PROCEEDINGS OF SCIENCE

Single Top-Quark Production Cross Section Using the ATLAS Detector at the LHC

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Recent measurements of the production of single top quarks in proton–proton collisions at centre-of-mass energies of $\sqrt{s} = 7\,\text{TeV}$, $8\,\text{TeV}$ and $13\,\text{TeV}$ with the ATLAS detector at the LHC are presented. Four measurements of the production cross sections for single top quarks via the s- and t-channel exchange of a W boson as well as in association with a W boson are discussed. The results are compared to state-of-the-art theoretical calculations, and used to extract the value of the CKM matrix element V_{tb}. Recently found evidence for the production of single top quarks in the s-channel at 8 TeV is presented. Finally, the determination of anomalous couplings at the W–t–b vertex from an analysis of top-quark decays is shown.

38th International Conference on High Energy Physics
3-10 August 2016
Chicago, USA

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PoS(ICHEP2016)664

1. Overview

The production of single top quarks at the LHC opens an opportunity to test the Standard Model (SM) of particle physics, to probe new physics phenomena, and directly measure the Cabibbo-Kobayashi-Maskawa (CKM) matrix element V_{tb}. Single top quarks are produced via the electroweak interaction in the three different ways illustrated in Figure 1: involving the s-channel or t-channel exchange of a W boson, or in association with a W boson (Wt mode). These proceedings present the latest cross-section measurements for single top quarks in proton–proton collisions at centre-of-mass energies of $\sqrt{s} = 8$ TeV and 13 TeV using the ATLAS detector [1], with integrated luminosities of 20 fb^{-1} and 3.2 fb^{-1}, respectively. In addition, a recent analysis of anomalous W–t–b couplings at 7 TeV using 4.6 fb^{-1} of data is shown.

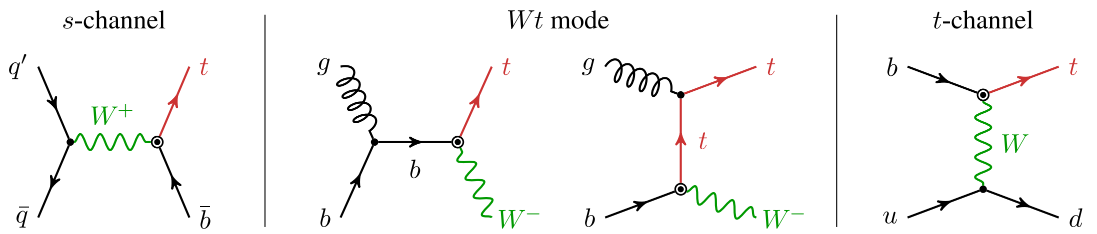


Figure 1: Representative Feynman diagrams for the production of single top quarks at leading order in QCD. The initial b-quarks and gluons arise from the sea in the proton.

The measurements were carried out using final states where a top quark with large transverse momentum decays into a b-quark and a leptonically decaying W boson, giving rise to a b-quark jet, a (charged) lepton, and missing energy in the ATLAS detector. Isolated leptons and jets with a pseudorapidity of $|\eta| < 2.5$ were considered, unless noted otherwise. The anti-k_{T} algorithm with a distance parameter of 0.4 was used to defined jets. b-quark jets were identified (*tagged*) based on the characteristic signature of the decays of b-hadrons. The thresholds for the transverse momenta of the leptons and the jets were about 30 GeV, varying slightly between the analyses. In order to reduce QCD-induced multijet production in the single-lepton analyses, cuts on the missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}}$, and the transverse mass of the W boson candidate were employed. The main backgrounds were top-quark pair ($t\bar{t}$) production, and the production of a W boson in

Channel		$\sqrt{s}$ [TeV]	σ^{theo} [pb]	Precision	Ref.
$t\bar{b}$,$\bar{t}b$	(s-channel)	8	5.61±0.22	NLO+NNLL	[2, 4]
tW^-,$\bar{t}W^+$	(Wt mode)	8	22.37±1.52	NLO+NNLL	[3, 4]
		13	71.7 ±3.8		
tq	(t-channel)	13	136.0 $^{+5.4}_{-4.6}$	NLO	[5]
$\bar{t}q$			81.0 $^{+4.1}_{-3.6}$		

Table 1: Theoretical predictions [2, 4, 3, 5] for the inclusive cross-section measurements presented in these proceedings. The uncertainties include variations of the renormalisation and factorisation scales as well as the parton density functions of the proton.

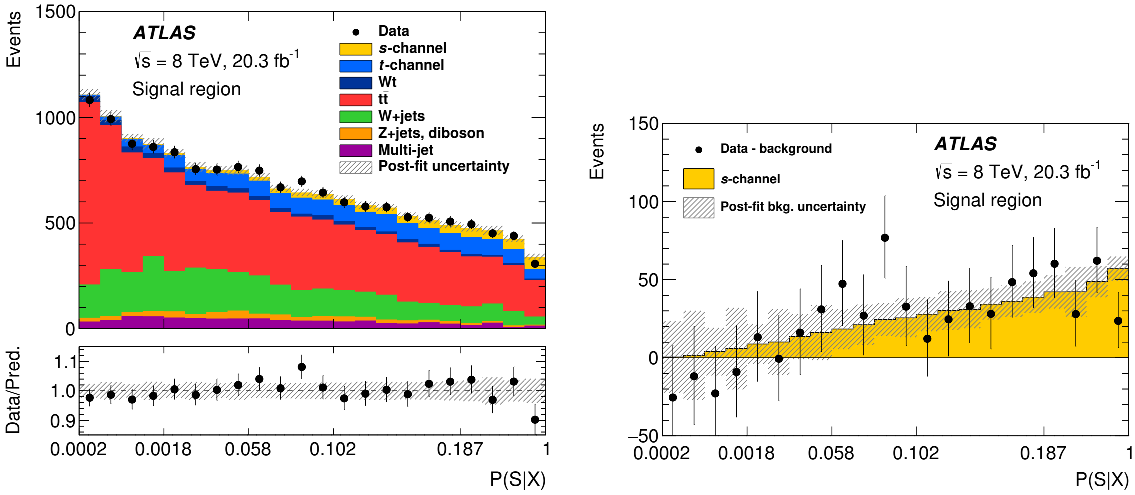


Figure 2: Distribution of the ME-based discriminant used for the measurement of the s-channel cross section [6] before and after subtracting the backgrounds.

association with jets (W+jets).

The cross sections were extracted by constructing a discriminant, and fitting simulated templates for the signal and the backgrounds to the distribution of the discriminant in the observed data. The results were compared to the SM predictions calculated at next-to-leading order (NLO) in QCD, possibly including the re-summed next-to-next-to-leading-log (NNLL) corrections, as shown in Table 1. The measured cross section were interpreted in terms of V_{tb} using the relation:

$$V_{tb}^2 = \sigma^{\text{meas}} / \sigma^{\text{theo}}, \tag{1.1}$$

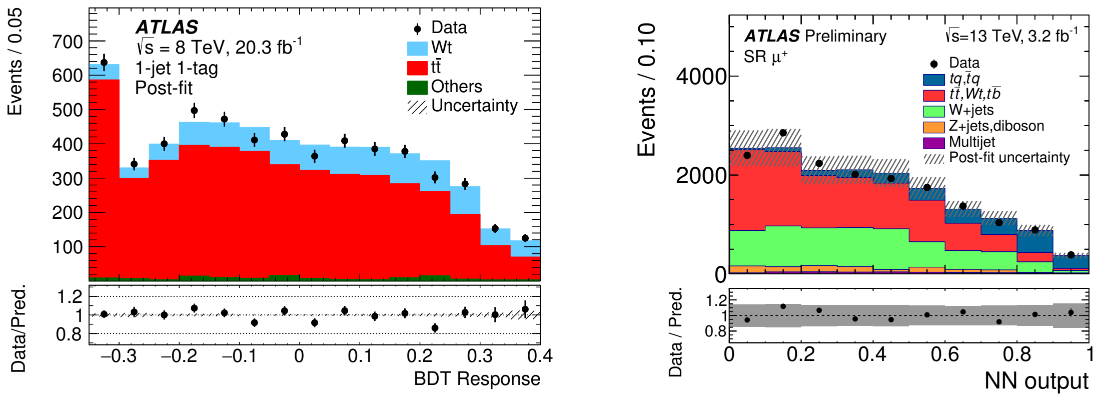
requiring moderate assumptions: $|V_{ts}|$ and $|V_{td}|$ must be negligible compared to $|V_{tb}|$; the structure of the W–t–b coupling must not be modified by physics beyond the SM, i.e. the W–t–b vertex must be described by a left-handed vector coupling without an additional form factor ($f_{\text{LV}} = 1$); the top quark must decay almost always into a b-quark and a W boson. Neither the unitarity of the CKM matrix nor assumptions on the number of quark generations are required.

2. *s*-channel

The s-channel production of single top quarks was measured at 8 TeV [6] using events with one lepton, missing transverse momentum, and two jets, which had to be b-tagged. The signal-to-background ratio after the selection was 1 : 20. In order to detect this small signal, a discriminant (Figure 2) based on the Matrix Element (ME) method was built. The method assigns to every event a probability of being signal, using the theoretical computations of the partonic cross section for the signal and the background processes folded with transfer functions that model detector effects. The advantage over other multivariate techniques such as Boosted Decision Trees (BDTs) was the avoidance of the training on (unrealistically) large simulated samples for the W+jets background.

The measured cross section is:

$$\sigma = 4.8 \pm 0.8\,(\text{stat.})\,^{+1.6}_{-1.3}\,(\text{syst.})\,\text{pb}, \tag{2.1}$$



(a) Wt mode at 8 TeV (b) t-channel at 13 TeV

Figure 3: Distributions of the discriminants used for the measurements of the Wt production [7] as well as the measurement of the t-channel production [10] in the respective signal regions.

consistent with the SM expectation, and corresponding to $|V_{tb}| = 0.93^{+0.18}_{-0.20}$. The uncertainty of 34 % is mainly due to the statistical errors on the data as well as the simulated samples. With an observed statistical significance of 3.2 standard deviations, first evidence for s-channel production of single top quarks at the LHC was found.

3. *Wt* mode

The Wt production was measured at 8 TeV [7] as well as 13 TeV [8] in events with two oppositely charged leptons and a b-tagged jet. Events with exactly one jet were selected for the signal region. The contribution from the production of a Z boson in association with jets was reduced by cuts on the invariant mass of the lepton pairs, the missing transverse momentum, and the pseudorapidity of the system of all reconstructed objects. The signal-to-background ratio in the signal region was 1 : 4. A BDT discriminant (Figure 3a) was constructed from variables such as the transverse momentum of the system of all reconstructed objects. Two additional control regions with different numbers of (b-tagged) jets were used in the fits, which helped to constrain the normalization as well as uncertainties due to theory modelling of the template for the $t\bar{t}$ background.

The measured cross sections are consistent with the SM:

$$\begin{aligned} \sigma &= 23.0 \pm 1.3\,(\text{stat.})\,^{+3.2}_{-3.5}\,(\text{syst.}) \pm 1.1\,(\text{lumi.})\ \text{pb at}\ \sqrt{s}=8\,\text{TeV}, \\ \sigma &= 94 \pm 10\,(\text{stat.})\,^{+28}_{-23}\,(\text{syst.})\ \text{pb at}\ \sqrt{s}=13\,\text{TeV}, \end{aligned} \tag{3.1}$$

with relative uncertainties of 17 % respectively 30 %, mainly due to the theory modelling and the jet reconstruction. A value of $|V_{tb}| = 1.01 \pm 0.10$ was extracted at 8 TeV.

Large theory uncertainties can often be reduced by avoiding the extrapolation to the inclusive cross section, and instead measuring in a smaller *fiducial* volume, which is defined by cuts modelled after the event selection. Such a fiducial cross-section measurement was performed for the sum of the Wt and the $t\bar{t}$ production at 8 TeV. Combining these two very similar physics processes helped to further reduce the uncertainty to just 8.5 %, and is useful for studies of event generators for $W^+W^-b\bar{b}$ final states. In order to facilitate such studies, an analysis routine for the Rivet framework [9] was released.

4. *t*-channel

The t-channel production of single top quarks at 13 TeV was measured [10]. Compared to the other production modes, the t-channel production has the largest cross section, and a better isolation of the signal from the backgrounds is possible. By separating $\sigma(tq)$ and $\sigma(\bar{t}q)$, the up-quark density and the down-quark density inside the proton can be probed.

Events with exactly one muon candidate, one b-tagged jet and one b-untagged jet were selected. The latter was required to be an in extended pseudorapidity range of $|\eta| < 4.5$, as t-channel events have a characteristic forward jet from the spectator quark (cf. Figure 1). A signal-to-background ratio of 1 : 7 was achieved. Using variables such as the reconstructed mass of the top-quark candidate and the pseudorapidity of the b-untagged jet, a discriminant (Figure 3b) based on a neural network was constructed.

The cross sections for the t-channel production were measured:

$$\begin{aligned} \sigma(tq) &= 156 \pm 5\,(\text{stat.}) \pm 24\,(\text{syst.})\ \text{pb}, \\ \sigma(\bar{t}q) &= \ \ 91 \pm 4\,(\text{stat.}) \pm 14\,(\text{syst.})\ \text{pb}, \end{aligned} \tag{4.1}$$

consistent with the predicted cross sections (Table 1). The relative total uncertainty was 15 %, with the theory modelling of the templates for the signal as the main source of uncertainty.

5. Anomalous *W*–*t*–*b* couplings

A measurement of angular distributions in top-quark decays was carried out using t-channel events at 7 TeV [11]. These distributions are sensitive to possible corrections of the effective W–t–b vertex by physics beyond the SM, in particular to a modified strength of the left-handed vector coupling as well as the presence of a right-handed tensor coupling. In the SM, the former has the coefficient of $V_{\mathrm{L}} = V_{tb}$, while the latter has the coefficient of $g_{\mathrm{R}} = 0$. The measurement does not assume that the coefficients are real-valued, setting it apart from other measurements of the coefficients.

Using four additional kinematic cuts on top of an event selection similar to the one presented in Section 4, a relatively pure (80 %) sample of t-channel events was obtained. A suitable coordinate system was defined from the kinematics of the reconstructed W boson and the spectator quark, exploiting that the polarization of the top quark is along the direction of flight of the spectator quark in the top-quark rest frame. The expectations for the two-dimensional angular distribution of the lepton were expanded in terms of spherical harmonics, and analytically folded with detector effects. An unbinned maximum-likelihood fit was performed in order to measure the fraction of events with transverse W bosons, and phase between transverse and longitudinal W bosons, from which the complex value of $g_{\mathrm{R}}/V_{\mathrm{L}}$ was extracted:

$$\mathrm{Re}\left[\frac{g_\mathrm{R}}{V_\mathrm{L}}\right] = -0.13 \pm 0.07\,(\mathrm{stat.}) \pm 0.10\,(\mathrm{syst.}),$$

$$\mathrm{Im}\left[\frac{g_\mathrm{R}}{V_\mathrm{L}}\right] = 0.03 \pm 0.06\,(\mathrm{stat.}) \pm 0.07\,(\mathrm{syst.}),$$

consistent with the SM. The contour of the likelihood in the complex plane is shown in Figure 4. The correlation between the estimators for the real and the imaginary part was $\rho = 0.11$. The main source of uncertainty from these physics objects was the jet energy scale.

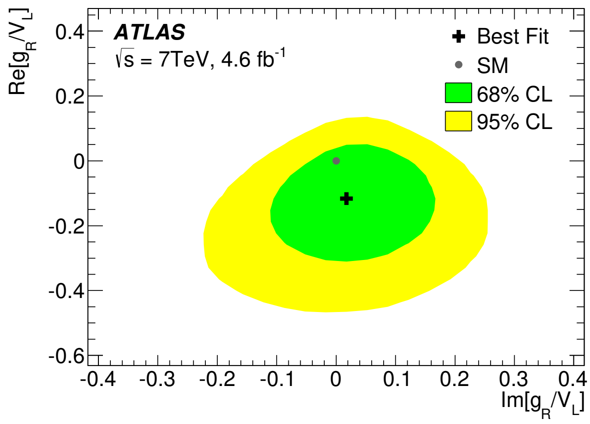


Figure 4: Contour of the likelihood function for the measurement of $g_\mathrm{R}/V_\mathrm{L}$ [11].

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