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Top quark pair production cross section using the ATLAS detector at the LHC

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on behalf of the ATLAS collaboration

Abstract

Measurements of the inclusive top quark pair production cross sections in proton-proton collisions with the ATLAS detector at the Large Hadron Collider are presented. The measurements are performed requiring one or two electrons or muons in the final state. Various experimental techniques are compared. The most accurate result in obtained requiring opposite sign electrons and muons, achieves a precision of a few percent, and is in good agreement with a recent NNLO+NNLL QCD calculation. In addition, a differential measurement of the top transverse momentum and kinematic properties of the top pair system are presented. This measurement requires one electron or muon in the final state and probes our understanding of top pair production in the TeV regime and is compared to recent Monte Carlo generators and theory calculations.

Keywords: top quark, cross section, ATLAS, LHC

The top quark is the heaviest known elementary particle. Due to its large mass, it is expected to play a special role in several beyond the standard model (BSM) theories. Therefore, it is essential to measure precisely the production cross-sections of the known top-quark production modes, either for a comparison with the standard model (SM) predictions, or for establishing a reliable modelling of this important background for direct BSM searches. In the standard model, the top quark is mainly produced by pairs via strong interactions. The ATLAS collaboration has measured the top-quark pair ($t\bar{t}$) production cross-sections using several decay channels, in proton-proton (pp) collisions delivered by the Large Hadron Collider (LHC) at a center-of-mass energy of 7 and 8 TeV. Measurements of the inclusive $t\bar{t}$ production cross-section in the single lepton and dilepton channels, in which exactly one and two isolated leptons (electron or muons) with high transverse momentum (p_{T}) are produced in the decay of the top quarks respectively, are presented in Section 1, together with a summary of the ATLAS current results. A measurement of the differential $t\bar{t}$ production cross-section in the single lepton channel as a function of different kinematic variables is also presented in Section 2.

1. Inclusive cross-section measurements

1.1. Single lepton channel at $\sqrt{s} = 8$ TeV

The ATLAS collaboration released a preliminary result for the measurement of the inclusive $t\bar{t}$ production cross-section in the single lepton channel using pp collisions data delivered in 2012 by the LHC, corresponding to an integrated luminosity of 5.8 fb^{-1} at a centre-of-mass energy of $\sqrt{s} = 8$ TeV [1].

Signal event candidates are selected using single isolated electron or muon triggers. The offline selection in the electron (muon) channel requires the presence of exactly one electron (muon) with $\mathrm{p_T} > 40$ GeV and $|\eta| < 2.5$,[1] and satisfying tracker and calorimeter isolation requirements, together with three or more jets

[1] The ATLAS experiment uses a right-handed coordinate system

satisfying $p_T > 25$ GeV and $|\eta| < 2.5$, at least one of which is required to be identified as likely to have originated from a b-quark (b-tagged), using a multivariate discriminant such as the b-quark jets tagging efficiency is approximately 70%. Criteria on the modulus of the missing transverse momentum E_T^{miss} and on the W transverse mass $m_T(W)$ are applied[2]; events in the electron (muon) channel are required to satisfy $E_T^{miss} > 30$ GeV and $m_T(W) > 30$ GeV ($E_T^{miss} > 20$ GeV and $E_T^{miss} + m_T(W) > 60$ GeV).

The $t\bar{t}$ signal is modelled with a Monte-Carlo (MC) simulated event sample generated using the MC@NLO matrix element generator with the CT10 parton distribution functions, and using HERWIG for parton showering and JIMMY for the underlying event. The top-quark mass is set at 172.5 GeV. A likelihood based on the event aplanarity and on the lepton pseudo-rapidity is used to discriminate the $t\bar{t}$ signal and the backgrounds. A fit of the expected likelihood distribution for signal and backgrounds to the distribution observed on data allows to extract the number of signal events. Table 1 gives the number of signal events as extracted by the fit.

Channel	$N_{t\bar{t}}$
Electron	31050±350
Muon	45000±400
Combined	76000±500

Table 1: Number of $t\bar{t}$ signal events as extracted by the fit of the likelihood distribution for the electron and muon channels separately and for the two channels combined. The quoted uncertainty indicates the error due to the statistics.

The cross-section $\sigma_{t\bar{t}}$ is calculated from the number of signal events $N_{t\bar{t}}$ extracted for the two channels combined, using the formula:

$$\sigma_{t\bar{t}} = \frac{N_{t\bar{t}}}{L \times BR \times \epsilon_{\text{sig}}}, \quad (1)$$

where L denotes the integrated luminosity, BR the branching ratio for the single lepton channel, and ϵ_{sig} the efficiency of the selection for the signal. The measured cross-section is:

$$\sigma_{t\bar{t}} = 241 \pm 2 \pm 31 \pm 9 \text{ pb}, \quad (2)$$

where the errors indicate the uncertainties due to data statistics, due to experimental and theoretical uncertainties, and to the knowledge of the luminosity, and is compatible with the predicted value of 253^{+13}_{-15} pb, obtained using calculations at next-to-next-to leading order (NNLO) in QCD including resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms.[3] The main systematic uncertainties are the ones due to the MC modelling of the signal, and to the jet energy scale and resolution.

1.2. $e\mu$ channel at $\sqrt{s} = 7$ TeV and 8 TeV

The inclusive production cross-section is measured at 7 and 8 TeV in the $e\mu$ dilepton channel, using the full datasets recorded by the ATLAS detector in 2011 and 2012, corresponding to integrated luminosities of 4.6 fb^{-1} and 20.3 fb^{-1} respectively [15].

Signal event candidates are selected using single isolated electron or muon triggers. The offline selection requires the presence of exactly one electron and one muon with $p_T > 40$ GeV and $|\eta| < 2.5$ with opposite electric charge, and satisfying tracker and calorimeter isolation requirements. Jets are selected such as to satisfy $p_T > 25$ GeV and $|\eta| < 2.5$, and are b-tagged using a discriminant with a 70% b-tagging efficiency. The distributions of the number of b-tagged jets for events satisfying the above described pre-selection are shown on Figure 1, without any requirement on the number of additional jets failing the b-tagging requirement.

The cross-section $\sigma_{t\bar{t}}$ is calculated from the number of observed events with exactly one (N_{1tag}) and two (N_{2tag}) b-tagged jets, using the following system of equations:

$$N_{1tag} = L\,\sigma_{t\bar{t}}\,\epsilon_{e\mu}\,2\,\epsilon_b(1 - C_b\epsilon_b) + N_{1tag}^{bkg} \quad (3)$$

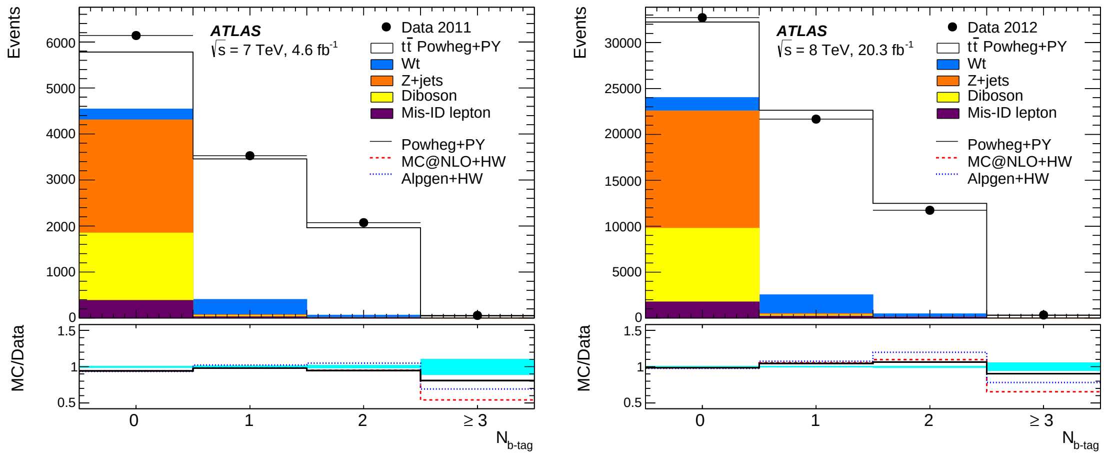
$$N_{2tag} = L\,\sigma_{t\bar{t}}\,\epsilon_{e\mu}\,C_b\,\epsilon_b^2 + N_{2tag}^{bkg}, \quad (4)$$

where L represents the integrated luminosity, $\epsilon_{e\mu}$ the efficiency for signal events to satisfy the pre-selection, ϵ_b

with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

[2]The W transverse mass is defined as $m_T(W) = \sqrt{2p_T(\ell)E_T^{miss}(1 - \cos\Delta\phi(p_T(\ell), E_T^{miss}))}$, where $p_T(\ell)$ denotes the lepton transverse momentum, and $\Delta\phi(p_T(\ell), E_T^{miss})$ its difference in azimuth with the missing transverse momentum.

[3]The $t\bar{t}$ cross section for pp collisions at a centre-of-mass energy of $\sqrt{s} = 8$ TeV is $\sigma_{t\bar{t}} = 253^{+13}_{-15}$ pb for a top quark mass of 172.5 GeV. It has been calculated at NNLO in QCD including resummation NNLL soft gluon terms with top++2.0 [2, 3, 4, 5, 6, 7, 8]. The PDF and α_S uncertainties were calculated using the PDF4LHC prescription [9] with the MSTW2008 68% CL NNLO [10, 11], CT10 NNLO [12, 13] and NNPDF2.3 5f FFN [14] PDF sets, and added in quadrature to the scale uncertainty.



(a) (b)

Figure 1: Distributions of the number of b-tagged jets in opposite-sign $e\mu$ events (a) on 7 TeV and (b) on 8 TeV data [15]. The data are shown 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, normalised to the same integrated luminosity as the data. The lower parts of the figure show the ratios of simulation to data, using various $t\bar{t}$ signal samples generated with Powheg + Pythia6 (PY) [16, 17], MC@NLO + Herwig (HW) [18, 19] and Alpgen + Herwig [19, 20], and with the cyan band indicating the statistical uncertainty.

the probability for a jet arising from a $t \to Wq$ decay to fall within the acceptance of the detector, to be reconstructed and to be b-tagged, C_b a b-tagging correlation factor close to unity, and N^{bkg}_{1tag} (N^{bkg}_{2tag}) the number of background events with exactly one (two) b-tagged jets. C_b and $\epsilon_{e\mu}$ are estimated using MC simulation and the system of equation is solved to extract $\sigma_{t\bar{t}}$ and ϵ_b.

The measured cross-sections at 7 and 8 TeV are:

$$\sigma_{t\bar{t}}\,(7\text{ TeV}) = 182.9 \pm 3.1 \pm 4.2 \pm 3.6\text{ pb} \qquad (5)$$

$$\sigma_{t\bar{t}}\,(8\text{ TeV}) = 242.4 \pm 1.7 \pm 5.5 \pm 7.5\text{ pb}, \qquad (6)$$

where the errors indicate the uncertainties due to data statistics, due to experimental and theoretical uncertainties, and to the knowledge of the luminosity. The results are compatible with the predicted value of 177^{+10}_{-11} and 253^{+13}_{-15} pb at 7 and 8 TeV respectively, obtained using calculations at next-to-next-to leading order (NNLO) in QCD including resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms. The ratio $R_{t\bar{t}} = \sigma_{t\bar{t}}(8\text{ TeV})/\sigma_{t\bar{t}}(7\text{ TeV})$ of the two total cross-sections is measured to be:

$$R_{t\bar{t}} = 1.326 \pm 0.056, \qquad (7)$$

in comparison with the QCD NNLO+NNLL predicted value of 1.430 ± 0.013.

Furthermore, the ATLAS collaboration provides measurements of the inclusive $t\bar{t}$ cross-sections for the two centre-of-mass energies in a fiducial volume, in order to separate the systematic uncertainties due to the modelling of the signal in the fiducial volume from the ones due to the extrapolation to the total cross-section.

Thanks to the theoretical dependence of the total cross-sections on the top quark mass, the measurement of the cross-sections is also used to determine the pole mass of the top quark. The measured value is:

$$m_t^{\text{pole}} = 172.9^{+2.5}_{-2.6}\text{ GeV}, \qquad (8)$$

combining the datasets at 7 and 8 TeV, providing the best measurement of the top-quark pole mass so far.

Finally, the measured $t\bar{t}$ total cross-sections are used to set constraints on supersymmetry (SUSY) models. In a scenario where top squark $\tilde{t}_1$ decays into a top quark and a neutralino $\tilde{\chi}^0_1$, the pair production of top squarks would lead to an intermediate final state $t\bar{t}\tilde{\chi}^0_1\tilde{\chi}^0_1$, with an experimental signature similar to $t\bar{t}$ with additional missing transverse momentum due to the neutralinos. Assuming a 100% $\tilde{t}_1 \to t\,\tilde{\chi}^0_1$ branching ratio, and a neutralino mass of 1 GeV, the measured $t\bar{t}$ cross-sections allow to exclude the $\tilde{t}_1$ mass range between the top mass threshold and 177 GeV, at the 95% confidence level (CL).

1.3. Summary of ATLAS results for inclusive cross-section measurements

Figure 2 shows the best measurements of the total $t\bar{t}$ cross-sections provided by the ATLAS experiment as a

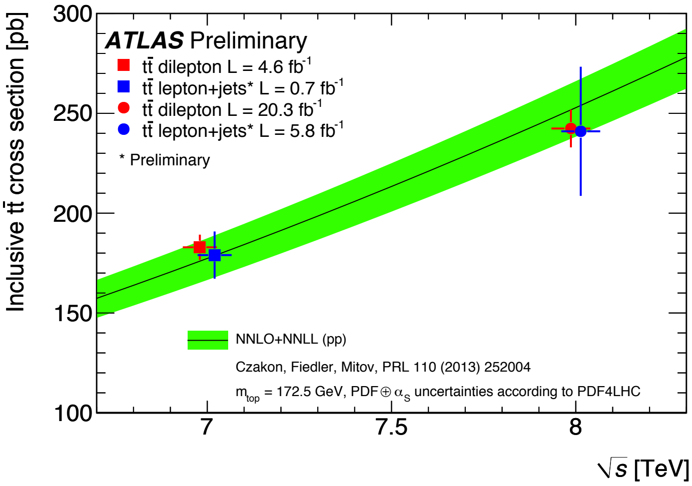


Figure 2: ATLAS best measurements of the inclusive $t\bar{t}$ production cross-section as a function of the centre-of-mass energy, in the single-lepton and di-lepton channels. The quoted measurement in the single lepton channel at $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 8 TeV are extracted from Reference [21] and [1] respectively, while the quoted measurements in the di-lepton channel at both energies are extracted from Reference [15].

function of the centre-of-mass energy, at $\sqrt{s}$ = 7 TeV and 8 TeV, in the single lepton and di-lepton channels. In addition to the result in the single lepton channel at 8 TeV presented in Section 1.1 and in the $e\mu$ channel at 7 TeV and 8 TeV presented in Section 1.2, the result in the single lepton channel at 7 TeV from Reference [21] is shown.

2. Differential cross-section measurement in the single lepton channel at $\sqrt{s}$ = 7 TeV

ATLAS provides a measurement of the $t\bar{t}$ differential cross-section as a function of different kinematic variables at a center-of-mass energy of 7 TeV [22]. This measurement is performed in the single lepton channel, using the whole *pp* collision data recorded in 2011 by the ATLAS detector, corresponding to an integrated luminosity of 4.6 fb^{-1}.

Signal event candidates are selected using single isolated electron or muon triggers. The offline selection in the electron (muon) channel requires the presence of exactly one electron (muon) with $\mathrm{p_T}$ > 25 GeV and $|\eta|$ < 2.5, and satisfying tracker and calorimeter isolation requirements, together with four or more jets satisfying $\mathrm{p_T}$ > 25 GeV and $|\eta|$ < 2.5, at least one of which is required to be *b*-tagged, using a multivariate discriminant such as the *b*-quark jets tagging efficiency is approximately 70%. Events are required to satisfy $E_{\mathrm{T}}^{\mathrm{miss}}$ > 30 GeV and $m_{\mathrm{T}}(W)$ > 35 GeV.

The $t\bar{t}$ kinematics is reconstructed using a likelihood fitter, which associates the kinematic variables of the reconstructed objects to a leading order (LO) representation of the $t\bar{t}$ system. The likelihood is maximised, associating jets to partons. Of all possible permutations, the solution with the highest likelihood is chosen.

The normalised $t\bar{t}$ differential cross-section is determined as a function of the transverse momentum of the hadronically decaying top quark p_T^t, and of the invariant mass $m_{t\bar{t}}$, the transverse momentum $p_T^{t\bar{t}}$ and of the absolute value of the rapidity $y_{t\bar{t}}$ of the $t\bar{t}$ system. To correct for the detector effects, an unfolding procedure is applied to the distributions observed on data, separately in the electron and muon channels. The migration matrices are estimated from a simulated $t\bar{t}$ event sample generated with the Alpgen LO multileg generator [20] using the CTEQ6L1 parton distribution functions (PDF) [23], Herwig for parton showering and hadronisation [19], and Jimmy for multiple parton interactions and the underlying event [24]. The regularised SVD method [25] is used to unfold the parton-level distributions. The results obtained in the electron and muon channels are compatible with each other up to less than two standard deviations. The two channels are combined using an asymmetric BLUE method [26]. The main systematic uncertainties are the ones due to the MC modelling of the $t\bar{t}$ signal, to the jet energy scale, and to *b*-tagging.

The measured normalised differential cross-sections were compared to predictions resulting from different MC generators, as shown on Figure 3, to NLO QCD predictions obtained based on MCFM [27] with the CT10 PDF [12], to NLO+NNLL calculations [28, 29,

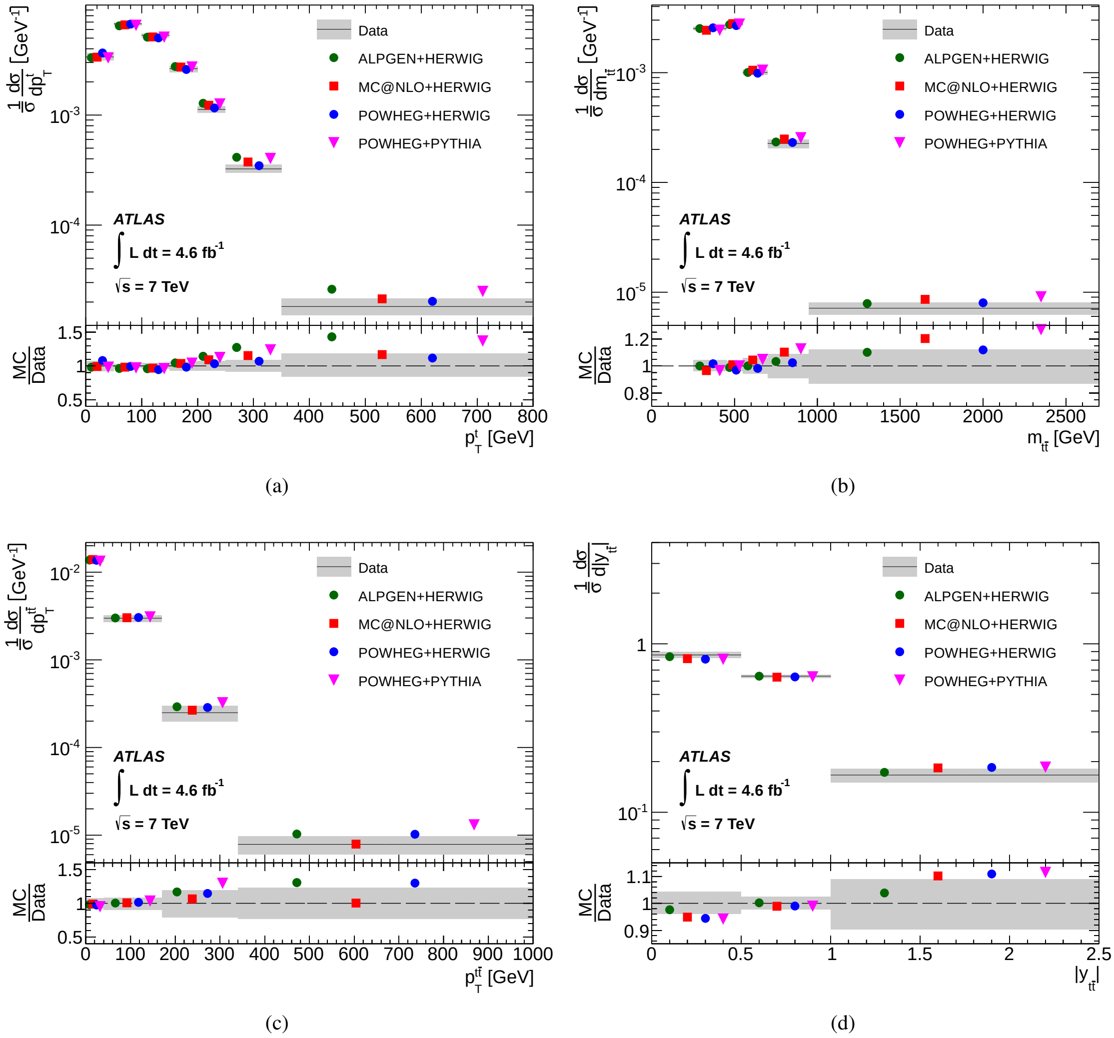


Figure 3: Normalized differential $t\bar{t}$ cross-sections for (a) the transverse momentum of the hadronically decaying top quark (p_T^t), (b) the mass ($m_{t\bar{t}}$), (c) the transverse momentum ($p_T^{t\bar{t}}$) and (d) the absolute value of the rapidity ($y_{t\bar{t}}$) of the $t\bar{t}$ system. Generator predictions are shown as markers for Alpgen+Herwig (circles) [20, 19], MC@NLO+Herwig (squares) [18, 19], Powheg+Herwig (triangles) [16, 19] and Powheg+Pythia (inverted triangles) [16, 17]. The markers are offset within each bin to allow for better visibility. The gray bands indicate the total uncertainty on the data in each bin. The lower part of each figure shows the ratio of the generator predictions to data. For $p_T^{t\bar{t}}$ the Powheg+Pythia marker cannot be seen in the last bin of the ratio plot because it falls beyond the axis range. The cross-section in each bin is given as the integral of the differential cross-section over the bin width, divided by the bin width. The calculation of the cross-sections in the last bins includes events falling outside of the bin edges, and the normalization is done within the quoted bin width. The bin ranges along the horizontal axis (and not the position of the markers) can be associated with the normalized differential cross-section values along the vertical axis.

30, 31] using the MSTW2008NLO PDF [10], and to NLO QCD predictions using different PDF sets [10, 12, 14, 32].

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