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DOI
10.1103/PhysRevD.95.072003

Publication date
2017

Document Version
Final published version

Published in
Physical Review D. Particles and Fields

PHYSICAL REVIEW D **95**, 072003 (2017)

Measurement of the $t\bar{t}$ production cross section in the $\tau + \text{jets}$ final state in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector

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(Received 1 March 2017; published 7 April 2017)

A measurement of the inclusive $pp \to t\bar{t} + X$ production cross section in the $\tau + \text{jets}$ final state using only the hadronic decays of the τ lepton is presented. The measurement is performed using 20.2 fb^{-1} of proton-proton collision data recorded at a center-of-mass energy of $\sqrt{s} = 8$ TeV with the ATLAS detector at the Large Hadron Collider. The cross section is measured via a counting experiment by imposing a set of selection criteria on the identification and kinematic variables of the reconstructed particles and jets, and on event kinematic variables and characteristics. The production cross section is measured to be $\sigma_{t\bar{t}} = 239 \pm 29$ pb, which is in agreement with the measurements in other final states and the theoretical predictions at this center-of-mass energy.

DOI: 10.1103/PhysRevD.95.072003

I. INTRODUCTION

An important component of the Large Hadron Collider (LHC) [1] physics program is the measurement of the properties of the top quark, which is the most massive fundamental particle observed to date. With approximately one top-quark pair produced every second, the data sample used in this analysis is significantly larger than previously available samples, allowing for precise measurements of top-quark properties using final states that were previously limited by their statistical uncertainty. This article reports on a measurement of the $t\bar{t}$ production cross section in the $\tau + \text{jets}$ final state, where the hadronic final states of the τ lepton (τ_{had}) are used exclusively. This measurement, which is of comparable precision to the $\mu + \text{jets}$ and $e + \text{jets}$ cross-section measurements by the ATLAS Collaboration [2], provides a cross-check of the $t\bar{t}$ production cross-section measurements in the other final states. In addition, differences between measurements or between measurement and theory could lead to the discovery of non-Standard-Model physics or to limits on its possible extensions. Previous measurements in this final state have been performed by the D0 [3] and CDF [4] collaborations at the Tevatron operating at $\sqrt{s} = 1.96$ TeV and by the ATLAS [5] and CMS [6] collaborations at the LHC operating at $\sqrt{s} = 7$ TeV. Besides the measurement in the $\ell + \text{jets}$ ($\ell = e, \mu, \tau$) final state at $\sqrt{s} = 8$ TeV, the $t\bar{t}$ production cross section has also been measured in the dilepton (e^+e^-, $\mu^+\mu^-$, and $e^\pm\mu^\mp$) final state by the ATLAS and CMS collaborations [7,8]. Since the different channels in which this measurement has been performed have different backgrounds and systematic uncertainties, each measurement serves as a cross-check of the others.

The final state of the process used in this measurement, $t\bar{t} \to \tau + \text{jets}$, includes one top quark decaying as $t \to Wb \to \tau\nu_\tau b$ while the other decays as $t \to Wb \to qq'b$, leading to the final-state topology of one τ lepton, an imbalance of momentum in the plane transverse to the beam axis ($E_{\text{T}}^{\text{miss}}$), and four quark jets with two of these being b-quark jets.

The decay $t \to \tau\nu_\tau b$ provides a unique system in which to investigate the couplings of the third-generation fermions—the top and bottom quarks, the τ lepton, and the τ neutrino ν_τ—in a single process. In the framework of the Standard Model (SM), the branching ratio (BR) of the top quark decaying to a W boson and a b quark is approximately 100%. Hence, the final state is determined by the SM BRs of the W boson, which are well measured [9]. In the SM, electroweak symmetry-breaking introduces mass- and flavor-dependent couplings. Since the top quark is the most massive quark and the τ lepton the most massive lepton, these fermions along with the b quark have the largest Yukawa couplings to the Higgs boson and, hence, could lead to non-SM mass- or flavor-dependent couplings that can change the top-quark decay rate into final states with τ leptons. Therefore, any observed deviation in the BR of $t \to \tau\nu_\tau b$ from that predicted by the SM would be an indication of non-SM physics. For example, in type-2 two-Higgs-doublet models (2HDM) [10], such as required by the minimal supersymmetric Standard Model [11], the top quark can have a significant BR to a charged Higgs boson ($H^\pm$) and a b quark if $m_{H^\pm} < m_{\text{top}} - m_b$. For large values of $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets, the charged Higgs boson preferentially decays to $\tau\nu_\tau$. This thereby increases the BR of $t \to \tau\nu_\tau b$

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relative to the SM prediction and leads to a larger measured value of $\sigma_{t\bar{t}} \times \mathrm{BR}(t\bar{t} \to \tau + \mathrm{jets})$ [12–14]. Small values of $\tan\beta$, however, would decrease the number of $t\bar{t} \to \tau + \mathrm{jets}$ events relative to the SM prediction.

The 2HDM can also produce an excess of $t \to \tau + X$ decays if flavor-changing neutral couplings are allowed as in type-3 models [15,16]. For example, this allows $t \to cH$ and if the Higgs boson decays as $H \to \tau^+\tau^-$, an excess of events with $t \to \tau + X$ decays would be observed relative to the SM. The SM predicts $\mathrm{BR}(t \to cH) \approx 10^{-15}$ [17], whereas type-3 models predict $\mathrm{BR}(t \to cH)$ to be as large as 10^{-3} [17–19].

This article presents an analysis using the $\tau_{\mathrm{had}} + \mathrm{jets}$ final state to measure the $t\bar{t}$ production cross section in $\sqrt{s} = 8$ TeV proton-proton (pp) collisions. The data sample for this measurement was recorded using the ATLAS detector and corresponds to an integrated luminosity of 20.2 fb^{-1}. The ATLAS detector is briefly described in Sec. II. Section III presents the data and simulated event samples used in this measurement. The reconstruction of jets, τ leptons, and missing transverse momentum is discussed in Sec. IV. The event selection is described in Sec. V and the methods used to estimate the backgrounds are discussed in Sec. VI. The calculation of the production cross section is given in Sec. VII and the estimation of the various systematic uncertainties is presented in Sec. VIII. The results of the analysis and the interpretations are discussed in Sec. IX. Finally, the analysis is summarized in Sec. X.

II. ATLAS DETECTOR

The ATLAS detector [20] 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 (ID) is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range $|\eta| < 2.5$, where η is the pseudorapidity of the particle.[1]

The high-granularity silicon pixel detector covers the interaction region and typically provides three position measurements per track. It is followed by the silicon microstrip tracker, which usually provides four two-dimensional measurement points per track. 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 above a higher energy-deposition 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/scintillator-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 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 innermost layer of 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 [21]. 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 that together reduce the event rate to about 400 Hz.

III. DATA AND SIMULATION SAMPLES

The pp collision data sample used in this measurement was collected with the ATLAS detector at the LHC and corresponds to the full 20.2 fb^{-1} of integrated luminosity collected at this energy with the requirement of stable beam conditions and an operational detector.

In order to estimate the effects of detector resolution and acceptance on signal and background, and to estimate the backgrounds, a full GEANT4-based detector simulation is utilized [22,23]. In addition, to estimate the modeling uncertainties of the various physics processes in an efficient manner, a detector simulation using parameterized calorimeter showers is also used [24]. To account for an average of 20.7 interactions per bunch crossing, pp interactions are generated using PYTHIA v8.165 [25,26] and overlaid on the signal and background Monte Carlo (MC) simulation samples in accordance with the average observed number of interactions per bunch crossing. All simulated samples are reconstructed and analyzed with the same algorithms

[1]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

TABLE I. List of the $t\bar{t}$ MC samples used in studying the modeling uncertainties. The PDF set used for all event generators is CT10.

Systematic uncertainty	Generator	Parton shower	Tune set
Nominal	POWHEG	PYTHIA	Perugia 2011C
Parton shower	POWHEG	HERWIG	AUET2
Generator	MC@NLO	HERWIG	AUET2
ISR/FSR	POWHEG	PYTHIA	Perugia 2012 radLo
ISR/FSR	POWHEG	PYTHIA	Perugia 2012 radHi

and techniques as for the recorded pp collision data. Only events with at least one charged lepton (e, μ, τ) in the final state are generated.

To estimate the acceptance of the event selection for $t\bar{t}$ events, several MC samples are generated with the top-quark mass set to $m_{\mathrm{top}} = 172.5$ GeV. The nominal sample is generated using the next-to-leading-order (NLO) matrix element (ME) event generator POWHEG-BOX [27–30] with the CT10 [31] NLO parton distribution functions (PDF). The output of POWHEG-BOX is then processed by PYTHIA v6.426 [25] to perform the parton showering (PS), hadronization, and generation of the underlying event (UE). For the UE generation to agree with data, PYTHIA v6.426 uses the leading-order (LO) CTEQ6L1 PDF set [32] and a set of tuned parameters referred to as the Perugia 2011C tune [33]. To regulate high-p_{T} radiation in POWHEG-BOX and provide ME/PS matching, the resummation damping factor h_{damp} is set to m_{top} [34]. The $t\bar{t}$ sample is normalized using the theoretical production cross section, which for pp collisions at $\sqrt{s} = 8$ TeV is $\sigma_{t\bar{t}} = 253^{+13}_{-15}$ pb assuming a top-quark mass of 172.5 GeV. It has been calculated at next-to-next-to-leading order (NNLO) in α_{S} including resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms with top++2.0 [35–41]. The systematic uncertainty in the cross section due to the uncertainties in the PDF and α_{S} is calculated using the PDF4LHC prescription [42] with the MSTW2008 68% CL NNLO [43,44], CT10 NNLO [31,45], and NNPDF2.3 five flavor number [46] PDF sets and added in quadrature to the uncertainties due to the renormalization and factorization scales.

Systematic uncertainties associated with the $t\bar{t}$ modeling are evaluated using alternative sets of simulated events that are compared to the nominal sample, with the nominal and alternative sets processed using the parameterized detector simulation [24]. Since the choice of the ME event generator can affect the estimate of the acceptance, the ME event generator MC@NLO v4.01 [47] and the PS/UE simulator HERWIG v6.520 [48], with JIMMY v4.31 [49] is compared to the POWHEG-BOX [29] event generator where the PS is simulated by HERWIG+JIMMY. The effect of the PS and hadronization models on the acceptance is investigated by comparing the POWHEG+PYTHIA event generator with $h_{\mathrm{damp}} = \infty$ to the POWHEG+HERWIG event generator. Finally, the effect of initial- and final-state radiation (ISR and FSR) is estimated using two $t\bar{t}$ samples generated in the same manner as the nominal sample, but with the renormalization and factorization scales multiplied by 2.0 (0.5), the regularization parameter h_{damp} set to m_{top} ($2m_{\mathrm{top}}$), and using the Perugia 2012 radLo (radHi) UE tune, giving less (more) radiation. Table I summarizes the samples used to calculate the systematic uncertainties for the $t\bar{t}$ process.

A variety of MC event generators are used to simulate the backgrounds containing charged leptons in the final state, which are summarized in Table II. Vector-boson production with additional jets ($pp \to V + \mathrm{jets}$, with $V = W$, Z and two to seven jets) is simulated using the LO parton-level ME event generator ALPGEN [50] with the PS/UE generated by PYTHIA v6.426, as for the nominal $t\bar{t}$ samples. In order to avoid double counting, final states generated by the LO parton-level event generator ALPGEN and the parton-level shower evolution of PYTHIA, the MLM matching algorithm is used [51]. The matching algorithm is applied inclusively to the $V + 5$ light-parton events and exclusively to the other events. Associated production of vector bosons with heavy-flavor partons ($V + c + \mathrm{jets}$, $V + c\bar{c} + \mathrm{jets}$, $V + b\bar{b} + \mathrm{jets}$) is simulated separately. Inclusive $V + \mathrm{jets}$ samples are formed by combining the light- and heavy-quark samples according to their respective cross section. An overlap removal scheme is used to avoid double counting the contribution of additional heavy flavor partons. The cross sections used to normalize the samples are calculated at NNLO [52,53].

Electroweak production of the top quark (single-top) is simulated using POWHEG-BOX [54] and PYTHIA v6.426 with the CT10 PDF set. The MC sample for the t-channel process is normalized using the NNLO calculation in Ref. [55] while the s-channel sample is normalized with

TABLE II. The matrix element event generators and the parton shower simulators used to generate the MC simulated background events. The parton distribution functions used by the event generators and the set of tuned parameters used in the parton shower simulators are also shown.

Process	Generator	Parton shower	PDF set	Tune set
$W + \mathrm{jets}$	ALPGEN	PYTHIA	CTEQ6L1	Perugia 2011C
$Z + \mathrm{jets}$	ALPGEN	PYTHIA	CTEQ6L1	Perugia 2011C
Single top (Wt-channel)	POWHEG	PYTHIA	CT10	Perugia 2011C
Dibosons (WW, WZ, ZZ)	HERWIG	HERWIG	CTEQ6L1	AUET2B

the NNLO + NNLL cross section in Ref. [56] and the Wt channel is normalized with the NNLO + NNLL calculation in Ref. [57]. In order to remove the overlap with $t\bar{t}$ production, the Wt sample is produced using the "diagram removal" generation scheme [58].

In addition, diboson (WW, WZ) production samples are generated using HERWIG with the CTEQ6L1 PDF set. These samples are normalized using the NLO calculation in Ref. [59].

IV. OBJECT RECONSTRUCTION

The final state in this measurement contains four quark jets of which two are b-quark jets, a W boson decaying to a neutrino and a τ lepton that decays to hadrons (τ_{had}) and a neutrino. Jets are reconstructed using the anti-k_t algorithm [60,61] with the radius parameter set to $R = 0.4$. To account for inhomogeneities and the noncompensating response of the calorimeter, the reconstructed jet energies are corrected through p_{T}- and η-dependent factors that are derived in MC simulation and validated in data. Any remaining discrepancies in the jet energy scale are calibrated using an *in situ* technique where a well-defined reference object is momentum-balanced with a jet [62]. To ensure that jets originate from the vertex that produced the event, the fraction of the scalar p_{T} sum of all tracks matched to the jet and originating at this vertex (jet vertex fraction) to the scalar p_{T} sum of all tracks associated with this jet but originating from any vertex must be > 0.5 for jets with $E_{\text{T}} < 50$ GeV and $|\eta| < 2.4$.

To identify jets initiated by b quarks (b-tagging), a multivariate algorithm is employed [63]. This algorithm uses the impact parameter and reconstructed secondary vertex information of the tracks contained in the jet as input for a neural network. Jets initiated by b quarks are selected by setting the algorithm output threshold such that a 70% selection efficiency is achieved in simulated $t\bar{t}$ events with a 1% misidentification rate for light-flavor jets. Since the b-quark selection efficiency differs between data and MC simulation, p_{T} dependent correction factors are derived to correct for this difference [63]. These correction factors differ from unity by less than 3% over the entire p_{T} range.

Decays of the τ lepton into hadrons and a neutrino are classified as either single prong ($\tau_{\text{1-prong}}$), where the τ lepton decays to a single charged particle, or three prong ($\tau_{\text{3-prong}}$), where the decay products are three charged particles with a net unit charge, and for each classification zero or more π^0 mesons can be present. Identification of a τ_{had} begins with a reconstructed jet, as described above, having $p_{\text{T}} > 10$ GeV and $|\eta| < 2.5$. The τ_{had} classification is achieved by counting the number of tracks with $p_{\text{T}} > 1$ GeV in a cone of size $\Delta R = 0.2$ around the jet axis. To discriminate against quark- or gluon-initiated jets, a set of discriminating variables is used to train a multivariate boosted decision tree (BDT) separately for single-prong and three-prong τ decays using τ_{had} from simulated samples of vector-bosons decaying into τ leptons that cover the kinematic range expected in data and a background sample enriched in dijet events from data [64]. Three categories of discriminating variables are used. The first category comprises those variables that apply to all candidates. These are associated with the jet shape in both the tracking system and calorimeter. The second category are those variables that apply only to the single-prong τ lepton decays. These include the impact parameter significance and the number of tracks in an isolation region ($0.2 < \Delta R < 0.4$) around the jet axis. The third and final category are those that apply to the three-prong τ lepton decays. These variables include the decay length significance in the transverse plane, the invariant mass of the reconstructed tracks, and the maximum track separation (ΔR) from the jet axis. An additional set of variables is used for those τ_{had} containing π^0 mesons. These include the number of π^0 mesons, the invariant mass of the tracks plus π^0 mesons, and the ratio of track plus π^0 p_{T} to the calorimeter energy only measurement. Furthermore, any jet that satisfies $\Delta R < 0.2$ of a τ_{had} is removed. In addition, a BDT that includes discriminating variables against electrons is trained to reduce the electron contamination for the $\tau_{\text{1-prong}}$ candidates. Low p_{T} muons that stop in the calorimeter and overlap with energy deposits from other sources can mimic a τ_{had}. These are characterized by a large fraction of energy deposited in the electromagntic calorimeter and a small ratio of track-p_{T} to calorimeter-E_{T}. Muons that produce large energy deposits in the calorimeter can also be misidentified as a τ_{had}. These are characterized by a small fraction of energy in the electromagnetic calorimeter and a large track-p_{T} to calorimeter-E_{T} ratio. Strict selection requirements based on the two variables described are applied to avoid muons being misidentified as τ_{had}. In addition, the reconstructed four-vector of the τ_{had} candidate is not corrected for the unobserved neutrino kinematics.

Since undetected neutrinos occur in the final state, a momentum imbalance in the transverse plane is expected. The missing transverse momentum ($E_{\text{T}}^{\text{miss}}$) is calculated as the negative of the vector sum of the transverse momentum of all reconstructed objects and of the calorimeter energy deposits not associated to any reconstructed object after the appropriate energy corrections have been applied [65].

V. EVENT SELECTION

Events are selected that satisfy the $E_{\text{T}}^{\text{miss}} > 80$ GeV trigger with an offline reconstruction requirement of $E_{\text{T}}^{\text{miss}} > 150$ GeV. This is the point at which the trigger has almost reached full efficiency. Furthermore, events are required to contain a hard collision primary vertex with at least four associated charged particle tracks of $p_{\text{T}} > 0.4$ GeV. If there are multiple primary vertices in an event, the one with the largest sum of track p_{T}^2 is selected. To reduce contamination from events with

$t\bar{t} \to e(\mu) + \text{jets}$, an event is rejected if it contains an electron ($p_T^e > 25$ GeV) [66] or a muon ($p_T^\mu > 20$ GeV) candidate [67], each with $|\eta| < 2.5$ that satisfy the corresponding selection in the ATLAS $t\bar{t} \to e(\mu) + \text{jets}$ cross-section measurement [2]. The event must also contain at least two jets with $E_T > 25$ GeV and $|\eta| < 2.5$. In addition, at least two of the jets in the event must be identified as b-quark jets using a b-tagging requirement with 70% efficiency. Each event is also required to contain at least one τ_{had} that decays to either one or three charged particles with $E_T > 20$ GeV and $|\eta| < 2.5$ and a τ lepton identification requirement that discriminates against quark and gluon initiated jets such that the efficiency is 40% for single-prong and 35% for three-prong τ_{had} with a rejection factor between 100 and 1000 depending on the p_T and η for each. This identification requirement defines the standard τ_{had} selection. Since the background for $\tau_{\text{1-prong}}$ and $\tau_{\text{3-prong}}$ identification is different, the two samples are analyzed separately with the $\tau_{\text{1-prong}}$ ($\tau_{\text{3-prong}}$) analysis requiring one or more $\tau_{\text{1-prong}}$ ($\tau_{\text{3-prong}}$) only. In each case, the highest-p_T τ_{had} is used with less than 1% of events containing more than a single τ_{had}. The combined result is produced by requiring an event to contain either one or more $\tau_{\text{1-prong}}$ or $\tau_{\text{3-prong}}$ and selecting the highest-p_T τ_{had} in the event. In order to preferentially select events where the τ_{had} and E_T^{miss} originate from W-boson decays, the transverse mass is required to satisfy $m_T < 90$ GeV, where m_T comprises the τ_{had} with the largest p_T and the value of the E_T^{miss} of the event. The square of the transverse mass is defined as $m_T^2 = p_T^{\tau_{\text{had}}} E_T^{\text{miss}}[1 - \cos\Delta\phi(\tau_{\text{had}}, E_T^{\text{miss}})]$ and $\Delta\phi(\tau_{\text{had}}, E_T^{\text{miss}})$ is the azimuthal angle between the direction of the τ_{had} and the E_T^{miss} of the event.

VI. BACKGROUND ESTIMATION

To determine the number of $pp \to t\bar{t} + X \to \tau_{\text{had}} + \text{jets}$ events in the data sample, estimates of the various backgrounds are subtracted. These originate from two sources: the backgrounds with real τ_{had} and those with misidentified τ_{had} in the final state. The backgrounds containing real τ_{had} in the final state include single-top-quark events, $V + \text{jets}$ events, and diboson events. These backgrounds are estimated in simulation and normalized using their theoretical cross sections as discussed in Sec. III. The misidentified (fake) τ_{had} background consists of events from processes where a charged lepton ($e^\pm$ and $\mu^\pm$) is misidentified as a τ_{had} and multijet events that have a mismeasured E_T^{miss} and a quark- or gluon-initiated jet that is misidentified as a τ_{had}.

Misidentification of electrons and muons as τ_{had} is significantly reduced by applying the selection criteria discussed in Sec. IV. The $t\bar{t}$ background where an electron or a muon is misidentified as a τ_{had} is simulated in POWHEG+PYTHIA and normalized using the theoretical $t\bar{t}$ production cross section. The contribution from other processes where an electron or a muon is misidentified as a τ_{had} is found to be negligible.

To estimate the fraction of events in which a jet is misidentified as a τ_{had}, a data-based method is used where this fraction is evaluated in a control sample that is divided into two components: one with the standard τ_{had} selection and the other with an inverted τ_{had} selection. The transfer factor is the ratio of the number of events with misidentified τ_{had} in the nominal sample to that in the inverted sample. This transfer factor, which is referred as the fake-factor FF, is then applied to the signal sample with the inverted τ_{had} selection, which yields the fraction of misidentified τ_{had} in the signal sample with the nominal τ_{had} selection. The inverted τ_{had} selection is determined such that the fraction of quark- and gluon-jets that can be misidentified as a τ_{had} is similar to the fractions when the standard τ_{had} selection is applied, as derived from MC simulation. All other requirements are the same as for the signal sample. This technique, known as the fake-factor method, has been used in previous ATLAS measurements [68].

To ensure a large fraction of events with jets misidentified as τ_{had}, the control sample is required to satisfy a muon trigger with only a single reconstructed muon satisfying the requirement $p_T > 25$ GeV and $|\eta| < 2.5$. In addition, each event is also required to satisfy the following criteria: (1) contain a primary vertex with at least four associated tracks, (2) contain at least two jets and no jet in the event satisfying the b-jet criteria, and (3) contain a single τ_{had} satisfying selection criteria that are less restrictive than the nominal. The control sample is then separated into a component satisfying the standard τ_{had} identification and a second component that satisfies the inverted identification criteria. This set of selections ensures that the control sample is enriched with misidentified τ_{had} for both the standard and the inverted τ_{had} identification criteria. The number of data events selected with the standard τ_{had} identification is 28 397, where the contribution from real τ_{had} is 38% as estimated from simulation. For the inverted τ_{had} identification, the number of data events is 84 975 with a contribution of 9% from real τ_{had}. The transfer factor is calculated in bins of p_T and η after the real τ_{had} contributions are subtracted. The FF averaged over the full kinematic range of this measurement has a value of $0.23 \pm 0.01(\text{stat})$.

To extract the number of misidentified τ_{had} in the signal sample, the nominal selection with the inverted τ_{had} identification is applied to data. To correct for real τ_{had} in this sample, an estimate of the number of real τ_{had} is derived from simulation and subtracted from this sample. Next, the derived FF is applied to the resulting data sample according to the p_T and η of the selected τ_{had} taking into account the number of τ_{had} in the event. This yields the number of misidentified τ_{had} in the signal sample.

In order to validate this procedure, the derived FF is applied to a data set that does not overlap with the nominal

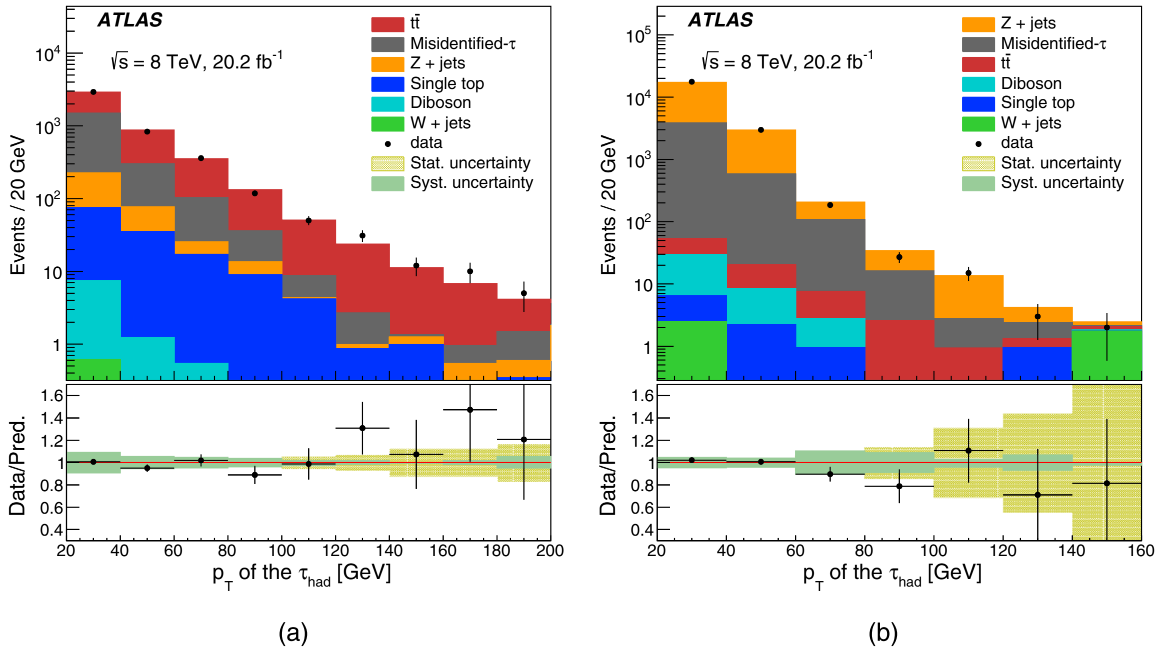

FIG. 1. The transverse momentum distribution of the τ_{had}: (a) in the $t\bar{t} \to \mu\tau + X$ sample dominated by misidentified τ_{had}, and (b) in the $Z \to \tau\tau \to \mu\tau + X$ sample dominated by real τ_{had}. The lower portion of each plot shows the ratio of the data over prediction, illustrating the level of agreement achieved between the data and the predicted backgrounds including the estimated number of misidentified τ_{had}.

analysis sample. Each event in the sample is required to satisfy a single-muon trigger and contain only one reconstructed muon of $p_{\mathrm{T}} > 25$ GeV. In addition, a single τ_{had} satisfying the same criteria as the signal sample is required. The validation is performed for different jet multiplicities and numbers of b-quark jets by dividing the sample into the following six categories: (1) two inclusive jets; (2) three inclusive jets; (3) four inclusive jets; with each listed jet multiplicity containing either zero b-quark jets or at least one b-quark jet. Good agreement between the data and the background estimate is seen in all categories. An additional validation sample that is dominated by real τ_{had} is formed by selecting $Z \to \tau^+\tau^-$ events, where one τ lepton decays to a final state containing a μ and the other containing hadrons. This sample is selected by requiring: (1) $\cos\Delta\phi(\mu, E_{\mathrm{T}}^{\mathrm{miss}}) + \cos\Delta\phi(\tau_{\mathrm{had}}, E_{\mathrm{T}}^{\mathrm{miss}}) > -0.15$; (2) $\Delta\phi(\mu, \tau_{\mathrm{had}}) > 2.4$; (3) $m_{\mathrm{T}}^{\mu} < 50$ GeV, where m_{T}^{μ} is the transverse mass of the μ and the $E_{\mathrm{T}}^{\mathrm{miss}}$ of the event; (4) $(42 < m(\mu, \tau_{\mathrm{had}}) < 82)$ GeV, the invariant mass of the μ-τ_{had} system; (5) $(25 < p_{\mathrm{T}}^{\mu} < 40)$ GeV. Figure 1 shows an example of a comparison between the data and the prediction for regions dominated by misidentified and real τ_{had}.

VII. EXTRACTION OF THE $t\bar{t}$ PRODUCTION CROSS SECTION

In order to determine the $t\bar{t}$ cross section, the estimated background, given in Table III, is subtracted from the number of recorded events after the event selection is applied, then normalized to the integrated luminosity $\int \mathcal{L}(t)dt$ and corrected by the efficiency $\epsilon_{t\bar{t}} = 5 \times 10^{-4}$, which is calculated from the fraction of events satisfying the geometric, kinematic, trigger, and object identification selection, and the effects of the detector reconstruction. Therefore, the cross section is given as

$$\sigma(pp \to t\bar{t} + X) = \frac{N_{\mathrm{data}} - N_{\mathrm{bkg}}}{\mathrm{BR} \times \epsilon_{t\bar{t}} \times \int \mathcal{L}(t)dt}. \qquad (1)$$

Furthermore, since the calculated efficiency corresponds to all $t\bar{t}$ final states containing leptons only, the $\mathrm{BR}(t\bar{t} \to \ell + X) = 0.54$ is used. The number of background events (N_{bkg}) comprises backgrounds with real τ_{had} that are estimated from the simulated samples and events containing a misidentified τ_{had} that is estimated using the fake-factor method discussed in Sec. VI. As also discussed in Sec. VI, to estimate the number of misidentified τ_{had}, the real τ_{had} contribution must be subtracted including those from $t\bar{t}$ events. Since this would require the use of the $t\bar{t}$ cross section, which is the quantity being measured, Eq. (1) is reformulated as

$$\sigma(pp \to t\bar{t} + X) = \frac{N_{\mathrm{data}} - N_{\mathrm{bkg\text{-}non}t\bar{t}}}{\mathrm{BR} \times (\epsilon_{t\bar{t}} - \epsilon_{\mathrm{FF}-t\bar{t}}) \times \int \mathcal{L}(t)dt}, \qquad (2)$$

where $N_{\mathrm{bkg\text{-}non}t\bar{t}}$ represents the backgrounds estimated from the simulated samples and the misidentified τ_{had} component estimated using the fake-factor method but excludes the subtraction of the $t\bar{t}$ component. The efficiency $\epsilon_{\text{FF-}t\bar{t}} = 7 \times 10^{-5}$ represents $t\bar{t}$ events satisfying the inverted τ_{had} identification.

VIII. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties are grouped into those pertaining to object identification along with its energy and momentum measurement, theoretical modeling, background evaluation, and the luminosity. The systematic uncertainties are evaluated by performing a variation of each parameter related to the associated quantity and propagating the overall uncertainty to the cross section assuming that the individual uncertainties are uncorrelated. The procedures and results for the individual quantities considered are summarized below. The systematic uncertainties are calculated for the $\tau_{\text{1-prong}}$, $\tau_{\text{3-prong}}$, and the combined τ_{had} analyses separately, with the resulting values given in Table IV.

The uncertainty in the cross section due to jet reconstruction is split into three components: the jet energy scale, its energy resolution, and its reconstruction efficiency. The uncertainty from the jet energy scale is calculated by varying the jet energies according to the uncertainties derived from simulation and the *in situ* calibration using a model containing 22 independent components [62]. The difference between the jet energy resolution in data and MC simulated events is evaluated by smearing the jet p_{T} in the MC sample according to the measured jet resolution in bins of η and p_{T} [69]. The uncertainty in the jet reconstruction efficiency is evaluated by randomly removing jets according to the difference in data and MC jet reconstruction efficiencies [62]. The variation in the jet energies is also propagated to the $E_{\text{T}}^{\text{miss}}$ calculation.

In the nominal analysis, the b-tagging efficiency in simulation is corrected to agree with data by using p_{T}- and η-dependent correction factors. The uncertainty in the correction factors is obtained independently for b-jets, c-jets, and light-flavor jets assuming that they are uncorrelated. The uncertainties of the inefficiency correction factors that are applied when a jet is not tagged are treated as fully anticorrelated with the corresponding efficiency correction factor [63]. This uncertainty is propagated to the cross section by varying the correction factors by one standard deviation with respect to the central value.

As in b-tagging, correction factors are used to correct for the difference in the τ_{had}-tagging efficiency and the τ_{had} electron veto efficiency between data and simulation. The uncertainties in the correction factors depend on p_{T}, η, and the τ_{had} identification criteria. In addition, the τ_{had} energy scale can affect the final result due to the τ_{had} p_{T} requirement. The energy of the τ_{had} is calculated using MC simulation to correct the observed energy to the true energy scale [64]. Additional small data-based corrections are then applied. The uncertainties due to each of these effects are propagated to the cross section by varying the correction factors by one standard deviation.

The systematic uncertainty of $E_{\text{T}}^{\text{miss}}$ is evaluated along with the systematic uncertainty of the associated energy and momentum of the reconstructed objects as discussed above. Not included in that calculation are the contributions from low-p_{T} jets and energy deposits in the calorimeter cells not associated with a reconstructed object. This source of uncertainty is evaluated using the difference between

TABLE IV. Relative percent uncertainties in the measured cross section in the $\tau_{\text{1-prong}}$, $\tau_{\text{3-prong}}$ and combined $\tau_{\text{1-prong}}$ and $\tau_{\text{3-prong}}$ (τ_{had}) final states. In the $\tau_{\text{1-prong}}$ ($\tau_{\text{3-prong}}$) analysis, all τ_{had} in the event are required to be $\tau_{\text{1-prong}}$ ($\tau_{\text{3-prong}}$). For the combined analysis, the τ_{had} in an event could be of either type.

Uncertainty	$\tau_{\text{1-prong}}$	$\tau_{\text{3-prong}}$	τ_{had}
Total Systematic	−11 / + 11	−16 / + 14	−12 / + 12
Jet energy scale	−4.0 / + 4.2	−8.4 / + 5.7	−5.0 / + 4.5
b-tag efficiency	−4.7 / + 5.0	−4.8 / + 5.0	−4.7 / + 5.0
c-mistag efficiency	−1.6 / + 1.6	−1.5 / + 1.5	−1.6 / + 1.6
Light-jet mistag efficiency	−0.3 / + 0.3	−0.5 / + 0.5	−0.4 / + 0.4
$E_{\text{T}}^{\text{miss}}$	−0.3 / + 0.5	−1.7 / + 0.5	−0.6 / + 0.4
τ_{had} identification	−3.5 / + 3.4	−6.0 / + 5.6	−4.1 / + 3.9
τ_{had} energy scale	−2.1 / + 2.0	−1.2 / + 1.4	−1.9 / + 1.9
Jet vertex fraction	−0.1 / + 0.3	−0.3 / + 0.3	−0.2 / + 0.3
Jet energy resolution	−1.4 / + 1.4	−0.2 / + 0.2	−1.1 / + 1.1
Generator	−1.5 / + 1.5	−2.5 / + 2.5	−2.1 / + 2.1
Parton Shower	−2.0 / + 2.0	−2.6 / + 2.6	−2.1 / + 2.1
ISR/FSR	−6.2 / + 6.2	−8.5 / + 8.5	−6.7 / + 6.7
Misidentified-τ_{had} background	−1.3 / + 1.4	−2.0 / + 2.2	−1.6 / + 1.6
W + jets background	−2.9 / + 2.9	−3.6 / + 3.6	−3.0 / + 3.0
Statistics	−2.2 / + 2.2	−5.6 / + 5.6	−1.7 / + 1.7
Luminosity	−2.3 / + 2.3	−2.3 / + 2.3	−2.3 / + 2.3

TABLE III. The number of events observed in data and obtained from simulation along with the associated statistical uncertainty for background and expected signal processes for the different τ_{had} types and the combined sample. The $\tau_{\text{1-prong}}$ ($\tau_{\text{3-prong}}$) samples require all τ_{had} in an event to be of that type, while the combined sample can have either τ_{had} type.

Event counts	$\tau_{\text{1-prong}}$	$\tau_{\text{3-prong}}$	τ_{had}
$t\bar{t} \to e/\mu$ + jets	21.8 ± 4.7	6.8 ± 2.5	28.3 ± 5.3
Single top	107 ± 10	33.9 ± 5.8	141 ± 12
W + jets	71.7 ± 8.5	27.1 ± 5.2	99 ± 10
Z + jets	7.2 ± 2.7	1.6 ± 1.3	8.7 ± 3.0
Diboson	1.0 ± 1.0	0.4 ± 0.6	1.5 ± 1.2
Misidentified-τ_{had}	46.6 ± 6.8	24.9 ± 5.0	74.9 ± 8.7
Expected $t\bar{t} \to \tau$ + jets	1084 ± 33	312 ± 18	1398 ± 37
Total Expected	1339 ± 37	407 ± 20	1751 ± 42
Data	1278	395	1678

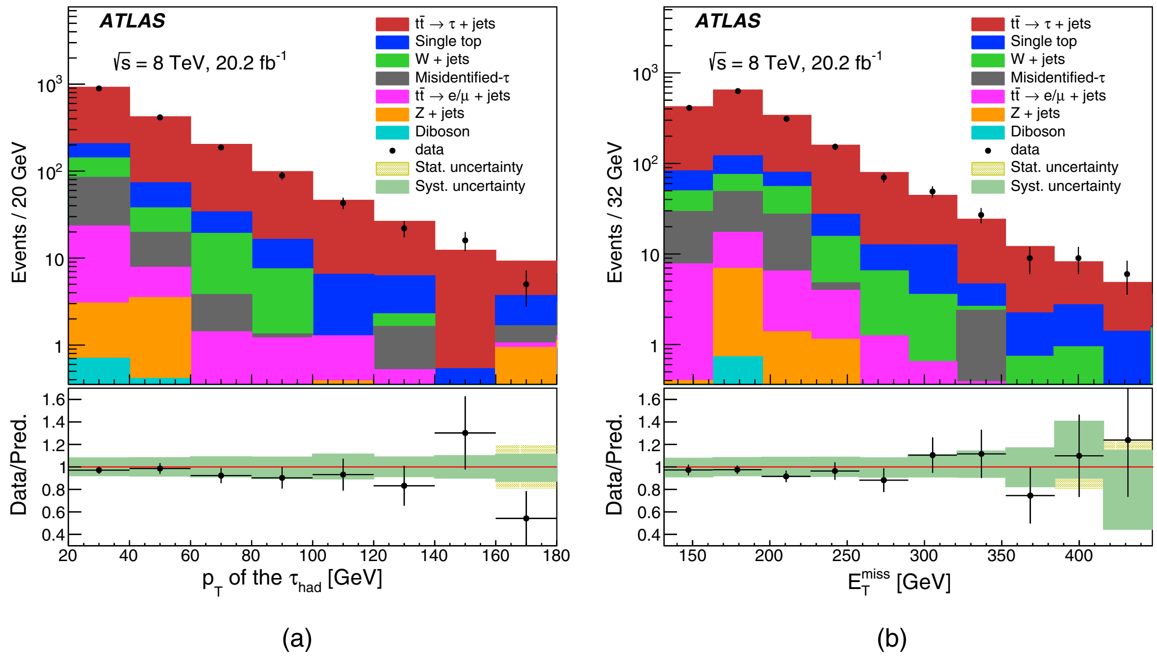

FIG. 2. The distribution of the (a) p_T of the τ_{had} having highest transverse momentum in the event and (b) the missing transverse momentum, E_T^{miss}. The observed data are compared to the predictions.

data and simulated $Z \to \mu^+\mu^-$ events containing no jets, which is similar to the procedure used in Ref. [65].

The systematic uncertainty due to $t\bar{t}$ modeling is split into two components. The first is that associated with the choice of ME event generator and PS/UE event simulation. The uncertainty associated with the choice of ME event generator is estimated by comparing the acceptance from the MC@NLO event generator with that from the POWHEG-BOX event generator. Events from both event generators are processed through the PS/UE simulator HERWIG+JIMMY. The uncertainty due to the PS on the acceptance is estimated by comparing the POWHEG+PYTHIA event generator to the POWHEG+HERWIG event generator. The second component of the modeling uncertainty corresponds to the effect of ISR and FSR on the event selection due to possible extra jets and changes in the kinematics of the final-state particles and jets. The nominal $t\bar{t}$ sample is compared to samples with variations of the renormalization and factorization scales and the regularization parameter as described in Sec. III.

The systematic uncertainties due to the various backgrounds that contain real τ_{had}, are derived using the MC samples described in Sec. III and the uncertainties of the theoretical cross sections. The two largest sources of real τ_{had} backgrounds are single-top and $W+$jets events. All other background contributions to the systematic uncertainty are negligible. For single-top, the uncertainty in the cross section of the MC sample is varied by one standard deviation and propagated to the cross section. For the $W+$jets background, the same procedure is followed but is validated using a method based on the W-boson charge asymmetry in data as described in Refs. [70–72], which gives agreement with the estimation based on the theoretical uncertainty.

To estimate the systematic uncertainty in the number of misidentified τ_{had}, the effect of variations of the main components of this analysis are examined. The main components are: (1) the MC-based background subtraction of the real τ_{had}, (2) uncertainty in the flavor dependence of the FF, (3) uncertainty associated with the η-p_T binning of the FF. In calculating the FF, the largest contribution from real τ_{had} is from $Z+$jets events, as the final state $Z \to \tau^+\tau^- \to \tau_{had}\mu + X$ satisfies the selection. To estimate this component of the uncertainty, the $Z+$jets cross section is varied by ± 1 standard deviation. This variation leads to an average uncertainty of 5% over the p_T-η range for this component of the FF. The FF is calculated in a sample dominated by light-flavor jets. To estimate the systematic uncertainty of the flavor composition, the FF is also derived in a gluon-jet-dominated sample with four jets and low E_T^{miss}. Using this sample the FF is calculated and applied to the signal sample, resulting in an uncertainty of 20% in the number of misidentified τ_{had} events. Since the FF is calculated in p_T-η bins, the bin size is also varied to estimate the uncertainty in the final result. The uncertainty in the final result is found to be approximately 5% of the calculated number of misidentified τ_{had} events.

The absolute luminosity scale is derived from beam-separation scans performed in November 2012. From the calibration of the absolute luminosity scale, the uncertainty in the total integrated luminosity is evaluated following the procedure described in Ref. [73] and is found to be 1.9%.

This uncertainty is then propagated to the cross-section measurements yielding a 2.3% uncertainty, which is reported independent of the other systematic uncertainties.

IX. RESULTS AND INTERPRETATION

The number of events observed for each τ_{had} type and for the combined analysis are reported in Table III along with the predicted number of background events. The uncertainties associated with the cross-section measurement from each of the different sources are reported in Table IV. Figure 2 shows the kinematic distributions of the predicted background and signal processes with the observed data superimposed, where the signal-to-background ratio is approximately 4:1.

The cross sections for each τ_{had} type measured separately are

$$\sigma_{t\bar{t}}(\tau_{1\text{-prong}}+\text{jets}) = 237 \pm 5(\text{stat}) \pm 26(\text{syst}) \pm 5(\text{lumi})\ \text{pb},$$
$$\sigma_{t\bar{t}}(\tau_{3\text{-prong}}+\text{jets}) = 243 \pm 14(\text{stat})^{+34}_{-38}(\text{syst}) \pm 6(\text{lumi})\ \text{pb},$$

and the cross section for the combined analysis is

$$\sigma_{t\bar{t}} = 239 \pm 4(\text{stat}) \pm 28(\text{syst}) \pm 5(\text{lumi})\ \text{pb}.$$

The combined cross section has an uncertainty of 12% and is in agreement with the previous measurements of the ATLAS Collaboration for the $e+\text{jets}$ and $\mu+\text{jets}$ final states [2]. Since the analysis is performed at a fixed top-quark mass, samples are generated at various masses to study the dependence of the measured cross section on m_{top}. The variation is found to be $(\Delta\sigma/\sigma)/\Delta m_{\mathrm{top}} = -2.6\%\ \mathrm{GeV}^{-1}$.

In order to quantify the compatibility of this result with the SM and explore the allowed range for non-SM processes, a frequentist significance test using a background-only hypothesis is used to compare the observed number of events with the SM prediction. In this procedure, the $t\bar{t} \to \tau + X$ process is considered a background and estimated according to the SM prediction taking into account the corresponding uncertainty. This statistical analysis is also used to derive a limit in a model-independent manner on possible beyond-the-SM (BSM) physics. A confidence level for the background-only hypothesis (CL_b) of 0.48 corresponding to a p-value of 0.52 is observed, which indicates good agreement between the observed data and the SM processes. An upper limit at 95% confidence level (CL) on the number of BSM events is derived using the CL_s likelihood ratio method described in Ref. [74]. The upper limit is calculated with the observed number of events, the expected background, and the background uncertainty. Dividing the upper limits on the number of BSM events by the integrated luminosity of the data sample, the resulting value can be interpreted as the upper limit on the visible BSM cross section, $\sigma_{\mathrm{vis}} = \sigma \times \epsilon$, where σ (ϵ) is the production cross section (efficiency) for the BSM process. Table V summarizes the observed number of events, the estimated SM background yield, and the expected and observed upper limits on the event yields and on the σ_{vis} from any BSM process. The efficiency for each SM process used to calculate this limit is reported in Table VI.

Using the same data sample as the cross-section measurement, an upper limit on the flavor changing process $t \to qH \to q\tau^+\tau^-$ is set by performing a modified analysis and then calculating a limit in a manner that is similar to that of the model-independent limit. In the modified analysis, exactly one identified b-jet and two τ_{had} are required. Performing the same statistical analysis as for the cross-section measurement, a 95% CL observed (expected) upper limit of 0.6% (0.9%) is set on the $\mathrm{BR}(t \to qH) \times \mathrm{BR}(H \to \tau\tau)$. At present, this is the only analysis that can explore the channel $t \to qH \to q\tau\tau$ and, hence, is the first search using the $H \to \tau\tau$ final state. Assuming the SM $\mathrm{BR}(H \to \tau\tau) = 6\%$, the 95% CL observed (expected) upper limit set on the $\mathrm{BR}(t \to qH)$ is 10% (15%). A dedicated ATLAS measurement achieves a 95% CL upper limit of 0.45% on the $\mathrm{BR}(t \to qH)$ in the combination of Higgs boson final states $H \to bb$, $H \to \gamma\gamma$ and $H \to \text{multilepton}(e, \mu)$ [75].

TABLE V. Limits on possible BSM events in this sample. Top to bottom: Number of observed events, expected SM processes yield, 95% CL observed (expected) upper limits on the number of BSM events and the visible cross section ($\langle\epsilon\sigma\rangle^{95}_{\mathrm{obs(exp)}}$).

Observed data	1678
Expected SM background	1751 ± 42
$S^{95}_{\mathrm{obs(exp)}}$	$446\ (444^{+40}_{-21})$
$\langle\epsilon\sigma\rangle^{95}_{\mathrm{obs(exp)}}$ [fb]	$22\ (22^{+2}_{-1})$

TABLE VI. The efficiency for each SM process estimated in simulation.

Process	Efficiency (ϵ)
$t\bar{t} \to \tau + \text{jets}$	5.0×10^{-4}
$t\bar{t} \to e/\mu + \text{jets}$	1.0×10^{-5}
Single top	1.6×10^{-4}
$W + \text{jets}$	3.7×10^{-7}
$Z + \text{jets}$	2.4×10^{-7}
Diboson	2.8×10^{-6}

X. SUMMARY

A measurement of the $pp \to t\bar{t} + X$ cross section at $\sqrt{s} = 8$ TeV using 20.2 fb^{-1} of integrated luminosity collected with the ATLAS detector has been performed in the $t\bar{t} \to \tau\nu_\tau q\bar{q}'b\bar{b}$ final state using hadronic decays of the τ lepton. The cross section is measured separately for hadronic decays of the τ lepton into one or three charged particles. A single analysis using a combination of both decay modes is also performed. The cross section measured in the single analysis is $\sigma_{t\bar{t}} = 239 \pm 4(\mathrm{stat}) \pm 28(\mathrm{syst}) \pm 5(\mathrm{lumi})$ pb, assuming a top-quark mass of $m_{\mathrm{top}} = 172.5$ GeV. The measured cross section is in agreement with the SM prediction of 253^{+13}_{-15} pb. A statistical analysis is performed to check the consistency of the observed number of events in data with the predicted number of events from various SM processes. Following a frequentist approach, the confidence level observed with the SM-only hypothesis is 0.48 and the calculated p-value is 0.52, which indicates good agreement of the SM prediction with the observed data. A model-independent upper limit on the visible cross section for any non-SM process is also calculated. The observed (expected) upper limit at 95% confidence level on the visible cross section of any non-SM processes is $22(22^{+2}_{-1})$ fb.

ACKNOWLEDGMENTS

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [76].

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