron cross section as a function of its $p_{\mathrm{T}}(H_b)$ and $|\eta(H_b)|$, the cross section is compared with those of the theoretical approaches.

Angular analysis of $B_d^0 \to K^{*0}\mu^+\mu^-$. The decay $B^0 \to K^{*0}\mu^+\mu^-$ with $K^{*0} \to K^+\pi^-$ is a FCNC decay which in the SM is forbidden at tree level and goes only through loops, giving the branching BR=$(1.06 \pm 0.1)\times 10^{-6}$ [1]. The analysis of this decay takes into account the invariant mass of $\mu^+\mu^-$-pair (q^2) and three angles θ_{L}, θ_{K} and ϕ (θ_{L} is the angle between the μ^+ and the direction opposite to the B_d^0 in the di-muon rest frame, θ_{K} is the angle between the K^+ and the direction opposite to the B_d^0 in the K^{*0} rest frame, and ϕ is the angle between the plane defined by the two muons and the plane defined by the kaon-pion system in the B_d^0 rest frame). The result of analysis is K^{*0} longitudinal polarisation fraction, F_{L}, and the lepton forward-backward asymmetry, A_{FB}, extracted from the angular distribution of the decay products:

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{dq^2 d\cos\theta_{\mathrm{L}}} = \frac{3}{4}F_{\mathrm{L}}\left(1-\cos^2\theta_{\mathrm{L}}\right) + \frac{3}{8}F_{\mathrm{L}}\left(1+\cos^2\theta_{\mathrm{L}}\right) + A_{\mathrm{FB}}\cos\theta_{\mathrm{L}}, \tag{4}$$

where Γ is the decay length and a similar distribution can be written also for the angle θ_{K}. The analysis was carried out using the data sample of 4.9 fb^{-1} recorded at 7 TeV [39]. A likelihood fit was applied to the angular distributions and the quantities F_{L} and A_{FB} were found for six q^2 bins. Table 3 shows the measured ATLAS values of F_{L} and A_{FB} as a function of q^2. The values are in good agreement with the BaBar, Belle, CDF and LHCb experiments (for details see ref. [39]) as well as with the theoretical predictions.

q^2 bin (GeV^2)	A_{FB}	F_{L}
$2.00 < q^2 < 4.30$	$0.22 \pm 0.28 \pm 0.14$	$0.26 \pm 0.18 \pm 0.06$
$4.30 < q^2 < 8.68$	$0.24 \pm 0.13 \pm 0.01$	$0.37 \pm 0.11 \pm 0.02$
$10.09 < q^2 < 12.86$	$0.09 \pm 0.09 \pm 0.03$	$0.50 \pm 0.09 \pm 0.04$
$14.18 < q^2 < 16.00$	$0.48 \pm 0.19 \pm 0.05$	$0.28 \pm 0.16 \pm 0.03$
$16.00 < q^2 < 19.00$	$0.16 \pm 0.10 \pm 0.03$	$0.35 \pm 0.08 \pm 0.02$
$1.00 < q^2 < 6.00$	$0.07 \pm 0.20 \pm 0.07$	$0.18 \pm 0.15 \pm 0.03$

Table 3: Summary of the fit results: the extracted asymmetry A_{FB} and longitudinal polarisation F_{L} for different bins in q^2 including the statistical and systematic uncertainties.

Study of CP violation in $B_{\mathrm{S}}^0 \to J/\psi\phi$.

In the decay $B_{\mathrm{S}}^0 \to J/\psi(\mu^+\mu^-)\phi \to K^+K^-$ the CP violation is a result of interference between the $B_{\mathrm{S}} - \bar{B}_{\mathrm{S}}$ mixing followed by $\bar{B}_{\mathrm{S}}$ decay and the direct $B_{\mathrm{S}}(\to J/\psi\phi)$ decay. The CP violation phase ϕ_{S} is a phase difference between the mention amplitudes. The SM expectation is $\phi_{\mathrm{S}}^{\mathrm{SM}} \approx -0.0363^{+0.0016}_{-0.0015}$ [40]. The ATLAS study was carried out at 7 TeV using the data sample of 4.9 fb^{-1} [41]. The trigger used to select events requires two opposite charge muons identifying a $J/\psi \to \mu^+\mu^-$ decay.

The final state of B_S^0 decay was analyzed with the aim to disentangle CP-even states (CP = 1) corresponding to an orbital momentum $L = 0$ or 2 and CP-odd states (CP = -1). The analysis was performed in the transversity coordinate system (for details see ref. [41]) and resulted in extraction of several physical parameters among them ϕ_S and $\Delta\Gamma_S$ (the width difference between the heavy and light mass eigenstates of B_S^0 meson). The extracted values are:
$\phi_S = 0.12 \pm 0.25(\text{stat.}) \pm 0.11(\text{syst.})$ rad,
$\Delta\Gamma_S = 0.053 \pm 0.021(\text{stat.}) \pm 0.009(\text{syst.})\ \text{ps}^{-1}$.
Figure 10 shows that the obtained values for ϕ_S and $\Delta\Gamma_S$ are consistent, within uncertainties, with the SM expectations.

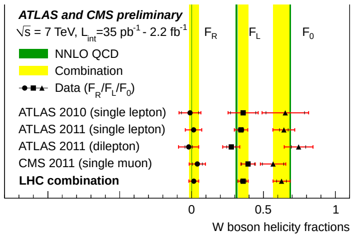

Figure 10: Likelihood contours in ϕ_S - $\Delta\Gamma_S$ plane. The blue and red contours show the 68% and 95% likelihood contours, respectively. The green band is the SM prediction of mixing-induced CP violation.

Production cross section of upsilonia. Study of Υ(nS), $b\bar{b}$ bound states, is an important test of QCD. The dominant production mechanism is gluon fragmentation. The ATLAS measurement is carried out using the data of 1.5 fb^{-1} at 7 TeV [42]. The analysis is based on reconstruction of the dimuon decay mode. Total production cross sections for Υ(1S), Υ(2S), Υ(3S) and differential cross sections as a function of upsilonium p_T and η are measured. The measured integrated cross sections are summarized in Table 4. The study also provides the differential cross sections of Υ(1S), Υ(2S) and Υ(3S) as functions of p_T for $|\ \eta\ | < 1.2$ (see for details in ref. [42]).

State	$\sigma(pp \to \Upsilon)\times\text{Br}(\Upsilon \to \mu^+\mu^-)$
Υ(1S)	8.01 ± 0.02 ± 0.36 ± 0.31 [nb]
Υ(2S)	2.05 ± 0.01 ± 0.12 ± 0.08 [nb]
Υ(3S)	0.92 ± 0.01 ± 0.07 ± 0.04 [nb]

Table 4: The integrated production cross section of upsilonia for the kinematic range: $p_T <$ 70 GeV and $|\ \eta\ | < 2.25$, with the statistical, systematic and luminosity uncertainties.

7 Bibliography

References

[1] J. Beringer et al., Phys. Rev. D**86**, 010001 (2012).

[2] The ATLAS Experiment at the CERN Large Hadron Collider, 459 JINST **3**, (2008) S08003.

[3] ATLAS Collaboration, ATLAS-CONF-2013-012.

[4] ATLAS public web page, https://twiki.cern.ch/twiki/bin/view/AtlasPublic

[5] CMS public web page, http://cms.web.cern.ch/org/cms-papers-and-results

[6] B. de Carlos and J. A. Casas, Phys. Lett. B309(1993) 320328

[7] A. Djouadi, Physics Reports **459**, 1-241 (2008).

[8] P. Fayet and S. Ferrara, Physics Reports **32**, 249 (1977).

[9] N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Physics Letters **B429**, 263 (1998).

[10] ATLAS Collaboration, PRD 88, 072001 (2013), arXiv.1308.4075v1.

[11] E. Eichten, K. Lane, A. Martin, and E. Pilon, Phys.Rev. D86 (2012) 074015

[12] ATLAS Collaboration, Search for a dijet resonance produced in association with a leptonically decaying W or Z boson with the ATLAS detector at $\sqrt{s}$ = 8 TeV, ATLAS-CONF-2013-074.

[13] M. Czakon, P. Fiedler and A.Mitov, Phys.Rev.Lett. 110 (2013) 252004, arXiv:1303.0693 [hep/ph]

[14] Phys.Rev.D 83, 091503(R) (2011), Phys.Rev.D 82, 054028 (2010), Phys.Rev.D 82, 054028 (2010)

[15] Czarnecki et al., Nucl. Phys. B544 (1999) 520.

[16] ATLAS Collaboration, ATLAS-CONF-2012-149.

[17] ATLAS Collaboration, arXiv:1012.1792 [hep-ex], Eur. Phys. J. C71 (2011), 1577.

[18] CMS collaboration, CMS PAS TOP-12-006

[19] CMS collaboration, CMS PAS TOP-12-007

[20] ATLAS Collaboration, ATLAS-CONF-2012-024, ATLAS Collaboration, ATLAS-CONF-2012-131, ATLAS Collaboration, EPJ C73 (2013) 2328, ATLAS Collaboration, PLB717 (2012) 89, ATLAS Collaboration, ATLAS-CONF-2012-031.

[21] M. Aliev et al., Comput.Phys.Commun. 182 (2011) 1034-1046.

[22] ATLAS Collaboration, Eur. Phys. J. C (2013) 73: 2261.

[23] ATLAS Collaboration, ATLAS-CONF-2013-046.

[24] M. Kobayashi, T. Maskawa, Prog. Theor. Phys. 49 (1973).

[25] T. M. P. Tait, C. P. Yuan, Phys. Rev. D 63 (2000) 014018, [arXiv:hepph/0007298].

[26] ATLAS Collaboration, Physics Letters B 717 (2012) 330-350.

[27] ATLAS Collaboration, ATLAS-CONF-2012-132.

[28] ATLAS Collaboration, ATLAS-CONF-2012-056.

[29] A. Czarnecki, J. Korner, J. Piclum, Phys. Rev. D 81 (2010)111503, ArXiv:10005.2625[hep-ph].

[30] ATLAS Collaboration, JHEP 1206(2012) 088.

[31] ATLAS and CMS Collaborations, Combination of the ATLAS and CMS measurements of the W-boson polarization in top-quark decays, ATLAS-CONF-2013-033, CMS PAS TOP-12-025

[32] W. Bernreuther and Z. G. Si, Nucl. Phys. B 837,90(2010).

[33] ATLAS Collaboration, Phys. Rev. Lett 108, 212001(2012)

[34] ATLAS Collaboration, arXiv:1307.4568v2, accepted to JHEP.

[35] ATLAS Collaboration, ATLAS-CONF-2013-076.

[36] LHCb collaboration, Measurement of the $B_s^0 \to \mu^+\mu^-$ branching fraction and search for $B^0 \to \mu^+\mu^-$ decays at the LHCb experiment, arXiv:1307.5024, submitted to Phys. Rev. Lett.

[37] CMS collaboration, Measurement of the $B_s^0 \to \mu^+\mu^-$ branching fraction and search for $B^0 \to \mu^+\mu^-$ with the CMS experiment, arXiv:1307.5025, submitted to Phys. Rev. Lett.

[38] ATLAS Collaboration, Nucl.Phys.B864(2012)341.

[39] ATLAS Collaboration, ATLAS-CONF-2013-038.

[40] UTfit Collaboration, M. Bona et al., Phys.Rev.Lett. 97 (2006) 151803, arXiv:hep-ph/0605213 [hep-ph].

[41] ATLAS Collaboration, ATLAS-CONF-2013-039.

[42] ATLAS Collaboration, Phys. Rev. D 87, 052004(2013)