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Measurement of the top quark pair production cross section in pp collisions at $\sqrt{s}=7$ TeV in dilepton final states with ATLAS ☆

ATLAS Collaboration *

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ABSTRACT

A measurement of the production cross section of top quark pairs ($t\bar{t}$) in proton–proton collisions at a center-of-mass energy of 7 TeV recorded with the ATLAS detector at the Large Hadron Collider is reported. Candidate events are selected in the dilepton topology with large missing transverse energy and at least two jets. Using a data sample corresponding to an integrated luminosity of 35 pb^{-1}, a $t\bar{t}$ production cross section $\sigma_{t\bar{t}} = 177 \pm 20(\text{stat.}) \pm 14(\text{syst.}) \pm 7(\text{lum.})$ pb is measured for an assumed top quark mass of $m_t = 172.5$ GeV. A second measurement requiring at least one jet identified as coming from a b quark yields a comparable result, demonstrating that the dilepton final states are consistent with being accompanied by b-quark jets. These measurements are in good agreement with Standard Model predictions.

1. Introduction

The study of top quarks probes the validity of the Standard Model (SM) and plays an important role in the search for new physics. At the Large Hadron Collider (LHC) the $t\bar{t}$ production cross section ($\sigma_{t\bar{t}}$) in proton–proton (pp) collisions at a center-of-mass energy $\sqrt{s}=7$ TeV is predicted by an approximate next-to-next-to-leading-order (NNLO) SM calculation to be 165^{+11}_{-16} pb [1,2]. A measurement of $\sigma_{t\bar{t}}$ in various decay channels tests perturbative QCD and the description of top quark decay. Moreover, $t\bar{t}$ production is an important background in searches for the Higgs boson and physics beyond the Standard Model. The study of $t\bar{t}$ events may provide evidence for new physics that modifies the production and/or decay of top quarks.

In the SM the top quark decays to a W boson and a b quark ($t \to Wb$) with a branching ratio close to 100% [3–5]. The $t\bar{t}$ event topologies are determined by the decays of the two W bosons: a pair of quarks ($W \to qq'$) or a lepton–neutrino pair ($W \to \ell\nu_\ell$), where ℓ refers to an electron, muon or tau lepton and ν_ℓ is the corresponding neutrino. Top quark production in dilepton final states has been previously studied using proton–antiproton collisions at $\sqrt{s}=1.96$ TeV [6,7] and LHC measurements have recently been reported in several final states [8,9]. In this Letter, we present a measurement of the $t\bar{t}$ production cross section using the dilepton channel, in which both W bosons decay to leptons. A selected event should exhibit two opposite-sign leptons, unbalanced transverse momentum indicating the presence of neutrinos from the W-boson decays and two b-quark jets. The measurement is performed with ten times more data than the previous ATLAS observation of $t\bar{t}$ production [9].

The $t\bar{t}$ dilepton final states can be efficiently selected using kinematic requirements on the final state objects. To further reduce backgrounds and verify that the dilepton final states are accompanied by b-quark jets, a separate measurement is performed requiring the presence of a jet identified as coming from a b quark and relaxing the kinematic selection. Both cross section measurements are reported in this Letter. Leptons are either well-identified electron or muon candidates or, to reduce losses from lepton identification inefficiencies, isolated tracks (referred to as track-lepton candidates). Selected events have either two well-identified lepton candidates (ee, $\mu\mu$ and $e\mu$), or one well-identified lepton candidate and one track-lepton candidate (eTL and μTL), together creating five separate dilepton channels. Each selected dilepton channel is exclusive, i.e. has no overlap with the other channels. Tau leptons are not explicitly reconstructed, but reconstructed leptons can arise from leptonic tau decays and a track-lepton can arise from all one-prong tau decay modes.

The number of candidate events in the selected sample is corrected for background contributions from $Z/\gamma^* +$ jets, single top and diboson production, and from events with misidentified lepton candidates. The cross section is measured taking into account the $t\bar{t}$ signal acceptance. The primary background contributions are estimated using complementary data samples to reduce the uncertainties associated with the simulation and theoretical calculations of background rates.

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* E-mail address: atlas.publications@cern.ch.

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2. Detector and data sample

The ATLAS detector [10] at the LHC covers nearly the entire solid angle[1] around the collision point. It consists of an inner tracking detector (ID) comprising a silicon pixel detector, a silicon microstrip detector (SCT), and a transition radiation tracker, providing tracking capability within $|\eta| < 2.5$. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field, and by liquid-argon (LAr) electromagnetic sampling calorimeters with high granularity. An iron-scintillator tile calorimeter provides hadronic energy measurements in the central rapidity range ($|\eta| < 1.7$). The end-cap and forward regions are instrumented with LAr calorimetry for both electromagnetic and hadronic energy measurements up to $|\eta| < 4.9$. The calorimeter system is surrounded by a muon spectrometer incorporating three superconducting toroid magnet assemblies.

A three-level trigger system is used to select the high-p_T events for this analysis. The level-1 trigger is implemented in hardware and uses a subset of the detector information to reduce the 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 200 Hz. The analyses use collision data with a center-of-mass energy of $\sqrt{s} = 7$ TeV recorded in 2010 with an integrated luminosity of 35.3 ± 1.2 pb^{-1} [11].

3. Simulated samples

Monte Carlo (MC) simulation samples are used to calculate the $t\bar{t}$ acceptance and to evaluate the contributions from those background processes that are difficult to estimate from complementary data samples. All MC samples are processed with the GEANT4 [12] simulation of the ATLAS detector [13] and events are passed through the same analysis chain as the data.

The generation of $t\bar{t}$ and single top quark events uses the MC@NLO generator [14–16] with the CTEQ6.6 [17] parton distribution function (PDF) set and a top quark mass of 172.5 GeV. The $t\bar{t}$ cross section is normalized to the prediction of HATHOR [18] that employs an approximate NNLO perturbative QCD calculation. Single top quark production with MC@NLO includes the s, t and Wt channels, and the diagram-removal scheme [19] is used to reduce overlap with the $t\bar{t}$ final state.

Drell–Yan events ($Z/\gamma^* +$ jets) are modeled with the ALPGEN generator using the MLM matching scheme [20] and the CTEQ6L1 [21] PDF set. The $Z/\gamma^* +$ jets samples, including light and heavy flavor jets, are normalized to NNLO calculations from the FEWZ program [22] with a K-factor of 1.25. Background contributions from the $W +$ jets final states come primarily from events where the W boson decays leptonically and the second lepton candidate is a misidentified jet. They are estimated using auxiliary data samples. All MC simulated events are hadronized using the HERWIG shower model [23,24] supplemented by the JIMMY underlying event model [25]. Both hadronization programs are tuned to data using the ATLAS MC10 tune [26]. Diboson WW, WZ and ZZ events are modeled using the ALPGEN generator normalized with K-factors of 1.26 (WW), 1.28 (WZ) and 1.30 (ZZ) to match the total cross section from NLO QCD predictions using calculations with the MCFM program [27].

For backgrounds, such as $W +$ jets and QCD multijet events, that are mainly selected through non-prompt or misidentified leptons, simulated MC samples are not used, but instead data-driven estimations are employed (see Section 6).

4. Object selection

Electron candidates are reconstructed from energy deposits in the calorimeter, which are then associated to reconstructed tracks of charged particles in the ID. The candidates are required to pass a stringent selection [28], which uses calorimeter and tracking variables, and are required to have $p_T > 20$ GeV and $|\eta| < 2.47$. Electrons in the transition region between the barrel and endcap calorimeters, defined as $1.37 < |\eta| < 1.52$, are excluded.

Muon candidates are reconstructed [29] by searching for track segments in different layers of the muon chambers. These segments are combined starting from the outermost layer and matched with tracks found in the ID. The candidates are refit using the complete track information from both detector systems and are required to satisfy $p_T > 20$ GeV and $|\eta| < 2.5$.

Both lepton candidates are required to be isolated to reduce backgrounds arising from jets and to suppress the selection of leptons from heavy flavor decays inside jets. For electron candidates, the transverse energy (E_T) deposited in the calorimeter and not associated to the electron is summed in a cone in η–ϕ space of radius $\Delta R = 0.2$ around the electron. This E_T is required to be less than 4 GeV. For muon candidates, both the corresponding calorimeter isolation E_T and the analogous track isolation transverse momentum (p_T) must be less than 4 GeV in a cone of $\Delta R = 0.3$. The track isolation p_T is calculated from the sum of the track transverse momenta for tracks with $p_T > 1$ GeV around the muon candidate. Additionally, muon candidates must be separated by a distance $\Delta R > 0.4$ from any jet with $p_T >$ 20 GeV, further suppressing muon candidates from heavy flavor decays.

Muon candidates arising from cosmic rays are rejected by removing candidate pairs that are back-to-back in the r–ϕ plane and that have transverse impact parameter relative to the beam axis $|d_0| > 0.5$ mm.

Track-lepton candidates are defined by an ID track with $p_T >$ 20 GeV and a series of quality cuts optimized for high efficiency and discrimination between signal and the main background (non-Z boson background, see Section 6). Tracks must have at least six SCT hits and at least one hit in the innermost pixel layer. They also must have $|d_0| < 0.2$ mm, and the uncertainty on the momentum measurement must be less than 20%. Tracks have to be isolated from other nearby tracks: the track isolation as defined for muon candidates, but using tracks with $p_T > 0.5$ GeV, must be less than 2 GeV. The use of track-lepton candidates primarily recovers acceptance losses from uninstrumented regions in the muon system and calorimeter transition regions.

Jets are reconstructed with the *anti*-k_t algorithm [30] with radius parameter $R = 0.4$ starting from energy clusters of adjacent calorimeter cells. These jets are calibrated by first correcting the jet energy using the scale established for electromagnetic objects and then performing a further correction to the hadronic energy scale using p_T- and η-dependent correction factors obtained from simulation [31]. Jets are corrected for additional energy deposits from the presence of multiple pp interactions. The jets used in the analysis are required to have no electron candidate or, in case of lepton + track events (see Section 5), no track-lepton candidate within $\Delta R = 0.4$, $p_T > 20$ GeV and $|\eta| < 2.5$.

Jets are identified as b-quark candidates using the JETPROB b-tagging algorithm [32]. This algorithm takes all well-measured

[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 upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Distances in η–ϕ space are given as $\Delta R = \sqrt{\phi^2 + \eta^2}$.

tracks associated with a given jet and forms a p-value[2] for the hypothesis that the set of tracks comes from a common primary vertex of a pp interaction, taking into account the track measurement uncertainties. The p-value requirement results in a b-tagging efficiency of $\approx 70\%$ per jet in $t\bar{t}$ candidate events, and a mistag rate of order 1% for both light-quark and gluon jets.

The missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) calculation begins with the vector sum of transverse momenta of all jets with $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 4.5$. The transverse energies of electron candidates are added. The contributions from all well-identified muon candidates and calorimeter clusters not belonging to a reconstructed object are also included. To suppress backgrounds from $Z/\gamma^* +$ jets, the $E_{\mathrm{T}}^{\mathrm{miss}}$ is corrected by the p_{T} of the track-lepton in muon + track events if the $\Delta\phi$ between the $E_{\mathrm{T}}^{\mathrm{miss}}$ and track direction is less than 0.15 and there is no muon candidate within $\Delta R = 0.05$ of the track-lepton candidate. This properly accounts for the contribution to $E_{\mathrm{T}}^{\mathrm{miss}}$ of track-lepton candidates.

5. Event selection

The analysis requires events selected online by an inclusive single-lepton trigger (e or μ). The detailed trigger requirements vary through the data-taking period, due to the rapidly increasing LHC luminosity and the commissioning of the trigger system, but with a trigger threshold that ensures full efficiency for the lepton candidates with $p_{\mathrm{T}} > 20$ GeV that are used in the analysis. To ensure that the event was triggered by the selected lepton candidates, one of the well-identified leptons and the trigger object are required to match within $\Delta R < 0.15$.

Events are required to have a primary interaction vertex with at least five tracks. The event is discarded if any jet with $p_{\mathrm{T}} > 20$ GeV fails quality cuts designed to reject jets arising from out-of-time activity or calorimeter noise [33]. If an electron candidate and a muon candidate share a track, the event is also discarded.

The selection of events in the signal region consists of a series of kinematic requirements on the reconstructed objects. The requirements on $E_{\mathrm{T}}^{\mathrm{miss}}$, the dilepton invariant mass ($m_{\ell\ell}$), and the scalar p_{T} sum of all selected jets and leptons (H_{T}) are optimized using simulated events for maximum significance, defined as $S/\sqrt{S + \sigma_B^2}$ where S is the expected number of signal events and σ_B is the total uncertainty on the number of background events, B.

The presence of exactly two oppositely-charged well-identified lepton candidates is required. If only one well-identified lepton candidate is found, the event is retained if an oppositely charged track-lepton candidate is present, forming a lepton + track candidate event. Events must have at least two jets with $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$. Furthermore, events in all channels other than $e\mu$ are required to have $m_{\ell\ell} > 15$ GeV in order to reject backgrounds from bottom quark production and vector meson decays.

The following additional kinematic requirements are made:

- Events in the ee and $\mu\mu$ channels must satisfy $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV, and $m_{\ell\ell}$ must differ by at least 10 GeV from the Z-boson mass, m_Z, to suppress backgrounds from $Z/\gamma^* +$ jets and multijet events.
- Events in the $e\mu$ channel have no $E_{\mathrm{T}}^{\mathrm{miss}}$ or $m_{\ell\ell}$ cuts applied. In this case, remaining background from $Z/\gamma^* +$ jets production is suppressed by requiring $H_{\mathrm{T}} > 130$ GeV.
- The lepton + track event candidates must have $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV, H_{T} (including the track-lepton) > 150 GeV, $|m_{\ell\ell} - m_Z| > 10$ GeV.

The requirement of at least one b-tagged jet using the JetProb algorithm allows for a kinematic event selection that can be optimized further. To define the b-tagged sample, the selection described above is modified to require only events with two well-identified lepton candidates; the lepton + track candidates are discarded. The dilepton invariant mass must satisfy $|m_{\ell\ell} - m_Z| > 5$ GeV, and the $E_{\mathrm{T}}^{\mathrm{miss}}$ and H_{T} requirements are modified to $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV and $H_{\mathrm{T}} > 110$ GeV.

The overall $t\bar{t}$ signal efficiencies with respect to all $t\bar{t}$ events (to all dilepton events) are 1.69% (16.1%) and 1.23% (11.7%) for the untagged and tagged analysis, respectively.

6. Backgrounds

The $t\bar{t}$ event selection is designed to reject $Z/\gamma^* +$ jets events. However, a small fraction of such events will remain in the signal sample primarily due to $E_{\mathrm{T}}^{\mathrm{miss}}$ mismeasurements. These events are difficult to model properly in simulations due to large uncertainties on the non-Gaussian tails of the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution, on the Z boson cross section for higher jet multiplicities and on the lepton energy resolution. To estimate the $Z/\gamma^* +$ jets background (the $Z \to \tau\tau$ channel is not considered here) in a data-assisted way, the number of $Z/\gamma^* +$ jets events is measured in a control region orthogonal to the $t\bar{t}$ dilepton signal region. The control region is formed by events with the same jet requirements as the signal region, but with $|m_{\ell\ell} - m_Z| < 10$ GeV and a lower $E_{\mathrm{T}}^{\mathrm{miss}}$ cut ($E_{\mathrm{T}}^{\mathrm{miss}} > 15$ GeV for the lepton + track event candidates and $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV for the others). Contamination in the control region from signal and background processes considered in the analysis is predicted by MC simulations and is subtracted. A scale factor, the ratio between the number of events predicted in the signal and control regions, is determined using MC simulations and is used to extrapolate the $Z/\gamma^* +$ jets event rate from the control region measured in data into the signal region. Although the predictions from MC calculations agree with the data-driven estimates, the estimates have smaller uncertainties.

Non-Z boson backgrounds mainly come from $W +$ jets, $t\bar{t}$ production with a single lepton in the final state and single top production. Such background events contain non-prompt leptons (e.g. leptons coming from b-hadron decays) or misidentified leptons arising from jets (e.g. lighter hadron decays with a leading π^0 decaying to photons). The term "fake lepton" refers to both misidentified and non-prompt lepton candidates.

The yield of background events with two well-identified lepton candidates that contain at least one fake lepton is estimated from data using a matrix method [9]. From data control regions the probability for single loose leptons to pass the full identification cuts (tight leptons) is measured. A loose lepton refers to a lepton candidate that passes looser isolation criteria. The control regions are selected such that either dominantly real or fake leptons are selected by the looser cuts. The probability for real leptons is measured from the $Z \to ee$ and $Z \to \mu\mu$ control regions. The probability for fake leptons is measured in a data sample dominated by dijet production with events containing one loose lepton candidate and having low $E_{\mathrm{T}}^{\mathrm{miss}}$. These probabilities enter a matrix that relates the numbers of observed dilepton candidate events with every combination of loose or tight leptons with the numbers of events from the sources of either real leptons or objects that might result in a fake lepton candidate. The matrix is inverted in order to estimate the real and fake content of the observed event sample.

In the lepton + track channels, the largest source of non-Z boson backgrounds are events with a fake track lepton candidate. This background rate is determined from a $\gamma +$ jets data sample selected with photon triggers. The fake rate is applied to a second

[2] Probability value for a jet formed by the individual track probabilities.

sample enriched in $W+$jets events with exactly one lepton and no track leptons but using the same kinematic cuts as for the signal sample. In this second sample the fake probabilities are summed over all jets in all events and the fake rates are calculated as a function of the jet multiplicity.

The contributions from other electroweak background processes with two real leptons (other EW), such as single top, $Z \to \tau\tau$, WW, ZZ and WZ production are estimated from Monte Carlo simulations and found to be relatively small. The numbers of background events estimated with each method are included in Table 1.

The modeled acceptances, efficiencies and data-driven background estimation methods are validated by comparing Monte Carlo predictions with data in control regions that are depleted of $t\bar{t}$ events but have similar kinematics. In particular, the $E_{\mathrm{T}}^{\mathrm{miss}}$, $m_{\ell\ell}$ and jet multiplicity distributions in a sample of Z boson candidates defined by requiring $|m_{\ell\ell} - m_Z| < 10$ GeV and low $E_{\mathrm{T}}^{\mathrm{miss}}$ are compared to MC predictions and are in good agreement with data.

The background contributions after requiring at least one b-tagged jet are determined using the same techniques described above to evaluate the rate of the background sources before making the b-tag requirement. Measured light quark and gluon jet rejection factors [34] are then applied to estimate the number of background events that remain in the candidate sample.

7. Systematic uncertainties

The uncertainties due to MC simulation modeling of the lepton trigger, lepton and track-lepton reconstruction and selection efficiencies are assessed using $Z \to ee$ and $Z \to \mu\mu$ candidate events found in the same data sample used for the $t\bar{t}$ analyses before applying Z boson veto requirements. Scale factors are applied to MC samples when calculating acceptances to account for any observed differences in predicted and observed efficiencies. The modeling of lepton momentum scale and resolution is studied using the m_{ll} distributions of Z/γ^* candidate events, and the simulation is adjusted accordingly. The acceptance uncertainty from the lepton modeling is dominated by the electron selection efficiency uncertainty.

The jet energy scale (JES) and its uncertainty are derived by combining information from test-beam data, LHC collision data and simulation [35]. For the selected jets, the JES uncertainty varies in the range 2–8% as a function of jet p_{T} and η. The jet energy resolution and jet reconstruction efficiency measured in data and in simulation are compared and are in good agreement. The statistical uncertainties on the comparisons, 10% and 1–2% for the energy resolution and the efficiency, respectively, are taken as systematic uncertainties associated with these effects. The effect on the acceptance is dominated by the JES uncertainty.

The systematic uncertainty in the efficiency of the JetProb tagging algorithm has been estimated to be 6% for b-quark jets, based on b-tagging calibration studies using inclusive lepton and multi-jet final states [34]. The uncertainties on the tagging efficiencies for light and charm quarks are several times higher, but are not a large source of uncertainty due to the intrinsically high signal-to-background ratios in the dilepton final states. The acceptance uncertainty due to b-tagging ranges from 4 to 6% depending on the channel.

The uncertainty in the kinematic distribution of the $t\bar{t}$ signal events gives rise to systematic uncertainties in the signal acceptance, with contributions from the choice of generator, the modeling of initial and final state radiation (ISR/FSR) and the PDFs. The generator uncertainty is evaluated by comparing the MC@NLO MC predictions with those of the Powheg MC [36–38] interfaced to both Herwig or Pythia [39] shower models. The uncertainty due to ISR/FSR is evaluated using the AcerMC generator [40] interfaced to the Pythia shower model, and by varying the parameters controlling ISR and FSR in a range consistent with experimental data [41]. Finally, the PDF uncertainty is evaluated using a range of current PDF sets [9]. The dominant uncertainty in this category of systematics is the modeling of ISR/FSR and generator choice.

For $Z/\gamma^* +$ jets background events the normalization uncertainty is modeled by separately considering events with a given jet multiplicity. While the cross section in the 0-jet multiplicity sample has 4% uncertainty, the extrapolation to each following jet multiplicity increases the uncertainty by an additional 24% [42].

Overall normalization uncertainties on the backgrounds from single top quark and diboson production are taken to be 10% [43, 44] and 5% [45], respectively.

The systematic uncertainties from the background estimates employing complementary samples include the statistical uncertainties as well as the systematic uncertainties arising from the objects and MC estimates that are used in the methods. The uncertainty on the data-driven $Z/\gamma^* +$jets estimation is included by varying the $E_{\mathrm{T}}^{\mathrm{miss}}$ cut in the control region by ± 5 GeV. An additional systematic uncertainty for the fake track-lepton estimate is derived from the difference in the observed and predicted number of fake events in control regions, defined as opposite sign events with zero or one jet without an H_{T} cut or as same sign-events with more than one jet. Both data-driven methods are limited primarily by the statistical uncertainty in the number of events in the respective control regions.

8. Cross section measurement

The expected and measured numbers of events in the signal region after applying all selection cuts for each of the individual dilepton channels are shown in Table 1. A total of 154 candidate events is observed for the analysis without b-tagging, 104 events in the well-identified dilepton channels and 50 events in the lepton + track channels. A total of 98 candidate events are observed in the analysis using b-tagging, with 84 events in common with the untagged analysis.

In Fig. 1 the distributions of the jet multiplicity are shown for the ee, $\mu\mu$ and $e\mu$ channels and the sum of all five channels together with the expectation for 35 pb^{-1}. The distributions of $E_{\mathrm{T}}^{\mathrm{miss}}$ for the sum of the ee and $\mu\mu$ channels, the sum of the track-lepton channels and of H_{T} for the $e\mu$ channel are shown in Fig. 2 and for the b-tag analysis in Fig. 3. All requirements are applied except on the variable whose distribution is shown in the figure.

The dominant background in the ee and $\mu\mu$ channels is Z/γ^*+ jets production. The next largest background are events with fake leptons. From simulation it is found that this is mainly $W+$jets production with an additional lepton candidate (mostly from b-quark decays).

The cross section results are obtained with a likelihood fit [46] in which the probability of observing a number of signal and background events, N_i^{obs}, in each channel i is modeled by a Poisson distribution, $\mathcal{P}$, given an expected number of events, $N_{i,\mathrm{tot}}^{\mathrm{exp}}$. The integrated luminosity, L, is modeled with a Gaussian distribution, $\mathcal{G}$, about its central value, L_0. The variation in $N_{i,\mathrm{tot}}^{\mathrm{exp}}$ due to each systematic source j is modeled with a Gaussian distribution, $\mathcal{G}_j$, for the associated nuisance parameter α_j, where $\alpha_j = \pm 1$ represents the ± 1 standard deviation variation of the systematic source. The cross section, σ_{sig}, is left as a free parameter in the fit of the likelihood function:

$$\mathcal{L}(\sigma_{\mathrm{sig}}, L, \vec{\alpha}) = \prod_{i \in \{\mathrm{channel}\}} \mathcal{P}\big(N_i^{\mathrm{obs}} \big| N_{i,\mathrm{tot}}^{\mathrm{exp}}(\vec{\alpha})\big)$$

Table 1
Full breakdown of the expected $t\bar{t}$ signal and background events compared to the observed event yields for each dilepton channel. For the expected number of events a $t\bar{t}$ cross section of 165^{+11}_{-16} pb [1,2] is used. All systematic uncertainties are included and correlations between different background sources are taken into account. The fake leptons category includes both misidentified and non-prompt lepton candidates.

	Untagged					Tagged		
	ee	$\mu\mu$	$e\mu$	eTL	μTL	ee	$\mu\mu$	$e\mu$
$Z/\gamma^* \to ee/\mu\mu$	1.1 ± 0.5	3.5 ± 1.4	–	7.1 ± 1.5	2.2 ± 0.9	2.6 ± 1.3	5.0 ± 1.7	–
$Z/\gamma^* \to \tau\tau$	0.4 ± 0.3	1.2 ± 0.6	3.0 ± 1.3	1.9 ± 1.0	2.2 ± 0.9	0.2 ± 0.1	0.2 ± 0.1	0.8 ± 0.4
Fake leptons	1.0 ± 0.9	0.4 ± 0.5	1.9 ± 1.7	8.1 ± 2.9	8.2 ± 2.9	0.5 ± 0.5	0.4 ± 0.5	0.2 ± 1.1
Single top	0.6 ± 0.1	1.2 ± 0.2	2.4 ± 0.3	0.5 ± 0.1	0.6 ± 0.1	0.6 ± 0.1	1.1 ± 0.2	1.8 ± 0.3
Diboson	0.5 ± 0.1	0.9 ± 0.1	$2.0^{+0.3}_{-0.2}$	0.5 ± 0.1	0.4 ± 0.1	0.2 ± 0.1	0.2 ± 0.0	0.4 ± 0.1
Total background	3.6 ± 1.2	7.2 ± 1.6	9.4 ± 2.5	18.1 ± 3.4	13.8 ± 3.2	4.1 ± 1.4	6.9 ± 1.8	3.2 ± 1.2
Predicted $t\bar{t}$	10.9 ± 1.2	19.4 ± 1.5	45.7 ± 3.7	10.2 ± 1.3	11.0 ± 1.8	11.1 ± 1.4	$20.6^{+1.7}_{-2.2}$	$38.9^{+3.5}_{-4.4}$
Total	14.5 ± 1.7	26.6 ± 2.1	55.1 ± 4.4	28.3 ± 3.6	24.6 ± 3.7	15.2 ± 2.0	$27.5^{+2.5}_{-2.9}$	$42.1^{+3.7}_{-4.6}$
Observed	17	30	57	29	21	17	32	49

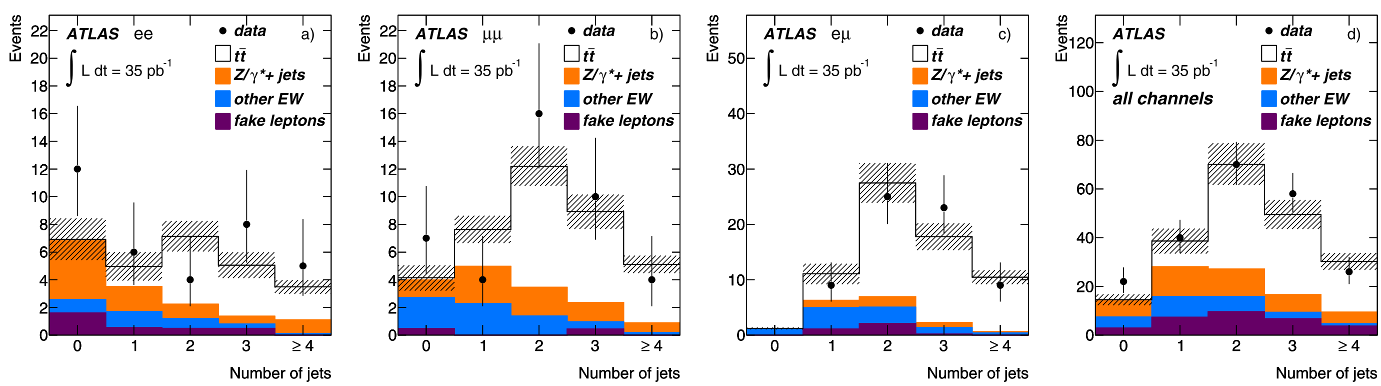

Fig. 1. Jet multiplicity distributions for the signal region omitting the $N_{\text{jets}} \geqslant 2$ requirement in (a) the ee channel, (b) the $\mu\mu$ channel, (c) the $e\mu$ channel and (d) all five channels combined. The fake lepton contribution in (d) is the sum of the fake track-lepton and the fake lepton contribution. Contributions from diboson and single top events are summarized as 'other EW'. The uncertainty on the data points are statistical uncertainties only, whereas the uncertainty bands include statistical and systematic uncertainties.

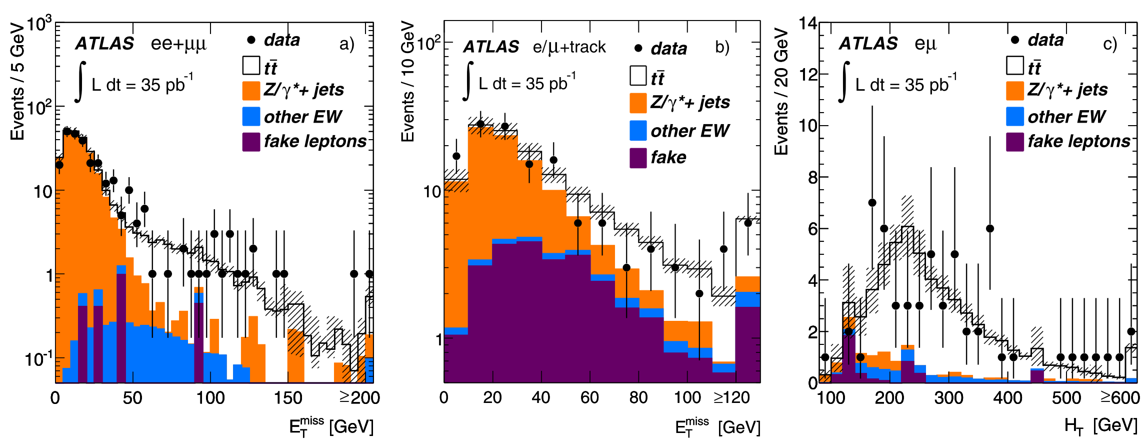

Fig. 2. The E_T^{miss} distribution in the signal region without the $E_T^{\text{miss}} > 40$ GeV requirement (a) for the ee and $\mu\mu$ channels and (b) for the lepton + track channels. Fake denotes the contribution from fake track-leptons. The H_T distribution in the signal region for the $e\mu$ channel is shown in (c) without the $H_T > 130$ GeV requirement. Contributions from diboson and single top events are summarized as 'other EW'. In all figures the last bin contains the overflow. The uncertainty on the data points are statistical uncertainties only, whereas the uncertainty bands include statistical and systematic uncertainties.

$$\times\, \mathcal{G}(L_0|L, \sigma_L) \times \prod_{j \in \text{syst}} \mathcal{G}_j(0|\alpha_j, 1).$$

The cross section is inferred from the profile likelihood ratio $\lambda(\sigma_{\text{sig}}) = \mathcal{L}(\sigma_{\text{sig}}, \hat{\hat{L}}, \hat{\hat{\alpha}})/\mathcal{L}(\hat{\sigma}_{\text{sig}}, \hat{L}, \hat{\alpha})$, where a single circumflex represents the maximum likelihood estimate (MLE) of the parameter and the double circumflex represents the conditional MLE for a given σ_{sig}. Ensembles of pseudo-data are generated for N_i^{obs} and the resulting estimate of $\hat{\sigma}_{\text{sig}}$ is confirmed to be unbiased. Additionally, the variance of $\hat{\sigma}_{\text{sig}}$ is found to be consistent with the curvature of the profile likelihood at its minimum and with the mean square spread observed in the ensemble tests. Table 2 lists the uncertainties for each contribution from the data and MC statistics, the uncertainties related to the object selection (grouped in lepton, track-lepton, jet/E_T^{miss} and b-jet uncertainties), the background estimation methods and the uncertainties on the simulated samples. The variation of the cross section due to the luminosity uncertainty is obtained by repeating the likelihood minimization while fixing the luminosity to the nominal value ± 1 standard deviation. For the final result the luminosity uncertainty is

Table 2
The $t\bar{t}$ cross section uncertainties. These include the uncertainties from the data and MC statistics, the uncertainties related to the object selection (grouped in lepton, track lepton eTL/μTL, jet/E_T^{miss} and b-tagging uncertainties), the background estimation methods ($Z/\gamma^* +$ jets and fakes), the uncertainties on the simulated samples (generator) and the luminosity uncertainty.

$\Delta\sigma/\sigma$ (%)	Untagged						Tagged			
	ee	$\mu\mu$	$e\mu$	eTL	μTL	comb.	ee	$\mu\mu$	$e\mu$	comb.
Statistics	$^{+33}/_{-29}$	$^{+26}/_{-23}$	$^{+17}/_{-15}$	$^{+53}/_{-46}$	$^{+67}/_{-58}$	$^{+12}/_{-11}$	$^{+35}/_{-29}$	$^{+24}/_{-21}$	$^{+16}/_{-15}$	$^{+12}/_{-11}$
MC stat.	$^{+5}/_{-1}$	$^{+4}/_{-3}$	$^{+2}/_{-1}$	$^{+12}/_{-14}$	$^{+10}/_{-12}$	$^{+1}/_{-2}$	$^{+3}/_{-5}$	$^{+4}/_{-3}$	$^{+1}/_{-1}$	$^{+1}/_{-2}$
Lepton	$^{+11}/_{-5}$	$^{+4}/_{-0}$	$^{+5}/_{-4}$	$^{+7}/_{-6}$	$^{+3}/_{-4}$	$^{+4}/_{-3}$	$^{+9}/_{-7}$	$^{+2}/_{-2}$	$^{+5}/_{-4}$	$^{+4}/_{-3}$
eTL/μTL	–	–	–	$^{+3}/_{-2}$	$^{+4}/_{-5}$	$^{+1}/_{-1}$	–	–	–	–
Jet/E_T^{miss}	$^{+5}/_{-4}$	$^{+4}/_{-3}$	$^{+3}/_{-3}$	$^{+13}/_{-11}$	$^{+12}/_{-7}$	$^{+3}/_{-4}$	$^{+5}/_{-4}$	$^{+6}/_{-4}$	$^{+2}/_{-2}$	$^{+4}/_{-3}$
$Z/\gamma^* +$ jets	$^{+4}/_{-4}$	$^{+4}/_{-3}$	–	$^{+0}/_{-5}$	$^{+4}/_{-6}$	$^{+1}/_{-1}$	$^{+6}/_{-8}$	$^{+5}/_{-6}$	–	$^{+2}/_{-2}$
Fake	$^{+8}/_{-6}$	$^{+3}/_{-1}$	$^{+3}/_{-4}$	$^{+25}/_{-27}$	$^{+39}/_{-41}$	$^{+3}/_{-3}$	$^{+2}/_{-5}$	$^{+2}/_{-2}$	$^{+3}/_{-2}$	$^{+1}/_{-2}$
Generator	$^{+6}/_{-4}$	$^{+5}/_{-6}$	$^{+4}/_{-4}$	$^{+16}/_{-11}$	$^{+17}/_{-17}$	$^{+5}/_{-5}$	$^{+10}/_{-8}$	$^{+7}/_{-5}$	$^{+5}/_{-4}$	$^{+6}/_{-4}$
b-tagging	–	–	–	–	–	–	$^{+3}/_{-4}$	$^{+5}/_{-3}$	$^{+5}/_{-4}$	$^{+5}/_{-4}$
Luminosity	$^{+4}/_{-4}$	$^{+4}/_{-4}$	$^{+4}/_{-4}$	$^{+4}/_{-4}$	$^{+5}/_{-5}$	$^{+4}/_{-4}$	$^{+4}/_{-3}$	$^{+4}/_{-3}$	$^{+4}/_{-4}$	$^{+3}/_{-4}$

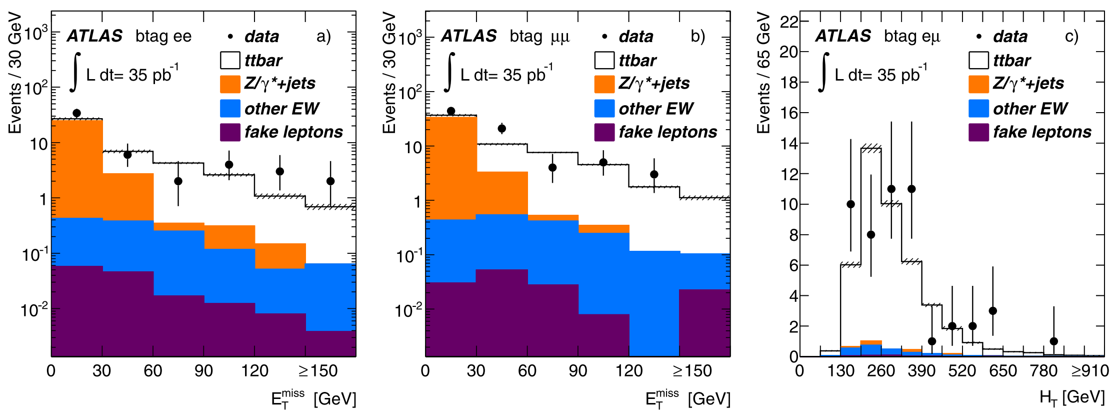

Fig. 3. The E_T^{miss} distributions for the (a) ee and (b) $\mu\mu$ channels omitting the E_T^{miss} requirement, and (c) the H_T distribution for the $e\mu$ channel omitting the H_T requirement, in each case after b-tagging has been applied. Contributions from diboson and single top events are summarized as 'other EW'. The last bin in all figures contains the overflow. The uncertainty on the data points are statistical uncertainties only, whereas the uncertainty bands include statistical and systematic uncertainties.

Table 3
Measured cross sections in each dilepton channel, and the combination of the untagged and tagged channels with their statistical and systematic uncertainties. The luminosity uncertainty is not included here.

Channel	$\sigma_{t\bar{t}}$ (pb)	b-tag $\sigma_{t\bar{t}}$ (pb)
ee	$202^{+67}_{-57}{}^{+30}_{-26}$	$190^{+66}_{-56}{}^{+36}_{-28}$
$\mu\mu$	$192^{+49}_{-44}{}^{+17}_{-15}$	$200^{+48}_{-42}{}^{+26}_{-20}$
$e\mu$	$172 \pm 27 \pm 13$	$193^{+31}_{-28}{}^{+18}_{-13}$
eTL	$175^{+92}_{-81}{}^{+65}_{-59}$	–
μTL	$110^{+74}_{-64}{}^{+56}_{-49}$	–
Combined	$171 \pm 22 \pm 15$	$194 \pm 23^{+18}_{-14}$

the difference of the total uncertainties for the likelihood function with and without the luminosity term. Table 3 summarizes the cross sections extracted from the profile likelihood ratio for the individual channels and for the combination of all channels for the analysis with and without a b-tagging requirement, respectively.

9. Results

The top quark pair production cross section is measured using events selected by requiring two oppositely-charged lepton candidates, at least two additional jets and missing transverse energy. The result is

$$\sigma_{t\bar{t}} = 177 \pm 20(\text{stat.}) \pm 14(\text{syst.}) \pm 7(\text{lum.})\ \text{pb}.$$

A measurement made requiring at least one of the jets to be identified as a b-quark jet results in

$$\sigma_{t\bar{t}} = 194 \pm 23(\text{stat.})^{+18}_{-14}(\text{syst.}) \pm 7(\text{lum.})\ \text{pb}.$$

The two measurements agree with each other, taking into account that from all events 14% (tagged analysis) and 45% (untagged analysis) of the events are uncorrelated, and that the b-tagging systematic uncertainty is also uncorrelated. The agreement confirms that the candidate events are consistent with arising from top quark pair production.

The measured cross sections are in good agreement with a similar measurement performed by the CMS Collaboration [8], ATLAS measurements made in the complementary lepton + jets channels [47] and the SM prediction of 165^{+11}_{-16} pb.

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Wooden [118], B.K. Wosiek [38], J. Wotschack [29], M.J. Woudstra [84], K. Wraight [53], C. Wright [53], B. Wrona [73], S.L. Wu [172], X. Wu [49], Y. Wu [32b,ab], E. Wulf [34], R. Wunstorf [42], B.M. Wynne [45], L. Xaplanteris [9], S. Xella [35], S. Xie [48], Y. Xie [32a], C. Xu [32b,ac], D. Xu [139], G. Xu [32a], B. Yabsley [150], S. Yacoob [145b], M. Yamada [66], H. Yamaguchi [155], A. Yamamoto [66], K. Yamamoto [64], S. Yamamoto [155], T. Yamamura [155], T. Yamanaka [155], J. Yamaoka [44], T. Yamazaki [155], Y. Yamazaki [67], Z. Yan [21], H. Yang [87], U.K. Yang [82], Y. Yang [61], Y. Yang [32a], Z. Yang [146a,146b], S. Yanush [91], W.-M. Yao [14], Y. Yao [14], Y. Yasu [66], G.V. Ybeles Smit [130], J. Ye [39], S. Ye [24], M. Yilmaz [3c], R. Yoosoofmiya [123], K. Yorita [170], R. Yoshida [5], C. Young [143], S. Youssef [21], D. Yu [24], J. Yu [7], J. Yu [32c,ac], L. Yuan [32a,ad], A. Yurkewicz [148], V.G. Zaets [128], R. Zaidan [63], A.M. Zaitsev [128], Z. Zajacova [29], Yo.K. Zalite [121], L. Zanello [132a,132b], P. Zarzhitsky [39], A. Zaytsev [107], C. Zeitnitz [174], M. Zeller [175], A. Zemla [38], C. Zendler [20], O. Zenin [128], T. Ženiš [144a], Z. Zenonos [122a,122b], S. Zenz [14], D. Zerwas [115], G. Zevi della Porta [57], Z. Zhan [32d], D. Zhang [32b,aa], H. Zhang [88], J. Zhang [5], X. Zhang [32d], Z. Zhang [115], L. Zhao [108], T. Zhao [138], Z. Zhao [32b], A. Zhemchugov [65], S. Zheng [32a], J. Zhong [151,ae], B. Zhou [87], N. Zhou [163], Y. Zhou [151], C.G. Zhu [32d], H. Zhu [41], J. Zhu [87], Y. Zhu [172], X. Zhuang [98], V. Zhuravlov [99], D. Zieminska [61], R. Zimmermann [20], S. Zimmermann [20], S. Zimmermann [48], M. Ziolkowski [141], R. Zitoun [4], L. Živković [34], V.V. Zmouchko [128,*], G. Zobernig [172], A. Zoccoli [19a,19b], Y. Zolnierowski [4], A. Zsenei [29], M. zur Nedden [15], V. Zutshi [106], L. Zwalinski [29]

[1] *University at Albany, Albany, NY, United States*
[2] *Department of Physics, University of Alberta, Edmonton, AB, Canada*
[3] [(a)] *Department of Physics, Ankara University, Ankara;* [(b)] *Department of Physics, Dumlupinar University, Kutahya;* [(c)] *Department of Physics, Gazi University, Ankara;* [(d)] *Division of Physics, TOBB University of Economics and Technology, Ankara;* [(e)] *Turkish Atomic Energy Authority, Ankara, Turkey*

[4] LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
[5] High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States
[6] Department of Physics, University of Arizona, Tucson, AZ, United States
[7] Department of Physics, The University of Texas at Arlington, Arlington, TX, United States
[8] Physics Department, University of Athens, Athens, Greece
[9] Physics Department, National Technical University of Athens, Zografou, Greece
[10] Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[11] Institut de Física d'Altes Energies and Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
[12] [(a)] Institute of Physics, University of Belgrade, Belgrade; [(b)] Vinca Institute of Nuclear Sciences, Belgrade, Serbia
[13] Department for Physics and Technology, University of Bergen, Bergen, Norway
[14] Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States
[15] Department of Physics, Humboldt University, Berlin, Germany
[16] Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
[17] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[18] [(a)] Department of Physics, Bogazici University, Istanbul; [(b)] Division of Physics, Dogus University, Istanbul; [(c)] Department of Physics Engineering, Gaziantep University, Gaziantep; [(d)] Department of Physics, Istanbul Technical University, Istanbul, Turkey
[19] [(a)] INFN Sezione di Bologna; [(b)] Dipartimento di Fisica, Università di Bologna, Bologna, Italy
[20] Physikalisches Institut, University of Bonn, Bonn, Germany
[21] Department of Physics, Boston University, Boston, MA, United States
[22] Department of Physics, Brandeis University, Waltham, MA, United States
[23] [(a)] Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; [(b)] Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
[24] Physics Department, Brookhaven National Laboratory, Upton, NY, United States
[25] [(a)] National Institute of Physics and Nuclear Engineering, Bucharest; [(b)] University Politehnica Bucharest, Bucharest; [(c)] West University in Timisoara, Timisoara, Romania
[26] Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
[27] Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[28] Department of Physics, Carleton University, Ottawa, ON, Canada
[29] CERN, Geneva, Switzerland
[30] Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
[31] [(a)] Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago; [(b)] Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[32] [(a)] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; [(b)] Department of Modern Physics, University of Science and Technology of China, Anhui; [(c)] Department of Physics, Nanjing University, Jiangsu; [(d)] High Energy Physics Group, Shandong University, Shandong, China
[33] Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
[34] Nevis Laboratory, Columbia University, Irvington, NY, United States
[35] Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
[36] [(a)] INFN Gruppo Collegato di Cosenza; [(b)] Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
[37] Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
[38] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
[39] Physics Department, Southern Methodist University, Dallas, TX, United States
[40] Physics Department, University of Texas at Dallas, Richardson, TX, United States
[41] DESY, Hamburg and Zeuthen, Germany
[42] Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
[43] Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
[44] Department of Physics, Duke University, Durham, NC, United States
[45] SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[46] Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3, 2700 Wiener Neustadt, Austria
[47] INFN Laboratori Nazionali di Frascati, Frascati, Italy
[48] Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
[49] Section de Physique, Université de Genève, Geneva, Switzerland
[50] [(a)] INFN Sezione di Genova; [(b)] Dipartimento di Fisica, Università di Genova, Genova, Italy
[51] Institute of Physics and HEP Institute, Georgian Academy of Sciences and Tbilisi State University, Tbilisi, Georgia
[52] II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[53] SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[54] II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
[55] Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
[56] Department of Physics, Hampton University, Hampton, VA, United States
[57] Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
[58] [(a)] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(b)] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(c)] ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
[59] Faculty of Science, Hiroshima University, Hiroshima, Japan
[60] Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
[61] Department of Physics, Indiana University, Bloomington, IN, United States
[62] Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[63] University of Iowa, Iowa City, IA, United States
[64] Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
[65] Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
[66] KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[67] Graduate School of Science, Kobe University, Kobe, Japan
[68] Faculty of Science, Kyoto University, Kyoto, Japan
[69] Kyoto University of Education, Kyoto, Japan
[70] Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[71] Physics Department, Lancaster University, Lancaster, United Kingdom
[72] [(a)] INFN Sezione di Lecce; [(b)] Dipartimento di Fisica, Università del Salento, Lecce, Italy
[73] Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[74] Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
[75] Department of Physics, Queen Mary University of London, London, United Kingdom
[76] Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
[77] Department of Physics and Astronomy, University College London, London, United Kingdom
[78] Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
[79] Fysiska Institutionen, Lunds Universitet, Lund, Sweden

[80] *Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain*
[81] *Institut für Physik, Universität Mainz, Mainz, Germany*
[82] *School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[83] *CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France*
[84] *Department of Physics, University of Massachusetts, Amherst, MA, United States*
[85] *Department of Physics, McGill University, Montreal, QC, Canada*
[86] *School of Physics, University of Melbourne, Victoria, Australia*
[87] *Department of Physics, The University of Michigan, Ann Arbor, MI, United States*
[88] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States*
[89] [(a)] *INFN Sezione di Milano;* [(b)] *Dipartimento di Fisica, Università di Milano, Milano, Italy*
[90] *B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus*
[91] *National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus*
[92] *Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States*
[93] *Group of Particle Physics, University of Montreal, Montreal, QC, Canada*
[94] *P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia*
[95] *Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*
[96] *Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia*
[97] *Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
[98] *Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
[99] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
[100] *Nagasaki Institute of Applied Science, Nagasaki, Japan*
[101] *Graduate School of Science, Nagoya University, Nagoya, Japan*
[102] [(a)] *INFN Sezione di Napoli;* [(b)] *Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy*
[103] *Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States*
[104] *Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
[105] *Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
[106] *Department of Physics, Northern Illinois University, DeKalb, IL, United States*
[107] *Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia*
[108] *Department of Physics, New York University, New York, NY, United States*
[109] *Ohio State University, Columbus, OH, United States*
[110] *Faculty of Science, Okayama University, Okayama, Japan*
[111] *Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States*
[112] *Department of Physics, Oklahoma State University, Stillwater, OK, United States*
[113] *Palacký University, RCPTM, Olomouc, Czech Republic*
[114] *Center for High Energy Physics, University of Oregon, Eugene, OR, United States*
[115] *LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France*
[116] *Graduate School of Science, Osaka University, Osaka, Japan*
[117] *Department of Physics, University of Oslo, Oslo, Norway*
[118] *Department of Physics, Oxford University, Oxford, United Kingdom*
[119] [(a)] *INFN Sezione di Pavia;* [(b)] *Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy*
[120] *Department of Physics, University of Pennsylvania, Philadelphia, PA, United States*
[121] *Petersburg Nuclear Physics Institute, Gatchina, Russia*
[122] [(a)] *INFN Sezione di Pisa;* [(b)] *Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
[123] *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States*
[124] [(a)] *Laboratorio de Instrumentacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal;* [(b)] *Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain*
[125] *Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic*
[126] *Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic*
[127] *Czech Technical University in Prague, Praha, Czech Republic*
[128] *State Research Center Institute for High Energy Physics, Protvino, Russia*
[129] *Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
[130] *Physics Department, University of Regina, Regina, SK, Canada*
[131] *Ritsumeikan University, Kusatsu, Shiga, Japan*
[132] [(a)] *INFN Sezione di Roma I;* [(b)] *Dipartimento di Fisica, Università La Sapienza, Roma, Italy*
[133] [(a)] *INFN Sezione di Roma Tor Vergata;* [(b)] *Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
[134] [(a)] *INFN Sezione di Roma Tre;* [(b)] *Dipartimento di Fisica, Università Roma Tre, Roma, Italy*
[135] [(a)] *Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca;* [(b)] *Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat;* [(c)] *Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000;* [(d)] *Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda;* [(e)] *Faculté des Sciences, Université Mohammed V, Rabat, Morocco*
[136] *DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France*
[137] *Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States*
[138] *Department of Physics, University of Washington, Seattle, WA, United States*
[139] *Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
[140] *Department of Physics, Shinshu University, Nagano, Japan*
[141] *Fachbereich Physik, Universität Siegen, Siegen, Germany*
[142] *Department of Physics, Simon Fraser University, Burnaby BC, Canada*
[143] *SLAC National Accelerator Laboratory, Stanford, CA, United States*
[144] [(a)] *Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava;* [(b)] *Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
[145] [(a)] *Department of Physics, University of Johannesburg, Johannesburg;* [(b)] *School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
[146] [(a)] *Department of Physics, Stockholm University;* [(b)] *The Oskar Klein Centre, Stockholm, Sweden*
[147] *Physics Department, Royal Institute of Technology, Stockholm, Sweden*
[148] *Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, United States*
[149] *Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
[150] *School of Physics, University of Sydney, Sydney, Australia*
[151] *Institute of Physics, Academia Sinica, Taipei, Taiwan*
[152] *Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel*
[153] *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
[154] *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*

[155] International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
[156] Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[157] Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[158] Department of Physics, University of Toronto, Toronto, ON, Canada
[159] [(a)] TRIUMF, Vancouver, BC; [(b)] Department of Physics and Astronomy, York University, Toronto, ON, Canada
[160] Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan
[161] Science and Technology Center, Tufts University, Medford, MA, United States
[162] Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
[163] Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
[164] [(a)] INFN Gruppo Collegato di Udine; [(b)] ICTP, Trieste; [(c)] Dipartimento di Fisica, Università di Udine, Udine, Italy
[165] Department of Physics, University of Illinois, Urbana, IL, United States
[166] Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[167] Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingenierá Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
[168] Department of Physics, University of British Columbia, Vancouver, BC, Canada
[169] Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
[170] Waseda University, Tokyo, Japan
[171] Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
[172] Department of Physics, University of Wisconsin, Madison, WI, United States
[173] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
[174] Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[175] Department of Physics, Yale University, New Haven, CT, United States
[176] Yerevan Physics Institute, Yerevan, Armenia
[177] Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

[a] Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal.
[b] Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
[c] Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
[d] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
[e] Also at TRIUMF, Vancouver, BC, Canada.
[f] Also at Department of Physics, California State University, Fresno, CA, United States.
[g] Also at Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland.
[h] Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
[i] Also at Università di Napoli Parthenope, Napoli, Italy.
[j] Also at Institute of Particle Physics (IPP), Canada.
[k] Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
[l] Also at Louisiana Tech University, Ruston, LA, United States.
[m] Also at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.
[n] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[o] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[p] Also at Manhattan College, New York, NY, United States.
[q] Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
[r] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
[s] Also at High Energy Physics Group, Shandong University, Shandong, China.
[t] Also at Section de Physique, Université de Genève, Geneva, Switzerland.
[u] Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
[v] Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
[w] Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
[x] Also at California Institute of Technology, Pasadena, CA, United States.
[y] Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
[z] Also at Department of Physics, Oxford University, Oxford, United Kingdom.
[aa] Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
[ab] Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.
[ac] Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France.
[ad] Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
[ae] Also at Department of Physics, Nanjing University, Jiangsu, China.
[*] Deceased.