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# Measurement of the cross section for top-quark pair production in $pp$ collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector using final states with two high-$p_{\mathrm{T}}$ leptons

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Abstract: A measurement is reported of the production cross section of top-quark pairs ($t\bar{t}$) in proton-proton collisions at a center-of-mass energy of 7 TeV recorded with the ATLAS detector at the LHC. Candidate events have a signature consistent with containing two isolated leptons, large missing transverse momentum, and at least two jets. Using a data sample corresponding to an integrated luminosity of 0.70 fb$^{-1}$, a $t\bar{t}$ production cross section $\sigma_{t\bar{t}} = 176 \pm 5(\text{stat.})^{+14}_{-11}(\text{syst.}) \pm 8(\text{lum.})$ pb is measured for an assumed top-quark mass of $m_t = 172.5$ GeV. This measurement is in good agreement with Standard Model predictions.

Keywords: top physics, heavy quark production, total cross section

## Contents



## 1 Introduction

As the heaviest known elementary particle, the top quark is a particularly interesting probe of the Standard Model (SM). The measurement of the $t\bar{t}$ production cross section in different decay modes is a sensitive test of perturbative QCD and the SM description of top-quark decay. The production cross section in proton-proton ($pp$) collisions at a center-of-mass energy $\sqrt{s} = 7$ TeV is calculated to be $165^{+11}_{-16}$ pb at approximate next-to-next-to-leading-order (NNLO) [1, 2], and the top quark is predicted to decay nearly 100% of the time to a $W$ boson and a $b$ quark. A measured cross section that differs from the SM prediction can be a sign of new physics. Furthermore, $t\bar{t}$ production is an important background in many searches for physics beyond the SM, and in searches for the SM Higgs boson.

The $t\bar{t}$ event topologies are determined by the decays of the two $W$ bosons. In increasing order of $t\bar{t}$ branching fraction: dilepton final states occur when both $W$ bosons decay to a charged lepton and a neutrino, 'lepton plus jets' final states when only one $W$ boson decays leptonically while the other decays to a pair of quarks, and all-hadronic final states when both $W$ bosons decay to pairs of quarks.

Top-quark production in dilepton final states has been studied using proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV [3, 4] and Large Hadron Collider (LHC) measurements of the production cross section in proton-proton collisions at $\sqrt{s} = 7$ TeV in the same final state have recently been reported [5, 6]. A measurement is presented of the $t\bar{t}$ production cross section using the dilepton channel, characterized by two opposite-sign leptons, unbalanced transverse momentum indicating the presence of neutrinos from the $W$-boson decays, and two $b$-quark jets. This result uses twenty times more data than the previous ATLAS measurement in the same final state, reported in Ref. [6].

The $t\bar{t}$ dilepton final states can be selected with a good signal-to-background ratio using simple kinematic requirements. With the additional requirement of the presence of a jet consistent with a $b$ quark ('$b$-tag'), the signal-to-background ratio can be further improved. Cross-section measurements with and without the $b$-tag requirement are reported here. Leptons are either well-identified electron or muon candidates that are selected using the full detector or, to reduce losses from lepton identification inefficiencies, isolated tracks. The well-identified electrons or muons are called 'identified leptons', and the isolated tracks are referred to as 'track-leptons'. The term 'lepton' is used to refer to identified leptons and track leptons collectively. Events with track-lepton candidates are called lepton+track events. Each dilepton channel is exclusive, i.e. has no overlap with the other channels. Channels with tau leptons are not explicitly reconstructed, but reconstructed leptons can arise from leptonic tau decays and a track lepton can arise from hadronic tau decay modes as well. The analysis with the $b$-tag requirement uses only identified leptons.

The measured cross section takes into account the $t\bar{t}$ signal acceptance and the expected background contributions from $Z/\gamma^*$+jets, single top quarks, $WW$, $WZ$, and $ZZ$ events, and events with misidentified leptons (primarily $W$+jets events). Background contributions from $Z/\gamma^* \to ee$+jets, $Z/\gamma^* \to \mu\mu$+jets and events with misidentified leptons are evaluated directly from the data. All other background contributions are evaluated using Monte Carlo (MC) simulation samples.

## 2 Detector and data sample

The ATLAS detector [7] at the LHC covers nearly the entire solid angle around the collision point. It consists of an inner tracking detector (ID) comprising a silicon pixel detector, a silicon microstrip detector (SCT), and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field, and by liquid-argon electromagnetic sampling calorimeters with high granularity (LAr). An iron-scintillator tile calorimeter provides hadronic energy measurements in the central pseudorapidity[1] range ($|\eta| < 1.7$). The end-cap and forward regions are instrumented with LAr calorimetry for both electromagnetic (EM) and hadronic energy measurements up to $|\eta| < 4.9$. The calorimeter system is surrounded by a muon spectrometer incorporating three superconducting toroid magnet assemblies, with bending power between 2.0 and 7.5 Tm.

A three-level trigger system is used to collect data. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the rate to at most 75 kHz. This is followed by two software-based trigger levels that together reduce the event rate to $\sim 300$ Hz.

[1]In the right-handed ATLAS coordinate system, the pseudorapidity $\eta$ is defined as $\eta = -\ln[\tan(\theta/2)]$, where the polar angle $\theta$ is measured with respect to the LHC beamline. The azimuthal angle $\phi$ is measured with respect to the $x$-axis, which points towards the centre of the LHC ring. The $y$-axis points up. Transverse momentum and energy are defined as $p_{\mathrm{T}} = p\sin\theta$ and $E_{\mathrm{T}} = E\sin\theta$, respectively.

The analysis uses collision data with a center-of-mass energy of $\sqrt{s} = 7$ TeV recorded in 2011, with an integrated luminosity of 0.70±0.03 fb$^{-1}$ [8, 9].

## 3 Simulated samples

Monte Carlo simulation samples are used to calculate the $t\bar{t}$ acceptance and to evaluate the background contributions from single top quarks, $WW$, $WZ$, and $ZZ$ events, and $Z/\gamma^* \to \tau\tau$+jets. All MC samples are processed with the GEANT4 [10] simulation of the ATLAS detector [11] and events are passed through the same analysis chain as the data.

The generation of $t\bar{t}$ and single top-quark events uses the MC@NLO generator [12–14] with the CTEQ6.6 [15] parton distribution function (PDF) set and a top-quark mass of 172.5 GeV. Expected $t\bar{t}$ yields are calculated with a cross section normalized to the prediction of HATHOR[16], which employs an NNLO perturbative QCD calculation. Single top-quark production with MC@NLO includes the $s$, $t$ and $Wt$ channels and the diagram-removal scheme [17] is used to reduce overlap with the $t\bar{t}$ final state.

Drell-Yan events ($Z/\gamma^*$+jets) are modeled with the ALPGEN generator, using the MLM matching scheme [18] and the CTEQ6L1 [19] PDF set. The $Z/\gamma^*$+jets samples, including both light and heavy flavor jets, are normalized to NNLO with a $K$-factor of 1.25. In the $Z/\gamma^* \to ee$ and $\mu\mu$ decay channels, the background from $Z/\gamma^*$+jets is evaluated using a data-driven technique that normalizes the MC expectation to the data observation near the $Z$ pole. Background contributions from the $W$+jets final states come primarily from events where the $W$ boson decays leptonically and the second lepton candidate is a misidentified jet or a heavy-flavor decay. Backgrounds from $W$+jets events are evaluated from the data.

All MC simulated events are hadronized using the HERWIG shower model [20, 21] supplemented by the JIMMY underlying event model [22]. Both hadronization programs are tuned to ATLAS data using the ATLAS MC10 tune [23]. Diboson events are modeled using the ALPGEN generator normalized with $K$-factors of 1.26 ($WW$), 1.28 ($WZ$) and 1.30 ($ZZ$) to match the total cross section from NLO QCD predictions using calculations with the MCFM program [24].

All Monte Carlo samples are generated taking into account that multiple $pp$ interactions can occur in the same LHC bunch crossing within a given event ('pile-up'). The MC events are re-weighted so that the distribution of interactions per crossing in the MC matches that observed in the data. The average number of interactions per crossing is 5.6 in this data set.

## 4 Object selection

Leptons are required to be isolated and have high transverse momentum, $p_{\mathrm{T}}$, consistent with originating from $W$-boson decay, with $p_{\mathrm{T}}$ thresholds chosen to ensure events are triggered with high efficiency.

Electron candidates are reconstructed from energy deposits (clusters) in the EM calorimeter, which are then associated to reconstructed tracks of charged particles in the inner detector. Stringent quality requirements on the conditions of the EM calorimeter at the time of data taking are applied to ensure a well measured reconstructed energy. A 'tight' selection [25] using calorimeter, tracking and combined variables, is employed to provide good separation between the signal electrons and background. Electron candidates are additionally required to have $p_{\mathrm{T}} > 25$ GeV and $|\eta_{cl}| < 2.47$, excluding electrons from the transition region between the barrel and endcap calorimeters defined by $1.37 < |\eta_{cl}| < 1.52$. The variable $\eta_{cl}$ is the pseudorapidity of the energy cluster associated with the candidate.

Muon candidate reconstruction is begun by searching for track segments in layers of the muon chambers. These segments are combined starting from the outermost layer, fitted to account for material effects, and matched with tracks found in the inner detector. The candidates are refitted using the complete track information from both detector systems, and required to satisfy $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$.

Lepton isolation requirements reduce backgrounds from misidentified jets and suppress the selection of leptons from heavy-flavor decays. For electron candidates, the transverse energy ($E_{\mathrm{T}}$) deposited in the calorimeter not associated to the electron is summed in a cone of radius $\Delta R = 0.2$, where $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$, around the electron and is required to be less than 3.5 GeV. For muon candidates, the isolation requirement is based on both calorimeter and track information. The track isolation requirement is based on the sum of the track transverse momenta for tracks with $p_{\mathrm{T}} > 1$ GeV in a cone $\Delta R = 0.3$ centered on the muon candidate, while the calorimeter isolation requirement is based on the sum of transverse energy in the same cone. Both the track and calorimeter sums are required to be less than 4 GeV. Additionally, muon candidates must have a distance $\Delta R > 0.4$ from any jet with $p_{\mathrm{T}} > 20$ GeV, further suppressing muon candidates from heavy flavor decays. Muon candidates arising from cosmic rays are rejected by removing candidate pairs that are back-to-back in the $r - \phi$ plane and with transverse impact parameters relative to the beam axis $|d_0| > 0.5$ mm.

Track-lepton (TL) candidates are defined by an ID track with $p_{\mathrm{T}} > 25$ GeV and a series of quality cuts optimized for high efficiency and a low rate of misidentification. The track must have at least six SCT hits and at least one hit in the innermost pixel layer. It also must have $|d_0| < 0.2$ mm and the uncertainty on the momentum measurement must be less than 20%. The track has to be isolated from other nearby tracks, following the track isolation defined above, in this case using tracks with $p_{\mathrm{T}} > 0.5$ GeV. The summed momentum cut is set to 2 GeV.

Jets are reconstructed with the anti-k$_t$ algorithm [26] with a radius parameter $R = 0.4$, starting from energy clusters in the calorimeter reconstructed using the scale established for electromagnetic objects. These jets are then calibrated to the hadronic energy scale using $p_{\mathrm{T}}$ and $\eta$ dependent correction factors [27]. Jets are removed if they are within $\Delta R = 0.2$ of a well-identified electron candidate or a TL. The jets used in the analysis are required to have $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$.

Jets are identified as $b$-quark candidates ('$b$-tagged') by an algorithm that forms a likelihood ratio of $b$- and light-quark jet hypotheses using the following discriminating variables: the signed impact parameter significance of well measured tracks associated with a given jet, the decay length significance associated with a reconstructed secondary vertex, the invariant mass of all tracks associated to the secondary vertex, the ratio of the sum of the energies of the tracks associated with the secondary vertex to the sum of the energies of all tracks in the jet assuming a pion hypothesis, and the number of two-track vertices that can be formed at the secondary vertex [28]. The cut on the combined likelihood ratio has been chosen such that a $b$-tagging efficiency of $\approx 80\%$ per $b$-jet in $t\bar{t}$ candidate events is achieved.

The missing transverse momentum is formed from the negative vector sum of transverse momenta of all jets with $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 4.5$ [29]. The contribution from cells associated with electron candidates is replaced by the candidates' calibrated transverse energy. The contribution from all muon candidates and calorimeter clusters (including those not belonging to a reconstructed object) is also included. The symbol $E_{\mathrm{T}}^{\mathrm{miss}}$ is used to denote the magnitude of the missing transverse momentum.

## 5 Event selection

The analysis requires collision data selected by an inclusive single electron or muon trigger with offline-reconstructed candidates satisfying $p_{\mathrm{T}} > 25$ GeV for electrons, and $p_{\mathrm{T}} > 20$ GeV for muons, to ensure a constant trigger efficiency. To ensure that the event was triggered by the lepton candidates used in the analysis, one of the identified leptons and the triggered lepton are required to match within $\Delta R < 0.15$.

Events are required to have a primary interaction vertex with at least five tracks with $p_{\mathrm{T}} > 400$ MeV. The event is discarded if any jet with $p_{\mathrm{T}} > 20$ GeV fails quality cuts designed to reject jets arising from calorimeter noise or activity inconsistent with the bunch-crossing time [27]. If an electron candidate and a muon candidate share a track, the event is also discarded.

The selection of events in the signal region consists of a series of kinematic requirements on the reconstructed objects. The requirements on $E_{\mathrm{T}}^{\mathrm{miss}}$, the lepton-lepton invariant mass ($m_{\ell\ell}$), and the scalar $p_{\mathrm{T}}$ sum of all selected jets and leptons ($H_{\mathrm{T}}$) are optimized to minimize the expected total uncertainty on the cross-section measurement. The resulting event selection, referred to as the 'non-$b$-tag' selection, is listed below.

- Events must have exactly two oppositely-charged identified-lepton candidates ($ee$, $\mu\mu$, $e\mu$), satisfying the selection criteria of Section 4, *or* if only one identified-lepton candidate is found, the event is retained if a track-lepton candidate is present, with opposite charge to the identified lepton, forming a lepton+track event ($e$TL or $\mu$TL).
- Events must have at least two jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$.
- Events in the $ee$, $\mu\mu$ $e$TL and $\mu$TL channels are required to have $m_{\ell\ell} > 15$ GeV in order to reject backgrounds from vector-meson decays. The requirement also helps to suppress backgrounds in these channels from $b$-quark production.
- Events in the $ee$ and $\mu\mu$ channels must satisfy $E_{\mathrm{T}}^{\mathrm{miss}} > 60$ GeV and $|m_{\ell\ell} - m_Z| > 10$ GeV, to suppress backgrounds from $Z/\gamma^*$+jets and multijets.

- Events in the $e\mu$ channel are required to satisfy $H_{\mathrm{T}} > 130$ GeV. No $E_{\mathrm{T}}^{\mathrm{miss}}$ or $m_{\ell\ell}$ cuts are applied.

- The lepton+track event candidates must have $E_{\mathrm{T}}^{\mathrm{miss}} > 45$ GeV, $H_{\mathrm{T}}$ (including the track lepton) $> 150$ GeV, and $|m_{\ell\ell} - m_Z| > 10$ GeV.

A parallel selection with the additional requirement of at least one $b$-tagged jet is made. Because of the enhanced background rejection afforded by the $b$-tag requirement, the selection is further optimized, resulting in an $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement for $ee$ and $\mu\mu$ events that is relaxed to $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV, while the $H_{\mathrm{T}}$ requirement for $e\mu$ events remains the same as for the non-$b$-tag selection, i.e. $H_{\mathrm{T}} > 130$ GeV. We refer to the analysis that requires at least one $b$-tagged jet as the '$b$-tag analysis', and the events selected therein as the '$b$-tagged sample'. The subset of the $b$-tagged sample with 40 GeV $< E_{\mathrm{T}}^{\mathrm{miss}} <$ 60 GeV is referred to as the 'exclusive $b$-tagged sample' and has no overlap with the non-$b$-tag sample.

The acceptance times the branching fraction of $t\bar{t}$ to dileptons, for the selection described above, is 0.96% for the $ee + \mu\mu + e\mu$ channels without $b$-tagging, 0.11% for the exclusive $b$-tagged sample, and 0.19% for $e$TL + $\mu$TL channels.

## 6 Background evaluation

The $t\bar{t}$ event selection rejects $Z/\gamma^*$+jets events with $ee$ and $\mu\mu$ invariant mass below 15 GeV, or within 10 GeV of the $Z$-boson mass. However, $Z/\gamma^*$+jets events with $ee$ or $\mu\mu$ invariant mass outside of these regions can enter the signal sample when there is large $E_{\mathrm{T}}^{\mathrm{miss}}$, typically from mismeasurement. These events are difficult to properly model in simulations due to uncertainties on the non-Gaussian tails of the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution, on the cross section for $Z$ boson production with multiple jets, and on the lepton energy resolution.

To evaluate the $Z/\gamma^*$+jets background in dielectron and dimuon events ($Z \to \tau\tau$ is considered below), the MC prediction for the number of events in the signal region is normalized to the data using the number of $Z/\gamma^*$+jets events measured in a control region [6]. The control region is formed by events with the same jet requirements as the signal region, but with $m_{\ell\ell}$ within 10 GeV of the $Z$-boson mass, and a $E_{\mathrm{T}}^{\mathrm{miss}}$ cut of $E_{\mathrm{T}}^{\mathrm{miss}} > 45$ GeV for the lepton+track candidates and $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV for the others. Contamination in the control region from other physics processes (signal and other background processes considered for the analysis) is subtracted according to MC predictions. The ratio of data events to MC expectation in the control region provides a scale factor that is used to correct the MC prediction for $Z/\gamma^*$+jets events in the signal region.

Other backgrounds mainly come from $W$+jets, $t\bar{t}$ lepton+jets, and single top-quark production with fake leptons. The term 'fake lepton' is used to refer to both misidentified and non-prompt lepton candidates, the latter category arising from hadron decays in flight. The yield of events with fake identified leptons is evaluated from the data using a matrix method [30]. In addition to the standard lepton selection requirements, a selection with a looser isolation requirement is defined. Dilepton events are selected using the loose isolation requirement and events are categorized according to whether each lepton passes the standard selection or the loose selection but not the standard selection. There are four such categories for the two leptons: loose-loose, loose-standard, standard-loose, and standard-standard. Each of the four categories is related to the number of events with two 'real' (prompt) leptons, two fake leptons, or one of each, through a set of linear equations with coefficients given by the products of probabilities for real or fake lepton satisfying the loose selection to also satisfy the standard selection. These linear expressions form a matrix that is inverted in order to extract the real and fake lepton content of the observed dilepton event sample. The probability for real leptons is measured as a function of jet multiplicity using data samples of $Z \to ee$ and $Z \to \mu\mu$ events. The corresponding probability for fake leptons is measured in a data sample dominated by dijet production, with events containing one lepton candidate passing the looser isolation cuts and having $E_{\mathrm{T}}^{\mathrm{miss}} < 20$ GeV. Contributions from real leptons due to $W$+jets final states are subtracted using simulated events.

For lepton+track events the largest background is from events with fake leptons, dominated by fake track leptons. The probability of a jet being reconstructed as a track lepton is determined from a $\gamma$+jets data sample selected with photon triggers. The fake probability is applied to a second sample enriched in $W$+jets events with exactly one identified lepton and no track leptons, but using the same kinematic cuts as for the signal sample. In this second sample the fake probabilities are summed for each jet in each event and the fake track-lepton contribution is calculated as a function of the number of jets.

The contributions from other electroweak background processes with two real leptons, such as single top quarks, $Z \to \tau\tau$, $WW$, $ZZ$ and $WZ$ production are determined from Monte Carlo simulations. The expected numbers of background events are given in Table 1. The absence of $Z/\gamma^*$+jets background in the $e\mu$ channel, coupled with the larger branching fraction for the $e\mu$ signal, allows relatively loose selection criteria to be used in this channel.

The background contributions for the $b$-tag analysis are determined using the same techniques described above, with the additional requirement of a $b$-tagged jet.

The modeled acceptances, efficiencies and data-driven background evaluation methods are validated by comparing predictions from Monte Carlo simulations with data in control regions with kinematics similar to the signal region but dominated by backgrounds. In particular, the $E_{\mathrm{T}}^{\mathrm{miss}}$, $m_{\ell\ell}$ and jet multiplicity distributions are studied in a sample of $Z$-boson candidates, defined by requiring $|m_{\ell\ell} - m_Z| < 10$ GeV and $E_{\mathrm{T}}^{\mathrm{miss}} < 60$ GeV. The predictions from MC simulations in the control regions are in reasonable agreement with data, although small discrepancies exist in regions that do not affect the $t\bar{t}$ cross-section measurement.

## 7 Systematic uncertainties

A summary of the systematic uncertainties on the measured $t\bar{t}$ production cross section is given in Table 2.

Lepton trigger and identified-lepton and track-lepton reconstruction and selection efficiencies are assessed using $Z \to ee$ and $Z \to \mu\mu$ events in the same data sample as used

| | $ee$ | $\mu\mu$ | $e\mu$ | $e$TL | $\mu$TL | $b$-tag $ee$ | $b$-tag $\mu\mu$ | $b$-tag $e\mu$ |
|---|---|---|---|---|---|---|---|---|
| $Z/\gamma^*$+ jets | $4.0^{+2.5}_{-1.2}$ | $14.4^{+5.4}_{-4.2}$ | - | $24.3^{+10.7}_{-9.4}$ | $22.0^{+5.3}_{-5.8}$ | $9.8^{+1.7}_{-1.3}$ | $20.3^{+1.8}_{-2.8}$ | – |
| $Z/\gamma^* \to \tau\tau$+jets | $4.9 \pm 2.6$ | $11.0 \pm 5.0$ | $43 \pm 16$ | $17.0^{+8.4}_{-7.6}$ | $25 \pm 11$ | $1.8^{+1.1}_{-1.2}$ | $7.6^{+3.3}_{-3.6}$ | $9.5^{+4.2}_{-3.9}$ |
| Fake leptons | $4.0 \pm 5.0$ | $6.3 \pm 4.1$ | $44 \pm 24$ | $74 \pm 15$ | $85 \pm 17$ | $7.5 \pm 6.5$ | $4.9 \pm 3.1$ | $20 \pm 13$ |
| Single top quark | $6.4^{+1.2}_{-1.1}$ | $16.0^{+1.9}_{-2.2}$ | $41.1 \pm 5.5$ | $5.7^{+1.0}_{-0.9}$ | $6.3^{+0.8}_{-1.1}$ | $7.3^{+1.3}_{-1.1}$ | $16.2^{+2.2}_{-2.3}$ | $33.5^{+4.8}_{-4.7}$ |
| Diboson | $5.9 \pm 1.1$ | $8.7^{+1.2}_{-1.5}$ | $32.9 \pm 4.9$ | $5.9^{+0.9}_{-0.8}$ | $4.8^{+0.6}_{-0.7}$ | $2.2 \pm 0.7$ | $2.6^{+0.9}_{-0.6}$ | $8.8^{+1.7}_{-1.6}$ |
| Total background | $25.2 \pm 6.4$ | $56.5 \pm 9.4$ | $161 \pm 34$ | $126^{+20}_{-19}$ | $142 \pm 21$ | $28.6 \pm 6.9$ | $51.6^{+5.6}_{-5.9}$ | $71.6 \pm 14.1$ |
| Predicted $t\bar{t}$ | $124 \pm 17$ | $241^{+15}_{-18}$ | $746 \pm 42$ | $112\ ^{+16}_{-18}$ | $110\ ^{+17}_{-16}$ | $159^{+17}_{-21}$ | $304^{+26}_{-35}$ | $675^{+57}_{-75}$ |
| Total | $149 \pm 18$ | $298^{+17}_{-20}$ | $907 \pm 54$ | $239 \pm 26$ | $253 \pm 27$ | $188^{+18}_{-22}$ | $356^{+27}_{-35}$ | $746^{+59}_{-76}$ |
| Observed | 165 | 301 | 963 | 236 | 255 | 201 | 365 | 834 |

**Table 1**. Breakdown of the expected $t\bar{t}$ signal and background events in the signal region compared to the observed event yields, for each of the dilepton channels. All systematic uncertainties are included, and correlations between different background sources are taken into account, when calculating the total background uncertainty.

for the $t\bar{t}$ analyses. Scale factors are evaluated by comparing these efficiencies with those determined with simulated $Z$-boson events. The scale factors are applied to MC samples when calculating acceptances to account for any differences between predicted and observed efficiencies. Systematic uncertainties on these scale factors are evaluated by varying the selection of events used in the efficiency measurements and by checking the stability of the measurements over the course of the data-taking period.

The modeling of lepton momentum scale and resolution is studied using reconstructed dilepton invariant mass distributions of $Z/\gamma^*$ candidate events, and the simulation is adjusted to match the data. Uncertainties in the scale and resolution are used to evaluate the systematic uncertainty due to these corrections. The acceptance uncertainty from the lepton modeling is dominated mostly by the electron selection efficiency uncertainty.

The jet energy scale (JES) and its uncertainty are derived by combining information from test-beam data, LHC collision data and simulation [27]. For jets within the acceptance, the JES uncertainty varies in the range 4–8% as a function of jet $p_{\mathrm{T}}$ and $\eta$. This uncertainty is higher than in the previous result [6] because of the additional uncertainty due to multiple $pp$ interactions at high instantaneous luminosity. The jet energy resolution and jet reconstruction/identification efficiency measured in data and in simulation are in good agreement. The statistical uncertainties on the comparisons, 10% and 1–2% for the energy resolution and the efficiency, respectively, are taken as systematic uncertainties associated with these effects. The effect on the acceptance is dominated by the JES uncertainty.

The systematic uncertainty on the efficiency of the $b$-tagging algorithm has been estimated to be 6% for $b$-quark jets, based on $b$-tagging calibration studies using inclusive lepton and multijet final states. The uncertainties on the tagging efficiencies for light and charm quarks are larger, but are not a significant source of uncertainty due to the intrinsically high signal-to-background ratios in the dilepton final states. The acceptance uncertainty due to $b$-tagging is about 3% for all three channels.

The uncertainty in the kinematic distributions of the $t\bar{t}$ signal events gives rise to systematic uncertainties in the signal acceptance, with contributions from the choice of generator, the modeling of initial- and final-state radiation (ISR/FSR) and the PDFs. The generator and parton-showering uncertainty (collectively labeled 'Generator' in Table 2) are evaluated by comparing the MC@NLO predictions with those of POWHEG [31–33] interfaced to either HERWIG or PYTHIA. The uncertainty due to ISR/FSR is evaluated using the ACERMC generator [34] interfaced to the PYTHIA shower model, and by varying the parameters controlling ISR and FSR in a range consistent with those used in the Perugia Hard/Soft tune variations [35]. Finally, the PDF uncertainty is evaluated using a range of current PDF sets [19]. The dominant uncertainties in this category of systematics are the modeling of ISR/FSR and the generator choice.

The overall normalization uncertainties on the backgrounds from single top quark and diboson production are taken to be 8.6% [36] and 5% [37], respectively. The systematic uncertainties from the background evaluations derived from the data include the statistical uncertainties in these methods as well as the systematic uncertainties arising from lepton and jet identification and reconstruction, and the MC estimates that are used. An uncertainty on the data-driven $Z/\gamma^*$+jets evaluation, based on the expected $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution in these events, is included by varying the $E_{\mathrm{T}}^{\mathrm{miss}}$ cut in the control region by $\pm 5$ GeV for $ee$ and $\mu\mu$ events, and $\pm 10$ GeV in lepton+track events where the $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution is poorer. The systematic uncertainty on the fake identified lepton background prediction is 50%, as measured using control regions with different flavor composition and photon conversion rates, as determined by Monte Carlo studies. A 20% systematic uncertainty is set on the prediction of the fake track-lepton background, derived from a comparison of predicted and observed fake track leptons in control regions defined as opposite-sign events with zero or one jet without an $H_{\mathrm{T}}$ cut, and same-sign events with more than one jet. The uncertainty on the measured integrated luminosity of the dataset is 3.7% [9].

Table 2 lists the contributions to the cross-section measurement of each of the systematic uncertainties considered, in percent, with the non-$b$-tag and the exclusive $b$-tag analyses combined in the $ee$ and $\mu\mu$ columns. Only non-$b$-tag events are used in the $e\mu$ channel. The relatively large 'Generator' uncertainty for $ee$ events is partly a result of the limited size of the MC data set. In the $e$TL and $\mu$TL columns the 'MC statistics' uncertainty is larger than in the $ee$, $\mu\mu$, and $e\mu$ case because the number of events available is reduced by the removal of events with two identified leptons. The combined uncertainty comes from the profile likelihood technique used to determine the cross section [6], and takes into account all correlations. The statistical uncertainty is determined by fixing all systematic uncertainties at their best-fit values in the likelihood function.

## 8 Cross-section measurement

The expected and measured numbers of events in the signal region, after applying all selection cuts for each of the individual dilepton channels, are shown in Table 1. A total of 1920 candidate events are observed for the analysis without $b$-tagging, and a total of 1400 candidate events are found for the $b$-tag analysis. There are 1221 events in common between the two selections, and 179 exclusive $b$-tagged events.

| Uncertainties $\Delta\sigma/\sigma$[%] | $ee$ | $\mu\mu$ | $e\mu$ | $e$TL | $\mu$TL | Combined |
|---|---|---|---|---|---|---|
| Data statistics | ±8.1 | ±6.1 | ±3.9 | ±14.1 | ±14.2 | ±2.9 |
| Luminosity | +4.4/-3.8 | +4.4/-3.9 | ±4.2 | +5.1/-4.2 | +5.4/-4.4 | ±4.3 |
| MC statistics | ±1.6 | ±1.2 | ±0.8 | ±5.5 | ±4.6 | +0.7/-0.6 |
| Lepton uncertainties | +6.2/-5.4 | +2.9/-1.3 | ±3.1 | ±4.1 | +1.8/-1.6 | +2.6/-2.2 |
| Track-leptons | — | — | — | ±4.4 | ±1.9 | +0.3/-0.2 |
| Jet/$E_{\mathrm{T}}^{\mathrm{miss}}$ uncertainties | +5.7/-5.7 | +6.4/-3.5 | +4.7/-3.2 | +14.8/-6.4 | ±13.1 | +4.4/-3.4 |
| $b$-tagging uncertainties | +1.2/-1.0 | ±0.7 | — | — | — | +0.4/-0.0 |
| $Z/\gamma^*$+ jets evaluation | ±0.4 | +0.5/-0.0 | — | ±6.2 | +2.4/-2.7 | +0.3/-0.2 |
| Fake lepton evaluation | ±3.3 | 1.5/-1.3 | ±3.0 | ±13.7 | ±15.1 | ±1.7 |
| Generator | +12/-11 | +4.5/-4.3 | +4.8/-4.5 | +14/-11 | +14/-13 | +5.1/-4.9 |
| All syst.(except lumi.) | +16.4/-14.4 | +8.8/-6.4 | +8.2/-6.8 | +27.9/-20.7 | +26.5/-23.7 | +8.0/-6.5 |
| Stat. + syst. | +18.9/-16.9 | +11.6/-9.5 | +10.1/-8.8 | +31.8/-25.2 | +30.7/-27.8 | +9.6/-8.2 |

**Table 2**. Overview of the $t\bar{t}$ cross-section uncertainties.

In Fig. 1 the number of selected jets and the expectation for 0.70 fb$^{-1}$ are shown for the non-$b$-tag analysis with the five channels combined, and for the $b$-tag analysis with the three channels combined. In the non-$b$-tag case, all requirements except the jet multiplicity selection are applied, and in the $b$-tag case all requirements except the $b$-tag requirement are applied. The $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions for the combination of the five non-$b$-tag and three $b$-tagged channels are shown in Fig. 2. All requirements except $E_{\mathrm{T}}^{\mathrm{miss}}$ are applied. The dominant backgrounds are $Z/\gamma^*$+jets and $W$+jets production with a fake lepton and, for the $b$-tag analysis, single-top events.

The cross-section results are obtained with a profile likelihood technique, as described in Ref. [6]. The branching fraction for $t \to Wb$ is taken to be 100%.

The top-quark pair production cross section measured by combining the seven channels, the non-$b$-tagged $ee$, $\mu\mu$, $e\mu$, $e$TL and $\mu$TL and the exclusive $b$-tagged $ee$ and $\mu\mu$, is

$$\sigma_{t\bar{t}} = 176 \pm 5(\text{stat.})^{+14}_{-11}(\text{syst.}) \pm 8(\text{lumi.})\ \text{pb}.$$

Figure 3 summarizes the cross sections for the individual channels, and the combination of the non-$b$-tag and the exclusive $b$-tagged data sets.

The measured cross section is in good agreement with a similar measurement made with 2010 data by the CMS collaboration [5], with an ATLAS measurement in the dilepton channel with earlier data [6], and with the SM prediction of $165^{+11}_{-16}$ pb. Compared to the earlier ATLAS measurement in the dilepton channel, the statistical uncertainty of the measurement has been reduced by a factor of four with the addition of more data, and a small reduction in the systematic uncertainty, which now dominates, has been achieved.

## 9 Acknowledgements

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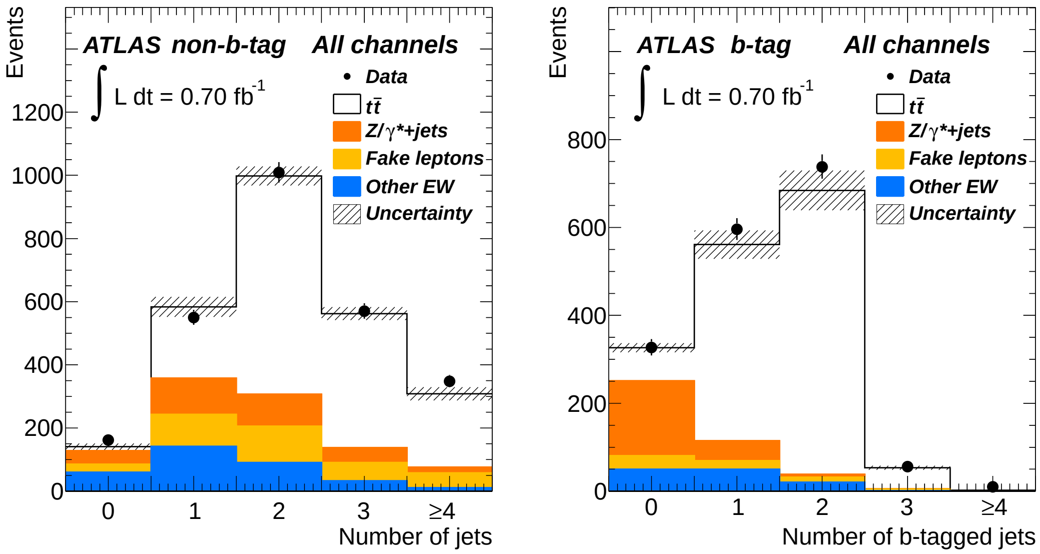


(a)

(b)

**Figure 1**. (a) Jet multiplicity distribution for $ee$+$\mu\mu$+$e\mu$+$e$TL+$\mu$TL events without a $b$-tagging requirement. (b) Multiplicity distribution of $b$-tagged jets in the $ee$+$\mu\mu$+$e\mu$ channels. Contributions from diboson and single top-quark events are summarized as 'Other EW'. The events in (b) are not a simple subset of those in (a) because the event selections for the $b$-tag and non-$b$-tag analyses differ. Uncertainties shown are statistical and systematic combined. The distributions are shown as stacked histograms.

China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

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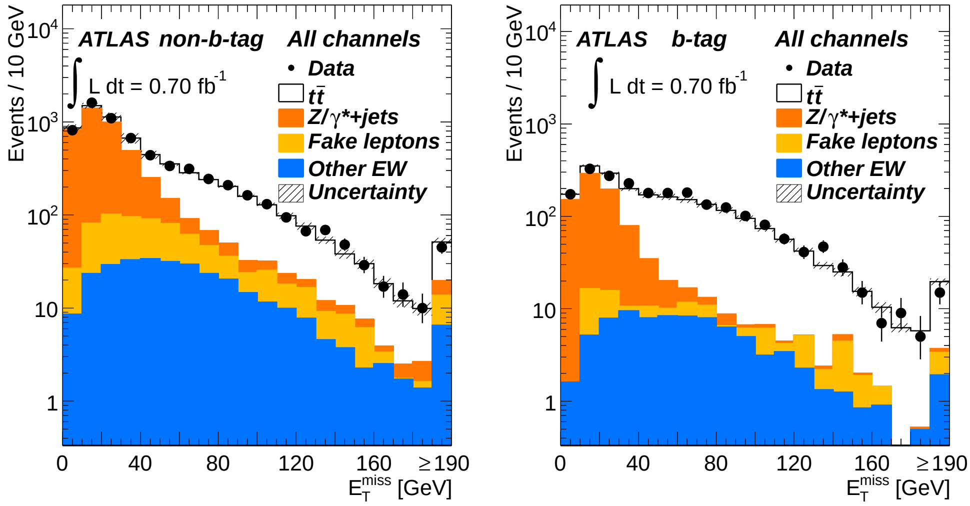


(a) (b)

**Figure 2**. The $E_T^{\rm miss}$ distribution in the signal region for (a) the five non-$b$-tag channels combined and, (b) the three $b$-tagged channels combined. Contributions from diboson and single top-quark events are summarized as ‘Other EW’. Uncertainties shown are statistical and systematic combined. The last bin in each figure is an overflow bin, including all events above 190 GeV. The distributions are shown as stacked histograms.

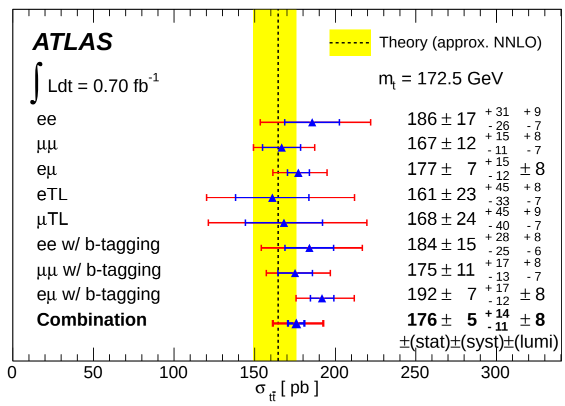


**Figure 3**. Summary of the individual cross section measurements and the combination of non-$b$-tag and exclusive $b$-tagged results. The vertical dashed line and yellow band are the approximate NNLO theory calculation and its uncertainty.

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