Single Top Physics at ATLAS

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The measurement of single-top production opens up a wide field for tests of the Standard Model and searches for phenomena beyond as e.g. charged Higgs H^+ or W'. Furthermore, many experimental benchmarks for physics object identification to be used for searches can be measured. In contrast to the top-pair production, top quarks are produced in electro-weak interactions. Making use of a luminosity from 0.7 fb^{-1} up to 2.05 fb^{-1} the ATLAS experiment was searching for all three channels predicted by the standard model. Where the t-channel was observed, upper limits at 95 % C.L. could be determined for the other two channels. Based on the Standard Model analysis, a search for Flavour Changing Neutral Currents was performed giving a new upper limit on the branching ratios.

1 Single Top Channels and Event Selection

Top quarks are predominantly produced as $t\bar{t}$ pairs via the flavour-conserving strong interaction. Alternatively, single-top quarks can be produced in weak interactions involving a $W - t - b$ vertex. Three sub-processes contribute to single-top quark 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 dominant process with the highest cross section at the LHC is the t-channel production (Fig. 1, left) followed by the associated Wt production (Fig. 1, middle) and finally the smallest contribution originates from the s-channel (Fig. 1, right). The production cross sections were predicted for a centre of mass energy of $\sqrt{s} = 7$ TeV for colliding protons at the LHC and a top quark mass of $m_t = 172.5$ GeV to be for the leading t-channel[1] as $\sigma_{t-\text{channel}} = (64.2\pm2.6)$ pb, for the associated Wt-production[2] to be $\sigma_{Wt-\text{channel}} = (15.6\pm1.3)$ pb and finally for the s-channel[3] a value of $\sigma_{s-\text{channel}} = (4.6 \pm 0.2)$ pb was calculated. In these proceedings searches for single-top quark production with the ATLAS experiment[4] are presented.

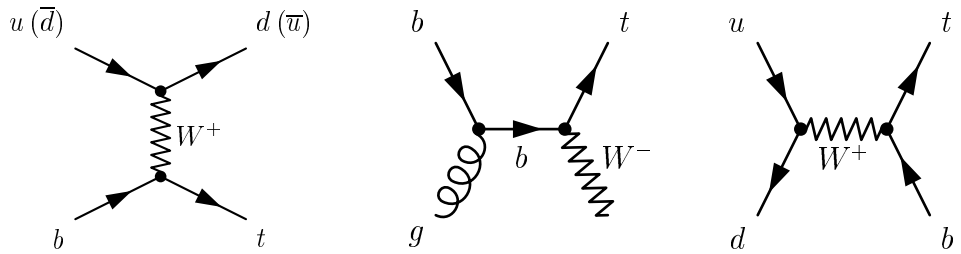

Figure 1: The Feynman graphs for the production channels of single-top quarks: t-channel (left), associated Wt-production (middle) and s-channel (right).

Single-top quark final states provide a direct probe of the $W - t - b$ coupling and are

sensitive to various models of physics beyond the Standard Model as e.g. Flavour Changing Neutral Currents (FCNC), searches for $W' \to tb$ or charged MSSM Higgs-Bosons $H^{\pm}$. At the LHC, the measurement of the single-top production in all channels could be established in cut-based and Neural Network (NN) analyses with the data collected in 2011 so far. The W boson from the top quark decay is reconstructed in the leptonic decay mode leading to one charged lepton (e or μ) in the final state at high transverse momentum p_{T} and missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$. Additionally, the requirement of at least one b-quark tagged jet depending on the final state is one of the most important possibilities to reduce the high background contamination further.

The event selection and the definition of the physics objects used is done for all top quarks analyses in common. The trigger used is based on the high p_T single lepton origin from the leptonic W-decay to suppress the high QCD background. Accordingly, the required exactly one charged lepton with $p_T > 25$ GeV must be trigger matched and isolated. The presence of at least one neutrino leads to a missing transverse energy of $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV for s, t-channels and $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV for the Wt-channel. Additionally, a QCD multi-jet veto is applied by $M_{\mathrm{T}}(W) + E_{\mathrm{T}}^{\mathrm{miss}} > 60$ GeV. Finally for the jets, an anti-kT algorithm with $\Delta R = 0.4$ [5] is used. They are required to have $p_{\mathrm{T}} > 25$ GeV (t, s-channel) and 30 GeV for the Wt-channel respectively. In rapidity, they are restricted to be within $|\eta| < 4.5$ for the t-channel and $|\eta| < 2.5$ for the Wt- and s-channel. If a b-tag is required, which is based on the probability density function of impact parameter and secondary vertex distributions, the rapidity region must be restricted to the acceptance of the tracking systems of $|\eta| < 2.5$.

The single-top quark analyses performed at the ATLAS experiment are all based on the object selection described above. In this summary, the following analyses are discussed:

- t-channel, with exactly one lepton, two or three jets (one b-tagged) and missing transverse energy in the final state;
- Wt-channel in the di-lepton decay, with two leptons, exactly one jet (b-tagged) and missing transverse energy in the final state;
- s-channel, with exactly one lepton, exactly two b-tagged jets and missing transverse energy in the final state.

The main background contributions are coming from top-pair events, QCD and W/Z with heavy flavour jets (c, b) in the final state. Additionally, the WW, WZ and ZZ productions can have similar signatures. Finally, for the di-lepton channel of the associated Wt-production there is a not negligible contribution from Z with jets in the final state. The search for FCNC was done based on the topology of the t-channel selection.

2 The t-Channel

The analysis for the t-channel [6] follows a cut based approach with a likelihood fit (2 and 3 jet selection) or is alternatively making use of a NN decision (2 jet selection only). The cuts chosen are: $|\eta(\mathrm{lepton} - \mathrm{jet})| > 2.0$, $H_T > 210$ GeV, 150 GeV $< M_{l\nu b} <$ 190 GeV and $\Delta\eta(\mathrm{b} - \mathrm{jet}_1, \mathrm{light} - \mathrm{jet}_1) > 1.0$ All variables are in good agreement between data and Monte Carlo simulation expectations. In Fig.2 the distribution of $M_{l\nu b}$ is shown after all cuts except the cut on $M_{l\nu b}$ itself.

The main backgrounds are from QCD multi-jet events, W boson production in association with jets and top-pairs $t\bar{t}$. Smaller backgrounds originate from Z+jets, Wt- and s-channel single-top production and di-boson production. The smaller background contributions as well as the $t\bar{t}$ background are normalised to their theory predictions.

A multi-jet event is counted to be as a candidate event, if one of the jets is misidentified as an isolated lepton or if the event has an isolated non-prompt lepton. The normalisation of the multi-jet background is obtained by the use of a binned maximum likelihood fit to the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in data, using a data-derived template for multi-jet background and MC templates for all other processes (top, W/Z+jets, di-bosons). On the other hand, the shape of the multi-jet background is derived from an orthogonal data sample enriched in multi-jets. The kinematic distribution for the W+jets background, containing contributions from $Wb\bar{b}$+jets, $Wc\bar{c}$+jets, Wc-jets and W+light-jets, are taken from MC samples, while the overall normalisation and the mostly poorly predicted flavour composition are derived from data.

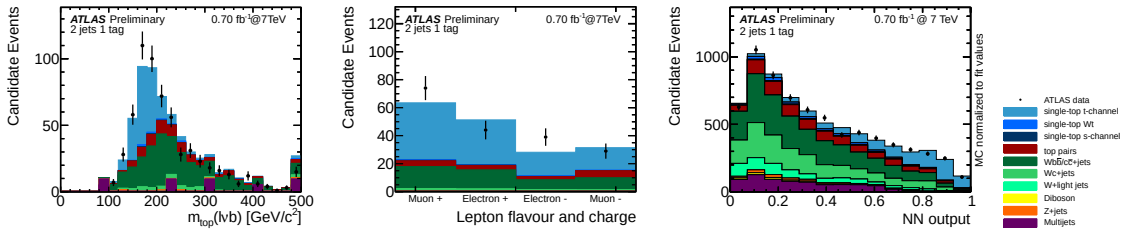

Figure 2: Results of the t-channel analysis: Distribution of the top quark mass $M_{l\nu b}$ in the 2-jet sample after all selection cuts except the cut on $M_{l\nu b}$ itself (left), distribution of the lepton flavour and charge after the cut based selection in the 2-jet bin (middle) and the neural network output in the 2-jet bin normalised to the result of the binned likelihood fit.

The obtained results based on 0.70 fb^{-1} of data are shown in Fig. 2. In the cut based analysis, a profile likelihood was used to evaluate the event yields and to incorporate the systematic uncertainties. To optimise the statistical power, a separation in lepton flavour and charge was done. The measured cross section of $\sigma_{\mathrm{t-channel}} = (90 \pm 9(\mathrm{stat.})^{+31}_{-20}(\mathrm{sys.}))$ pb is in good agreement with the SM prediction of $\sigma_{\mathrm{t-channel,SM}} = (64.2 \pm 2.6)$ pb. The dominating contributions to the systematic uncertainty origin from b-tagging ($^{+18}_{-13}\%$) and initial/final state radiation ($\pm 13\%$). As the cut based method uses both 2- and 3-jet channels and has a slightly smaller overall uncertainty ($\sigma_{\mathrm{t-channel,NN}} = (105 \pm 7(\mathrm{stat.})^{+36}_{-30}(\mathrm{sys.}))$ pb), it is chosen as the baseline result.

3 The Wt-Channel

In the case of the associated Wt-production, there are two W-bosons in the final state leading to two channels: one, where both W are decaying leptonically leading to two charged leptons and only one jet, and one, where one W decays leptonically where the other one decays hadronically leading to only one charged lepton and three jets in the final sate. In the analysis presented here [7], only the di-lepton final states are considered. For the final, cut based selection, exactly two opposite sign leptons (ee, $e\mu$, $\mu\mu$) and exactly one jet (not b-tagged) are required. Since the signal also contains neutrinos, the missing transverse energy is requested to be $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV. In the ee and $\mu\mu$-channel the large Drell-Yan background ($Z \to ll$) is drastically reduced by applying a veto cut on the Z-mass of $|M(ll) - M(Z)| > 10$ GeV. The remaining dangerous background originates finally from $Z \to \tau\tau$. This is reduced by applying a cut on the angle formed between each lepton and the direction of the reconstructed missing transverse momentum (triangle cut) as shown in Fig. 3. The value of the lower threshold is set to optimise the rejection of Z events while preserving as much signal events as possible to $\Delta\phi(l_1, E_{\mathrm{T}}^{\mathrm{miss}}) + \Delta\phi(l_1, E_{\mathrm{T}}^{\mathrm{miss}}) > 2.5$

The main sources of remaining backgrounds are fake leptons and Drell-Yan processes. Both contaminations are estimated based on data driven methods, in the case of fake leptons with the so called matrix method [8] and for the Drell-Yan processes with a method applying orthogonal cuts on two variables to define a set of signal- and background regions (ABCDEF method).

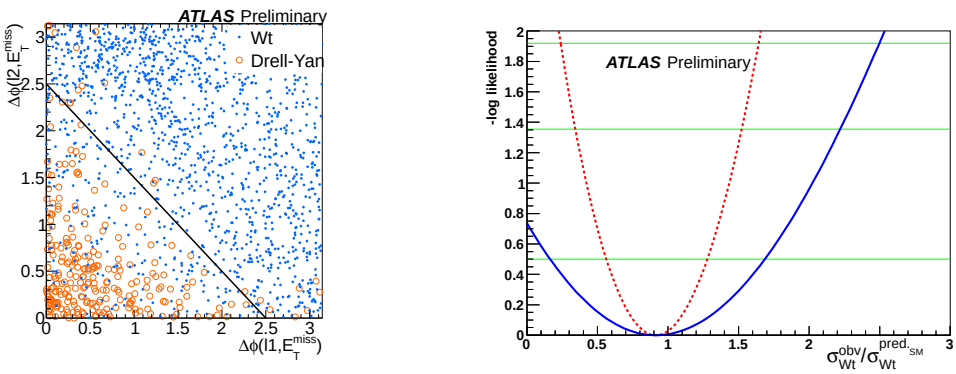

Figure 3: Results of the Wt-channel: Impact of the triangle cut indicated by a line (left) and the observed likelihood ratio (red dashed) and profile likelihood (blue solid) curves for the combined cross section extraction.

The background contamination in the signal region is measured using two background enriched regions extrapolating the rate into the signal region.

The extraction of the Wt-channel production cross section is treated a a counting experiment and modelled using a likelihood function including for each channel a Poisson term in the number of observed events with expectation values summing the expected contributions from signal and all MC- or data driven backgrounds. The main systematic uncertainties are originating from the jet energy scale ($^{+34}_{-35}$%), jet energy resolution ($^{+29}_{-32}$%), reconstruction efficiency ($^{+30}_{-33}$%) and MC generators ($^{+16}_{-11}$%). The observed cross section of $\sigma_{\mathrm{Wt-channel}} = (14.3 \pm^{+5.3}_{-5.1} (\mathrm{stat.})^{+9.7}_{-9.4}(\mathrm{sys.}))$ pb is in good agreement with the SM prediction of $\sigma_{\mathrm{t-channel,SM}} = (15.6 \pm 1.3)$ pb as can be seen in Fig. 3. The 95 % C.L. observed limit is $\sigma_{\mathrm{Wt-channel}} < 39$ pb. The probability to obtain an equivalent or higher cross section in the absence of a signal corresponds to a significance of 1.2 standard deviations.

4 The s-Channel

The s-channel production is particularly interesting at the LHC since it is sensitive to several models of new physics as W' or charged Higgs bosons production. Furthermore, techniques developed for the s-channel can be used for a search of $t\bar{b}$ resonances. However, with a prediction cross section in NLO calculations of (4.6 ± 0.3) pb this is the smallest contribution to the single-top quark production. The signature is similar to the t-channel selection expecting no forward jet and two central b-jets. The most efficient background reduction could achieved by a double b-tag.

The normalisation of the dominating background contribution, originating from multi-jets, is estimated using a binned likelihood fit to the E_T^{miss} distribution. The shape is taken from a sample, where a jet is required to have a similar detector signature as an electron instead of the isolated lepton. The distributions for the W+jets backgrounds are taken from Monte Carlo samples, while the overall normalisation and the flavour composition suffering from large theoretical uncertainties, are derived from data.

The extraction of the s-channel single-top quark signal is challenging since it is overwhelmed by large background processes with the same final state as W+jets and $t\bar{t}$. A simple cut based analysis method is applied using a few discriminate variables well modelled by the simulation. This is shown in Fig. 4 for the top quark mass. The main uncertainties of the measurement are coming from statistics (±100 %), b-tagging ($^{+20}_{-30}$%), luminosity (±50 %), MC generator modelling ($^{+20}_{-60}$%) and QCD normalisation (±40 %) leading to a total uncertainty of $^{+150}_{-160}$%.

The determination of the production cross section is treated as a counting experiment mod-

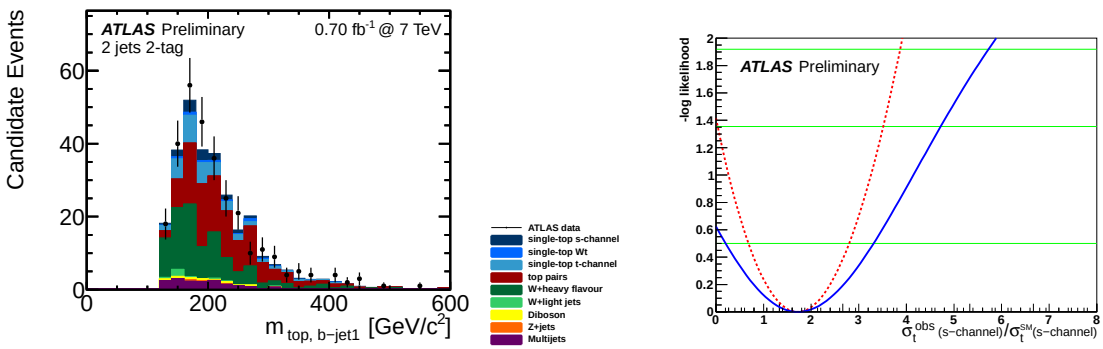

Figure 4: Results of the s-channel: the top quark mass distribution $M_{l\nu b}$ after the cut based selection (left) and the log-likelihood ratio (red) and profile likelihood (blue) for the observed limit as a function of the ratio $\sigma_{\rm obs}/\sigma_{\rm SM}$ (right). The lines are indicating the 68%, 90% and 95% confidence levels.

elled by a likelihood function including a Poisson term in the observed number of events $N^{\rm obs}$ with expectation value $N^{\rm exp}$, which is the sum of the expected contributions from signal and all backgrounds evaluated in MC or data-driven. The cross section is obtained by fitting the maximum likelihood estimate and the effect of the uncertainties is inferred from the shapes of the likelihood ratio and profile likelihood respectively (Fig. 4). A two-sided 95 % confidence interval is formed where the upper bound is quoted as the upper limit on the production cross section. An observed (expected) upper limit of 26.5 (20.5) pb is measured corresponding to about 5 times the Standard Model prediction of 4.6 pb.

5 Search for Flavour Changing Neutral Currents with Single Top Quarks

In the Standard Model, Flavour Changing Neutral Current (FCNC) are forbidden on the tree level and are highly suppressed at higher order due to the GIM-mechanism [10]. Extensions of the Standard Model with new sources of flavour predict higher rates for FCNCs involving the top quark. The FCNC top quark decay can be studied in principle directly by searching for final states with the corresponding decay particles. However, the $t \to qg$ mode, where q denotes either an up-quark u or a charm-quark c, is almost impossible to separate from generic multi-jets-production via QCD processes. The search preformed at the ATLAS experiment [11] with an integrated luminosity of 2.05 fb^{-1} is based on the single-top t-channel. Since the signal process gives rise to only one high-p_T b-quark jet, exactly one reconstructed jet with $p_T > 25$ GeV is required in contrast to the t-channel selection. Additionally, the selected jet has to be tagged as a b-jet.

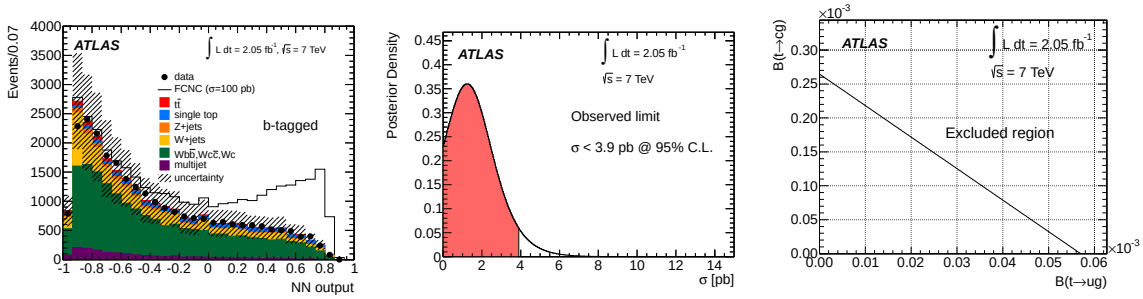

Figure 5: Results of the search for Flavour Changing Neutral Currents: Neural Network output distribution scaled to the number of observed events in the b-tagged sample (left), distribution of the posterior probability function including all uncertainties for the observed upper limit at 95% C.L. (middle) and the upper limit on the branching fractions $t \to ug$ and $t \to cg$ (right).

Given the large uncertainty of the expected background and the small number of expected signal events, a multivariate analysis technique is applied to separate signal events from background. The neural network output distribution scaled to the number of observed events is shown in Fig. 5. A Bayesian statistical analysis using a binned likelihood method is performed to set an upper limit on the the FCNC single-top quark production cross section. The posterior density function (PDF) is obtained by creating a large number of samples of systematic shifts. A separate likelihood distribution is obtained for each sample and the final PDF is the the sum over all individual likelihoods giving the probability of the signal hypothesis as a function of the signal cross section. Since no significant rate of FCNC single-top quarks are observed, upper limits are set by integrating the PDFs.

The resulting expected upper limit at 95 % confidence level (Fig. 5) on the anomalous FCNC single-top quark production cross section including all uncertainties is 2.4 pb, while the observed limit is at 3.9 pb. Using the NLO predictions for the FCNC single-top quark production cross section, the measured upper limit on the production cross section is converted into a limit on the coupling constants κ_{ugt}/Λ and κ_{cgt}/Λ. Assuming $\kappa_{cgt}/\Lambda = 0$ one finds $\kappa_{ugt}/\Lambda < 6.9 \cdot 10^{-3}$ TeV^{-1} and accordingly for $\kappa_{ugt}/\Lambda = 0$ the result is $\kappa_{cgt}/\Lambda < 1.6 \cdot 10^{-2}$ TeV^{-1}. With the NLO calculation, finally upper limits for the branching fractions of $\mathcal{B}(t \to ug) < 5.7 \cdot 10^{-5}$ ($\mathcal{B}(t \to cg) = 0$) and $\mathcal{B}(t \to cg) < 2.7 \cdot 10^{-4}$ ($\mathcal{B}(t \to ug) = 0$) were found (Fig. 5).

6 Conclusions

At the ATLAS experiment, the analyses for all single-top channels could be established with the data of 2011. The cross section measurements for the t-channel and the associated Wt production are compatible with the Standard Model expectations. For the s-channel, a 95 % C.L. could be set on the upper limit of the cross section, which is also in agreement with the prediction. Furthermore, the t-channel selection was used to derive uper limits for the branching ratios $t \to ug/cg$ (Flavour Changing Neutral Currents) using NLO calculations, but there was no evidence observed. In all analyses, the background estimations were done if possible data driven and advanced analysis methods based on Neural Networks could be established.

In the next upcoming analyses, ATLAS is updating all channels to the full 2011 data set of 4.7 fb^{-1} and more searches for physics beyond the SM are performed, as heavy W' bosons or charged Higgs. Accordingly, many beautiful results are expected soon in 2012.

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