EPJ Web of Conferences **71**, 00047 (2014)
DOI: 10.1051/epjconf/20147100047

Single top-quark production cross-section at the LHC in ATLAS

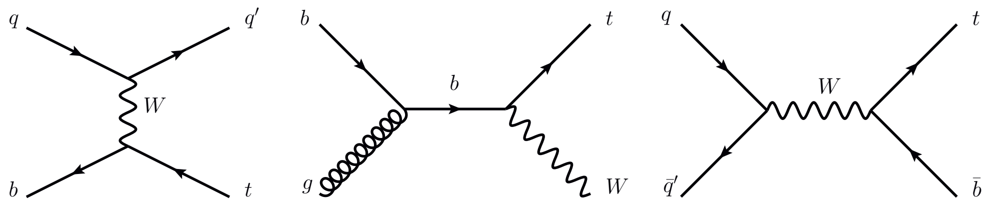
Conrad Friedrich[1,a] on behalf of the ATLAS collaboration

[1] *Deutsches Elektronen-Synchrotron (DESY), Platanenallee 6, 15738 Zeuthen, Germany*

Abstract. Measurements of the single top-quark production cross-sections with the ATLAS detector in pp collisions at the Large Hadron Collider (LHC) are presented. Results of measurements of single top-quark production in the t- and Wt-channel, as well as the determination of the CKM matrix element $|V_{tb}|$ are shown. Further, the separate measurement of the top- and antitop-quark t-channel production cross-section and the ratio of the two are presented, and several searches for exotic processes in single top-quark production are discussed. The latter include results from searches for flavour changing neutral currents, extra heavy charged gauge bosons (W'), excited quarks, and searches for anomalous CP-violating couplings in the Wtb vertex.

1 Introduction

At hadron colliders top-quarks are produced predominantly in the form of top- / antitop-quark ($t\bar{t}$) pairs in strong interactions. On the other hand, the Standard Model (SM) predicts top-quarks to be produced singly in three electroweak subprocesses via charged-current interactions in the Wtb vertex and at rates approximately half as high as those of the $t\bar{t}$ production. The three subprocesses of single top-quark production are categorised by the virtuality of the exchanged W-boson: the t-channel or s-channel production involves the exchange of a virtual (space-like or time-like) W-boson and the Wt-channel stands for the associated production of a single top-quark and a real (on-shell) W-boson. The leading-order Feynman diagrams of all three subprocesses are shown in Fig. 1.



(a) (b) (c)

Figure 1: Leading order Feynman diagrams for single top-quark production in the t-channel (a), Wt-channel (b) and s-channel (c).

---

[a] e-mail: conrad.friedrich@cern.ch

Table 1: Theory predictions for the cross-sections of single top-quark production in the t-,Wt-, and s-channel, calculated at (approximate) next-to-next-to-leading order (NNLO) [1–3].

process	σ_{theo} 7 TeV [pb]	σ_{theo} 8 TeV [pb]
t-channel	$64.6^{+2.6}_{-1.7}$	$87.8^{+3.4}_{-1.9}$
Wt-channel	15.7 ± 1.2	22.4 ± 1.5
t-channel	4.6 ± 0.2	5.6 ± 0.2

In contrast to single top-quark production at the Tevatron, where the t- and s-channel productions occurred at similar rates and the Wt-channel had an expected cross-section too small to be observed, the LHC energy provides sensitivity to investigate all three production processes. At the LHC, by far the most dominant subprocess is the t-channel production, followed by the Wt-channel and s-channel production processes. The respective theory cross-section predictions for pp collisions at the LHC are summarised in Table 1, for centre-of-mass energies of 7 and 8 TeV respectively. With a mass close to the electroweak symmetry breaking scale and its short life time, about 20 times smaller than the hadronisation time scale, the top-quark provides a unique probe for testing the SM predictions and for searches of physics beyond the SM. Studies of the properties and production cross-sections of single top-quark allow for a detailed testing of the Wtb vertex, for constraining the b-quark parton distribution function (PDF), and for measuring the up- to down-quark PDF ratio in the proton. Furthermore, the $|V_{tb}|$ element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix can be directly determined from the cross-section measurements which allows to test its unitarity. The single top-quark final state is a key to searches for physics beyond the SM. Many new physics models introduce additional particles which the top-quark could be a decay product of or could be coupling to. Any deviation of the observed top-quark properties, the production cross-sections or of the unitarity of the CKM matrix from the SM prediction provides a strong indicator for new physics, such as the existence of fourth generation fermions or the production of extra heavy gauge boson. New physics could emerge as well through the observation of anomalous couplings of top-quarks to the known SM particles, e.g. in CP-violating right-handed tensor couplings or flavour-changing neutral currents (FCNC).

The presented analyses are based on collision data taken with the ATLAS detector at the LHC in 2011 and 2012. ATLAS is a multi-purpose detector composed of an inner tracking system close to the interaction point, surrounded by a superconducting solenoid which provides a 2 T axial magnetic field, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer within a 0.5 T magnetic field from three superconducting toroids [4].

2 Event selection and background estimation

This section provides an overview of the basic event selection and background estimation common to all analyses introduced. Top-quarks decay almost 100% to a W-boson and a b-quark, where the former may undergo either a leptonic or hadronic decay. Since the hadronic mode is leading to a final state usually hard to distinguish from background, most single top-quark analyses make use of the leptonic (or dileptonic) decay channel. This contribution discusses only leptonic decays of W-bosons for the single top-quark event selection where backgrounds due to hadronic activity are small.

Events are selected using single lepton triggers with high transverse momentum thresholds. The leptons candidates are required to have a transverse momentum $p_{\text{T}} > 25$ GeV, and must be produced within a pseudorapidity $|\eta| < 2.5$. All selected leptons also have to fulfil isolation criteria with respect to energy depositions in the calorimeter and close-by reconstructed tracks. Jets are reconstructed using the anti-kt algorithm [5] with a radius parameter $R = 0.4$. Depending on the analysis and decay channel, jet candidates are required to have $p_{\mathrm{T}} > 25$ GeV or > 30 GeV, and to have $|\eta| < 2.5$ or $|\eta| < 4.5$. With the exception of the Wt-channel cross-section measurement, all presented analyses require at least one jet to be tagged as a b-quark jet. The tagging algorithms used are based on a neural network to combine several subalgorithms using information on the tracks associated to each jet and the reconstructed jet vertex, as well as on the the flight path topology of the b-hadron decay chain. The analyses usually use b-tagging working points ranging from 50% to 70% efficiency corresponding to a misidentification probability of roughly 1/500. The missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) is reconstructed from the vector sum of the transverse momenta of all physics objects, including soft jets and the transverse energy of calorimeter cells not associated to any physics object. Neutrinos in the final states are reconstructed from the $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$-vector in the events with their momenta along the beam direction derived using a W-boson mass constraint. To further reduce multijet background, usually a cut on the transverse mass of the reconstructed W-boson, $m_T(W)$[1], is applied. Further details on the object definition and reconstruction can be found in the respective references of the analyses presented here [6–8].

For single top-quark studies in ATLAS two types of backgrounds exist. One type originates from different SM production processes constituting a similar event signature. The other type, QCD multi-jet or fake events, is due to events arising from the mis-identification of physics objects, in particular jets reconstructed as leptons. The most dominant backgrounds are W-boson or Z-boson productions in association with (heavy flavour) jets, top-quark pair ($t\bar{t}$) and diboson production. Their kinematic shapes are obtained from MC simulations which are normalised to their respective NLO or NNLO theory cross-section prediction. In most of the presented analyses, the flavour composition and overall normalisation of the W+jets background is derived from data. Models for the multijet background are obtained using data-driven techniques by employing two different methods. The first, so-called matrix method, relates the reconstructed leptons in data events to either real or misidentified leptons by applying two different sets of lepton identification criteria. A shape template and its overall normalisation are obtained by making use of efficiencies for real and fake leptons to pass the looser or both selection criteria which were measured in control regions in data. Secondly, the jet-electron model is used, which derives a shape for the multijet background by selecting observed or simulated events with similar kinematics to the signal selection, but using jets with electron-like energy depositions in the calorimeter in place of the usual requirements for electron candidates. The obtained templates are normalised in a binned maximum-likelihood fit to data in the full $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution, together with the templates from all other MC simulated backgrounds.

3 Single top cross-section and $|\mathrm{V_{tb}}|$ measurements

In order to test the SM predictions, the precise measurement of the cross-section in each of the three production channels is one of the major tasks in single top-quark physics. Since all production channels involve a Wtb vertex, the cross-section measurements allows to impose direct constraints on the CKM matrix element $|V_{tb}|$.

3.1 t-channel cross-section measurements

The single top-quark t-channel production cross-section has been measured by ATLAS at both 7 TeV and 8 TeV centre-of-mass energies in the leptonic decay channel. t-channel production was first ob-

[1] The W-boson transverse mass is reconstructed from the lepton-$E_{\mathrm{T}}^{\mathrm{miss}}$ system as $m_T^2(W) = 2p_T E_{\mathrm{T}}^{\mathrm{miss}}\left[1 - \cos\left(\Delta\phi\left(\vec{l}, \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right)\right)\right]$, where p_{T} is the transverse momentum of the lepton and $\Delta\phi$ the azimuthal angle between the $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ vector and lepton direction.

served in ATLAS in 2011 using data of pp collision events at $\sqrt{s} = 7$ TeV corresponding to an integrated luminosity of $156\,\text{pb}^{-1}$ [9]. Later the analysis was updated using a larger dataset of the 2011 run corresponding to an integrated luminosity of $1.04\,\text{fb}^{-1}$ [10]. The event selection requires exactly one lepton of $p_\text{T} > 25$ GeV in the central pseudorapidity region of the detector ($|\eta| < 2.5$) and a missing transverse momentum of $E_\text{T} > 25$ GeV. In the t-channel jets with a p_T above 25 GeV are selected in an extended pseudorapidity range of $|\eta| < 4.5$ to account for the light (spectator) quark predominantly scattered in the forward direction. Exactly two or three jets are required in the final state of which at least one has to be tagged as a b-quark jet. An additional cut on the $m_T(W) + E_\text{T}^\text{miss}$-system at > 60 GeV is applied to further suppress the multijet background.

To discriminate signal from background events a multivariate analysis (MVA) using neural network (NN) techniques is applied separately to two samples of selected events with exactly two or three jets in the final state. For each jet category a neural network is trained using simulated events in the 12 (2-jet) or 18 (3-jet final state) highest ranked variables. These include e.g. the combined invariant mass of the lepton, b-jet and neutrino ($m_{\ell b\nu}$), $|\eta|$ or E_T of the highest p_T light jet, and angular differences between different final state objects. The resulting NN output distribution from applying the trained networks on data in the 2-jet final state is shown in Fig. 2 (a). Towards larger discriminator values a clear signal excess can be observed. The dominant backgrounds is W+jets production, in particular where jets originate from heavy flavour (HF), followed by $t\bar{t}$ production which becomes more important in the 3-jet final state. The multijet background is estimated from the jet-electron model using data, while all other backgrounds, except the W+jets background, are obtained from MC simulation normalised to their respective theory cross-section predictions. The heavy flavour composition of the W+jets sample is derived from data. The signal cross-section is determined from a combined template fit on the full NN output distributions of the 2-jet and 3-jet samples using a maximum likelihood method, from which the overall normalisation of the W+jets background is obtained simultaneously. The resulting cross-section at $\sqrt{s} = 7$ TeV is measured to be

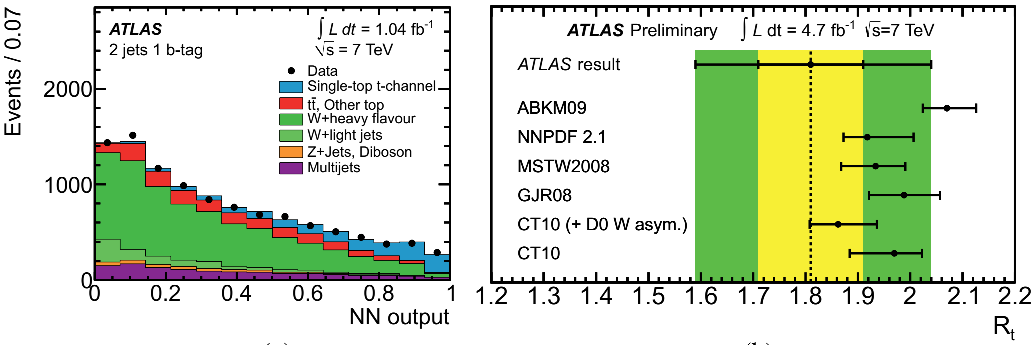
$$\sigma_t = 83 \pm 4\,(\text{stat.})\,^{+20}_{-19}\,(\text{syst.})\ \text{pb}\,,$$

which is in agreement with the SM predictions. The expected and observed significance of this measurement are determined using pseudo-experiments and amount to $6\,\sigma$ and $7.2\,\sigma$, respectively. The dominant systematic uncertainties arise mainly from the modelling of the initial and final-state radiation (ISR/FSR) (14%), the b-tagging efficiency (13%) and the jet energy scale (6%).

A similar analysis using the full 2011 7 TeV dataset corresponding to an integrated luminosity of $4.7\,\text{fb}^{-1}$ was performed to separately measure the t and $\bar{t}$ cross-section and their ratio [6]. The ratio $R_t = \sigma_t/\sigma_{\bar{t}}$ reflects the density of up and down-type quarks in the proton, given by their respective PDF. The expected ratio in the t-channel is roughly two for typical momentum fractions of x=[0.02,0.5] at the LHC energies. The charge of top-quark produced is reflected in the charge of the W-boson and its subsequent decay products. Keeping the event selection mostly similar to the 7 TeV cross-section analysis described above, separate neural networks are trained for the 2-jet and 3-jet categories and for samples of events with a positive or negative charged lepton in the final state respectively. Similarly, the signal cross-section is determined from a combined maximum likelihood fit on the full NN output distributions of the 2-jet and 3-jet samples, but for both lepton categories individually. The resulting cross-sections are determined as

$$\sigma_t = 53.2 \pm 1.7\,(\text{stat.}) \pm 10.6\,(\text{syst.})\ \text{pb} \quad \text{and}$$
$$\sigma_{\bar{t}} = 29.5 \pm 1.5\,(\text{stat.}) \pm 7.3\,(\text{syst.})\ \text{pb}\,,$$

which agree with the SM predictions and are compatible with the result of the former 7 TeV cross-section analysis. The largest systematic uncertainties for the individual cross-sections are jet energy



(a) (b)

Figure 2: (a) Neural network output distribution in the 2-jet bin signal sample in the 7 TeV t-channel cross-section analysis. The simulated backgrounds are normalised to the result of the final maximum-likelihood cross-section fit, the multijet background to the fit in the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution [10]. (b) Measured R_t value (top) and calculated values for different NLO PDF sets. The green error band denotes the combined statistical and systematic uncertainty of the measurement, the yellow error band the statistical uncertainty only [6].

scale (16/20%), followed by the b-tagging efficiency (6/9%) and MC generator modelling uncertainties (7%). The differences in their type and magnitude with respect to the earlier (combined) 7 TeV t-channel analysis arise from e.g. constraints on the ISR/FSR uncertainty using measurements of the jet activity and shape in observed $t\bar{t}$ events, or from differences in the kinematic variables used as input to the neural networks. The cross-section ratio is determined to be

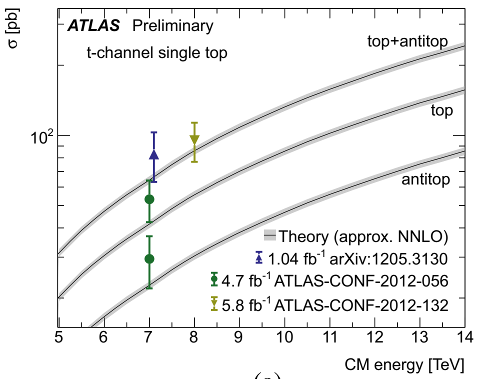
$$R_t = 1.81 \pm 0.10\,(\text{stat.})\,^{+0.21}_{-0.20}\,(\text{syst.})\,,$$

which is in agreement with predictions from theory calculations at next-to-leading order using different PDF sets as shown in Fig. 2 (b). As the systematic uncertainties largely cancel out in the ratio, the dominant uncertainty on the R_t measurement is statistical, with small contributions of systematic uncertainties on the background normalisations (5%), ISR/FSR (5%) and the jet energy scale (4%).

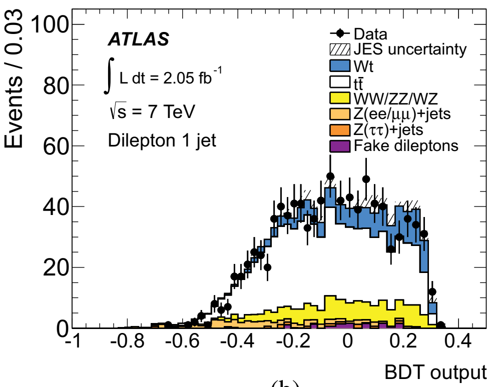
The cross-section measurement has been repeated with 5.8 fb^{-1} of 8 TeV data using a similar analysis strategy in 2012 [7]. Tighter cuts are applied in the event selection to account for the conditions of increased centre-of-mass-energy and higher pile-up. Jets are selected with $p_{\mathrm{T}} > 30$ GeV and the requirement on the missing transverse momentum was raised to $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV. To suppress the multijet background the transverse mass constructed from the lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ is required to be $m_T(W) > 50$ GeV. The modelling of the different backgrounds is done with the same methods as used in the previous 7 TeV analysis. Similarly, separate neural networks are trained on simulated events in the two and three jet categories, using eleven different variables as their input respectively. The measured cross-section for t-channel single top-quark production at $\sqrt{s} = 8$ TeV is

$$\sigma_t = 95 \pm 2\,(\text{stat.}) \pm 18\,(\text{syst.})\ \text{pb}\,,$$

which is in good agreement with the theory prediction. As for the 7 TeV measurement, the result is dominated by systematic uncertainties, the largest of which are the modelling of the ISR/FSR (9%), the b-tagging efficiency (9%) and the jet energy scale (8%). A summary of all presented measurements of the t-channel production cross-sections is shown in Fig. 3 (a).



(a)



(b)

Figure 3: (a) Summary of ATLAS single top-quark cross-section measurements in the t-channel at $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 8 TeV [6], and (b) $\sqrt{s}$ = 7 TeV Wt-channel analysis: BDT output for selected events in the 1-jet category with the Wt-channel signal normalised to the theory prediction [8].

3.2 Wt-channel cross-section measurement

First evidence for single top-quark production in the Wt-channel at the LHC was found by ATLAS in an analysis using 2.05 fb^{-1} of data from pp collision events at $\sqrt{s}$ = 7 TeV [8]. The Wt-channel provides an event signature with two leptons in the final state, in addition to the common single-leptonic decay channel. This allows for an efficient suppression of the dominant W+jets and multijet backgrounds. Consequently events are selected which have exactly two isolated, central ($|\eta| < 2.5$) and oppositely charged leptons with $p_T > 25$ GeV, at least one jet with $p_T > 30$ GeV within $|\eta| < 2.5$, and a substantial amount of missing transverse momentum of $E_T^{miss} > 50$ GeV to account for the two final state neutrinos from the leptonic decays of both W-bosons. No b-tagging requirement is imposed since it was not found to improve the sensitivity of the measurement. Additional cuts on the angular separation between the leptons and the E_T^{miss} vector and on the invariant dilepton mass are employed to veto against events from Z-bosons decaying leptonically in association with the production of additional jets. A multivariate analysis using boosted decision trees (BDTs) as an event classifier is applied to three disjoint samples of events with exactly one, exactly two or at least three jets in the final state. A single BDT is trained with the events from the 1-jet category using 22 different variables, the most sensitive one, p_T^{sys}, being the magnitude of the vectorial sum of the transverse momenta of the leading jet, leptons and the missing transverse momentum. The trained BDT is then applied to the different event sample, where only the BDT output of the 1-jet category is used for the actual signal extraction since it provides the highest signal-to-background ratio, see Fig. 3 (b). The BDT outputs from the other two samples are used to constrain the uncertainties of the different background contributions, in particular that of the dominant top-quark pair production background. To extract the signal cross-section a profile likelihood fit is applied to the BDT output resulting in an estimated cross-section of

$$\sigma_{Wt} = 16.8 \pm 2.9\,(\text{stat.}) \pm 4.9\,(\text{syst.})\ \text{pb}\,,$$

which provides the first evidence of single top-quark Wt-channel production at the LHC with a significance of 3.3σ (obs.) and 3.4σ (exp.). The result is in good agreement with theory predictions. The largest uncertainties arise from the statistical uncertainty of the data sample (17%), from systematic uncertainties of the jet energy scale (16%) and the parton shower and MC generator modelling (15%).

3.3 Determination of the $|V_{tb}|$ CKM matrix element

Since the production of single top-quarks in all three production channels is mediated via the Wtb vertex, the CKM matrix element $|V_{tb}|$ can be directly extracted, since the measured cross-section is proportional to $|V_{tb} \cdot f|^2$, where f is the coupling. Assuming $|V_{tb}| >> |V_{td}|, |V_{ts}|$ and assuming a left-handed weak coupling structure in the Wtb vertex like in the SM ($f = 1$), $|V_{tb}|$ can be calculated from the ratio of measured and predicted cross-sections. However, no assumptions on the number of fermion generations is necessary, which allows to probe the unitarity of the CKM matrix and hence to test higher fermion generation hypotheses. The value for $|V_{tb}|$ has been calculated from both, 7 and 8 TeV t-channel, and the Wt-channel cross-section measurements and show good agreement with the Standard Model predictions. Assuming the range of $|V_{tb}|$ lies within the interval [0,1] as required in the SM, lower limits are extracted from the t-channel cross-section measurements. All results discussed above are summarised in Table 2.

Table 2: Determined values of the $|V_{tb}|$ CKM matrix elements (for f=1) and lower 95% CL limits for $|V_{tb}| \in [0, 1]$.

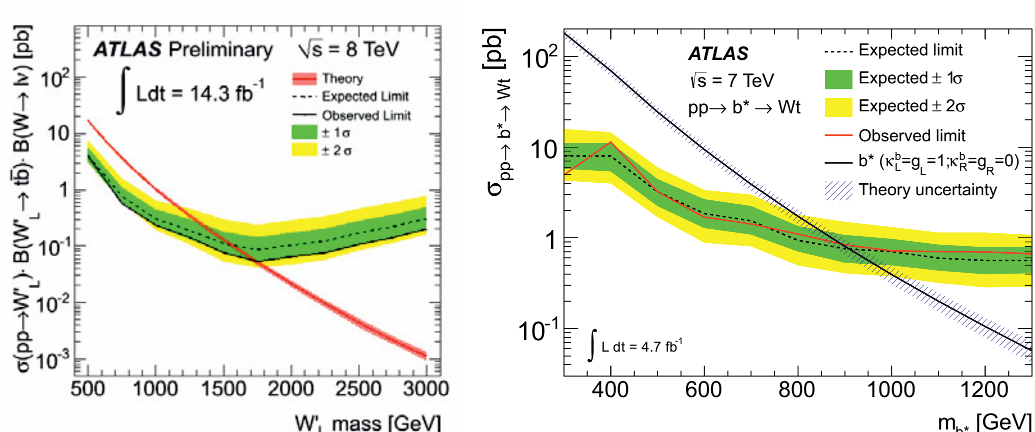
Measurement	$\|V_{tb}\|$	$\|V_{tb}\|$ 95% CL
7 TeV t-channel	$1.13^{+0.14}_{-0.13}$	> 0.75
8 TeV t-channel	1.04 ± 0.11	> 0.80
7 TeV Wt-channel	$1.03^{+0.16}_{-0.19}$	

4 Searches for physics beyond the Standard Model

The cross-section and $|V_{tb}|$ measurements described above can be seen as indirect and model-independent probes for physics beyond the SM. In addition, the three single top-quark production topologies offer various possibilities to search for certain classes of new physics models in a more direct approach. In the following sections four examples of recent analyses are presented, which search for different resonance-type interactions or anomalous couplings involving single top-quarks.

4.1 Search for heavy extra W' gauge bosons

New charged vector currents mediated by additional heavy charged gauge bosons (W') are predicted by several new physics models and were searched for in ATLAS [11] using 14.3 fb^{-1} of 8 TeV collision data. The analysis searches for t-b-resonances in the s-channel originating from a $W' \to tb \to \ell \nu bb$ decay, where both right-handed and left-handed W-boson chiralities are considered. The hadronic W' decay is in particular sensitive to leptophobic models and thereby complements searches in the leptonic decay channel which are mostly insensitive to these. Events are selected by requiring exactly one isolated and central ($|\eta| < 2.5$) lepton with $p_{\mathrm{T}} > 30$ GeV, missing transverse momentum and exactly two or three central ($|\eta| < 2.5$) jets with $p_{\mathrm{T}} > 25$ GeV, of which both have to be tagged as a b-jet. The analysis employs multivariate techniques based on boosted decision trees which were trained



(a) (b)

Figure 4: Observed and expected 95% CL limits on, (a) the left-handed W'-boson cross-section times branching ratio, as a function of the W'-boson mass, compared to the respective theory predictions (red) [11], and (b) on the cross-section times branching ratio for the production of excited b^*-quark via strong interactions in a purely left-handed coupling scenario as a function of the b^*-quark mass, compared to the respective theory predictions (red) [12].

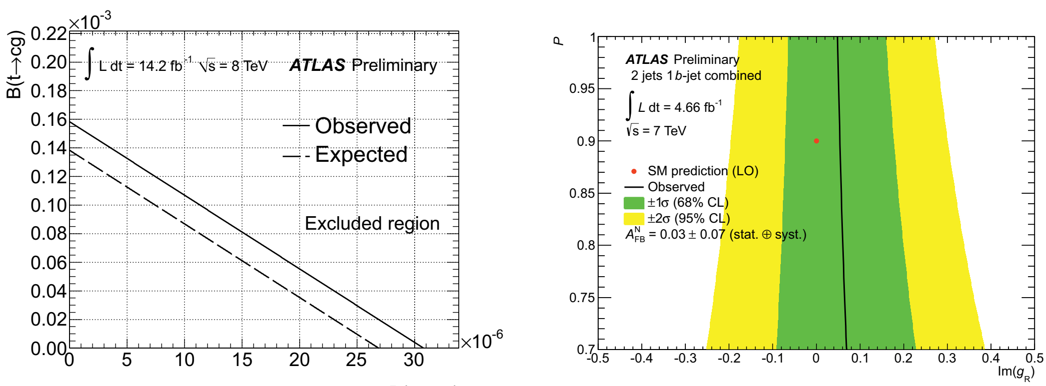
for each jet category using a reference signal MC sample for a right-handed W'-boson with a mass of $m_{W'} = 1.75$ TeV. BDT outputs are then calculated for several other signal samples to account for left and right-handed chiralities and different W-boson masses between 0.5 and 3.0 TeV. Since no excess is found, lower 95% CL limits on the left and right-handed W'-boson masses of $m_{W'_L} > 1.74$ TeV and $m_{W'_R} > 1.84$ TeV are derived, as shown in Fig. 4 (a).

4.2 Search for single excited b^*-quark production

A dataset corresponding to 4.7 fb^{-1} collision data from pp-collisions at 7 TeV is used to search for production of excited b^*-quark via strong interactions in the Wt-channel [12]. The event selection for b^*-quarks decaying via electroweak processes into a top-quark and a W-boson follows that of the single top-quark Wt-channel production cross-section measurement, but using both, the dileptonic and (single-)leptonic final states. The discriminating variables used in the cut-based analysis are H_{T} in the dilepton channel, defined as the scalar sum of $E_{\mathrm{T}}^{\mathrm{miss}}$ and the transverse momenta of both leptons and the jet, and the reconstructed invariant mass of the Wt system in the single-lepton channel. Since no signal excess has been observed in neither distribution, limits are computed for different coupling scenarios using a template fit resulting e.g. in the exclusion of b^*-quark masses below 870 GeV at 95% CL for a chromomagnetic coupling strength at unity and assuming a SM-like (purely left-handed) decay, as shown in Fig. 4 (b).

4.3 Searches for flavour-changing neutral currents

In the SM, transitions between top-quarks and other quark flavours mediated by neutral gauge bosons, so-called Flavour Changing Neutral Currents (FCNC), are forbidden at tree level and highly suppressed at higher orders due to the Glashow-Iliopoulos-Maiani (GIM) mechanism. However, several new physics models exist which predict significantly enhanced rates of FCNC processes. These could be measured in the production or decay of single top-quarks and hence may provide a strong indication for new physics. FCNC couplings involving Z-bosons or photons are usually searched for in the single top-quark decay mode. In ATLAS, searches for FCNC single top-quark production mediated via the strong interaction are performed using 7 and 8 TeV data [13, 14]. In the search at 8 TeV a dataset corresponding to an integrated luminosity of 14.2 fb^{-1} is used. FCNC events are searched for, in which a u- or c-quark interacts with a gluon to produce a single top-quark. Candidate events of top-quarks decaying leptonically are selected using a similar event selection to that of the t-channel cross-section measurement, but requiring a single central lepton with $p_{\mathrm{T}} > 30$ GeV and exactly one central jet which has to be identified as a b-quark jet. The analysis uses neural network techniques



(a) (b)

Figure 5: (a) Upper limit on the FCNC branching fractions $\mathcal{B}(t \to ug)$ (assuming $\mathcal{B}(t \to cg) = 0$) and $\mathcal{B}(t \to cg)$ (assuming $\mathcal{B}(t \to ug) = 0$) and possible combinations [14]. (b) Constraints on the imaginary part of the anomalous right-handed tensor coupling ($\Im(g_R)$), for different degrees of top-quark polarisation along the spectator quark direction (P). The red dot denotes the SM prediction at LO ($\Im(g_R) = 0$, $P = 0.9$) [15].

to classify signal- and background-like events. Two networks are trained with simulated FCNC and background events in the electron and muon channels, using 13 different kinematic variables as their input. Since no signal is observed, a new upper 95% CL limit on the FCNC production cross-sections times branching fraction of $\sigma_{qg\to t} \times \mathcal{B}(t \to bW) < 2.5$ pb is derived by using a Bayesian statistical approach. From that, improved limits with respect to the former 7 TeV analysis on the coupling strengths and branching ratios of the involved FCNC interactions are derived, the latter of which are shown in Fig. 5 (a).

4.4 Search for anomalous couplings in the Wtb vertex

An analysis using 4.7 fb^{-1} of data from pp collisions in 2011 searches for anomalous couplings in the production of single top-quarks in the t-channel topology [15]. The analysis is based on the measurement of an asymmetry in the angular distribution of the charged lepton from the W-boson decay to probe for anomalous couplings in Wtb vertex leading to charge-parity (CP) violation. Top-quarks produced via the t-channel process are expected to be highly polarised ($P \approx 0.9$) along the direction of the associated light (spectator) quark in the top-quark rest frame. Using the top-quark spin

($\vec{s}_t$) and the W-boson momentum direction in the helicity basis ($\vec{q}$), a reference plane ($\vec{N} = \vec{s}_t \times \vec{q}$ and $\vec{T} = \vec{N} \times \vec{q}$) and angles between the lepton momentum in the W-boson rest frame and the new reference directions are defined (Θ_N, Θ_T). The analysis then searches for a forward-backward asymmetry A_{FB}^N in the Θ_N-distribution using events selected with the same criteria as used in the t-channel cross-section analysis. The asymmetry A_{FB}^N is highly sensitive to the complex phase of the anomalous right-handed tensor coupling g_R. Any value incompatible with zero would provide strong evidence for a CP violating component in the top-quark decay. However, no such asymmetry is observed and a 95% CL limit on the imaginary part of the right-handed tensor coupling strength is derived under the assumption of small values of g_R and using SM predictions for the remaining left-handed tensor and the usual vector couplings. Fig. 5 (b) shows the resulting values and limits of g_R, derived for different assumptions on the degree of the top-quark polarisation along the spectator quark direction. The results are found to be compatible with the SM expectation.

5 Summary

Measurements of the single top-quark production cross-sections with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV and 8 TeV are presented. Single-top quark production has been observed with high significance in the t-channel in different analyses using the full 2011 and parts of the 2012 dataset, with measured cross-sections compatible to the theory predictions. First evidence for Wt-channel production has been found in an analysis using data from pp collision events at $\sqrt{s} = 7$ TeV with no deviation with respect to the SM cross-section prediction. From all cross-section measurements the $|V_{tb}|$ CKM-matrix element was calculated and is found to be compatible with the SM expectations. Further, separate measurements of the top- and antitop-quark t-channel production cross-sections and their ratio are presented which led to the derivation of the up-quark to the down-quark PDF ratio in the proton. Several searches for new physics processes in single top-quark production are discussed from which new limits on single top-quark production via flavour changing neutral currents, the production of exited b^*-quarks or W'-bosons, and limits on anomalous CP-violating tensor couplings in the Wtb vertex are derived.

References

[1] N. Kidonakis, Phys. Rev. **D 83**, 091503 (2011), `arXiv:1103.2792 [hep-ph]`
[2] N. Kidonakis, Phys. Rev. **D 82**, 054018 (2010), `arXiv:1005.4451 [hep-ex]`
[3] N. Kidonakis, Phys. Rev. **D 81**, 054028 (2010), `arXiv:1001.5034 [hep-ph]`
[4] ATLAS Collaboration, JINST **3**, S08003 (2008)
[5] M. Cacciari, G.P. Salam, G. Soyez, JHEP **0804**, 063 (2008), `arXiv:0802.1189 [hep-ph]`
[6] ATLAS Collaboration, ATLAS-CONF-2012-056 (2012), `cds.cern.ch/record/1453783`
[7] ATLAS Collaboration, ATLAS-CONF-2012-132 (2012), `cds.cern.ch/record/1478371`
[8] ATLAS Collaboration, Phys. Lett. **B 716**, 142 (2012), `arXiv:1205.5764 [hep-ex]`
[9] ATLAS Collaboration, ATLAS-CONF-2011-088 (2011), `cds.cern.ch/record/1356197`
[10] ATLAS Collaboration, Phys. Lett. **B 717**, 330 (2012), `arXiv:1205.3130 [hep-ex]`
[11] ATLAS Collaboration, ATLAS-CONF-2013-050 (2013), `cds.cern.ch/record/1547566`
[12] ATLAS Collaboration, Phys. Lett. **B 721**, 171 (2013), `arXiv:1301.1583 [hep-ex]`
[13] ATLAS Collaboration, Phys. Lett. **B 712**, 351 (2012), `arXiv:1203.0529 [hep-ex]`
[14] ATLAS Collaboration, ATLAS-CONF-2013-063 (2013), `cds.cern.ch/record/1562777`
[15] ATLAS Collaboration, ATLAS-CONF-2013-032 (2013), `cds.cern.ch/record/1527128`