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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

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(ATLAS Collaboration)

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A measurement is presented of the $t\bar{t}$ 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 $t\bar{t}$ production cross section was measured to be $260 \pm 1(\text{stat})_{-23}^{+22}(\text{stat}) \pm 8(\text{lumi}) \pm 4(\text{beam}) \text{ pb}$ assuming a top-quark mass of 172.5 GeV, in good agreement with the theoretical prediction of $253_{-15}^{+13} \text{ pb}$. The $t\bar{t} \rightarrow (e, \mu) + \text{jets}$ production cross section in the fiducial region determined by the detector acceptance is also reported.

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I. 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 $pp \rightarrow t\bar{t}$ cross section $\sigma_{t\bar{t}}$ at a center-of-mass energy of $\sqrt{s} = 8$ TeV has been calculated to be $253_{-15}^{+13} \text{ pb}$ 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++ 2.0 [2–7]. In these calculations, the renormalization scale μ_R and factorization scale μ_F were both set equal to m_{top} . The NNLO + NNLL value was found to be about 3% larger than the NNLO-only calculation as implemented in HATHOR 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 μ_R and μ_F by factors of 1/2 and 2, was combined in quadrature

with uncertainties on the coupling strength of the strong interaction, α_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 ℓ) and a corresponding neutrino (including the $W \rightarrow \tau\nu_\tau \rightarrow e\nu_\tau\nu_e$ and $W \rightarrow \tau\nu_\tau \rightarrow \mu\nu_\tau\nu_\mu$ 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^{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

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of new physics that changes the top-quark decay branching fractions, e.g. production of charged Higgs bosons H^+ via $t \rightarrow H^+ b$ 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 $t\bar{t} \rightarrow \ell\nu + \text{jets}$ detector acceptance.

The majority of the events in the selected sample originate from $t\bar{t}$ production. However, events from other SM processes ($W/Z + \text{jets}$, 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. II, followed by descriptions of the data and MC samples used in the analysis (Sec. III). The event selection and the backgrounds are outlined in Sec. IV. The measurement procedure is presented in Sec. V for the inclusive case, and in Sec. VI for the fiducial case. The estimation of the systematic uncertainties is presented in Sec. VII. Finally, the results and conclusions are given in Sec. VIII.

II. 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 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 end cap 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 end cap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimized for electromagnetic and hadronic measurements, respectively.

The muon spectrometer 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 end cap 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.

III. 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- or 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. I.

The dominant background to $t\bar{t}$ production is vector-boson production in association with jets, $V + \text{jets}$ ($V = W, Z/\gamma^*$). 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 $V + 5\text{-light-partons}$ ($2 \rightarrow 7$) production and exclusively for lower multiplicity samples. In addition to $V + \text{light partons}$, the production of vector bosons with additional heavy-flavor partons ($V + c + \text{jets}$, $V + c\bar{c} + \text{jets}$, $V + b\bar{b} + \text{jets}$) was also simulated. Inclusive $V + \text{jets}$ samples were formed by combining the samples of light and heavy quarks according to their respective cross sections. An alternative $W + \text{jets}$ sample simulated with SHERPA [30] with massive b/c quarks was produced to evaluate systematic uncertainties on $W + \text{jets}$ modeling. The $V + \text{jets}$ 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. VII 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).

IV. 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 cluster¹ $|\eta| < 2.47$, excluding the barrel-end cap 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 $\Delta R = 10 \text{ GeV}/p_T^\mu$ around the muon direction (excluding the muon track itself) to the p_T of the muon (p_T^μ). 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 η -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 fraction² 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 (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

¹Unlike 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.

²The 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 .

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: (i) removal of jets matched within $\Delta R = 0.2$ of electrons with $E_T > 25$ GeV; (ii) removal of electrons matched within $\Delta R = 0.4$ of jets with $p_T > 25$ GeV; (iii) rejection of events where the selected electron shares an inner detector track with a selected muon; and (iv) 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.³ 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^{miss} . The value of E_T^{miss} in the $t\bar{t} \rightarrow \ell\nu + \text{jets}$ 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^{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 $m_T(W) = \sqrt{2p_T^\ell p_T^\nu (1 - \cos(\varphi^\ell - \varphi^\nu))}$, where p_T^ℓ , φ^ℓ and p_T^ν , φ^ν refer to the transverse component and φ 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 $e + \text{jets}$ channel and 5.5% in the $\mu + \text{jets}$ 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 $e + \text{jets}$ 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_{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

$$\begin{aligned} N^{\text{tight}} &= N_{\text{real}}^{\text{tight}} + N_{\text{fake}}^{\text{tight}}, \\ N^{\text{loose}} &= N_{\text{real}}^{\text{loose}} + N_{\text{fake}}^{\text{loose}}. \end{aligned}$$

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

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

The probability ϵ_{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 ϵ_{fake} in the $\mu + \text{jets}$ channel was derived for muons with large track d_0 significance.⁴ In the $e + \text{jets}$ channel, ϵ_{fake} was determined in the $E_T^{\text{miss}} < 20$ GeV, $m_T(W) < 20$ 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 η , 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 $[(\epsilon_{\text{real}} - 1)\epsilon_{\text{fake}}/(\epsilon_{\text{real}} - \epsilon_{\text{fake}})]$ for events with tight leptons and $\epsilon_{\text{real}}\epsilon_{\text{fake}}/(\epsilon_{\text{real}} - \epsilon_{\text{fake}})$ 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.

³When the selection is applied to electrons as well as muons, the thresholds refer to p_T for muons and E_T for electrons.

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.

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

Event counts	$e + \text{jets}$	$\mu + \text{jets}$
$t\bar{t}$	123000^{+6000}_{-7000}	152000^{+8000}_{-9000}
$V + \text{jets}$	38000 ± 17000	47000 ± 21000
Single top	12100 ± 600	14900 ± 800
Dibosons	710 ± 40	880 ± 50
Multijets	2800 ± 2400	1500^{+300}_{-1500}
Total	177000^{+18000}_{-19000}	216000 ± 23000
Data	176286	220369

The numbers of observed and expected events are shown in Table I. 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 $V + \text{jets}$ events is evaluated based on a $\pm 4\%$ uncertainty on inclusive $V + \text{jets}$ production and a $\pm 24\%$ uncertainty on each additional jet [49], giving a total uncertainty of $\pm 45\%$ for $V + \text{jets}$ background. This large uncertainty does not have an impact on the final result, since the normalization of the $V + \text{jets}$ background is obtained from the data as described in Sec. V. The uncertainty on the multijet background is evaluated by varying the parameters of the matrix method as described in Sec. VII.

V. 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_i^s to the sum of signal and background likelihood functions $L_i^s + L_i^b$:

$$D_i = \frac{L_i^s}{L_i^s + L_i^b},$$

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 η_ℓ and transformed aplanarity $\mathcal{A}' = \exp(-8\mathcal{A})$. The aplanarity $\mathcal{A}$ is defined as 3/2 times the smallest eigenvalue of the momentum tensor $M_{ij} = \sum_{k=1}^{N_{\text{objects}}} p_{ik} p_{jk} / \sum_{k=1}^{N_{\text{objects}}} p_k^2$, where p_{ik} is the i th momentum component and p_k is the modulus of the momentum of object k . The objects included in the sum are leptons, jets, and E_T^{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 η_ℓ and $\mathcal{A}'$ 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-end cap transition region are excluded and have lower efficiency in the forward region, whereas the efficiency as a function of η_μ 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,

$$\mathbb{L}_j = -\ln L_j = 2 \sum_i (\nu_{ij} - n_{ij} + n_{ij} \ln n_{ij} - n_{ij} \ln \nu_{ij}),$$

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

$$\nu_{ij} = p^{t\bar{t}} s_{ij} + p_j^V b_{ij} + q_{ij},$$

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 $p^{t\bar{t}}$ and p_j^V are the parameters of the fit. The resulting value of the fit parameter $p^{t\bar{t}}$ 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 $\mathbb{L} = \sum_j \mathbb{L}_j$ 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

$$\sigma_{t\bar{t}} = \frac{N_{t\bar{t}}}{\epsilon_{t\bar{t}} \times \mathcal{B} \times \mathcal{L}}, \quad (1)$$

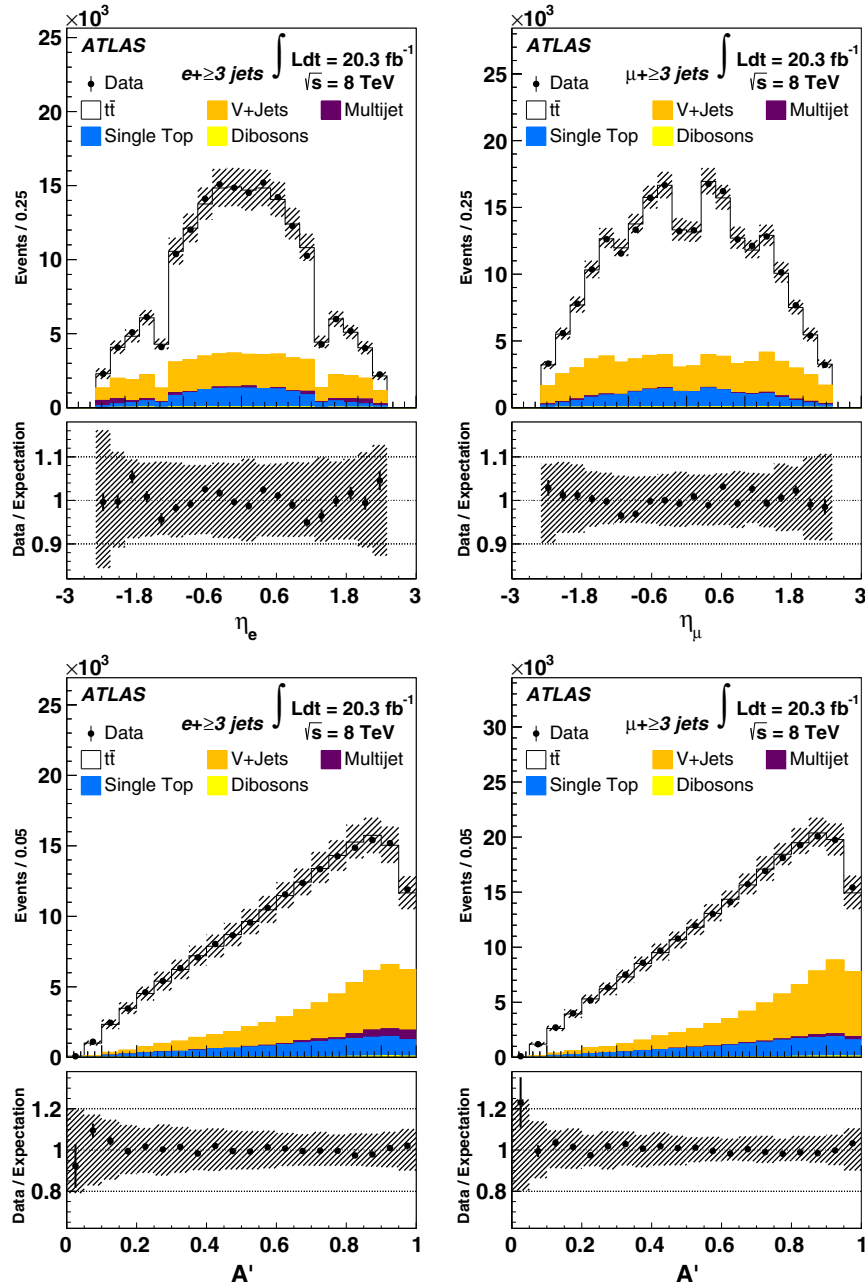


FIG. 1 (color online). Distributions of the lepton pseudorapidity (top) and the modified aplanarity (bottom) in the $e + \text{jets}$ (left) and $\mu + \text{jets}$ (right) channel. The data (dots) are compared to the SM expectation broken down into contributions from $t\bar{t}$, single top, $V + \text{jets}$, 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. VII 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.

where $\varepsilon_{t\bar{t}}$ is the signal-reconstruction efficiency (4.4% in the $e + \text{jets}$ channel and 5.5% in the $\mu + \text{jets}$ channel), $\mathcal{B}$ is the $t\bar{t} \rightarrow \geq 1$ lepton + jets branching ratio, and $\mathcal{L}$ is the total integrated luminosity.

VI. 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 $t \rightarrow Wb \rightarrow \ell \nu b$ decays, either directly or via a leptonically decaying τ , and to have $p_T > 40$ GeV and $|\eta| < 2.5$. The lepton momenta were corrected by

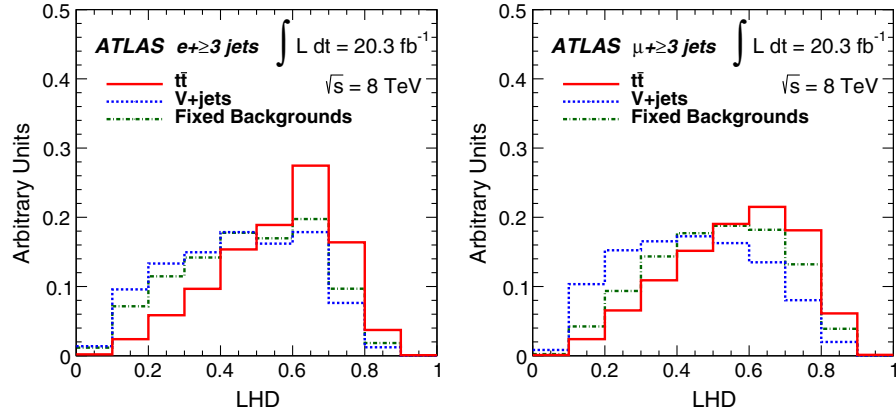


FIG. 2 (color online). The templates of the likelihood discriminant LHD in the $e + \text{jets}$ (left) and $\mu + \text{jets}$ (right) channels for signal, $V + \text{jets}$ background, and fixed backgrounds, which include single top, diboson and multijets background.

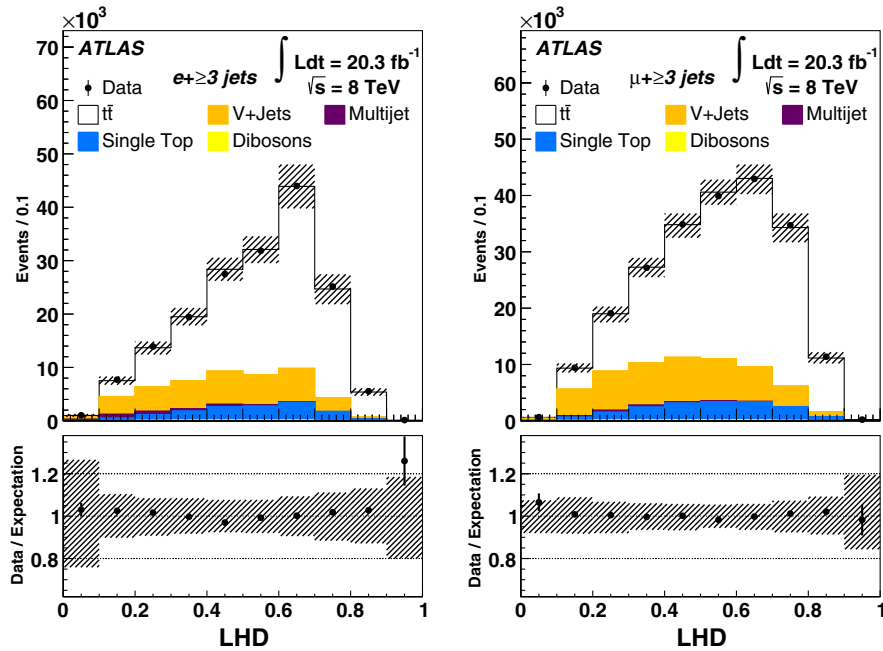


FIG. 3 (color online). Distributions of the likelihood discriminant LHD in the $e + \text{jets}$ (left) and $\mu + \text{jets}$ (right) data and a weighted sum of templates from the $t\bar{t}$ signal and various backgrounds. The contributions from $t\bar{t}$ and $V + \text{jets}$ production are normalized 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.

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

$$\sigma_{t\bar{t}}^{\text{fid}} = \frac{N_{t\bar{t}}^{\text{fid}}}{\epsilon_{t\bar{t}}^{\text{fid}} \times \mathcal{L}}, \quad (2)$$

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, $N_{t\bar{t}}^{\text{fid}}_{\text{reco}}$, to the total number of events passing the particle level selection, $N_{t\bar{t}}^{\text{fid}}$:

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

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

VII. 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 $e + \text{jets}$ 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 propagated to the E_T^{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 η [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 $Z \rightarrow ee/\mu\mu + \text{jets}$ 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^{miss} calculation. The E_T^{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^{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^{miss} measurement is not a significant source of systematic uncertainty (below $\pm 1\%$).

W + 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 + PYTHIA and was found to be small (below 1%) and to partially cancel out when combining the $e + \text{jets}$ and $\mu + \text{jets}$ channels.

W + heavy-flavor composition.—The heavy-flavor composition of $W + \text{jets}$ events was studied using W events with two additional jets split into W^+ and W^- samples.⁵ 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 ≥ 3 -jets, and MC modeling, following the procedure described in Ref. [60]. The uncertainties themselves are very large (about $\pm 50\%$), but the LHD template shapes for W bosons produced in association with different jet flavors are similar and since the normalization of the $W + \text{jets}$ background is derived from a fit to the data, the resulting systematic uncertainty on the $t\bar{t}$ production cross section is small ($\pm 1\%$).

Small backgrounds.—Uncertainties on single top-quark and diboson production were evaluated by varying the relevant theoretical cross sections within their uncertainties $\pm 1\sigma_{\text{theor}}$, which resulted in a $t\bar{t}$ production cross-section uncertainty of the order of $\pm 1\%$. The uncertainty on the multijet contribution was derived from a comparison with results with ϵ_{real} obtained using data control samples with large $m_T(W)$ ($\mu + \text{jets}$) or large E_T^{miss} ($e + \text{jets}$) depleted of fake leptons; the variation of ϵ_{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 I, the uncertainty on the number of multijet events is very large (about $\pm 100\%$), mainly due to uncertainties in ϵ_{fake} , but their fraction in the data sample is small due to the high lepton- p_T requirement, so the overall effect is about $\pm 1\%$.

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 $\pm 4\%$. 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 $\pm 0.1\%$) 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 (Λ_{QCD} , Q_{max}^2 scale, transverse momentum scale for spacelike 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 ($\pm 3\%$) but significantly reduced (below $\pm 1\%$) 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 $\pm 3\%$.

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 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 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

⁵The ratio of W^+ to W^- production cross sections at the LHC is predicted much more precisely than the cross sections themselves [59].

TABLE II. 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.

Uncertainty on inclusive $\sigma_{t\bar{t}}$	$e + \text{jets}$	$\mu + \text{jets}$	$\ell + \text{jets}$
Lepton reconstruction	+2.7 –2.6	+2.1 –1.9	+1.7 –1.6
Jet reconstruction and E_T^{miss}	+3.3 –3.9	+2.6 –3.2	+2.8 –3.4
b tagging	+2.1 –1.9	+2.2 –1.9	+2.1 –1.9
Backgrounds	+2.8 –3.0	+1.8 –2.1	+1.7 –2.1
Monte Carlo generator	–2.2 +2.2	–3.3 +3.3	–2.7 +2.7
Parton shower and fragmentation	+2.0 –2.0	+2.6 –2.6	+2.3 –2.3
Initial- and final-state radiation	–4.1 +4.1	–1.8 +1.8	–3.0 +3.0
Parton distribution functions	+6.2 –6.0	+5.6 –5.9	+5.9 –5.9
Total	+9.7 –9.8	+8.4 –8.7	+8.6 –8.9
Uncertainty on fiducial $\sigma_{t\bar{t}}$	$e + \text{jets}$	$\mu + \text{jets}$	$\ell + \text{jets}$
Monte Carlo generator	–2.1 +2.1	–3.5 +3.5	–2.8 –2.8
Parton shower and fragmentation	–2.6 +2.6	–3.1 +3.1	–2.9 +2.9
Initial- and final-state radiation	+0.4 –0.4	+0.2 –0.2	+0.3 –0.3
Total	+8.9 –9.0	+8.5 –8.8	+8.3 –8.6

luminosity scale derived from beam-separation scans performed in November 2012. By combining the change in $\mathcal{L}$ 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 $\epsilon_{t\bar{t}}$ 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 II.

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

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

$$\mu + \text{jets}: \sigma_{t\bar{t}} = 260 \pm 1(\text{stat})_{-23}^{+22}(\text{syst}) \pm 8(\text{lumi}) \\ \pm 4(\text{beam}) \text{ pb},$$

$$\ell + \text{jets}: \sigma_{t\bar{t}} = 258 \pm 1(\text{stat})_{-23}^{+22}(\text{syst}) \pm 8(\text{lumi}) \\ \pm 4(\text{beam}) \text{ pb},$$

where the four quoted uncertainties are due to the number of events in data (statistical uncertainty), systematic effects (as described in Sec. VII), 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 $(\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}})/\Delta m_{\text{top}} = -1.1\%/\text{GeV}$ in all channels.

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

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

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

$$\ell + \text{jets}: \sigma_{t\bar{t}}^{\text{fid}} = 22.8 \pm 0.1(\text{stat})_{-2.0}^{+1.9}(\text{syst}) \pm 0.7(\text{lumi}) \\ \pm 0.4(\text{beam}) \text{ pb},$$

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 or 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 or 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 $\sigma_{t\bar{t}} = 242.4 \pm 1.7(\text{stat}) \pm 5.5(\text{syst}) \pm 7.5(\text{lumi}) \pm 4(\text{beam})$ pb [15], where the four quoted uncertainties were due to the same sources as above.

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