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Measurement of the top pair production cross-section in 8 TeV proton–proton collisions using kinematic information in the lepton+jets final state with ATLAS

The ATLAS Collaboration

Abstract

A measurement is presented of the $\bar{t}t$ inclusive production cross-section in $pp$ collisions at a center-of-mass energy of $\sqrt{s} = 8$ TeV using data collected by the ATLAS detector at the CERN Large Hadron Collider. The measurement was performed in the lepton+jets final state using a data set corresponding to an integrated luminosity of 20.3 fb$^{-1}$. The cross-section was obtained using a likelihood discriminant fit and $b$-jet identification was used to improve the signal-to-background ratio. The inclusive $\bar{t}t$ production cross-section was measured to be $260 \pm 1({\text{stat.}}) \pm 22({\text{syst.}}) \pm 8({\text{lumi.}}) \pm 4({\text{beam}})$ pb assuming a top-quark mass of 172.5 GeV, in good agreement with the theoretical prediction of $253_{-13}^{+17}$ pb. The $\bar{t}t \to (e, \mu)$+jets production cross-section in the fiducial region determined by the detector acceptance is also reported.
1 Introduction

The measurement of the top-quark pair production cross-section is an important part of the physics program of the Large Hadron Collider (LHC) [1]. As the top-quark is the heaviest known fermion, it has the largest coupling to the recently discovered Higgs boson and plays a special role in many theories beyond the Standard Model (SM). New physics may result in additional top-quark decay channels or new mechanisms of \( t\bar{t} \) production that can cause the measured cross-section to deviate from the SM prediction. Also, \( t\bar{t} \) production is the dominant background to many searches for new physics.

The inclusive \( pp \to t\bar{t} \) cross-section \( \sigma_{t\bar{t}} \) at a center-of-mass energy of \( \sqrt{s} = 8 \text{ TeV} \) has been calculated to be \( 253^{+13}_{-15} \text{ pb} \) for a top-quark mass of \( m_{\text{top}} = 172.5 \text{ GeV} \). These calculations were performed at next-to-next-to-leading order (NNLO) in QCD including resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms using the program top++ [2–7]. In these calculations, the renormalization scale \( \mu_R \) and factorization scale \( \mu_F \) were both set equal to \( m_{\text{top}} \). The NNLO+NNLL value was found to be about 3\% larger than the NNLO-only calculation as implemented in Hather 1.5 [8]. As a result of recent progress in theoretical calculations, the \( t\bar{t} \) production cross-section has been evaluated with uncertainties below 6\%. In calculating these uncertainties, the scale uncertainty, evaluated by independent variations of \( \mu_R \) and \( \mu_F \) by factors of 1/2 and 2, was combined in quadrature with uncertainties on the coupling strength of the strong interaction, \( \alpha_S \), and the parton distribution functions (PDFs). The latter were calculated using the PDF4LHC prescription [9] with MSTW2008 NNLO (at the 68\% confidence level) [10, 11], CT10 NNLO [12, 13] and NNPDF2.3 5f FFN [14] PDF sets.

In the SM, the top-quark decays into a \( W \)-boson and a \( b \)-quark with a branching ratio close to 100\%. The present analysis aims to measure the \( t\bar{t} \) production cross-section in the lepton+jets final state, where one of the \( W \)-bosons decays into an electron or a muon (collectively called a lepton and denoted \( \ell \)) and a corresponding neutrino (including the \( W \to \tau\nu \rightarrow e\nu\nu_e \) and \( W \to \tau\nu \rightarrow \mu\nu\nu_\mu \) decays), and the other \( W \)-boson decays hadronically. The final state is characterized by the presence of a highly energetic isolated lepton, large missing transverse momentum (\( E_T^{\text{miss}} \)) due to the neutrino(s) escaping detection, and four jets due to the two \( b \)-quarks from the top-quark decays and the two quarks from the hadronic \( W \) decay. The selected events are required to have at least three jets, allowing one jet to be undetected due to limited detector acceptance and jet reconstruction inefficiency. At least one of the jets is further required to be identified as a \( b \)-jet.

The inclusive top-quark pair production cross-section in \( pp \) collisions at 8 TeV has been previously measured in the dilepton channel by both the ATLAS and CMS Collaborations [15, 16]. The results are found to be in good agreement with theoretical predictions. This paper presents the measurement of the \( t\bar{t} \) production cross-section of the ATLAS Collaboration in the lepton+jets channel, which provides a cross-check of the dilepton measurement that has different background conditions and systematic uncertainties, and contributes to the combined \( t\bar{t} \) production cross-section result. In addition, the measurement in the lepton+jets channel is important for probing the presence of new physics that changes the top-quark decay branching fractions, e.g. production of charged Higgs bosons \( H^\pm \) via \( t \to H^\pm b \) decays.

The measurement was performed using the full 8 TeV data set (20.3 fb\(^{-1} \)). In addition to the total \( t\bar{t} \) production cross-section, a fiducial cross-section was measured, defined using physics objects constructed of stable particles to approximate the \( t\bar{t} \to \ell\nu+jets \) detector acceptance.

The majority of the events in the selected sample originate from \( t\bar{t} \) production. However, events from other SM processes (\( W/Z+jets \), single top-quark, diboson, and multijet production) are also present. To determine the signal fraction, a discriminating variable (likelihood discriminant, LHD) was constructed.
based on the kinematic properties of Monte Carlo (MC) simulated signal and background events. A weighted sum of LHD distributions (“templates”) for the signal and for the background was fitted to the LHD distribution in data, and the resulting number of signal events was converted to the $t\bar{t}$ inclusive production cross-section using the signal-reconstruction efficiency (determined from MC simulation), known branching ratio for the lepton+jets final state, and the total integrated luminosity.

The paper is organized as follows. The ATLAS detector is briefly described in Sec. 2, followed by descriptions of the data and MC samples used in the analysis (Sec. 3). The event selection and the backgrounds are outlined in Sec. 4. The measurement procedure is presented in Sec. 5 for the inclusive case, and in Sec. 6 for the fiducial case. The estimation of the systematic uncertainties is presented in Sec. 7. Finally, the results and conclusions are given in Sec. 8.

2 The ATLAS detector

The ATLAS detector [17] at the LHC covers nearly the entire solid angle around the collision point. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting toroid magnets. The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged particle tracking in the range $|\eta| < 2.5$.

The high-granularity silicon pixel detector is closest to the interaction region and typically provides three measurements per track, the first hit being normally in the innermost layer. It is followed by the silicon microstrip tracker which has four layers in the barrel region. These silicon detectors are complemented by the transition radiation tracker, which enables radially extended track reconstruction up to $|\eta| = 2.0$. The transition radiation tracker also provides electron identification information based on the fraction of hits (typically 30 in total) above a higher energy deposit threshold corresponding to transition radiation.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) electromagnetic calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$, to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by the steel/scintillating-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadronic endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimised for electromagnetic and hadronic measurements respectively.

The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by superconducting air-core toroids. The precision chamber system covers the region $|\eta| < 2.7$ with three layers of monitored drift tubes, complemented by cathode strip chambers in the forward region, where the background is highest. The muon trigger system covers the range $|\eta| < 2.4$ with resistive plate chambers in the barrel, and thin gap chambers in the endcap regions. A three-level trigger system is used to select interesting events [18]. The Level-1 trigger is implemented in hardware and uses a subset of detector information to reduce the event rate to a design value of at most 75 kHz. This is followed by two software-based trigger levels which together reduce the event rate to about 200 Hz.
3 Data and simulated samples

The data were collected during the 2012 LHC running period at a center-of-mass energy of 8 TeV. After applying data-quality selection criteria, the data set used in the analysis corresponds to an integrated luminosity of 20.3 fb$^{-1}$.

Simulated $t\bar{t}$ events were generated with Powheg [19] interfaced to Pythia v6.426 [20] for the fragmentation and hadronization, with the next-to-leading order (NLO) CT10 PDF set. The Perugia2011C underlying event tune [21] with the CTEQ6L1 PDF set [22] was used. An alternative $t\bar{t}$ MC sample was produced with MC@NLO v4.01 [23] using the CT10 PDF set. In this sample, the parton shower and the underlying event simulations were performed with Herwig v6.520 [24] and Jimmy v4.31 [25], respectively, using the AUET2 tune [26]. To estimate the model dependence of the parton shower and fragmentation modeling, the signal sample generated with Powheg interfaced to Pythia was compared to that generated with Powheg interfaced to Herwig+Jimmy. Additional $t\bar{t}$ samples simulated with AcerMC [27] interfaced to Pythia based on the CTEQ6L1 PDF set were used to study the systematic uncertainties arising from initial- and final-state radiation. All $t\bar{t}$ samples were produced with a top-quark mass of 172.5 GeV and normalized to the NNLO+NNLL cross-section quoted in Sec. 1.

The dominant background to $t\bar{t}$ production is vector-boson production in association with jets, $V$+jets ($V = W, Z/\gamma^*$). Samples of events were generated using Alpgen [28] interfaced to Pythia v6.426 based on the CTEQ6L1 PDF set and the Perugia2011C tune. The MLM parton and jet matching procedure [29] was applied inclusively for $V$+5-light-partons ($2 \rightarrow 7$) production and exclusively for lower multiplicity samples. In addition to $V$+light partons, the production of vector-bosons with additional heavy-flavor partons ($V + c$+jets, $V + c\bar{c}$+jets, $V + b\bar{b}$+jets) was also simulated. Inclusive $V$+jets samples were formed by combining the samples of light and heavy quarks according to their respective cross-sections. An alternative $W$+jets sample simulated with Sherpa [30] with massive $b$/$c$-quarks was produced to evaluate systematic uncertainties on $W$+jets modeling. The $V$+jets processes were normalized to the NNLO calculations [31,32].

The background contribution from single-top production, including $t$- and $s$-channel contributions and $Wt$ production was simulated with Powheg interfaced to Pythia using the CT10 PDF set. Finally, diboson production ($WW$, $WZ$, $ZZ$) was simulated with Herwig using the CTEQ6L1 PDF set. All samples were scaled according to their theoretical production cross-sections: at approximate NNLO for the single top $t$-channel [33], and at NLO+NNLL for the single top $s$-channel [34] and $Wt$-production [35]. The diboson processes were normalized to the NLO [36] predictions.

Most of the $t\bar{t}$ samples and all the background samples were processed through the full ATLAS detector simulation [37] based on GEANT4 [38]. A few $t\bar{t}$ samples used for the evaluation of certain systematic effects (modeling of initial- and final-state radiation and parton showers – see Sec. 7 for details) were produced using the ATLAS fast simulation that employs parameterized showers in the calorimeters [39]. All MC samples were reconstructed using the same analysis chain as used for the data. Correction factors were applied in order to better reproduce the trigger, lepton reconstruction efficiency, and $b$-jet identification efficiency observed in the data. The simulations also included the effect of multiple $pp$ collisions per bunch crossing (pileup).
4 Event selection

The events were required to pass a logical OR of isolated and nonisolated single-lepton (e or μ) trigger conditions with transverse momentum $p_T$ thresholds of 24 GeV for isolated triggers and 60 (36) GeV for nonisolated single-e (single-μ) triggers. All events were also required to have a reconstructed hard collision primary vertex (the main PV) built of at least five particle tracks with $p_T > 0.4$ GeV.

The reconstructed objects used in the analysis include electrons, muons, jets, and missing transverse momentum. Electron candidates were reconstructed from an electromagnetic energy deposit matched to a track in the inner detector [40]. They were required to have transverse energy $E_T > 40$ GeV and pseudorapidity of the cluster$^1$ $|\eta| < 2.47$, excluding the barrel-endcap transition region $1.37 < |\eta| < 1.52$. Electron candidates were also required to originate from less than 2 mm along the $z$-axis from the main PV and satisfy isolation criteria. The latter involve a combination of calorimeter isolation (a requirement on a sum of energies of calorimeter cells within a cone of size $\Delta R = 0.2$ around the electron direction) and track isolation (a requirement on a scalar sum of track $p_T$ within a cone of size $\Delta R = 0.3$, in each case excluding the contribution from the electron itself). Both requirements were chosen to separately result in a 90% electron reconstruction efficiency for prompt electrons from $Z \rightarrow ee$ decays. Muon candidates were reconstructed using combined information from the muon spectrometer and the inner tracking detectors [41]. They were required to have $p_T > 40$ GeV and $|\eta| < 2.5$, and, like electrons, to originate from within 2 mm along the $z$-axis of the main PV. The muon isolation was defined in terms of the ratio of the scalar sum of the track $p_T$ in a cone of variable radius $\Delta R = 10$ GeV/$p_T^\mu$ around the muon direction (excluding the muon track itself) to the $p_T$ of the muon ($p_T^\mu$). This ratio was required to be less than 0.05, corresponding to a 97% selection efficiency for prompt muons from $Z \rightarrow \mu\mu$ decays.

Jets were reconstructed using the anti-$k_T$ algorithm [42, 43] with radius parameter $R = 0.4$. The measured jet energy was corrected for inhomogeneities and for the noncompensating nature of the calorimeter through jet $p_T$- and $\eta$-dependent factors derived from MC simulation and validated with data. Jets were calibrated using a combination of in-situ techniques based on the transverse momentum balance between a jet and a reference object [44]. The jets were required to have corrected $p_T > 25$ GeV and $|\eta| < 2.5$. Jets from pileup were suppressed by requiring the absolute value of the jet vertex fraction$^2$ for jets with $p_T < 50$ GeV and $|\eta| < 2.4$ to be above 0.5.

Jets were $b$-tagged (identified as originating from $b$-quarks) using the multivariate-based algorithm algorithm (MV1) [45]. This is a neural network-based algorithm that makes use of track impact parameters and reconstructed secondary vertices. Jets were identified as $b$-jets by requiring the MV1 output to be above a certain threshold value. This value was chosen such that the overall tagging efficiency for $b$-jets originating from top-quark decays in MC $t\bar{t}$ events is 70%. Tagging scale factors were applied to correct for the difference in the tagging efficiency between MC simulation and data, including the inefficiency scale factors applied when a jet was not tagged. The scale factors were derived as explained in Refs. [45–47].

To avoid double-counting objects in an event and to suppress leptons from heavy-flavor decays, the following procedure to remove overlaps was applied to the reconstructed objects: (1) removal of jets matched within $\Delta R = 0.2$ of electrons with $E_T > 25$ GeV; (2) removal of electrons matched within $\Delta R = 0.4$ of

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$^1$ Unlike the (regular) pseudorapidity determined using the object direction, the pseudorapidity of the cluster is defined using the position of the reconstructed cluster in the calorimeter with respect to the geometric center of the detector.

$^2$ The jet vertex fraction is defined using the tracks matched to a jet as the ratio of the scalar sum of the transverse momenta of tracks from the main PV to that of all tracks. A jet without any track matched is assigned a jet vertex fraction value of $-1$. 

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jets with $p_T > 25$ GeV; (3) rejection of events where the selected electron shares an inner detector track with a selected muon; and (4) removal of muons matched within $\Delta R = 0.4$ of jets with $p_T > 25$ GeV. After these steps, the events were required to have exactly one lepton (an electron or a muon) selected as above and matched to the trigger object that caused the event to be selected, and at least three jets, of which at least one was $b$-tagged. Events with a second lepton with $p_T > 25$ GeV were discarded. Finally, the events had to exceed minimum values for the $W$ transverse mass $m_T(W)$ and the magnitude of the missing transverse momentum $E_T^{\text{miss}}$. The value of $E_T^{\text{miss}}$ in the $t\bar{t} \rightarrow ℓν$+jets process is relatively large due to neutrino(s) from $W$ decays. It also includes energy losses due to detector inefficiencies as well as energy fluctuations in jet measurements. The missing transverse momentum value is calculated as the negative of the vector sum over the energies of all clusters in the calorimeters, and $E_T^{\text{miss}}$ is refined by the application of the object-level corrections for the contributions arising from identified electrons, muons, and jets. The $W$-boson transverse mass $m_T(W)$ is defined as $m_T(W) = \sqrt{2p_T^e p_T^\nu(1 - \cos(\varphi^e - \varphi^\nu))}$, where $p_T^e$, $\varphi^e$ and $p_T^\nu$, $\varphi^\nu$ refer to the transverse component and $\varphi$ value of the lepton momentum and the missing momentum, respectively. The events in this analysis were selected by requiring $E_T^{\text{miss}} > 30$ GeV and $m_T(W) > 30$ GeV.

After applying the selections listed above, the signal efficiency for $t\bar{t}$ events with at least one top-quark decaying leptonically was found to be $4.4\%$ in the $e$+jets channel and $5.5\%$ in the $\mu$+jets channel.

While the majority of events in the selected sample include ‘real’ leptons (prompt electrons and muons from vector-boson decays), a small fraction of events is due to leptons referred to as ‘fakes’ (which include nonprompt leptons and artifacts of the reconstruction). There are several sources of fake leptons. Fake muons predominantly come from semileptonic decays of heavy-flavor hadrons. In the $e$+jets channel, in addition to this source, there are electrons originating from conversions as well as photons and hadrons misidentified as electrons. The signal sample is composed of events with either real or fake leptons:

$$N = N_{\text{real}} + N_{\text{fake}}.$$ 

The estimation of $N_{\text{fake}}$ from MC simulation is difficult due to large uncertainties in the modeling of fake lepton production, and impractical due to a tiny fake rate requiring huge simulated samples. Therefore, the contribution of fakes was evaluated from data using the matrix method [48]. In addition to events from the signal data sample (labeled as “tight” events), a second (“loose”) set enriched with fake leptons was defined by removing the lepton isolation requirement. The number of events in each sample can be written as

$$N_{\text{tight}} = N_{\text{real}}^{\text{tight}} + N_{\text{fake}}^{\text{tight}},$$

$$N_{\text{loose}} = N_{\text{real}}^{\text{loose}} + N_{\text{fake}}^{\text{loose}}.$$

If the fractions of loose events that are also tight events are known, the number of events with fake leptons in the signal sample can be determined from a linear system of two equations. Given the probabilities for real and fake leptons that already passed the loose selection to also pass the tight selection, $\epsilon_{\text{real}} = N_{\text{real}}^{\text{tight}} / N_{\text{real}}^{\text{loose}}$ and $\epsilon_{\text{fake}} = N_{\text{fake}}^{\text{tight}} / N_{\text{fake}}^{\text{loose}}$, as well as the number of loose and tight events, the number of tight events with a fake lepton is

$$N_{\text{tight}}^{\text{fake}} = \frac{\epsilon_{\text{real}} N_{\text{loose}}^{\text{tight}} - N_{\text{tight}}^{\text{loose}}}{\epsilon_{\text{real}} - \epsilon_{\text{fake}}} \epsilon_{\text{fake}}.$$ 

The probability $\epsilon_{\text{real}}$ was determined with a tag-and-probe method [40] based on the identification of a tight lepton and a loose lepton in events originating from $Z \rightarrow ee/\mu\mu$ decays. The fake lepton probability

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3 When the selection is applied to electrons as well as muons, the thresholds refer to $p_T$ for muons and $E_T$ for electrons.
\( \varepsilon_{\text{fake}} \) in the \( \mu+jets \) channel was derived for muons with large track \( d_0 \) significance.\(^4\) In the \( e+jets \) channel, \( \varepsilon_{\text{fake}} \) was determined in the \( E_{T}^{\text{miss}} < 20 \text{ GeV}, m_{T}(W) < 20 \text{ GeV} \) region, where the number of events was corrected for the presence of real leptons. In both channels, the real and fake probabilities were parameterized in terms of lepton \( p_T \) and \( \eta \), the leading jet \( p_T \), the distance between the lepton and the closest jet \( (\Delta R_{\ell j}) \), the ratio of the \( p_T \) of the closest jet to \( \Delta R_{\ell j} \), the total number of jets, and the number of \( b \)-tagged jets. The product of one-dimensional parameterizations was used, since there are too few events for a multidimensional parameterization. Based on this procedure, each event in the loose set was assigned a weight

\[(\varepsilon_{\text{real}} - 1)\varepsilon_{\text{fake}}/(\varepsilon_{\text{real}} - \varepsilon_{\text{fake}}) \text{ for events with tight leptons and } \varepsilon_{\text{real}}\varepsilon_{\text{fake}}/(\varepsilon_{\text{real}} - \varepsilon_{\text{fake}}) \text{ for the rest},\]

and the weighted sample of data events selected using the loose object criteria was taken as the multijet contribution to the LHD background distribution.

The numbers of observed and expected events are shown in Table 1. Uncertainties on the numbers of expected \( t\bar{t} \), single top, and diboson events are derived from theoretical uncertainties on the respective production cross-sections. The uncertainty on \( V+jets \) events is evaluated based on a \( \pm 4\% \) uncertainty on inclusive \( V+jets \) production and a \( \pm 24\% \) uncertainty on each additional jet \([49]\), giving a total uncertainty of \( \pm 45\% \) for \( V+jets \) background. This large uncertainty does not have an impact on the final result, since the normalization of the \( V+jets \) background is obtained from the data as described in Sec. 5. The uncertainty on the multijet background is evaluated by varying the parameters of the matrix method as described in Sec. 7.

Table 1: Observed numbers of events in the \( e+jets \) and \( \mu+jets \) channel together with estimated contributions from the \( t\bar{t} \) signal and various background sources and associated uncertainties as described in the text.

<table>
<thead>
<tr>
<th>Event counts</th>
<th>( e+jets )</th>
<th>( \mu+jets )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t} )</td>
<td>123000(^{+6000}_{-7000} )</td>
<td>152000(^{+8000}_{-9000} )</td>
</tr>
<tr>
<td>( V+jets )</td>
<td>38000(\pm 17000 )</td>
<td>47000(\pm 21000 )</td>
</tr>
<tr>
<td>Single top</td>
<td>12100(\pm 600 )</td>
<td>14900(\pm 800 )</td>
</tr>
<tr>
<td>Dibosons</td>
<td>710(\pm 40 )</td>
<td>880(\pm 50 )</td>
</tr>
<tr>
<td>Multijets</td>
<td>2800(\pm 2400 )</td>
<td>1500(^{+300}_{-1800} )</td>
</tr>
<tr>
<td>Total</td>
<td>177000(^{+18000}_{-19000} )</td>
<td>216000(\pm 23000 )</td>
</tr>
<tr>
<td>Data</td>
<td>176286</td>
<td>220369</td>
</tr>
</tbody>
</table>

5 Determination of the \( t\bar{t} \) cross-section

The number of \( t\bar{t} \) events in each channel and their combination was obtained from the data using a template fit to the LHD distribution. The LHD function was constructed using the projective likelihood method defined in Ref. [50]. The LHD for event \( i \) is defined as the ratio of the signal \( L^s_i \) to the sum of signal and background likelihood functions \( L^s_i + L^b_i \):

\[
D_i = \frac{L^s_i}{L^s_i + L^b_i},
\]

\(^4\) \( d_0 \) is the distance of closest approach in the transverse plane of a track to the primary vertex of the event; the \( d_0 \) significance is the \( d_0 \) value divided by its fitted uncertainty.
where the likelihood functions \( L^s = \prod_j v_j^s \), \( L^b = \prod_j v_j^b \) are the products of the probability density functions of kinematic variables \( v_j \) for signal and background, respectively. The variables used in the LHD were lepton pseudorapidity \( \eta_l \) and transformed aplanarity \( A' = \exp(-8A) \). The aplanarity \( A \) is defined as \( 3/2 \) times the smallest eigenvalue of the momentum tensor \( M_{ij} = \sum_{k=1}^{N_{\text{objects}}} \frac{p_k p_{jk}}{\sum_{k=1}^{N_{\text{objects}}} p_k^2} \), where \( p_k \) is the \( i \)-th momentum component and \( p_{jk} \) is the modulus of the momentum of object \( k \). The objects included in the sum are leptons, jets, and \( E_{\text{T}}^{\text{miss}} \). The choice of variables followed the analysis in Ref. [51] and was motivated by optimization in terms of best separation between the signal and the background, the quality of the MC description of the variables in the data, and reduced sensitivity to the jet-energy scale. As the fraction of signal events in the selected data sample is large, two discriminating variables were found to be sufficient to provide an adequate signal-to-background separation.

The \( \eta_l \) and \( A' \) distributions for data and MC simulation are shown in Fig. 1. The correlation between these variables is found to be negligible in both signal and background. The LHD distributions for signal and background events are compared with the data in Fig. 2. The templates of LHD in the \( e+\text{jets} \) and \( \mu+\text{jets} \) channels are different due to the fact that electrons in the barrel-endcap transition region are excluded and have lower efficiency in the forward region, whereas the efficiency as a function of \( \eta_l \) is quite smooth.

A weighted sum of the templates for the \( t\bar{t} \) signal and all the backgrounds was fitted to a binned LHD distribution in the data. The contributions from single top and diboson events were fixed according to their theoretical cross-sections. The contribution from multijets events was obtained using the matrix method.

The normalizations of the signal and \( V+\text{jets} \) (the dominant background) were left as free parameters in the fit. In each channel \( j \), the fit was performed by minimizing the negative log-likelihood function for a Poisson model,

\[
\mathcal{L}_j = -\ln L_j = 2 \sum_i \left( v_{ij} - n_{ij} + n_{ij} \ln n_{ij} - n_{ij} \ln v_{ij} \right),
\]

summed over all bins \( i \), where \( n_{ij} \) is the observed number of events and \( v_{ij} \) is the expected number of events in each bin or channel. The latter is defined as

\[
v_{ij} = p_i^s s_{ij} + p_j^V b_{ij} + q_{ij},
\]

where \( s_{ij} \), \( b_{ij} \), and \( q_{ij} \) are the predicted numbers of events for the \( t\bar{t} \) signal, \( V+\text{jets} \), and small backgrounds (single top, dibosons, and multijets), respectively, and \( p_i^s \) and \( p_j^V \) are the parameters of the fit. The resulting value of the fit parameter \( p_i^s \) was used to extract the number of \( t\bar{t} \) events in the data. Figure 3 shows the distribution of the LHD for data and MC simulation. In both Figs. 1 and 3, the contributions from \( t\bar{t} \) and \( V+\text{jets} \) production are normalized according to the results of the LHD fit.

The channels were combined by minimizing \( \mathcal{L} = \sum_j \mathcal{L}_j \) where the sum is taken over the \( e+\text{jets} \) and \( \mu+\text{jets} \) channels.

After the number of \( t\bar{t} \) events in data \( N_{t\bar{t}} \) was obtained from the fit, the \( t\bar{t} \) production cross-section in each channel was determined as

\[
\sigma_{t\bar{t}} = \frac{N_{t\bar{t}}}{\epsilon_{t\bar{t}} \times B \times L}, \tag{1}
\]

where \( \epsilon_{t\bar{t}} \) is the signal-reconstruction efficiency (4.4% in the \( e+\text{jets} \) channel and 5.5% in the \( \mu+\text{jets} \) channel), \( B \) is the \( t\bar{t} \rightarrow \geq 1 \) lepton+jets branching ratio, and \( L \) is the total integrated luminosity.
Figure 1: Distributions of the lepton pseudorapidity (top) and the modified aplanarity (bottom) in the $e+$jets (left) and $\mu+$jets (right) channel. The data (dots) are compared to the SM expectation broken down into contributions from $t\bar{t}$, single top, $V+$jets, diboson, and multijet production. The hatched areas correspond to the combined statistical and systematic uncertainties excluding the uncertainty on the $t\bar{t}$ signal modeling with different MC generators (see Sec. 7 for details). The bottom part of each plot shows the ratio of the data to the predicted value together with combined statistical and systematic uncertainties.
Figure 2: The templates of the likelihood discriminant LHD in the $e+\text{jets}$ (left) and $\mu+\text{jets}$ (right) channels for signal, $V+\text{jets}$ background, and fixed backgrounds, which include single top, diboson and multijets background.

Figure 3: Distributions of the likelihood discriminant LHD in the $e+\text{jets}$ (left) and $\mu+\text{jets}$ (right) data and a weighted sum of templates from the $t\bar{t}$ signal and various backgrounds. The contributions from $t\bar{t}$ and $V+\text{jets}$ production are normalized according to the results of the likelihood discriminant fit, the single top and dibosons contributions are normalized according to their theoretical cross-sections, and the multijet background is normalized using the data-driven method explained in the text. The bottom part of each plot shows the ratio of the data to the predicted value together with combined statistical and systematic uncertainties.
6 Fiducial cross-section measurement

The $t\bar{t}$ cross-section in the fiducial volume was measured to allow for a more robust comparison to the theoretical prediction without extrapolating to regions outside of the detector acceptance. The definition of the fiducial volume is based on MC simulation and uses particle-level objects constructed using stable particles with a mean lifetime $\tau_{\text{particle}} > 0.3 \times 10^{-10}$ s. Electrons and muons were required to originate from $t \to Wb \to \ell \nu b$ decays, either directly or via a leptonically decaying $\tau$, and to have $p_T > 40$ GeV and $|\eta| < 2.5$. The lepton momenta were corrected by adding the energy and momentum of photons inside a cone of radius $\Delta R = 0.1$ around the lepton direction. Jets were created by clustering particles using the anti-$k_t$ algorithm with radius parameter $R = 0.4$ (neutrinos, electrons and muons from $W$-boson decays were excluded from particle-jet formation). Particles from the underlying event were included in this definition, but particles resulting from pileup were not. The particle-jets were required to have $|\eta| < 2.5$ and $p_T > 25$ GeV. The particle-jet $b$-identification was based on the presence of nearby $B$-hadrons with a $p_T$ of at least 5 GeV using the ghost tagging method [52]. The overlap removal procedure included the removal of particle-jets within $\Delta R = 0.2$ of the nearest electron with $E_T > 25$ GeV followed by removal of electrons and muons within $\Delta R = 0.4$ of the nearest remaining particle-jet with $p_T > 25$ GeV. The events were required to have exactly one lepton with $p_T > 40$ GeV, no second lepton with $p_T > 25$ GeV, and at least three particle-jets, of which at least one jet was identified as a $b$-jet. Missing transverse momentum was calculated using neutrinos from $W$ leptonic decays. Similar to the reconstructed event selection, $E_T^{\text{miss}} > 30$ GeV and $m_T(W) > 30$ GeV requirements were applied.

The simulated $t\bar{t}$ events were split into two categories: in-fiducial (satisfying the fiducial selection criteria) and out-of-fiducial (the rest).

The number of $t\bar{t}$ events $N_{t\bar{t}}$ obtained with the LHD fit was converted to the number of $t\bar{t}$ events in the fiducial volume $N_{t\bar{t}}^{\text{fid}}$ using the fraction of reconstructed MC events passing the fiducial selection. The number of $t\bar{t}$ events in the fiducial volume was further used to determine the fiducial cross-section $\sigma_{t\bar{t}}^{\text{fid}}$ as

$$\sigma_{t\bar{t}}^{\text{fid}} = \frac{N_{t\bar{t}}^{\text{fid}}}{\mathcal{L} \cdot \epsilon_{t\bar{t}}^{\text{fid}}}$$

where $\epsilon_{t\bar{t}}^{\text{fid}}$ is the fiducial signal-reconstruction efficiency. The latter is defined as the ratio of the number of events passing both the reconstruction requirements and the particle-level selection, $N_{t\bar{t}}^{\text{fid, reco}}$, to the total number of events passing the particle level selection, $N_{t\bar{t}}^{\text{fid, reco}}$:

$$\epsilon_{t\bar{t}}^{\text{fid}} = \frac{N_{t\bar{t}}^{\text{fid, reco}}}{N_{t\bar{t}}^{\text{fid, reco}}}$$

It was found to be 36% in the $e$+jets channel and 44% in the $\mu$+jets channel.

7 Systematic uncertainties

The systematic uncertainties in the $t\bar{t}$ cross-section measurement can be split into those related to the object reconstruction and momentum and energy measurements, those related to background evaluation, and those related to the signal modeling. The most important contribution to the total systematic uncertainty arises from effects related to the $t\bar{t}$ modeling, as discussed below.
To avoid statistical fluctuations, all systematic uncertainties were evaluated using ensemble tests. Simulated data sets (“ensembles”) were generated by picking random combinations of events from a pool of MC original (nominal) events according to the expected number of events due to signal and each background type. For each source of systematic uncertainty, the modified events that passed the regular event selection were used to construct the LHD templates used in the ensemble tests. A weighted sum of modified signal and background templates was fit to the LHD distributions for each ensemble. The results of the fits were averaged over ensembles using a Gaussian fit of the difference between the average number of $t\bar{t}$ events for the nominal and the modified template fits, and the fitted difference was propagated to the cross-section uncertainty. The MC statistical uncertainty associated to the limited signal and background sample size was found to be below $\pm 0.1\%$.

**Lepton reconstruction:** the uncertainties due to lepton trigger, identification, energy or momentum resolution and reconstruction efficiencies were estimated from $Z \rightarrow ee/\mu\mu$, $J/\psi \rightarrow ee/\mu\mu$, and $W \rightarrow e\nu$ processes using techniques discussed in Refs. [40, 53, 54]. These uncertainties are relatively small, dominated by the lepton identification in the $e\pm$-jets channel ($\pm 2\%$) and the muon triggering efficiency in the $\mu+\text{jets}$ channel ($\pm 3\%$). They are specific to each lepton flavor and therefore uncorrelated between the channels.

**Jet reconstruction:** the uncertainty on the $t\bar{t}$ cross-section due to the uncertainty on the jet-energy scale was estimated by varying the jet energies according to the uncertainties derived from simulation and in-situ calibration measurements using a model with 22 orthogonal components [44, 55]. The variations in jet energies were also propageted to the $E_T^{\text{miss}}$ value. The uncertainty due to the difference in jet-energy resolution between the data and MC events was evaluated by smearing the MC jet transverse momentum according to the jet resolution as a function of the jet $p_T$ and $\eta$ [56]. The uncertainty due to the jet reconstruction efficiency was estimated by randomly discarding jets according to the difference in jet reconstruction efficiency between the data and MC. The lower value of jet vertex fraction was varied between 0.4 and 0.6 as motivated by the $Z \rightarrow ee/\mu\mu$ studies [57]. The dominant jet reconstruction systematic uncertainty on the $t\bar{t}$ cross-section is due to the uncertainty on the jet-energy scale ($\pm 3\%$).

**$b$-tagging:** the uncertainties on the $b$-tagging scale factors were obtained separately for $b$-jets, $c$- jets and light flavor jets, and were treated as uncorrelated for each type of jet. The uncertainties on the inefficiency scale factors, applied when a jet was not tagged, were treated as fully anticorrelated to those from the efficiency scale factors. Since the efficiency to tag a $b$-jet is 70%, and only one of the two $b$-jets in the event is required to be tagged, the $t\bar{t}$ event tagging efficiency is large (about 90%) and its uncertainty is dominated by $b$-jet tagging uncertainties, which are small compared to non-$b$-jet ones. The resulting $b$-tagging contribution to the overall systematic uncertainty is about $\pm 2\%$.

**Missing transverse momentum:** the systematic uncertainties associated with the momenta and energies of reconstructed objects (leptons and jets) were also propagated to the $E_T^{\text{miss}}$ calculation. The $E_T^{\text{miss}}$ reconstruction also receives contributions from the presence of low-$p_T$ jets and calorimeter cells not included in reconstructed objects (“soft terms”). The systematic uncertainty on soft terms was evaluated using $Z \rightarrow \mu\mu$ events from the $E_T^{\text{miss}}$ data/MC ratio in events without jets and from the balance between soft terms and hard objects using methods similar to those used in Ref. [58]. The $E_T^{\text{miss}}$ measurement is not a significant source of systematic uncertainty (below $\pm 1\%$).

**$W+\text{jets}$ model:** this source of systematic uncertainty does not affect the number of $t\bar{t}$ events expected after applying the selection requirements but it does change the shape of the background template. This uncertainty was estimated using templates with $W+\text{jets}$ events generated by SHERPA instead of ALPGEN+PYTHA
and was found to be small (below 1%) and to partially cancel out when combining the $e+$jets and $\mu+$jets channels.

**W + heavy-flavor composition**: the heavy-flavor composition of $W+$jets events was studied using $W$ events with two additional jets split into $W^+$ and $W^-$ samples. Uncertainties were derived from contributions from $W+c$, $W+c\bar{c}$, and $W+b\bar{b}$ based on the statistical uncertainty, uncertainties on the extrapolation from 2-jets to $\geq3$-jets, and MC modeling, following the procedure described in Ref. [60]. The uncertainties themselves are very large (about $\pm50\%$), but the LHD template shapes for $W$-bosons produced in association with different jet flavors are similar and since the normalization of the $W+$jets background is derived from a fit to the data, the resulting systematic uncertainty on the $t\bar{t}$ production cross-section is small ($\pm1\%$).

**Small backgrounds**: uncertainties on single top-quark and diboson production were evaluated by varying the relevant theoretical cross-sections within their uncertainties $\pm1\sigma_{\text{theor}}$, which resulted in a $t\bar{t}$ production cross-section uncertainty of the order of $\pm1\%$. The uncertainty on the multijet contribution was derived from a comparison with results with $\epsilon_{\text{real}}$ obtained using data control samples with large $m_T(W)$ ($\mu+$jets) or large $E_T^{\text{miss}}$ ($e+$jets) depleted of fake leptons; the variation of $\epsilon_{\text{fake}}$ due to the change of the low $m_T(W)/E_T^{\text{miss}}$ region; and the choice of MC samples used to subtract the real leptons. As seen in Table 1, the uncertainty on the number of multijet events is very large (about $\pm100\%$), mainly due to uncertainties in $\epsilon_{\text{fake}}$, but their fraction in the data sample is small due to the high lepton-$p_T$ requirement, so the overall effect is about $\pm1\%$.

**Pileup**: the MC samples used in the analysis were reweighted to reproduce correctly the distribution of the number of $pp$ collisions per bunch crossing in the data. The accuracy of the average correction factor due to pileup reweighting was found to be $\pm4\%$. The pileup reweighting uncertainties originated from the modeling of pileup events, including uncertainties in the $pp$ inelastic cross-section. The resulting effect on the measured $t\bar{t}$ cross-section is small (about $\pm0.1\%$) but is still included in the total systematic uncertainty.

**Initial- and final-state radiation (ISR and FSR) modeling**: ISR or FSR changes the number of jets in the event. To evaluate the uncertainty linked to the modeling of the ISR or FSR, $t\bar{t}$ MC samples with modified ISR and FSR modeling were used. The MC samples used for the evaluation of this uncertainty were generated using the AcErMC generator interfaced to PyTHIA, where the parameters of the generation ($A_{\text{QCD}}, Q_{\text{max}}^2$ scale, transverse momentum scale for space-like parton-shower evolution [20]) were varied to span the ranges compatible with the results of a measurement of $t\bar{t}$ production with a veto on additional central jet activity [61]. This uncertainty is large for the total inclusive $t\bar{t}$ production cross-section ($\pm3\%$) but significantly reduced (below $\pm1\%$) for the fiducial cross-section measurement.

**MC generator**: the choice of MC generator used in the signal modeling affects the kinematic properties of simulated $t\bar{t}$ events and reconstruction efficiencies. For the purpose of addressing this effect, $t\bar{t}$ events simulated with MC@NLO interfaced to Herwig+JIMMY were used and compared to results obtained with Powheg interfaced to Herwig+JIMMY. The resulting systematic uncertainty was found to be $\pm3\%$.

**MC parton shower and fragmentation model**: the effect of the parton shower and fragmentation modeling was estimated by comparing the results obtained from the default MC sample simulated by Powheg interfaced to PyTHIA with a modified model simulated by Powheg interfaced to Herwig+JIMMY. The

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3 The ratio of $W^+$ to $W^-$ production cross-sections at the LHC is predicted much more precisely than the cross-sections themselves [59].
change in the number of expected $t\bar{t}$ events due to the modified selection efficiency and the LHD distribution was propagated to the systematic uncertainty on the $t\bar{t}$ production cross-section. Using this approach, the systematic uncertainty due to the MC parton shower and fragmentation model was found to be $\pm 2\%$.

**MC parton distribution functions (PDFs):** this uncertainty is one of the most significant ones in this analysis ($\pm 6\%$). An event-by-event reweighting was applied to the MC@NLO $t\bar{t}$ sample generated using the central value of the CT10 PDF. The CT10 variations, as well as both the central values and the variations of MSTW2008 NLO at the 68% confidence level and NNPDF23 were used to evaluate the systematic uncertainty, following the PDF4LHC recommendations [9]. For each PDF and its variations the change in the $t\bar{t}$ cross-section was calculated using ensemble tests. The final envelope of all variations was symmetrized and half of its size was quoted as the systematic uncertainty due to the PDF uncertainty. The effect arises primarily from the gluon PDF component, which is large for signal and small for background. Therefore the PDF uncertainty is dominated by the choice of PDF in the $t\bar{t}$ simulation. The PDF uncertainty affects both the LHD shape and the selection efficiency, and is significant for both the inclusive and the fiducial cross-section measurement.

**Luminosity:** this uncertainty was evaluated separately and not combined with the rest of the systematic uncertainties. Following the method described in Ref. [62], the uncertainty on the total integrated luminosity was determined to be $\pm 2.8\%$ from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012. By combining the change in $L$ in Eqs. (1) and (2) and the change in the contribution of single top and diboson events, the overall uncertainty due to the integrated luminosity was found to be $\pm 2.9\%$.

**LHC beam energy:** calibrations determined the beam energy to be $(0.30 \pm 0.66)\%$ smaller than the nominal value of 4 TeV per beam [63]. The measured $t\bar{t}$ cross-section value is not corrected for this shift. However, an uncertainty of $\pm 1.7\%$, corresponding to the expected change in $\sigma_{t \bar{t}}$ for a $\pm 0.66\%$ change in $\sqrt{s}$ is quoted separately in the final result. The effect of changing the LHC beam energy on $e_{t \bar{t}}$ is negligible.

The evaluation of the systematic uncertainties other than the $t\bar{t}$ MC dependence for the measurement in the fiducial volume is the same as for the inclusive measurement. For the systematic uncertainties obtained using different $t\bar{t}$ MC samples, the different signal-reconstruction efficiency in the fiducial volume was taken into account.

The systematic uncertainties due to the jet reconstruction and $E_T^{miss}$ measurement are grouped together, as well as the systematic uncertainties due to the background evaluation. A summary of the systematic uncertainties is given in Table 2.

8 Results and conclusions

Inclusive and fiducial $t\bar{t}$ production cross-sections have been measured at the LHC in $pp$ collisions at $\sqrt{s} = 8$ TeV using data collected with the ATLAS detector in 2012, corresponding to 20.3 fb$^{-1}$ of integrated luminosity. The measurements were in the lepton+jets final state using a likelihood discriminant
Table 2: Summary of the systematic uncertainties in the measurements of the $t\bar{t}$ production cross-section ($\%$). The bottom part of the table lists systematic uncertainties for the fiducial $t\bar{t}$ production cross-section for the cases where they are different from those for the inclusive one.

<table>
<thead>
<tr>
<th>Uncertainty on inclusive $\sigma_{t\bar{t}}$</th>
<th>$e$+jets</th>
<th>$\mu$+jets</th>
<th>$\ell$+jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton reconstruction</td>
<td>$+2.7$ $-$ $2.6$</td>
<td>$+2.1$ $-$ $1.9$</td>
<td>$+1.7$ $-$ $1.6$</td>
</tr>
<tr>
<td>Jet reconstruction and $E_T^{miss}$</td>
<td>$+3.3$ $-$ $3.9$</td>
<td>$+2.6$ $-$ $3.2$</td>
<td>$+2.8$ $-$ $3.4$</td>
</tr>
<tr>
<td>$b$-tagging</td>
<td>$+2.1$ $-$ $1.9$</td>
<td>$+2.2$ $-$ $1.9$</td>
<td>$+2.1$ $-$ $1.9$</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>$+2.8$ $-$ $3.0$</td>
<td>$+1.8$ $-$ $2.1$</td>
<td>$+1.7$ $-$ $2.1$</td>
</tr>
<tr>
<td>Monte Carlo generator</td>
<td>$-2.2$ $+$ $2.2$</td>
<td>$-3.3$ $+$ $3.3$</td>
<td>$-2.7$ $+$ $2.7$</td>
</tr>
<tr>
<td>Parton shower and fragmentation</td>
<td>$+2.0$ $-$ $2.0$</td>
<td>$+2.6$ $-$ $2.6$</td>
<td>$+2.3$ $-$ $2.3$</td>
</tr>
<tr>
<td>Initial- and final-state radiation</td>
<td>$-4.1$ $+$ $4.1$</td>
<td>$-1.8$ $+$ $1.8$</td>
<td>$-3.0$ $+$ $3.0$</td>
</tr>
<tr>
<td>Parton distribution functions</td>
<td>$+6.2$ $-$ $6.0$</td>
<td>$+5.6$ $-$ $5.9$</td>
<td>$+5.9$ $-$ $5.9$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$+9.7$ $-$ $9.8$</td>
<td>$+8.4$ $-$ $8.7$</td>
<td>$+8.6$ $-$ $8.9$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Uncertainty on fiducial $\sigma_{t\bar{t}}$</th>
<th>$e$+jets</th>
<th>$\mu$+jets</th>
<th>$\ell$+jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monte Carlo generator</td>
<td>$-2.1$ $+$ $2.1$</td>
<td>$-3.5$ $+$ $3.5$</td>
<td>$-2.8$ $-$ $2.8$</td>
</tr>
<tr>
<td>Parton shower and fragmentation</td>
<td>$-2.6$ $+$ $2.6$</td>
<td>$-3.1$ $+$ $3.1$</td>
<td>$-2.9$ $+$ $2.9$</td>
</tr>
<tr>
<td>Initial- and final-state radiation</td>
<td>$+0.4$ $-$ $0.4$</td>
<td>$+0.2$ $-$ $0.2$</td>
<td>$+0.3$ $-$ $0.3$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$+8.9$ $-$ $9.0$</td>
<td>$+8.5$ $-$ $8.8$</td>
<td>$+8.3$ $-$ $8.6$</td>
</tr>
</tbody>
</table>

fit. Assuming a top-quark mass of 172.5 GeV, the inclusive $t\bar{t}$ production cross-section is found to be

$$e+\text{jets} : \sigma_{t\bar{t}} = 256 \pm 2(\text{stat}) \pm 25(\text{syst}) \pm 7(\text{lumi}) \pm 4(\text{beam}) \text{ pb},$$

$$\mu+\text{jets} : \sigma_{t\bar{t}} = 260 \pm 1(\text{stat}) \pm 22(\text{syst}) \pm 8(\text{lumi}) \pm 4(\text{beam}) \text{ pb},$$

$$\ell+\text{jets} : \sigma_{t\bar{t}} = 258 \pm 1(\text{stat}) \pm 22(\text{syst}) \pm 8(\text{lumi}) \pm 4(\text{beam}) \text{ pb},$$

where the four quoted uncertainties are due to the number of events in data (statistical uncertainty), systematic effects (as described in Sec. 7), the imprecisely known integrated luminosity, and the LHC beam energy. Since the results were obtained using a fixed value of $m_{top}$, a set of $t\bar{t}$ samples with different top-quark masses was generated in order to study the $m_{top}$ dependence of the measured $t\bar{t}$ production cross-section, which is found to be $<\Delta \sigma_{t\bar{t}}/\sigma_{t\bar{t}}>/\Delta m_{top} = -1.1 \%/\text{GeV}$ in all channels.

The fiducial $t\bar{t}$ cross-section is found to be

$$e+\text{jets} : \sigma_{t\bar{t}}^{\text{fid}} = 11.3 \pm 0.1(\text{stat}) \pm 1.0(\text{syst}) \pm 0.3(\text{lumi}) \pm 0.2(\text{beam}) \text{ pb},$$

$$\mu+\text{jets} : \sigma_{t\bar{t}}^{\text{fid}} = 11.5 \pm 0.1(\text{stat}) \pm 1.0(\text{syst}) \pm 0.3(\text{lumi}) \pm 0.2(\text{beam}) \text{ pb},$$

$$\ell+\text{jets} : \sigma_{t\bar{t}}^{\text{fid}} = 22.8 \pm 0.1(\text{stat}) \pm 1.9(\text{syst}) \pm 0.7(\text{lumi}) \pm 0.4(\text{beam}) \text{ pb},$$

where the four quoted uncertainties represent the same sources as indicated before.

The largest systematic uncertainties are due to $t\bar{t}$ MC modeling, including the PDF uncertainty, the choice of MC generator, the parton shower and fragmentation model and initial- and final-state radiation. The systematic uncertainty from ISR or FSR is found to be reduced for the fiducial cross-section measurement compared to the inclusive case, while the uncertainties due to the choice of MC generator and the parton shower and fragmentation model are found to increase slightly in the fiducial cross-section measurement compared to the inclusive case.
The measured inclusive $t\bar{t}$ production cross-section is in good agreement with the NNLO+NNLL theory prediction, $\sigma_{t\bar{t}} = 253^{+13}_{-15}$ pb [2]. It is also consistent with the ATLAS and CMS measurements of the $t\bar{t}$ production cross-section in the dilepton channel [15, 16]. The ATLAS measurement had the result of $\sigma_{t\bar{t}} = 242.4 \pm 1.7(\text{stat.}) \pm 5.5(\text{syst.}) \pm 7.5(\text{lumi.}) \pm 4.4(\text{beam})$ pb [15], where the four quoted uncertainties were due to the same sources as above.

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References

10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12 Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
13 Institute of Physics, University of Belgrade, Belgrade, Serbia
14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19 (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston MA, United States of America
23 Department of Physics, Brandeis University, Waltham MA, United States of America
24 (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
26 (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
32 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaiso, Chile
33 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; (f) Physics Department, Tsinghua University, Beijing 100084, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington NY, United States of America
36 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
37 (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
38 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
39 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
Physics Department, Southern Methodist University, Dallas TX, United States of America
Physics Department, University of Texas at Dallas, Richardson TX, United States of America
DESY, Hamburg and Zeuthen, Germany
Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
Department of Physics, Duke University, Durham NC, United States of America
SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
INFN Laboratori Nazionali di Frascati, Frascati, Italy
Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
Section de Physique, Université de Genève, Geneva, Switzerland
SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
SUPA - School of Physics and Cosmology, Harvard University, Cambridge MA, United States of America
Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
Department of Physics, Indiana University, Bloomington IN, United States of America
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City IA, United States of America
Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
Department of Physics, Kyushu University, Fukuoka, Japan
Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, United Kingdom
INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
Louisiana Tech University, Ruston LA, United States of America
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Fysiska institutionen, Lunds universitet, Lund, Sweden
Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst MA, United States of America
Department of Physics, McGill University, Montreal QC, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
(a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
Group of Particle Physics, University of Montreal, Montreal QC, Canada
P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
National Research Nuclear University MEPhI, Moscow, Russia
D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
(a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
Department of Physics, Northern Illinois University, DeKalb IL, United States of America
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York NY, United States of America
Ohio State University, Columbus OH, United States of America
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
Department of Physics, Oklahoma State University, Stillwater OK, United States of America
Palacký University, RCPTM, Olomouc, Czech Republic
116 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
117 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
118 Graduate School of Science, Osaka University, Osaka, Japan
119 Department of Physics, University of Oslo, Oslo, Norway
120 Department of Physics, Oxford University, Oxford, United Kingdom
121 (a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
122 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
123 Petersburg Nuclear Physics Institute, Gatchina, Russia
124 (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
125 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
126 (a) Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa; (b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Department of Physics, University of Coimbra, Coimbra; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (e) Departamento de Física, Universidade do Minho, Braga; (f) Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); (g) Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
127 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
128 Czech Technical University in Prague, Praha, Czech Republic
129 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
130 State Research Center Institute for High Energy Physics, Protvino, Russia
131 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
132 Ritsumeikan University, Kusatsu, Shiga, Japan
133 (a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
134 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
135 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
136 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
137 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
138 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
139 Department of Physics, University of Washington, Seattle WA, United States of America
140 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
141 Department of Physics, Shinshu University, Nagano, Japan
142 Fachbereich Physik, Universität Siegen, Siegen, Germany
143 Department of Physics, Simon Fraser University, Burnaby BC, Canada
144 SLAC National Accelerator Laboratory, Stanford CA, United States of America
145 (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
146 (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics,