PROCEEDINGS OF SCIENCE

Top production measurements using the ATLAS detector at the LHC

Marino Romano[*†]
INFN, Sezione di Bologna and University of Bologna
E-mail: romano@bo.infn.it

This paper is an overview of recent results on top-quark production measurements obtained by the ATLAS collaboration from the analysis of pp collisions at $\sqrt{s} = 7$ and 8 TeV at the Large Hadron Collider. Total and differential top-quark pair ($t\bar{t}$) cross section and total single top cross section measurements are presented.

The European Physical Society Conference on High Energy Physics
22–29 July 2015
Vienna, Austria

[*]Speaker.
[†]On behalf of the ATLAS Collaboration.

PoS(EPS-HEP2015)322

Introduction

The top quark is the heaviest quark, significantly heavier than its partner, the bottom quark. Once the bottom quark was experimentally discovered in 1977, the existence of a charge $2/3$ quark in the third quark generation was expected to preserve the Standard Model (SM) renormalizability. The top quark was eventually discovered by both the CDF [1] and DØ [2] collaborations in 1995 at the Tevatron collider.

The top quark is special not only due to its large mass, but also due to its short lifetime which prevents it from hadronizing before decaying, i.e. there are no bound state hadrons made of top quarks. This allows to experimentally test the properties of the bare top quark itself through its decay products without diluting information in the hadronization process.

As the properties of the top quark are precisely predicted by the SM, top quark physics provides a sensitive probe to test the validity of the SM and a tool to investigate the Higgs boson properties and to potentially discover physics beyond the SM.

This overview describes some of the recent measurements of top-pair and single-top production cross section, covering only a selection of the top physics results achieved by the ATLAS Collaboration using data collected in 2011 (with an integrated luminosity $L = 4.6\,\mathrm{fb}^{-1}$ at a center of mass energy $\sqrt{s} = 7\,\mathrm{TeV}$) and in 2012 ($L = 20.3\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$). A more complete list with updated results is available at the ATLAS public top result website.[1] The ATLAS detector and its performance are described in [3].

1. Top pair cross section measurements

Top quark pairs, $t\bar{t}$, are produced in proton-proton collisions via the strong interaction of the colliding partons. At $\sqrt{s} = 8$ TeV about 85% of $t\bar{t}$ pairs are produced by gluon-gluon interactions. The remaining 15% is produced in quark and anti-quark annihilation processes. A top quark decays almost exclusively into a W boson and b quark. Therefore, $t\bar{t}$ events can be classified through the decay products of the two W bosons. W bosons can decay into a quark pair or a lepton-neutrino pair. The ATLAS experiment has measured the total $t\bar{t}$ production cross section in different final states. A summary of the top pair cross section measurements using Run I data at the LHC is shown in Fig. 1.

1.1 Measurement of the inclusive cross section of top pair in the $e\mu$ channel

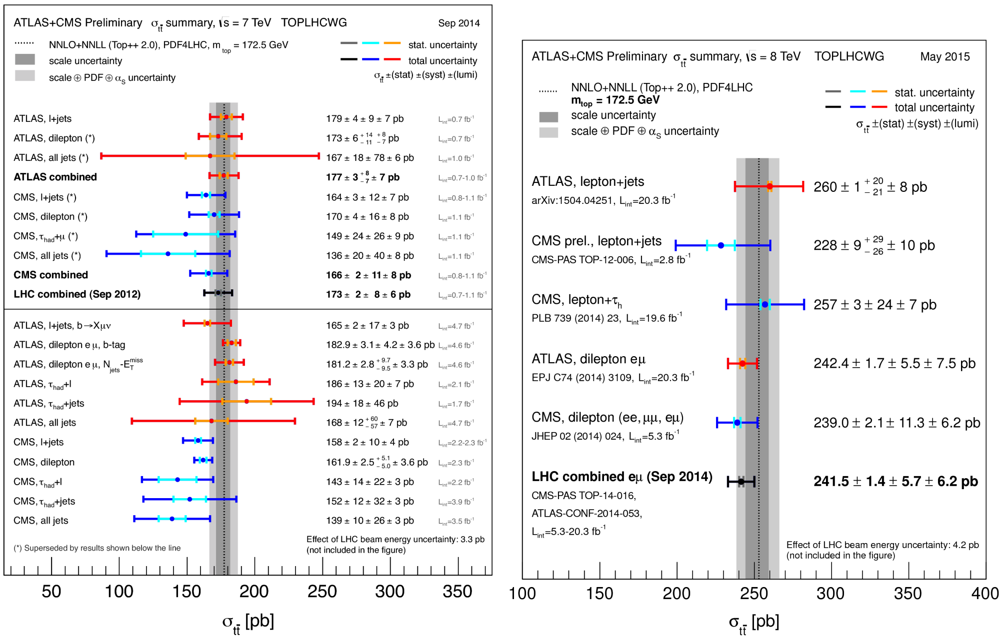
The most precise measurement of the inclusive cross section of the top quark pair production $\sigma_{t\bar{t}}$ in pp collisions at $\sqrt{s} = 7$ and $8\,\mathrm{TeV}$ was performed in the final state containing a pair oppositely charged $e\mu$ [4]. The measurement was performed with the 7 TeV dataset taken in 2011 corresponding to an integrated luminosity of $4.6\,\mathrm{fb}^{-1}$, and the 8 TeV dataset taken in 2012 of $20.3\,\mathrm{fb}^{-1}$.

The number of events with exactly one and exactly two b-tagged jets were counted and used to simultaneously determine $\sigma_{t\bar{t}}$ and the efficiency to tag a jet from a top quark decay as a b-quark jet. This method allows a significant reduction of the associated systematic uncertainties. The cross section was measured in the fiducial (one electron and one muon with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $|\eta| < 2.5$) phase space and then extrapolated to the total phase space.

The total cross sections at $\sqrt{s} = 7$ and $8\,\mathrm{TeV}$ are measured to be

$$\begin{aligned} \sigma_{t\bar{t}}^{\mathrm{tot}}(7\,\mathrm{TeV}) &= 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\,\mathrm{pb} \\ \sigma_{t\bar{t}}^{\mathrm{tot}}(8\,\mathrm{TeV}) &= 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2\,\mathrm{pb}. \end{aligned} \tag{1.1}$$

[1] https://twiki.cern.ch/twiki/bin/viewAtlasPublic/TopPublicResults



(a) (b)

Figure 1: Summary of measurements of the top-pair production cross section at $\sqrt{s} = 7$ TeV (a) and 8 TeV (b).

where the four uncertainties arise from data statistics, systematic uncertainties, knowledge of the integrated luminosity and of the LHC beam energy. The results are consistent with the theoretical QCD calculations at the NNLO [5]:

$$\begin{aligned}\sigma_{t\bar{t}}^{\text{th}}\,(7\,\text{TeV}) &= 177.3 \pm 9.0^{+4.6}_{-6.0}\,\text{pb}\\ \sigma_{t\bar{t}}^{\text{th}}\,(8\,\text{TeV}) &= 252.9 \pm 11.7^{+6.4}_{-8.6}\,\text{pb},\end{aligned} \tag{1.2}$$

where the first uncertainty is due to PDF and α_s uncertainties, and the second is due to QCD scale uncertainties.

1.2 Top pair differential cross section measurements

Since the predictions for the $t\bar{t}$ production cross section are in very good agreement with the measurements and considering the rapid increase of the integrated luminosity, the focus is starting to switch to the “differential” measurements of the top properties, such as the cross section as a function of the $t\bar{t}$ system kinematic variables. Such experimental measurements, performed in different channels, allow precision tests of the predictions of perturbative QCD. New physics may also give rise to additional $t\bar{t}$ production mechanisms or modifications of the top quark decay channels, that can be discovered looking at the differential spectra.

To reconstruct the kinematic of the $t\bar{t}$ events, two topologies are usually considered: *resolved* topology, for top quarks with low-p_{T}, where the top quark decay products are well isolated and can be reconstructed individually; *boosted* topology, for high-p_{T} top quarks, where the top decay products are not well isolated and can be reconstructed as a single large-R jet.

The ATLAS experiment has measured the $t\bar{t}$ fiducial differential cross section $\frac{d\sigma}{dX}$ and total relative $\frac{1}{\sigma}\frac{d\sigma}{dX}$ cross section at 7 TeV as a function of the mass, transverse momentum, absolute rapidity of the system using the resolved approach [6, 7] and the total and fiducial differential cross section as a function of the transverse momentum of the hadronically decaying top ($\frac{d\sigma}{dp_{\mathrm{T},t_{had}}}$) at 8 TeV, using the boosted approach [8].

All these analyses have been performed by selecting events in the lepton (e/μ) + jets channel. Once the reconstructed kinematic distributions are extracted, the cross section is calculated in the fiducial phase space at particle level and in the full phase space at parton level via unfolding methods. The measurements have been compared to predictions from Monte Carlo generators. In general, all measurements show good agreement with the theory, as shown in Figs. 2–4. All the analyses observed a trend where the theoretical predictions overestimate the data at high p_{T}.

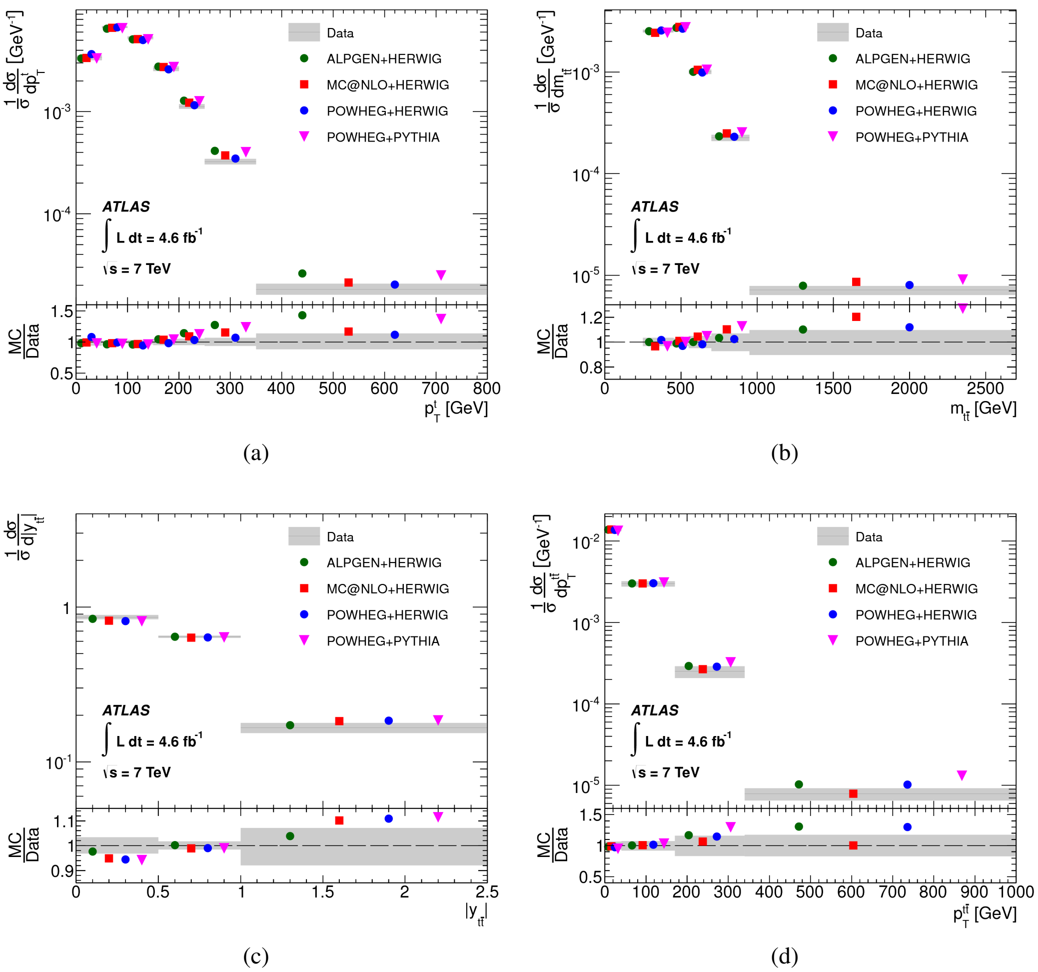


Figure 2: Normalized differential $t\bar{t}$ cross section at $\sqrt{s} = 7\,\mathrm{TeV}$ as a function of the transverse momentum of the top (a) and mass (b), rapidity (c) and transverse momentum (d) of the $t\bar{t}$ system in the full phase space using the resolved approach.

2. Single top cross section measurements

At the LHC, top quarks can be produced individually through the electroweak interaction involving the tWb vertex. The t-channel process is the dominant single top production mode. The

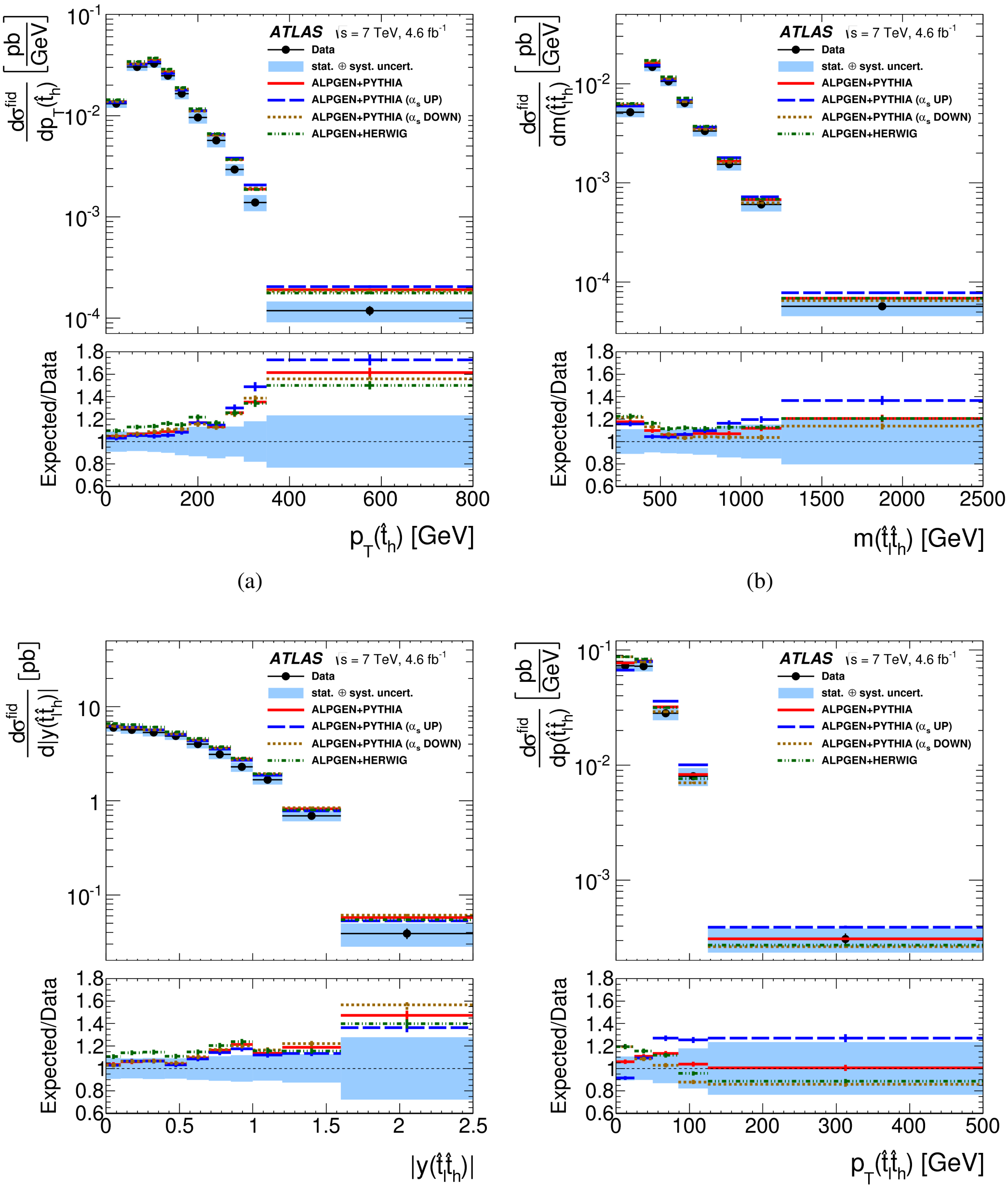
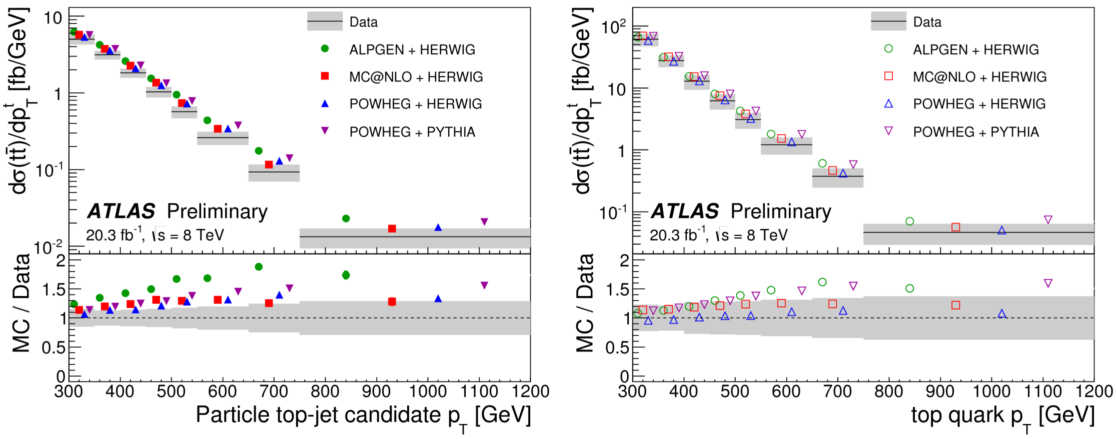


Figure 3: Differential $t\bar{t}$ cross section at $\sqrt{s} = 7\,\text{TeV}$ as a function of the transverse momentum of the top (a) and mass (b), rapidity (c) and transverse momentum (d) of the $t\bar{t}$ system in the fiducial phase space using the resolved approach.



(a) (b)

Figure 4: Differential $t\bar{t}$ cross section at $\sqrt{s} = 8\,\text{TeV}$ as a function of the transverse momentum of the top in the fiducial (a) and full (b) phase space.

W-associated production (Wt), recently observed at the LHC [9], occurs with a moderate rate whereas the s-channel process is so rare that it has been only possible to set an upper limit for its cross section. A summary of the single top cross section measurements using Run I data is shown in Fig. 5.

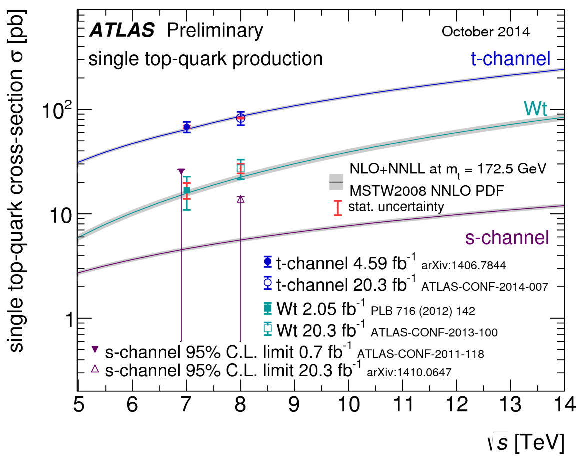


Figure 5: ATLAS summary plot for single-top cross section measurements.

2.1 Single top t-channel cross section measurement at $\sqrt{s} = 8\,\text{TeV}$

At $\sqrt{s} = 8\,\text{TeV}$ the single-top quark production inclusive and fiducial cross section has been measured in the t-channel production mechanism using the lepton+jets decay topology [10].

To separate t-channel single top-quark signal events from the expected background, several kinematic variables have been combined into one discriminant by employing a neural network (NN).

A binned maximum-likelihood fit to the NN output distribution is performed simultaneously for the two-jet and three-jet samples to extract the t-channel single top-quark cross section. The rates of the background processes have also been fitted within their uncertainties.

The fiducial cross section of t-channel single top-quark production is measured to be

$$\sigma_{\text{fid}} = 3.37 \pm 0.05(\text{stat.}) \pm 0.47(\text{syst.}) \pm 0.06(\text{lumi.})\,\text{pb},$$

which is in very good agreement with the SM predictions provided by LO and NLO generators, as shown in Fig. 6a.

Using various MC generator models, the fiducial cross section can be extrapolated to the full phase space and can be compared to the NLO+NNLL calculation. Using aMC@NLO generator [11] an extrapolated total inclusive cross section of

$$\sigma_{\text{tot}} = 82.6 \pm 1.2(\text{stat.}) \pm 11.4(\text{syst.}) \pm 3.1(\text{PDF}) \pm 2.3(\text{lumi.})\,\text{pb}$$

is obtained. The measured cross section is in good agreement with the prediction at next-to-leading order plus contribution due to the resummation of soft-gluon bremsstrahlung (NLO+NNLL) [12] $\sigma_{tot}^{NLO+NNLL} = 87.8^{+3.4}_{-1.9}\,\text{pb}$.

2.2 Cross section measurements of W-associated production

The Wt production has been observed in ATLAS in the dilepton ($e\mu$) final state, using 20.3 fb^{-1} of the 8 TeV data by selecting events with one electron, one muon, one jet and one b-jet (1J1B region) or 2 jets and one b-jet (2J1B region) [13]. Multivariate techniques based on Boosted Decision Tree (BDT) have been employed to increase the discrimitation power respect to the dominating $t\bar{t}$ background. A fit to the BDT output is simultaneously performed in the 1J1T (Fig. 6b) and 2J1T regions. Templates for signal and backgrounds are taken from simulation and systematic uncertainties evaluated by means of pseudo-experiments with the main contribution coming from the Wt and $t\bar{t}$ modeling. The measurement results in an observed (expected) significance of σ ($4.0\,\sigma$). This corresponds to

$$\sigma(Wt) = 27.2 \pm 2.8(\text{stat.}) \pm 5.4(\text{syst.})\,\text{pb}$$

in good agreement with the NLO+NNLL prediction of 22.4 ± 1.5 pb [14].

2.3 Single top s-channel cross section measurement at $\sqrt{s} = 8\,\text{TeV}$

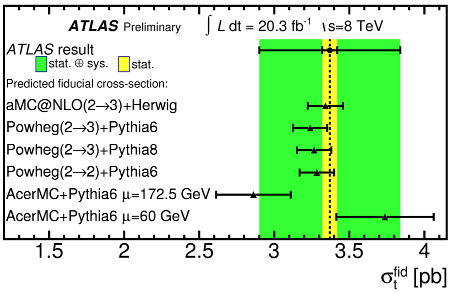
The production of single top in the s-channel is characterized by a very low rate pp collisions. ATLAS has measured the s-channel cross section in the channel with one lepton, two b-tag and $E_{\text{T}}^{\text{miss}}$ [15]. Similary to the Wt cross section measurement, a multivariate technique based on Boosted Decision Tree (BDT) has been employed to enhance the signal significance. The signal contribution to the selected sample of data is extracted by performing a binned maximum-likelihood fit to the BDT output distribution. The simulated BDT distribution of the signal events renormalized to the observed upper limit is presented in Fig. 6c for comparison with the signal distribution extracted from the data.

The systematic uncertainties on the measurement are determined using pseudo-experiments involving variations of the signal and background rates and of the shape of the BDT distributions.

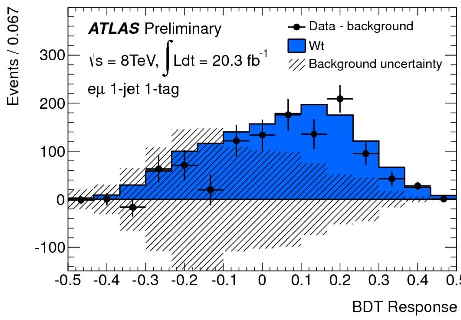
The observed (expected) significance of the s-channel single top measurement is found to be 1.3 (1.4) standard deviations and an observed (expected) upper limit on the production cross section of 14.6 pb (15.7 pb) is set at the 95% confidence level. The fitted value of the cross section is found to be:

$$\sigma = 5.0 \pm 1.7(\text{stat.}) \pm 4.0(\text{syst.})\,\text{pb};$$

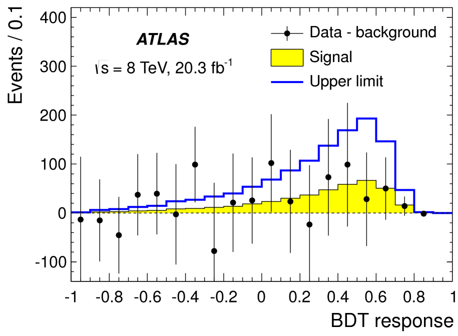
this measurement should be compared with the cross section of 5.61 ± 0.22 pb calculated at approximate NNLO [16].



(a)



(b)



(c)

Figure 6: (a): predicted t-channel single top-quark fiducial cross section for different NLO MC generators and the matched LO generator AcerMC [17] together with the measured value. The uncertainty on the prediction consists of the scale uncertainty and the uncertainty on the PDFs. (b): background-subtracted Wt BDT classifier for 1-jet events, using the fit result for signal and backgrounds. (c): observed and predicted signal distributions of the s-channel BDT response after background subtraction.

Conclusions

The study of top quarks can answer fundamental questions on the SM. This quark is undoubtedly a peculiar particle, with a Yukawa coupling of the order of one and it is a powerful probe of physics beyond the SM. Its production mechanism in pp collisions is described very well by the SM, as well as its decay. All the measurements shown in this paper are limited by systematic uncertainties. As more data is being analyzed the understanding of the detector is improving and calibrations are being refined. ATLAS is looking forward to refine the current measurements, as well as to produce new results using the latest data collected at $\sqrt{s} = 13\,\text{TeV}$.

References

[1] F. Abe *et al.* (CDF Collaboration), *Observation of Top Quark Production in $\bar{p}p$ collisions*, *Phys. Rev. Lett.*, **74** (1995) 2632 [arXiv:hep-ex/9503002].

[2] S. Abachi *et al.* (D∅ Collaboration), *Observation of the top quark*, *Phys. Rev. Lett.*, **74** (1995) 2626 [arXiv:hep-ex/9503003].

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

[4] ATLAS Collaboration, *Measurement of the $t\bar{t}$ production cross-section using $e\mu$ events with b -tagged jets in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector*, *Eur. Phys. J.*, **C4** (2014) 3109 [arXiv:hep-ex/1406.5375].

[5] M. Czakon and A. Mitov, *Top++: A Program for the Calculation of the Top-Pair Cross-Section at Hadron Colliders*, *Comput. Phys. Commun.*, **185** (2014) 2930 [arXiv:hep-ph1112.5675].

[6] ATLAS Collaboration, *Differential top-antitop cross-section measurements as a function of observables constructed from final-state particles using pp collisions at $\sqrt{s} = 7$ TeV in the ATLAS detector*, *JHEP*, **06** (2014) 100 [arXiv:hep-ex/1502.05923].

[7] ATLAS Collaboration, *Measurements of normalized differential cross sections for $t\bar{t}$ production in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector*, *Phys. Rev. D*, **90** (2014) 072004 [arXiv:hep-ex/1407.0371].

[8] ATLAS Collaboration, *Measurement of the differential cross-section of highly boosted top quarks as a function of their transverse momentum using the ATLAS detector in $\sqrt{s}$ = 8 TeV proton-proton collisions*, ATLAS-CONF-2014-057, `http://cds.cern.ch/record/1951328`.

[9] CMS Collaboration, *Observation of the associated production of a single top quark and a W boson in pp collisions at $\sqrt{s}$ =8 TeV*, *Phys. Rev. Lett.*, **112** (2014) 231802 [arXiv:hep-ex/1401.2942].

[10] ATLAS Collaboration, *Measurement of the Inclusive and Fiducial Cross-Section of Single Top-Quark t-Channel Events in pp Collisions at $\sqrt{s}$ = 8 TeV*, ATLAS-CONF-2014-007, `http://cds.cern.ch/record/1668960`.

[11] J. Alwall *et al.*, *MadGraph 5 : Going Beyond*, JHEP 1106 (2011) 128, [arXiv:hep-ph/1106.0522].

[12] N. Kidonakis, *Next-to-next-to-leading-order collinear and soft gluon corrections for t-channel single top quark production*, *Phys. Rev. D*, **83** (2011) 091503 [arXiv:hep-ph/1103.2792].

[13] ATLAS Collaboration, *Measurement of the cross-section for associated production of a top quark and a W boson at $\sqrt{s} = 8$ TeV with the ATLAS detector*, ATLAS-CONF-2013-100, `https://cds.cern.ch/record/1600799`.

[14] N. Kidonakis, *Two-loop soft anomalous dimensions for single top quark associated production with a W- or H-*, *Phys. Rev. D*, **82** (2010) 054018 [arXiv:hep-ph/1005.4451].

[15] ATLAS Collaboration, *Search for s-channel single top-quark production in protonâĂŞproton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, *Phys. Lett. B*, **740** (2015) 118 [arXiv:hep-ex/1410.0647].

[16] N. Kidonakis, *NNLL resummation for s-channel single top quark production*, *Phys. Rev. D*, **81** (2010) 054028 [arXiv:hep-ph/1001.5034].

[17] B.P. Kersevan and E. Richter-Was, *The Monte Carlo event generator AcerMC version 2.0 with interfaces to PYTHIA 6.2 and HERWIG 6.5*, *Comput. Phys. Commun.*, **184** (2013) 919 [arXiv:hep-ph/0405247]