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Highlights of top quark cross-section measurements at ATLAS

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Abstract. The highlights of the measurements of top quark production in proton-proton collisions at the Large Hadron Collider with the ATLAS detector are presented. The inclusive measurements of the top-pair production cross section have reached high precision and are compared to the best available theoretical calculations. The differential cross section measurements, including results using boosted top quarks, probe our understanding of top-pair production in the TeV regime. The results are compared to Monte Carlo generators implementing LO and NLO matrix elements matched with parton showers. Measurements of the single top quark production cross section are presented in the t-channel and s-channel, and with associated production with a W boson. For the t-channel production, results on the ratio between top quark and antitop quark production cross sections and differential measurements are also included.

1 Introduction

Millions of top quarks have been produced in proton-proton collisions at the Large Hadron Collider (LHC) at three different center-of-mass energies: $\sqrt{s} = 7$ TeV, $\sqrt{s} = 8$ TeV, and $\sqrt{s} = 13$ TeV allowing us to precisely measure its production cross sections. There are two main production modes at the LHC: top-pair ($t\bar{t}$) production and single top production. The single top production consists of three separate physics processes: t-channel production, s-channel production and production associated with a W boson (Wt). A pair of top quarks or a single top quark can be produced in association also with other objects (e.g. Z boson, Higgs boson), which is not covered in this overview.

There are several important reasons to measure precisely the top quark production cross sections. First of all, the measurements are precision tests of the Standard Model (SM). The $t\bar{t}$ production probes Quantum Chromodynamics (QCD) and the single top production probes the electroweak theory. The measurements are sensitive to many physics models beyond the SM. In particular, the measurements of the $t\bar{t}$ differential cross sections probe the TeV scale, and therefore a new particle with large coupling to the top quark can cause a significant increase in the $t\bar{t}$ invariant mass spectrum or can modify the top p_{T} spectrum. Furthermore, the measurements can constrain parton density function (PDF) fits and the parameters of the SM Monte Carlo (MC) generators. The measurement of the single top cross sections can be used to estimate the CKM matrix element V_{tb} and various differential cross section measurements can be used to extract the top quark pole mass.

In this overview, a selection of measurements from the ATLAS experiment [1] are presented. The top quark decays almost in ∼100% of the cases to a W boson and a b-quark, and therefore the

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signature of the top quark events in the detector depends on the decay mode of the W boson, which can be leptonic or hadronic.

2 $t\bar{t}$ production

2.1 $t\bar{t}$ inclusive cross sections

Precise measurements of the $t\bar{t}$ inclusive cross sections are performed in full and fiducial phase spaces at $\sqrt{s}$ = 7 TeV, $\sqrt{s}$ = 8 TeV [2], and $\sqrt{s}$ = 13 TeV [3] using events containing exactly one isolated electron (e) and one isolated muon (μ) of opposite charge. Further selection requirements are on the missing transverse energy and on the number of jets tagged by a track-based algorithm which identifies jets containing a b-quark (b-tagged jets). Figure 1 shows the number of b-tagged jets, in which the prediction is consistent with data. The number of events with one b-tagged jet and two b-tagged jets is used to determine the b-tagging efficiency in data which reduced the systematic uncertainty due to the difference of the b-tagging efficiencies between data and MC. The main systematic uncertainties arise from the luminosity and LHC beam energy measurements, as well as from the modeling of the $t\bar{t}$ events. The total uncertainty is ~4% for measurements at each of the three center-of-mass energies. The result of the full phase space measurement is compared to theoretical QCD calculations at next-to-next-to-leading order (NNLO), and it is found that all measurements are consistent with it.

Figure 2 summarizes the $t\bar{t}$ inclusive measurements in the full phase space as a function of the center-of-mass energy compared to the NNLO QCD prediction complemented with NNLL resummation (NNLO+NNLL QCD). The measurements from the two LHC experiments, ATLAS and CMS,

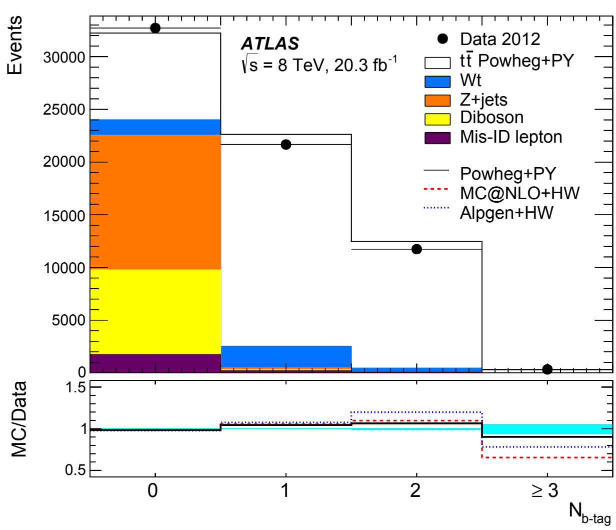

Figure 1. Distribution of the number of b-tagged jets in preselected opposite-charge $e\mu$ events in $\sqrt{s}$ = 8 TeV data [2]. The data are compared to the expectation from simulation, broken down into contributions from $t\bar{t}$, Wt single top, Z+jets, dibosons, and events with misidentified electrons or muons. The lower part of the figure shows the ratios of simulation to data, using various $t\bar{t}$ samples generated with Powheg + Pythia6 (PY), MC@NLO + Herwig (HW) and Alpgen + Herwig, and with the cyan band indicating the statistical uncertainty.

and also a combination of the Tevatron measurements from proton-antiproton collisions are shown. All the existing measurements of the $t\bar{t}$ inclusive cross section are consistent with the NNLO+NNLL QCD calculation.

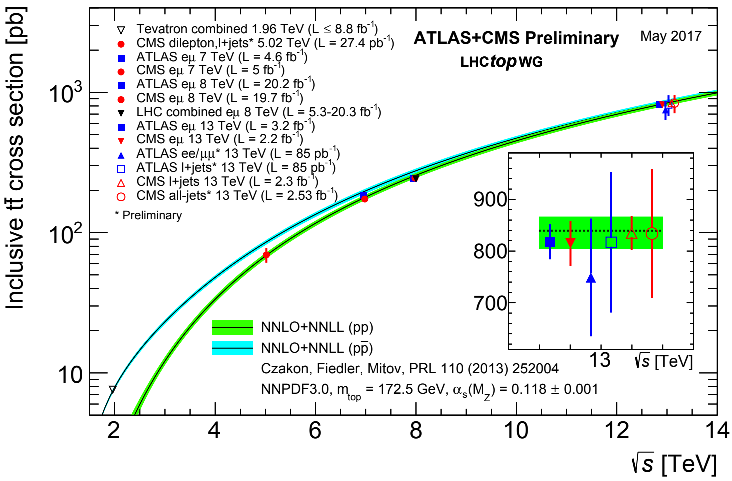

Figure 2. Summary of LHC and Tevatron measurements of the top-pair production cross-section as a function of the center-of-mass energy compared to the NNLO QCD calculation complemented with NNLL resummation (top++2.0) [4]. The theory band represents uncertainties due to the renormalisation and factorisation scale, parton density functions and the strong coupling. The measurements and the theory calculation assume m_{top} = 172.5 GeV. Measurements made at the same center-of-mass energy are slightly offset for clarity.

2.2 $t\bar{t}$ differential cross sections

The ATLAS experiment has an extensive program on the $t\bar{t}$ differential cross sections exploring them in various decay channels and phase spaces, and at all center-of-mass energies. Two measurements are described in the following.

The differential cross-section for $t\bar{t}$ events containing highly energetic top quarks is measured using all the recorded data (20.3 fb^{-1}) at $\sqrt{s}$ = 8 TeV [5]. The event selection focuses on the semileptonic $t\bar{t}$ decay in the boosted regime and consists of the following main criteria: one electron or one muon with $p_{\text{T}} > 25$ GeV, $E_{\text{T}}^{\text{miss}} > 20$ GeV, at least one large radius jet with $p_{\text{T}} > 300$ GeV (clustered with algorithm anti-k_t with distance parameter $R = 1$), and at least one b-tagged small radius jet ($R = 0.4$) with $p_{\text{T}} > 25$ GeV. Jet substructure criteria are applied for the large radius jets to identify hadronically decaying top quarks contained in these large radius jets. The measurement is performed in the full phase space and unfolded to parton level, where the differential cross section is expressed as a function of the p_{T} of the top quark. Additionally, the unfolding was performed to particle level with the differential cross section expressed as a function of the p_{T} of the large radius jet in a fiducial phase space similar to the selection criteria. The parton level result is shown in Figure 3 and it is compared to the predictions of next-to-leading-order (NLO) and leading-order (LO) matrix-element MC generators interfaced with various parton shower (PS) MC generators. The main uncertainties arise from signal modeling and jet energy scale (JES) of large radius jets. The measurement probes the top quarks at the TeV scale and it is consistent within uncertainties with all the tested QCD MC predictions.

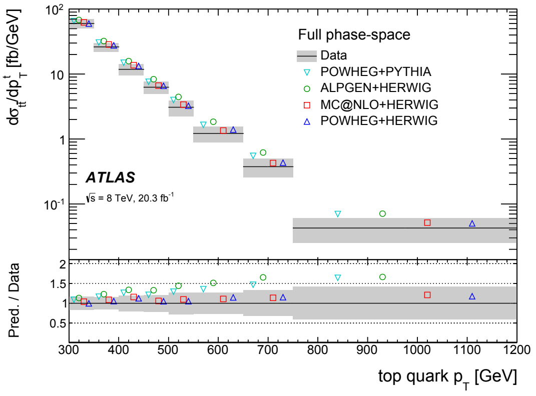

Figure 3. Parton-level differential cross-section as a function of the hadronically decaying top quark p_T [5]. Powheg+Pythia, Alpgen+Herwig, MC@NLO+Herwig, and Powheg+Herwig predictions are compared with the final results. MC samples are normalized to the NNLO+NNLL inclusive cross-section $\sigma^{t\bar{t}}$ = 253 pb. No electroweak corrections are applied to the predictions. The lower part of the figure shows the ratio of the MC prediction to the data. The shaded area includes the total statistical plus systematic uncertainties. The points of the various predictions are spaced along the horizontal axis for presentation only; they correspond to the same p_T range.

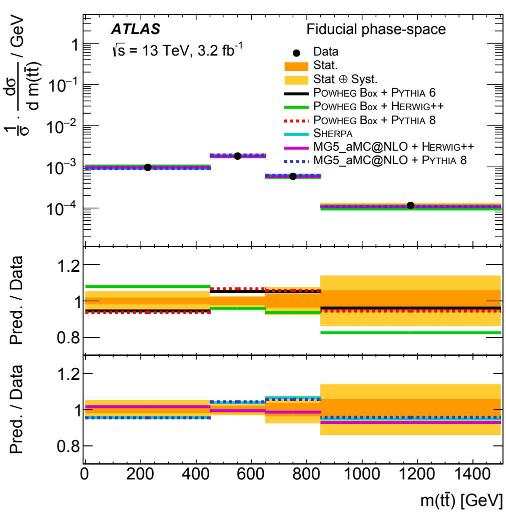

Figure 4. The measured normalized fiducial differential cross-section as a function of the particle-level invariant mass of the $t\bar{t}$ system [6]. The data are compared to the predictions from Powheg-Box (top ratio panel), Sherpa, and MG5_aMC@NLO (bottom ratio panel) interfaced to various PS generators.

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The dilepton decay channel is exploited in a differential cross section measurement using data $\sqrt{s}$ = 13 TeV corresponding to an integrated luminosity of 3.2 fb^{-1} [6]. The differential cross section is measured in a fiducial phase space as a function of the p_T and absolute rapidity of the top quark, and of the p_T, absolute rapidity and invariant mass of the $t\bar{t}$ system, where the top quark is defined using particle-level objects. The event selection requires an electron and a muon with opposite charge, and at least two jets, from which at least one is b-tagged. Figure 4 shows the normalized spectrum of the invariant mass of the $t\bar{t}$ system compared to the predictions from various QCD MC generators. All the predictions are consistent with the measured data, except the one from Powheg-Box interfaced with Herwig++. A similar inconsistency between data and the Powheg-Box + Herwig++ prediction is observed also for the top quark p_T spectrum, while the other MC predictions are consistent with data.

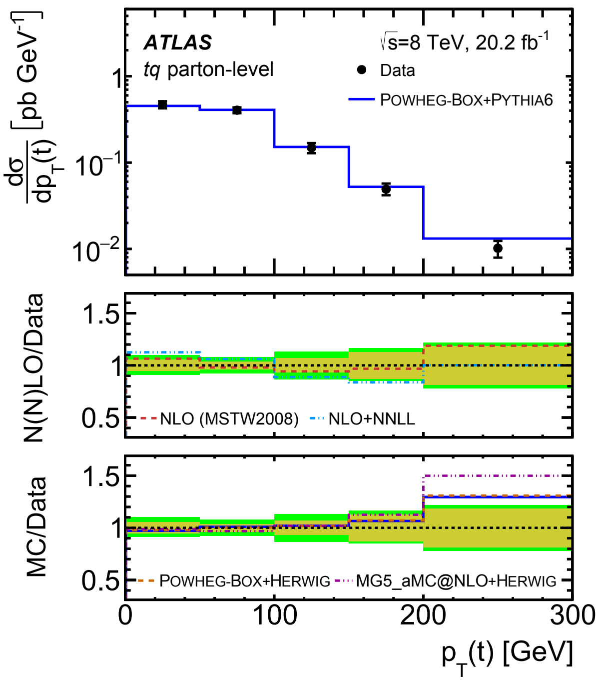

Figure 5. Absolute unfolded differential cross-section as a function of the p_T of the top quark (t) [7]. The unfolded distributions are compared to QCD NLO and NLO+NNLL calculations as well as various MC predictions. The vertical error bars on the data points denote the total uncertainty. The dashed (red) line in the central distribution shows the NLO prediction calculated using MCFM. The dash-dot (blue) line is the NLO+NNLL prediction. The bottom distribution compares the data with the MC predictions from Powheg-Box (orange dashed line) and MadGraph5_aMC@NLO (purple dash-dotted line). The inner (yellow) band in the bottom part of each figure represents the statistical uncertainty of the measurement, and the outer (green) band the total uncertainty.

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3 Single top production - *t*-channel

Inclusive and differential cross sections for the t-channel single top production are measured in detail at $\sqrt{s} = 8$ TeV in ATLAS [7]. The leptonic decay of the top quark is selected by requiring one electron or muon, missing transverse energy, and two jets, of which one is b-tagged. Several kinematic variables are used to derive a neural-network discriminant. The charge of the lepton allows to distinguish between top quark particle and antiparticle (t and $\bar{t}$). The measured inclusive cross sections in the full phase space for t and $\bar{t}$ production have uncertainties of ~7% and ~9%, respectively, and are in agreement with the NNLO QCD predictions. The inclusive cross sections are measured as well in a fiducial phase space with lower uncertainties of ~6% and ~8% for t and $\bar{t}$ productions, respectively. The differential cross sections as a function of the p_T and rapidity of t and $\bar{t}$ are measured at parton and particle levels. Figure 5 shows the measured parton-level p_T spectrum of t compared to NLO QCD and NLO+NLL QCD calculations, and to various MC predictions. All the differential cross section measurements are in good agreement with the SM.

The ratio of the t and $\bar{t}$ production cross sections, R_t, is an interesting observable which can be determined more precisely than the individual cross sections due to the cancellation of several systematic uncertainties in the ratio. This observable is sensitive to the difference between PDFs for u and d quarks. The measured observable R_t is shown in Figure 6 as a function of the center-of-mass energy. It is compared to NLO QCD calculations using various PDF sets (CT14, NNPDF 3.0 and MMHT2014). All the measurements of R_t are consistent with all the predictions.

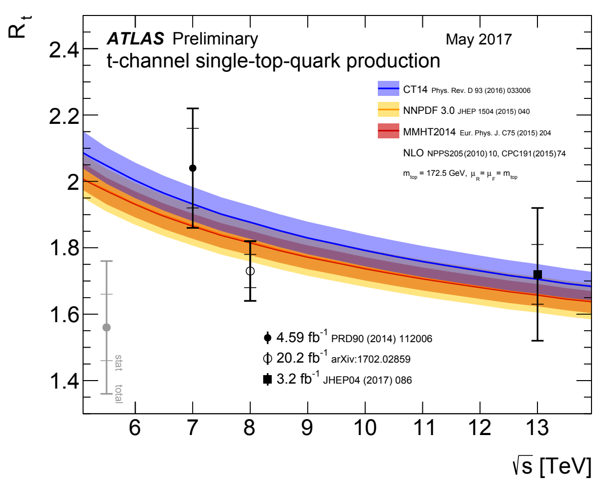

Figure 6. Summary of the ATLAS measurements of R_t, the ratio of the t-channel top-quark production cross-section to the t-channel antitop-quark production cross-section [4]. The data measurements are compared to NLO QCD calculations using the CT14, NNPDF 3.0 and MMHT2014 PDF sets. The coloured bands represent the uncertainties on the theoretical predictions (scale and PDF uncertainties).

4 Single top production - associated with a W boson

The inclusive cross section for Wt production at $\sqrt{s} = 8$ TeV is measured in the full phase space [8]. Two oppositely charged leptons (e or μ) and one b-tagged jet are required, but due to the overwhelming $t\bar{t}$ background, further discrimination is provided by boosted decision trees. The inclusive cross section in the full phase space has an uncertainty of ~20%, and it is consistent with the NLO+NNLL QCD prediction. Assuming both, Wt and $t\bar{t}$, processes as signal, the cross section is measured as well in a fiducial phase space, which is defined at particle level. The main requirements for the fiducial phase space are: two leptons with $p_T > 25$ GeV, one jet with $p_T > 20$ GeV, and $E_T^{miss} > 20$ GeV. The measured value of the fiducial cross section is shown in Figure 7 and it is compared to various MC NLO QCD predictions interfaced with PS generators. The predictions differ in the used PDF set, the scheme to handle the Wt and $t\bar{t}$ interference, overall normalization, and used MC generators. All the tested predictions are consistent with the measurement.

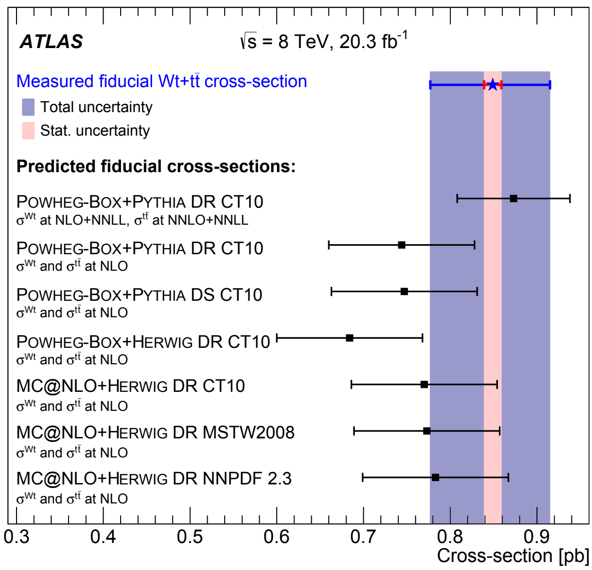

Figure 7. Comparison of the measured fiducial cross-section to theoretical predictions in a fiducial phase space requiring two leptons with $p_T > 25$ GeV and $|\eta| < 2.5$, one jet with $p_T > 20$ GeV and $|\eta| < 2.5$, and $E_T^{miss} > 20$ GeV [8]. The predictions are computed at NLO accuracy for the fiducial acceptance and the inclusive cross-section, except for the first one, for which the inclusive cross-sections for Wt and $t\bar{t}$ are computed at NLO+NNLL and NNLO+NNLL accuracy, respectively.

5 Single top production - *s*-channel

Evidence for the s-channel single top production at LHC was first published by ATLAS using $\sqrt{s}$ = 8 TeV data [9]. Events containing one electron or muon, large missing transverse momentum and two b-tagged jets are selected. The measurement is very challenging due to the low cross section and the large background contributions, which are mainly due to $t\bar{t}$ and W boson production in association with heavy-flavor jets. The matrix element (ME) method is optimized to derive a discriminant which allows to separate signal from background events. Figure 8 shows this discriminant for data and prediction. One can observe that there is reasonable agreement between data and prediction, and that the discriminant has good discrimination power between signal and background. The observed (expected) signal significance is 3.2 (3.9) standard deviations. The measured s-channel single top inclusive cross section of $\sigma = 4.8 \pm 0.8(\text{stat.})^{+1.6}_{-1.3}(\text{syst.})$ pb is consistent with the SM expectation.

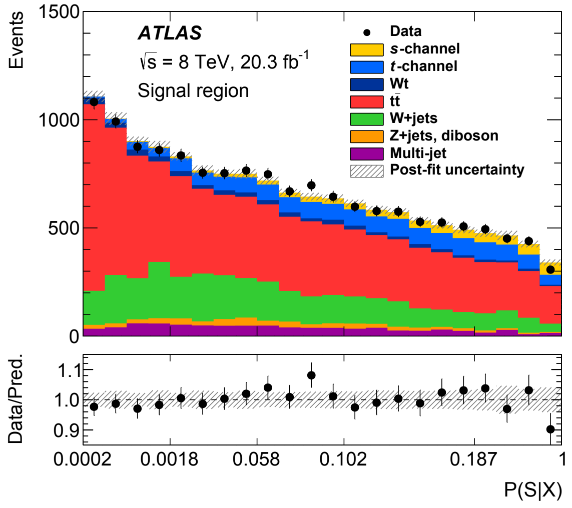

Figure 8. Post-fit distribution of the ME discriminant in the signal region [9]. All samples are scaled by the fit result utilizing all fit parameters. The hatched bands indicate the total uncertainty of the post-fit result including all correlations. The ME distributions are made using the optimized, non-equidistant binning which is also applied in the signal extraction fit.

6 Summary and outlook

The ATLAS experiment has an extensive program of inclusive and differential top cross section measurements. The uncertainties of the $t\bar{t}$ inclusive cross section measurements are only of a few percent. The $t\bar{t}$ differential cross section measurements probe the TeV scale and their main uncertainties are due to signal modeling and JES. There is evidence for s-channel single top production, while the t-channel and Wt productions have been explored in detail. The single top production measurements are dominated by data statistics, JES and MC modeling uncertainties. All the performed measurements are consistent with the SM.

The top quark production cross section measurements are further on-going at the ATLAS experiment while there are more data delivered by the LHC. More data allow to explore higher scales in the $t\bar{t}$ differential cross section measurements and they make the single top cross section measurements more precise.

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