PROCEEDINGS OF SCIENCE

Single top quark production cross section using the ATLAS detector at the LHC

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This proceedings contains a summary of the single top quark production cross section measurements based on $\sqrt{s} = 8$ and 13 TeV datasets collected by the ATLAS experiment at the LHC, presented at the European Physical Society Conference on High Energy Physics. In the t-channel, the fiducial and the inclusive production cross sections of the top quark and top antiquark, and the ratio of top quark and top antiquark cross sections are presented. In addition, the measurements of the differential cross sections are presented. Measurements of the inclusive and the differential production cross sections of a single top quark in association with a W boson are included, as well as the first measurement of the quantum interference between tW and top quark and top antiquark pairs. The first evidences of the single top quark production through s-channel and the single top quark production in association with a Z boson are presented.

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1. Introduction

Many theories that try to extend the Standard Model theory of particle physics (SM) predict particles strongly coupled to the heaviest elementary particle known, the top quark. According to the SM, the top quark can be produced singly via weak interactions, which at leading order (LO) proceeds through three main production modes: t-channel with the highest production rate, Wt with the second largest production cross section, and then through the s-channel which has the smallest production rate and is very challenging at the LHC. In addition, the SM predicts electroweak production of rare processes such as the single top quark in association with a Z boson (tZq), which has not yet been observed by the ATLAS experiment [1] at the LHC[1].

Single top quark production allow to validating the SM. In particular, the production cross section is proportional to the V_{tb} CKM matrix element, therefore it tests the unitarity of the CKM matrix; in addition, it helps constrain the Parton distribution functions (PDF) and tuning Monte Carlo (MC) event generators.

2. t-channel cross section measurements

The production of the top quark through the t-channel occurs when a light quark from one of the colliding protons interacts with a b-quark from the other proton by exchanging a virtual W boson as seen in Figure 1.

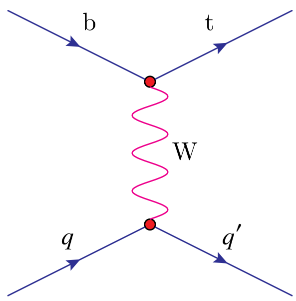

Figure 1: An example Feynman diagram of the LO for the t-channel process.

Single top quark production through the t-channel is studied using 20.2 fb^{-1} of integrated luminosity at $\sqrt{s} = 8$ TeV [3]. Leptonic decay mode of the W boson only is considered and events are selected with exactly one reconstructed well isolated lepton (e or μ) with high transverse momentum, $p_{\mathrm{T}} > 25$ GeV within $|\eta| < 2.5$, and high missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV. In addition, events are required to have exactly two jets with $p_{\mathrm{T}} > 30$ GeV within $|\eta| < 4.5$. To reduce the major background, Wc production, one jet is required to be b-tagged using an algorithm that is optimised to reject c-quark jets. The remaining jet is untagged and is typically produced at large $|\eta|$.

To enhance the signal to background ratio (S/B), two neural networks (NN) are trained, where the variables making the most significant contribution are the invariant mass of the untagged jet and the b-tagged jet system $m(jb)$, and the η of the untagged jet.

[1] While writing this proceedings, ATLAS Collaboration announced the observation of the tZq process with an observed cross section uncertainty of $\pm 15\%$ [2].

To reduce the systematic uncertainties related to the MC generators, the fiducial cross section is measured first, where the fiducial volume is defined using stable particles selected by cuts very close to those applied in the event selection. Two fiducial cross sections are measured using binned maximum likelihood fits performed on the full NN distributions for the top quark and the top antiquark production channels, separately. The resulting fiducial cross sections are $\sigma_{\mathrm{fid.}}(tq) = 9.78 \pm 0.57$ pb for the top quark and $\sigma_{\mathrm{fid.}}(\bar{t}q) = 5.77 \pm 0.45$ pb for the top antiquark. The full cross sections are measured by extrapolating fiducial cross sections into the full phase space, resulting in $\sigma_{tq}^{\mathrm{tot.}} = 56.7^{+4.3}_{-3.8}$ pb for the top quark and $\sigma_{\bar{t}q}^{\mathrm{tot.}} = 32.9^{+3.0}_{-2.7}$ pb for the top antiquark.

The ratio between the top quark and top antiquark production cross sections is measured to be $R_t = 1.72 \pm 0.09$ and compared with predictions made using different proton PDF sets. The sum of the full cross sections of the top and top antiquarks is used to extract the CKM matrix element V_{tb} multiplied by the left handed form factor, f_{LV}, which is exactly 1 in the SM. The result is $f_{LV}.|V_{tb}|$ =1.029±0.048 without using the assumption of unitarity on the CKM matrix.

The differential cross sections as a function of the p_{T} and absolute rapidity ($|y|$) for both the top quark and the top antiquark are measured at both the parton and particle levels. The p_{T} and $|y|$ differential cross sections of the untagged jet are also measured but only at the particle level. The differential distributions are measured from a signal enriched sample by selecting events with NN output > 0.8. Two examples of absolute unfolded differential cross sections at the particle level for top quarks as a function of $p_{\mathrm{T}}(\hat{t})$) and $|y(\hat{t})|$ are shown Figure 2.

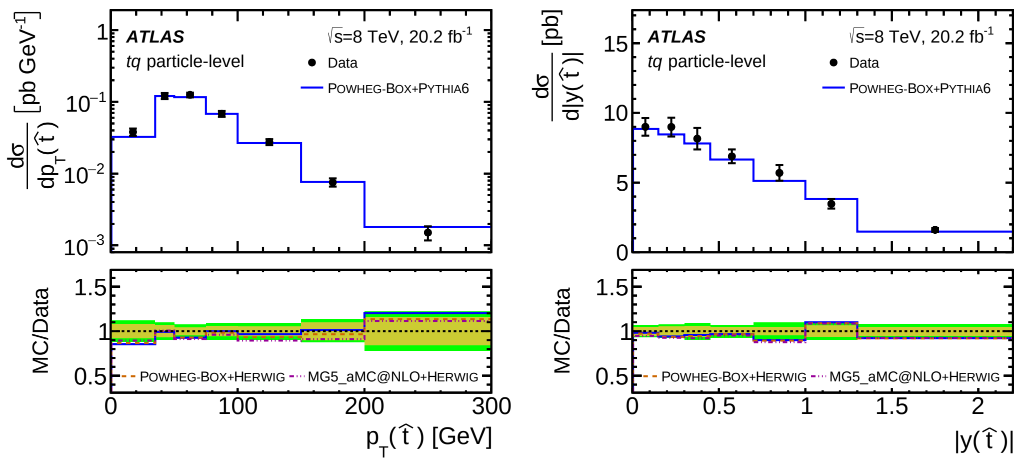

Figure 2: Left) Absolute unfolded differential cross section as a function of $p_{\mathrm{T}}(\hat{t})$ for top quarks. Right) Absolute unfolded differential cross section as a function of rapidity, $|y(\hat{t})|$, for top quarks. The unfolded distributions are compared to various MC predictions. The vertical error bars on the data points denote the total uncertainty. The yellow band in the lower panel represents the statistical uncertainty of the measurement, and the green band the total uncertainty [3].

All the t-channel measurements: the fiducial and the inclusive cross sections, the R_t and differential cross sections are compared to different MC predictions at fixed-order QCD calculations. The SM predictions provide good descriptions of the data.

Following a similar strategy, the analysis is performed again using 3.2 fb^{-1} of integrated luminosity collected in 2015 at $\sqrt{s} = 13$ TeV [4]. The extracted cross sections: $\sigma_{\mathrm{tot.}}(tq) = 156 \pm$

28 pb, $\sigma_{\text{tot.}}(\bar{t}q) = 91 \pm 19$ pb. The cross section ratio of tq and $\bar{t}q$ production is found to be $R_t = 1.72 \pm 0.20$. The total top quark and antiquark production cross section is calculated to be $\sigma_{\text{tot.}}(tq+\bar{t}q) = 247 \pm 46$ pb and is used to extract the $f_{LV} \cdot |V_{tb}| = 1.07 \pm 0.09$. These measured cross sections are in good agreement with the SM predictions and are dominated by systematic uncertainties.

3. tW channel cross section measurements

The total production cross section of the Wt process in pp collisions at $\sqrt{s} = 8$ TeV is measured using 20.3 fb^{-1} of integrated luminosity [5]. The measurement is performed in the dilepton final state where both W bosons decay to an electron or a muon and a neutrino ($e\nu$ or $\mu\nu$). Events are selected by requiring two opposite sign leptons (ee, $e\mu$, $\mu\mu$) with high p_{T}, high $E_{\text{T}}^{\text{miss}}$ and exactly one b-tagged jet with high p_{T} within $|\eta| < 2.5$.

Three separate Boosted decision trees (BDT) are used to enhance signal and background separation. The cross section is extracted using a profile likelihood fit of the full BDT distributions in the signal and background control regions. The observed Wt cross section is $\sigma_{tW} = 23.0 \pm 1.3(\text{stat.})^{+3.2}_{-3.5}(\text{syst.}) \pm 1.1(\text{lumi.})$ pb, and the total cross section is used to extract $|f_{LV} \cdot V_{tb}| = 1.01 \pm 0.10$.

The Wt production cross section measurement is repeated using 3.2 fb^{-1} of integrated luminosity collected in 2015 at $\sqrt{s}$ =13 TeV [6] employing similar techniques as in the 8 TeV measurement. The cross section is extracted using a profile likelihood fit of the full BDT distributions in the signal background control regions. The resulting cross section is $\sigma_{tW} = 94 \pm 10(\text{stat.})^{+28}_{-22}(\text{syst.}) \pm 2(\text{lumi})$ pb. The tW differential cross sections as a function of many kinematic variables are measured by ATLAS at $\sqrt{s} = 13$ TeV [7]. These variables are: $E(b)$, $m(\ell_1 b)$, $m(\ell_2 b)$, $E(\ell\ell b)$, $m_T(\ell\ell\nu\nu b)$ and $m(\ell\ell b)$. To start with a signal enriched sample, events are selected with high BDT score. To reduce systematic uncertainties, the signal distributions are normalised to the measured fiducial cross section. These differential cross sections are compared to the predictions made by several MC generators and found to be in good agreement. Figure 3 shows two examples of the unfolded particle-level normalised differential cross sections as a function of $E(\ell\ell b)$ and $m_{\text{T}}(\ell\ell\nu\nu b)$.

At NLO, the tW process has an identical final state as the $t\bar{t}$ process at leading LO, resulting in a quantum interference. The tW and the $t\bar{t}$ processes are simulated separately, and this leads to event double counting. To reduce this effect, two schemes are employed by MC generators: diagram removal (DR) and diagram subtractions (DS) [9]. The difference between the two schemes is taken as a systematic uncertainty. Traditional measurements of the tW production are designed to be insensitive to such effect, but many searches design analyses such that selected events often end up in a phase space sensitive to the interference and the systematic effects can be large. A fixed-order NLO calculation that includes a proper treatment of the interference has become available [8]. However, there are no measurements available to assess the modelling. Unlike traditional measurements of tW production, the analysis is designed to target the region where the interference effect and the difference between DS and DR are big with the goal of measuring the interference effect [10]. A variable sensitive to the interference $m_{\ell b}^{\text{minimax}}$ is measured and the unfolded distribution is compared with theoretical models with various implementations of interference effects. The

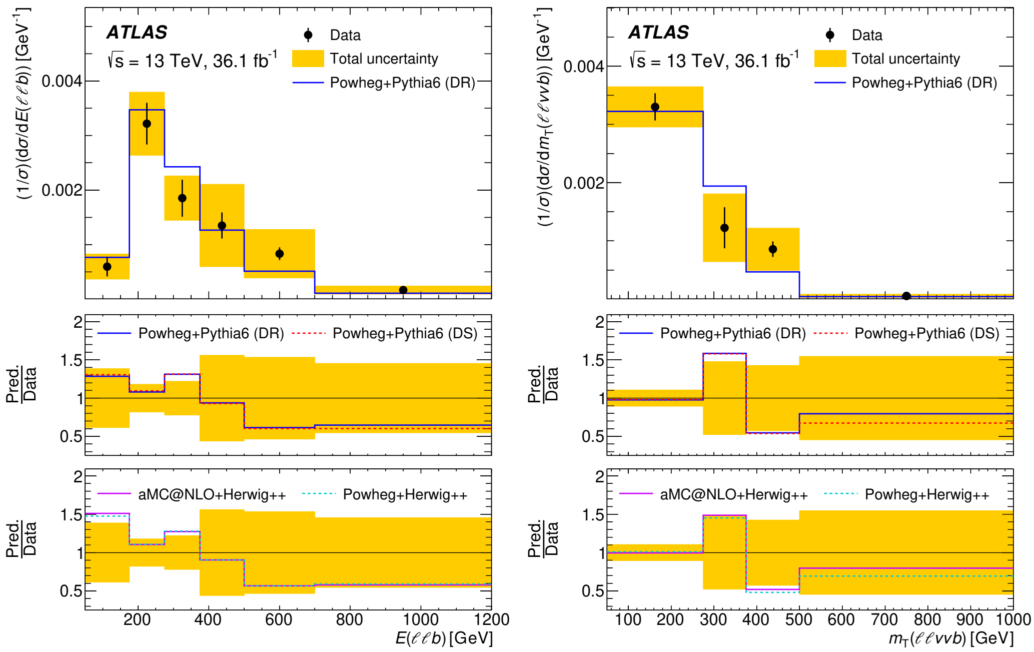

Figure 3: Normalised differential cross-sections unfolded from data, compared with selected MC models. Left) with respect to $E(\ell\ell b)$ and right) with respect to $m_{\mathrm{T}}(\ell\ell\nu\nu b)$. Data points are placed at the horizontal centre of each bin, and the error bars on the data points show the statistical uncertainties [7].

Powheg-Box-Res MC generator is found to model the $m_{\ell b}^{\mathrm{minimax}}$ well across the full distribution, and beyond the top quark mass where DR and DS diverge.

Figure 4 presents a summery of ATLAS measurements of the single top production cross sections in various channels as a function of the centre of mass energy (CME) compared with theoretical calculations based on next-to-leading order QCD. As it can be seen, the data supports the SM.

4. First evidence of the SM s-channel production mode

The ATLAS collaboration searched for single top quark production through the s-channel at $\sqrt{s} = 8$ TeV using 20.3 fb^{-1} of integrated luminosity [12]. Events are selected with exactly one high-p_{T} well isolated lepton, e or μ, missing transverse momentum, exactly two b-tagged jets, one from the decaying top quark and the other from the associated production.

A matrix element method is used to improve the S/B, and binned maximum likelihood to extract the signal. The observed signal significance is 3.2 standard deviations (s.d.) compared to the predicted significance of 3.9 s.d., with a measured cross section of $\sigma_s = 4.8 \pm 0.8(\mathrm{stat.})^{+1.6}_{-1.3}(\mathrm{syst.})$ pb.

5. First evidence of the SM tZq production mode

The SM predicts the electroweak production of a single top quark in association with a Z boson (tZq), which has recently been discovered. The tZq production process is interesting since it is sensitive to the tZ and WWZ couplings, it is a background for many searches such as the

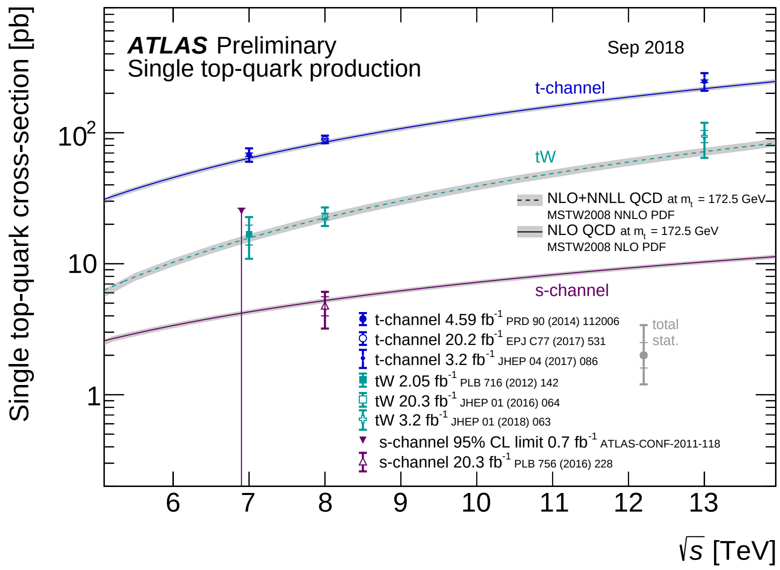

Figure 4: Summary of ATLAS measurements of the single top production cross sections in various channels as a function of the CME compared with theoretical calculations based on next-to-leading order QCD [11].

production of tZ through Flavour Changing Neutral Current (FCNC) processes, and is the first step in the search of tH production. ATLAS collaboration searched for tZq at $\sqrt{s} = 13$ TeV using 36.1 fb^{-1} of integrated luminosity [13].

The analysis is performed using the trilepton channel, since it is the most promising for first observation despite the small branching fraction. Events are required to have exactly three well isolated leptons, e or μ, with different p_{T} cuts to maximise the S/B. The Z boson is reconstructed from a pair of leptons with an opposite charge and same flavour with an invariant mass within a window from the Z boson mass. The remaining lepton is associated to the W boson that is assumed to come from the top quark decay. Events are required to have exactly two jets. One jet is required to be b-tagged and used to reconstruct the top quark, the other jet is called the untagged jet and tends to be in the forward direction. An NN is used to combine many input variables to enhance the separation between the signal and the background, where the $|\eta|$ and p_{T} of the untagged jet are the most effective variables.

The tZq cross section is extracted using a binned maximum likelihood fit that is performed on the full NN output distribution. The measured cross section of $\sigma_{tZq} = 600 \pm 170(\text{stat.}) \pm 140(\text{syst.})$ fb is compared to the 800 fb predicted using NLO calculation. The observed signal significance is 4.2 s.d. compared to the predicted significance of 5.4 s.d.

6. Summary

The ATLAS collaboration at the LHC performed comprehensive analysis of the single top quark processes: t-channel and Wt-channel at 8 TeV and 13 TeV, and has evidences for the s-channel and the tZq production processes. Many precision measurements of single top quark processes are being done using the full Run2 dataset, and single top quark rare production processes will be investigated.

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