PROCEEDINGS OF SCIENCE

Single top quark production cross section measurements using the ATLAS detector.

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This proceeding contains single top quark production measurements based on 8 and 13 TeV datasets collected by the ATLAS experiment at the LHC. In the t-channel, the total production cross section, the ratio of top quark and top antiquark cross sections, as well as measurements of inclusive and differential cross sections are shown. Measurements of the inclusive production cross section of a single top quark in association with a W boson are included, as well as the first evidence of single top quark production in association with a Z boson.

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PoS(EPS-HEP2017)424

1. Introduction

The top quark is the most massive elementary particle known. In addition, it decays before hadronising, which allows for the study of the properties of a free quark. The top quark provides a framework in the search for new physics since many new particles are predicted to be coupled to it. According to the standard model (SM), the top quark can be produced in top and top antiquark pairs via the strong interaction or singly via the weak interaction through three production modes: t-channel, Wt, and s-channel. The top quark is predicted to decay almost exclusively into a W boson and a b quark.

The production mode through the t-channel that has the highest production rate allows validating the SM since extensions of the SM predict a significant enhancement of its rate. The production cross section is proportional to the V_{tb} CKM matrix element, therefore it tests the unitarity of the CKM matrix, in constraining Parton distribution functions (PDF), and helps in tuning the Monte Carlo (MC) event generators.

The second production channel is the Wt channel, where the top quark is produced associated to a W boson. The remaining production mode is through the s-channel, which has the smallest production rate. This channel is a useful probe of new physics, but it is very challenging at the LHC.

The SM also predicts an electroweak production of the single top quark in association with a Z boson (tZq), which has not been observed yet. The tZq is an interesting process since it is sensitive to the tZ and WWZ couplings, is a background in the search for tZ production via FCNC and is the first step in the search of tH production.

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.

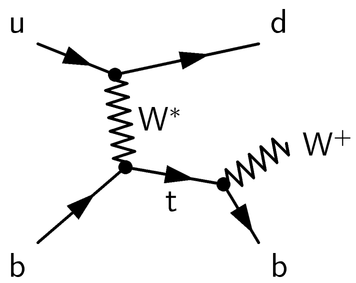

Figure 1: LO single top quark production Feynman graph.

ATLAS [1] studied the t-channel using 20.2 fb^{-1} integrated luminosity collected in 2012 at $\sqrt{s} = 13$ TeV [2]. Events are selected using a single lepton (e or μ) trigger and are required to have exactly one reconstructed well isolated lepton with $p_{\mathrm{T}} > 25$ GeV within $|\eta| < 2.5$. The missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}}$, is required to be > 30 GeV. In addition, events are required to have exactly two jets with $p_{\mathrm{T}} >$30 GeV within $|\eta| < 4.5$, in which exactly one jet is required to be b-tagged by an algorithm optimised to reject c quark jets, this is necessary to reduce the major background, Wc production. The remaining jet is an untagged and is typically produced at large η.

Given the large number of expected background events, a neural networks (NN) is trained to enhance the signal to the background ratio(S/B). The NN is trained using simulated events with seven input kinematic variables, where the variables making the most significant contribution are the invariant mass of the untagged jet, the b-tagged jet system $m(jb)$, and the η of the untagged jet. The fiducial cross section is extracted using a binned maximum likelihood fit performed on the full NN distribution separately for the top quark and the top antiquark channels. Measuring the fiducial cross section has the advantage of reducing the systematic uncertainties related to the MC generators.

The fiducial volume is defined using stable particles selected with cuts applied as close as possible to the final selections. The resulting fiducial cross sections are $\sigma_{\text{fid.}}(tq) = 9.78 \pm 0.57$ pb for the top quark and $\sigma_{\text{fid.}}(\bar{t}q) = 5.77 \pm 0.45$ pb for the top antiquark. The fiducial cross sections are extrapolated into full phase space to measure the full cross sections, resulting in $\sigma^{\text{tot.}}_{tq} = 56.7^{+4.3}_{-3.8}$ pb for the top quark and $\sigma^{\text{tot.}}_{\bar{t}q} = 32.9^{+3.0}_{-2.7}$ pb for the top antiquark. The full cross section is compared to predictions made by different MC generators. The ratio between the top quark and top antiquark production cross sections is calculated to be $R_t = 1.7 \pm 0.09$ and compared with predictions made by different proton PDFs. The sum of the full cross sections of the top and top antiquarks is used to extract the CKM $|f_{LV}.V_{tb}|$ element, where f_{LV} is a form factor and 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. Figure 2 left) shows the measured total cross section for top quark production compared with the NLO predictions made by different MC generators, while Figure 2 right) shows the measured cross section ratio of the top quark and top antiquarks compared to predictions made by different proton PDFs.

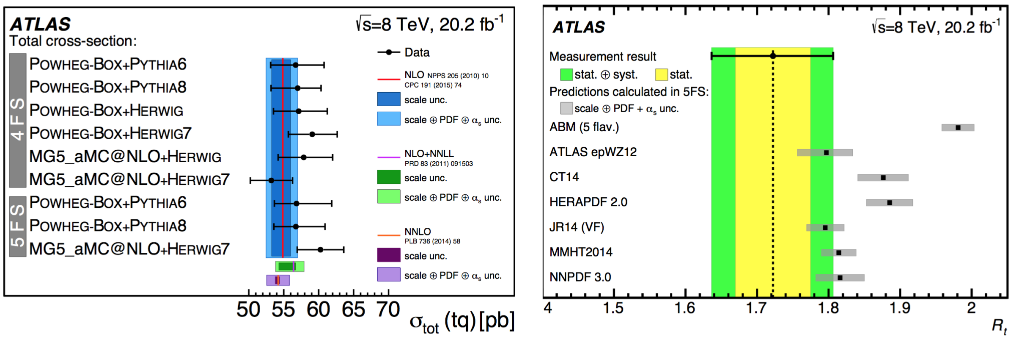

Figure 2: (Left) Extrapolated single top quark production cross sections compared with predictions made by different MC generator. (Right) Measured R_t compared with predictions made by different PDFs [2].

The differential cross sections as a function of the p_{T} and absolute rapidity ($|y|$) for both the top quark and the top antiquark and the differential cross sections 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. These distributions are unfolded and directly compared to predictions made by different MC generators.

PoS(EPS-HEP2017)424

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 [3]. A binned maximum likelihood fit to NN distribution is used to extract the cross sections: $\sigma_{\mathrm{tot.}}(tq) = 156 \pm 28$ pb, $\sigma_{\mathrm{tot.}}(\bar{t}q) = 91 \pm 19$ 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 and top antiquark production cross section is calculated to be $\sigma_{\mathrm{tot.}}(tq + \bar{t}q) = 247 \pm 46$ pb and is used to extract the $|f_{LV} \cdot V_{tb}| = 1.07 \pm 0.09$. Those measured parameters are in good agreement with the SM prediction and are dominated by systematic uncertainties.

3. Wt channel cross section measurements

The 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 collected in 2012 [4]. 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ and exactly one jet with high p_{T} within $|\eta| < 2.5$, this jet is required to be b-tagged. To constrain backgrounds, control regions enriched with background events are defined using the jets and b-tagged jet multiplicity.

Three separate Boosted decision trees (BDT) are used to enhance S/B. Figure 3 shows the BDT output distribution in the signal region(1j1b). 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 $\sigma_{tW} = 23.0 \pm 1.3(\mathrm{stat.})^{+3.2}_{-3.5}(\mathrm{syst.}) \pm 1.1(\mathrm{lumi.})$ pb with a signal significance of 7.6 σ. The total cross section is used to calculate $V_{tb} = 1.01 \pm 0.10$.

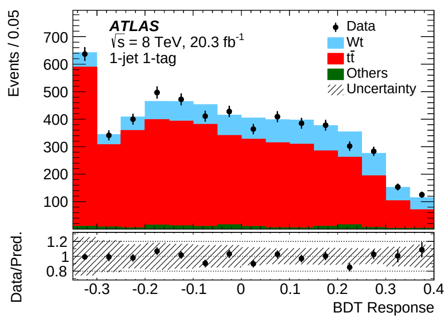

Figure 3: BDT response for the signal region where exactly one b-tagged jet is required [4].

The Wt production cross section measurement is repeated using 3.2fb^{-1} of integrated luminosity collected in 2015 at $\sqrt{s}$ =13 TeV [5] employing similar techniques as in the 8 TeV measurement. However, some significant changes are made: an optimisation of cuts to reduce the background, modifications to the BDT training, and the binning of the distribution used in the likelihood fit.

The cross section is extracted using simultaneous binned likelihood of the BDT distributions in the signal regions (1j1b and 2j1b), and 1 bin distribution the the CR region (2j2b). The resulting cross section is $\sigma_{tW} = 94 \pm 10(\mathrm{stat.})^{+28}_{-22}(\mathrm{syst.}) \pm 2(\mathrm{lumi})$ pb corresponding to an observed significance of 4.5σ compared to predicted significance of 3.9σ.

PoS(EPS-HEP2017)424

4. 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), this process has not been observed. Figure 4 shows examples of the lowest order Feynman diagrams for the process.

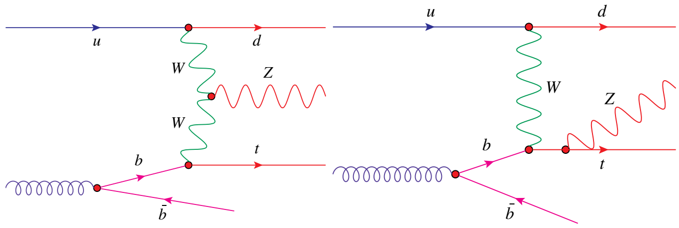

Figure 4: Example of Feynman graphs used to calculate the lowest order amplitudes.

ATLAS has performed a searched for tZq using 36.1 fb^{-1} of integrated luminosity collected in 2015 and 2016 at $\sqrt{s} = 13$ TeV [6]. The tZq process has many possible final states, however, the analysis is performed using the trilepton channel, where both the Z boson and the top quark decay leptonically. This channel is the most promising for first observation despite the small branching fraction (2.2%).

The tZq events are selected using a single lepton (e or μ) trigger. The events are required to have exactly three leptons, e or μ, well isolated with different p_{T} cuts to maximise S/B and with $|\eta| < 2.5$. The Z boson is reconstructed from a pair of leptons with an opposite sign, same flavour (OSSF), if the event had two pairs, the pair that had the invariant mass closest to the Z mass is chosen. The OSSF is required to have an invariant mass within 10 GeV of the Z boson mass. The remaining lepton is associated to the W boson that is assumed to come from the top quark decay, this lepton together with $E_{\mathrm{T}}^{\mathrm{miss}}$ is used to construct the transverse mass $m_{\mathrm{T},W} = \sqrt{2p_{\mathrm{T,lep}}E_{\mathrm{T}}^{\mathrm{miss}}(1-\cos(\Delta\phi(\mathrm{lep},\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}))}$ variable and $m_{\mathrm{T},W}$ is required to be > 20 GeV. Events are required to have exactly two jets with $p_{\mathrm{T}} > 30$ GeV and $|\eta|$ <4.5. Exactly 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 as in t-channel.

A neural network is used to combine many kinematic variables to enhance S/B. The NN is trained using 10 input variables, where the variables most contributing in separating signal from background are the $|\eta|$ and p_{T} of the untagged jet, the mass of the reconstructed top quark and the p_{T} the lepton associated to the W boson. The NN output can be seen in Figure 5.

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

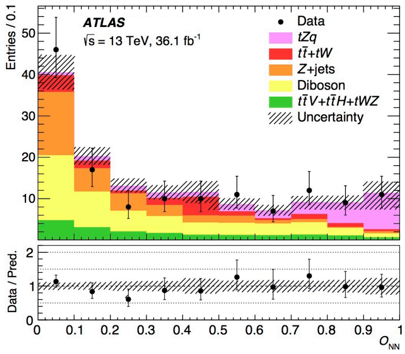

Figure 5: Post fit NN output distributions. Signal and backgrounds are normalised to the number of events extracted by the fit [6].

References

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

[2] ATLAS Collaboration, *Fiducial, total and differential cross-section measurements of t-channel single top-quark production in pp collisions at 8 TeV using data collected by the ATLAS detector*, *Eur. Phys. J.* **C 77** (2017) 531, [hep-ex/1702.02859].

[3] ATLAS Collaboration, *Measurement of the inclusive cross-sections of single top-quark and top-antiquark t-channel production in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, *JHEP* **1704** (2017) 086 [hep-ex/1609.03920].

[4] ATLAS Collaboration, *Measurement of the production cross section of a single top quark in association with a W boson at 8 TeV with the ATLAS experiment*, *JHEP* **1601** (2016) 064, [hep-ex/1510.03752].

[5] ATLAS Collaboration, *Measurement of the cross-section for producing a W boson in association with a single top quark in pp collisions at $\sqrt{s} = 13$ TeV with ATLAS*, hep-ex/1612.07231.

[6] ATLAS Collaboration, *Measurement of the production cross-section of a single top quark in association with a Z boson in proton–proton collisions at 13 TeV with the ATLAS detector*, hep-ex/1710.03659

PoS(EPS-HEP2017)424