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Measurement of the top quark pair production cross-section with ATLAS in the single lepton channel ☆

ATLAS Collaboration ⋆

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ABSTRACT

A measurement of the production cross-section for top quark pairs ($t\bar{t}$) in pp collisions at $\sqrt{s} = 7$ TeV is presented using data recorded with the ATLAS detector at the Large Hadron Collider. Events are selected in the single lepton topology by requiring an electron or muon, large missing transverse momentum and at least three jets. With a data sample of 35 pb^{-1}, two different multivariate methods, one of which uses b-quark jet identification while the other does not, use kinematic variables to obtain cross-section measurements of $\sigma_{t\bar{t}} = 187 \pm 11(\text{stat.})^{+18}_{-17}(\text{syst.}) \pm 6(\text{lumi.})$ pb and $\sigma_{t\bar{t}} = 173 \pm 17(\text{stat.})^{+18}_{-16}(\text{syst.}) \pm 6(\text{lumi.})$ pb respectively. The two measurements are in agreement with each other and with QCD calculations. The first measurement has a better a priori sensitivity and constitutes the main result of this Letter.

1. Introduction

Measurements of the production and decay properties of top quarks are of central importance to the Large Hadron Collider (LHC) physics programme. Uncertainties on the theoretical predictions for the top quark pair production cross-section are now less than 10%, and comparisons with experimental measurements allow a precision test of the predictions of Quantum Chromodynamics. Furthermore, top quark pair production is an important background in many searches for physics beyond the Standard Model (SM). New physics may also give rise to additional $t\bar{t}$ production mechanisms or modifications of the top quark decay channels, which can affect the measured $t\bar{t}$ cross-section.

In the SM the $t\bar{t}$ production cross-section in pp collisions is calculated to be 165^{+11}_{-16} pb [1–3] at a centre-of-mass energy $\sqrt{s} = 7$ TeV, assuming a top quark mass of 172.5 GeV. Top quarks are predicted to decay to a W-boson and a b-quark ($t \to Wb$) nearly 100% of the time. Events with a $t\bar{t}$ pair can be classified as 'single lepton', 'dilepton', or 'all hadronic' according to the decays of the two W-bosons: each can decay into quark–antiquark pairs ($W \to q_1\bar{q}_2$) or a lepton-neutrino pair ($W \to \ell\nu$). Events in the single lepton channel, when the lepton is an electron or a muon, are characterised by an isolated, prompt, energetic lepton, jets, and missing transverse momentum from the neutrino. At the Tevatron the $t\bar{t}$ cross-sections at $\sqrt{s} = 1.8$ TeV and at $\sqrt{s} = 1.96$ TeV have been measured by CDF [4,5] and DØ [6,7] in most channels. ATLAS and CMS have measured the $t\bar{t}$ cross-section at $\sqrt{s} = 7$ TeV at the LHC [8–11].

This Letter describes measurements of the $t\bar{t}$ cross-section in the single lepton plus jets channel with 35 pb^{-1} of data recorded by ATLAS in 2010. Taking advantage of the increased data sample, the measurement techniques developed in Ref. [8] were extended to employ kinematic likelihood discriminants to separate signal from background and measure the cross-section. Two multivariate methods, one that includes b-quark jet identification (b-tagging) and one which does not, use several variables each to discriminate $t\bar{t}$ events from the background. The two analyses are sensitive to different sources of systematic uncertainty. For instance, the analysis without b-tagging is more sensitive to the multijet background, whereas the analysis with b-tagging is sensitive to the background from W-boson production in association with b- and c-quarks. The clearer separation of signal and background leads to a smaller statistical uncertainty for the analysis with b-tagging. Another significant difference between the two measurements is that the analysis with b-tagging uses a profile likelihood that implements an *in situ* fit of the dominant systematic uncertainties, which improves its performance considerably.

2. The ATLAS detector

The ATLAS detector [12] consists of an inner tracking system (inner detector, or ID) surrounded by a thin superconducting solenoid providing a 2 T magnetic field, electromagnetic and hadronic calorimeters and a muon spectrometer (MS). The ID consists of silicon pixel and microstrip detectors, surrounded by a transition radiation tracker. The electromagnetic calorimeter is

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☆ © CERN for the benefit of the ATLAS Collaboration.

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

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a lead/liquid-argon (LAr) detector. Hadron calorimetry is based on two different detector technologies, with scintillator tiles or LAr as active media, and with either steel, copper, or tungsten as the absorber material. The MS includes three large superconducting toroids arranged with an eight-fold azimuthal coil symmetry around the calorimeters, and a system of three stations of chambers for the trigger and for track measurements.

A three-level trigger system is used to select interesting events. 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, level-2 and the event filter, which together reduce the event rate to about 200 Hz which is recorded for analysis.

The nominal pp interaction point at the centre of the detector is defined as the origin of a right-handed coordinate system. The positive x-axis is defined by the direction from the interaction point to the centre of the LHC ring, with the positive y-axis pointing upwards, while the z-axis is along the beam direction. The azimuthal angle ϕ is measured around the beam axis and the polar angle θ is the angle from the z-axis. The pseudorapidity is defined as $\eta = -\ln\tan(\theta/2)$.

3. Simulated event samples

Monte Carlo (MC) simulation was used for various aspects of the analysis. The simulation consists of an event generator interfaced to a parton shower and hadronisation model, the results of which are passed through a full simulation of the ATLAS detector and trigger system [13,14]. MC simulation was used when data-driven techniques were not available or to evaluate relatively small backgrounds and certain sources of systematic uncertainty.

For the calculation of the acceptance of the $t\bar{t}$ signal the next-to-leading order (NLO) generator MC@NLO v3.41 [15] was used with the top quark mass set to 172.5 GeV and with the NLO parton density function (PDF) set CTEQ66 [16].

W- and Z-boson production in association with jets was simulated with Alpgen v2.13, which implements the exact leading order (LO) matrix elements for final states with up to six partons and uses the 'MLM' matching procedure to remove the overlaps between samples with n and $n+1$ final state partons [17]. The LO PDF set CTEQ6L1 [16] was used to generate $W+$jets and $Z+$jets events with up to five partons. Diboson, WW, WZ and ZZ events were generated with Herwig [18,19]. Like the diboson production, single-top is also a relatively small background and is simulated using MC@NLO, invoking the 'diagram removal scheme' [20] to remove overlaps between single-top and $t\bar{t}$ final states.

Unless otherwise noted, all events were hadronised with Herwig, using Jimmy [21] for the underlying event model. Details of the generator and underlying event tunes used are given in Ref. [22].

3.1. Systematic uncertainties on signal and background modelling

The use of simulated $t\bar{t}$ samples to calculate the signal acceptance gives rise to various sources of systematic uncertainty. These arise from the choice of the event generator and PDF set, and from the modelling of initial and final state radiation (ISR and FSR). The uncertainties due to the choice of generator and parton shower model were evaluated by comparing the results obtained with MC@NLO to those of Powheg [23], with events hadronised with either Herwig or Pythia [24]. The uncertainty due to the modelling of ISR/FSR was evaluated using the AcerMC generator [25] interfaced to Pythia and by varying the parameters controlling the ISR/FSR emission by a factor of two up and down. The variation ranges used are comparable to those in [26] for ISR and [27] for FSR. Finally, the uncertainty in the PDF set used to generate $t\bar{t}$ samples was evaluated using a range of current PDF sets with the procedure described in Refs. [28–30].

The production of the $W+$jets background based on MC simulation has uncertainties on the total cross-section, on the contribution of events with jets from heavy-flavour (b, c) quarks, and on the shape of kinematic distributions. The predictions of the total cross-section have uncertainties of order 50% [31], increasing with jet multiplicity. Total $W+$jets cross-section predictions were not used in the cross-section measurement as this background was extracted from the fit to the data (see Section 7), but were used in the MC simulation shown in Figs. 1 to 4. A combination of the fitting method described in [32] and a counting method described here, both relying upon final states with one and two jets, was used to estimate the heavy flavour fractions in $W+$jets events. Since these bins are dominated by $W+$jet events, the total $W+$jet contribution to these events can be obtained, both with and without requiring at least one b-tagged jet. These four numbers are then used to constrain the following four event types which make up the $W+$jets sample: $W+b\bar{b}$, $W+c\bar{c}$, $W+c$ and $W+$light flavours. Additionally it was assumed that the k-factors for $W+b\bar{b}$ and $W+c\bar{c}$ are equal. MC simulation with Alpgen was used to estimate the b-tagging efficiencies for each sub-sample as well as to extrapolate from the one-jet to the two-jet bin. The dominant uncertainties in this method arise from jet energy scale and b-tagging uncertainties. As a result of this study, it was found that the $W+b\bar{b}$ and $W+c\bar{c}$ sub-samples of events in the Alpgen MC simulation were to be rescaled by 1.30 ± 0.65, whereas $W+c$ events were rescaled by 1.0 ± 0.4. An additional 25% relative uncertainty per jet bin was assigned to these flavour fractions when applied to the signal region based upon studies with Alpgen MC simulation.

The uncertainty on the shape of $W+$jets kinematic distributions was assessed by changing the factorisation and renormalisation scales by a factor of two up and down; and by varying the minimum p_T of the final state quarks and gluons from 10 to 25 GeV, with 15 GeV being the default.

For the smaller backgrounds arising from $Z+$jets, single-top and diboson production, only the overall normalisation uncertainties were considered, taken to be 30% for $Z+$jets production, 10% for single-top production, determined from comparisons of MCFM [33] and MC@NLO predictions, and 5% for diboson production, determined from MCFM studies of scale and PDF uncertainties.

4. Object selection

Single lepton $t\bar{t}$ events are characterised by the presence of an electron or muon, jets, and missing transverse momentum, which is an indicator of undetected neutrinos, in the final state. The events used in this analysis were triggered by single lepton triggers. The electron trigger required a level-1 electromagnetic cluster in the calorimeter with transverse momentum $E_T > 10$ GeV. A more refined cluster selection was applied in the level-2 trigger, and a match between the electromagnetic cluster and an ID track was required in the event filter. The muon trigger required a track with transverse momentum $p_T > 10$ GeV in the muon trigger chambers at level-1, matched to a muon of $p_T > 13$ GeV reconstructed in the precision chambers and combined with an ID track at the event filter.

The same object definition used for the previous $t\bar{t}$ cross-section measurement [8] was used in this analysis, except for more stringent electron selection criteria and ID track quality requirements for muons. Electron candidates were defined as electromagnetic clusters consistent with the energy deposition of an electron in the calorimeters and with an associated well-measured track.

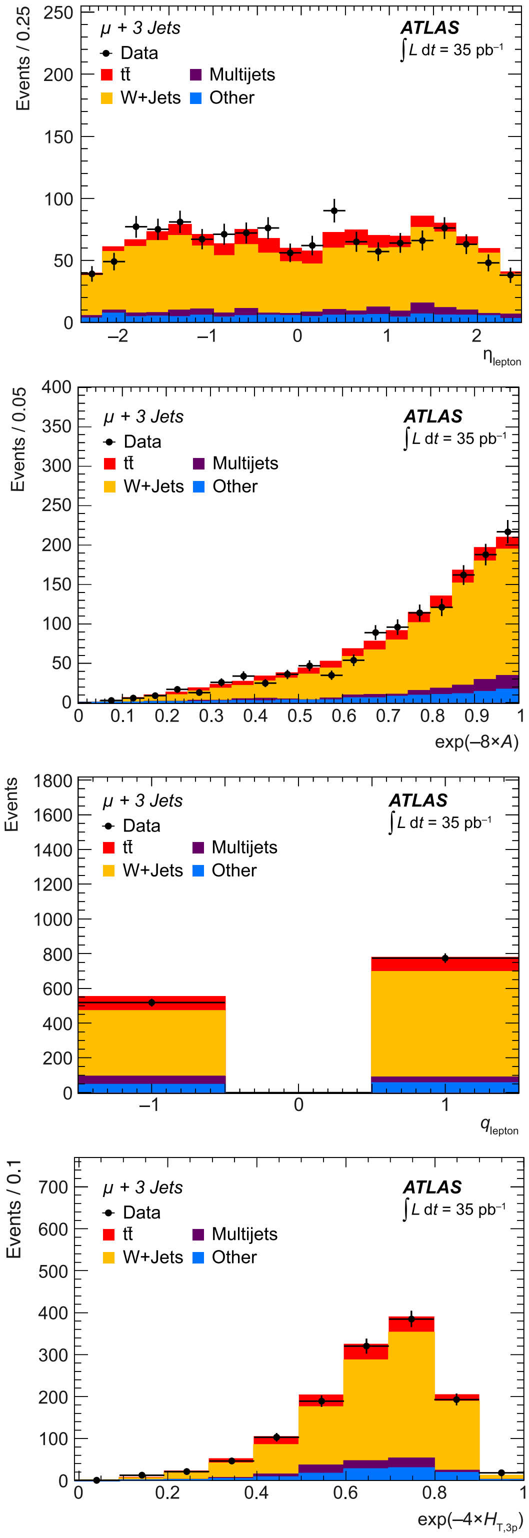

Fig. 1. Input variables to the likelihood discriminants in the exclusive three-jet bin for the muon channel: lepton η (top), $\exp(-8 \times \mathcal{A})$ (second from top), lepton charge (third from top) and $\exp(-4 \times H_{\mathrm{T},3p})$ (bottom). All simulated processes are normalised to theoretical SM predictions, except the multijet background which uses the normalisation presented in Section 6. The two top distributions are used in the untagged and the tagged analyses, the third distribution in the untagged analysis, and the bottom distribution in the tagged analysis.

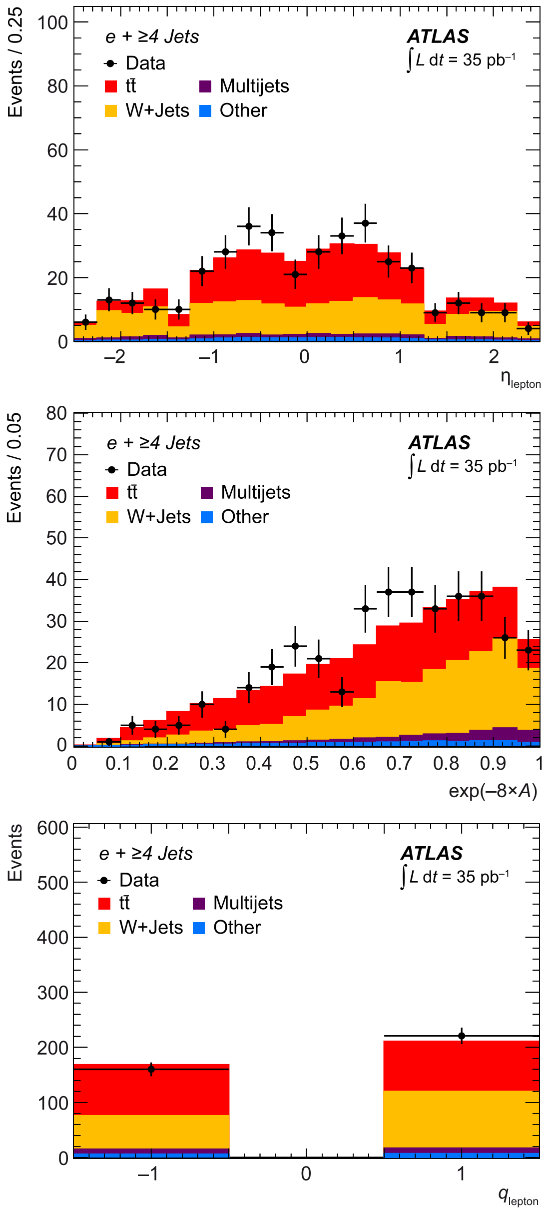

Fig. 2. Input variables to the likelihood discriminants in the inclusive four-jet bin for the electron channel: lepton η (top), $\exp(-8 \times \mathcal{A})$ (middle) and lepton charge (bottom). All simulated processes are normalised to theoretical SM predictions, except the multijet background which uses the normalisation presented in Section 6. These distributions are used in the untagged analysis.

They were required to satisfy $p_T > 20$ GeV and $|\eta_{\mathrm{cluster}}| < 2.47$, where η_{cluster} is the pseudorapidity of the cluster associated with the candidate. Candidates in the barrel to endcap calorimeter transition region $1.37 < |\eta_{\mathrm{cluster}}| < 1.52$ were excluded. Muon candidate tracks were reconstructed from track segments in the different layers of the muon chambers. These segments were combined starting from the outermost layer, with a procedure that takes material effects into account, and matched with tracks found in the inner detector. The final candidates were refitted using the complete track information from both detector systems and required to satisfy $p_T > 20$ GeV and $|\eta| < 2.5$.

To further reduce background from leptons produced in heavy-flavour or in-flight hadron decays the selected leptons were required to be 'isolated'. For electrons the transverse momentum, E_T, deposited in the calorimeter cells inside an isolation cone of

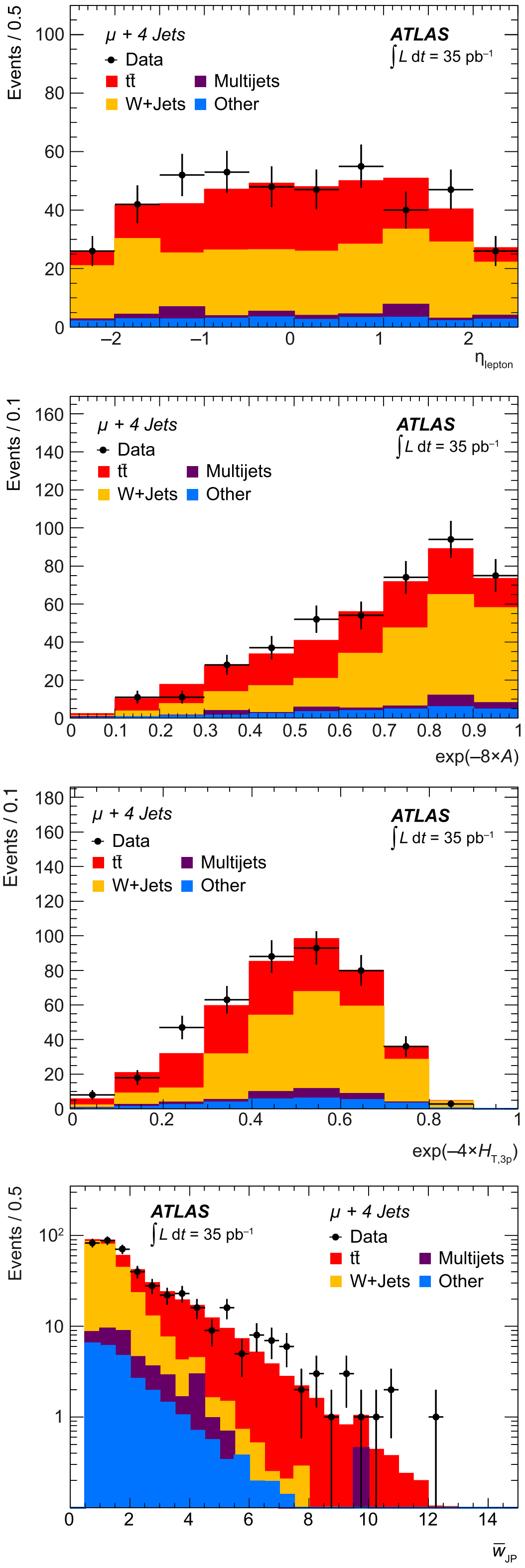

Fig. 3. Input variables to the likelihood discriminants in the exclusive four-jet bin for the muon channel: lepton η (top), $\exp(-8 \times \mathcal{A})$ (second from top), $\exp(-4 \times H_{\mathrm{T},3p})$ (third from top) and $\overline{w}_{\mathrm{JP}}$ (bottom). All simulated processes are normalised to theoretical SM predictions, except the multijet background which uses the normalisation presented in Section 6. These distributions are used in the tagged analysis.

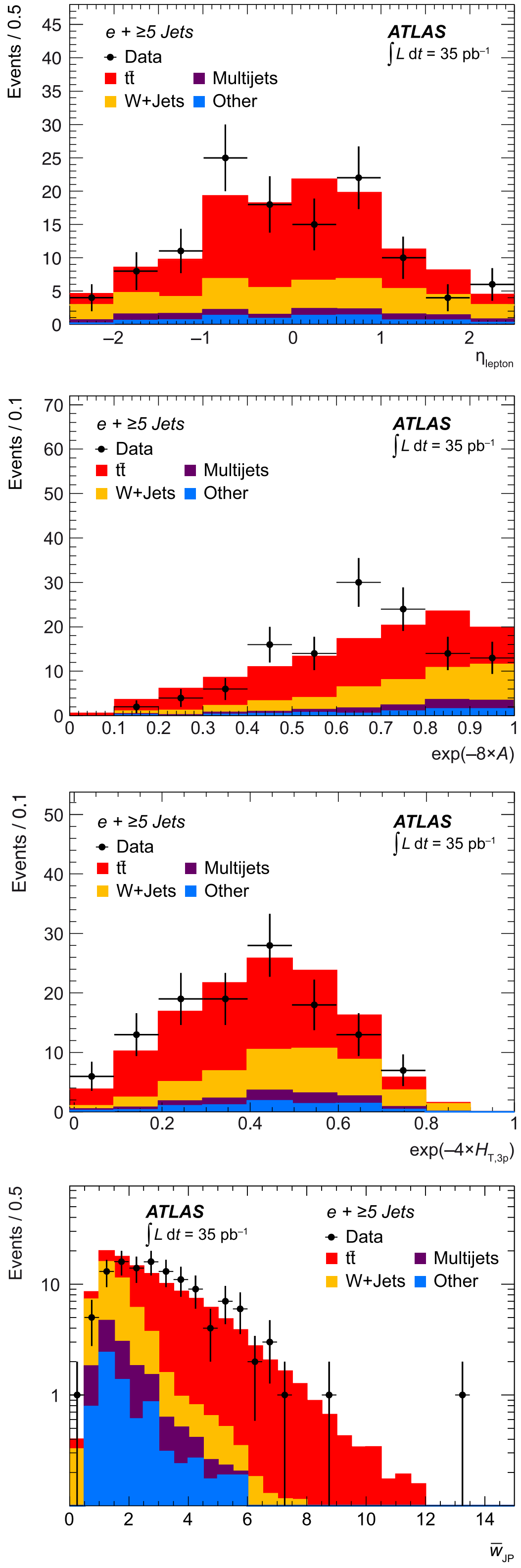

Fig. 4. Input variables to the likelihood discriminants in the inclusive five-jet bin for the electron channel: lepton η (top), $\exp(-8 \times \mathcal{A})$ (second from top), $\exp(-4 \times H_{\mathrm{T},3p})$ (third from top) and $\overline{w}_{\mathrm{JP}}$ (bottom). All simulated processes are normalised to theoretical SM predictions, except the multijet background which uses the normalisation presented in Section 6. These distributions are used in the tagged analysis.

size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ around the electron position was corrected to take into account the leakage of the electron energy into this cone. The remaining E_T was required to be less than 4 GeV. Muons were required to have a distance ΔR greater than 0.4 from any jet with $p_T > 20$ GeV, which suppresses muons from heavy-flavour decays inside jets. Furthermore, the calorimeter transverse momentum in a cone of size $\Delta R = 0.3$ around the muon direction was required to be less than 4 GeV, and the sum of track transverse momenta, other than the muon track, in a cone of size $\Delta R = 0.3$ was required to be less than 4 GeV.

Pure samples of prompt muons and electrons were obtained from Z-boson events in the data and were used to correct the lepton trigger, and the reconstruction and selection efficiencies in MC simulation to match those in the data. The corrections were found to be small.

Jets were reconstructed [34] with the anti-k_t algorithm [35, 36] with radius parameter 0.4 from clusters of adjacent calorimeter cells. If the closest object to an electron candidate (before the above electron isolation requirement) was a jet within a distance $\Delta R < 0.2$, the jet was removed. The jet energy scale (JES) and its uncertainty were derived by combining information from test-beam data, LHC collision data and simulation. The JES uncertainty was found to vary from 2% to 7% as a function of jet p_T and η [37].

Jets arising from the hadronisation of b-quarks were identified using an algorithm (JetProb) [38] which relies upon the transverse impact parameter d_0 of each track in the jet: this is the distance of closest approach in the transverse x–y plane of a track to the primary vertex. It is signed with respect to the jet direction: the sign is positive if the track crosses the jet axis in front of the primary vertex, negative otherwise. The signed impact parameter significance, d_0/σ_{d_0}, of each selected track is compared to a resolution function for prompt tracks, to assess the probability that the track originates from the primary vertex. Here, σ_{d_0} is the uncertainty on d_0. The individual track probabilities are then combined into a global probability that the jet originates from the primary vertex. The simulated data were smeared to reproduce the resolution found in collision data.

The b-tagging efficiencies and mistag rates were calibrated with data for a wide range of b-tagging efficiency requirements. The efficiency was measured in a sample of jets containing muons, making use of the transverse momentum of the muon relative to the jet axis. The mistag rates were measured on an inclusive jet sample with two methods, one using the invariant mass spectrum of tracks associated to reconstructed secondary vertices to separate light- and heavy-flavour jets, and the other based on the fraction of secondary vertices in data with negative decay-length significance. The results of these measurements were applied in the form of p_T-dependent scale factors to correct the b-tagging performance in simulation to match the data. For a b-tagging efficiency around 50%, the scale factor was found to be approximately 0.9 in all bins of jet p_T, and the relative b-tagging efficiency uncertainty was found to range from 5% to 14% depending on the jet p_T [38]. The mistag rate and mistag scale factors are approximately 1% and 1.1, respectively, in the jet p_T region of interest, $20 < p_T < 100$ GeV. The analysis including b-tagging used the probabilities returned by the JetProb algorithm as a discriminating variable, as explained in Section 7.

The reconstruction of the missing transverse momentum E_T^{miss} [39] was based upon the vector sum of the transverse momenta of the reconstructed objects (electrons, muons, jets) as well as the transverse energy deposited in calorimeter cells not associated with these objects. The electrons, muons and jets were used in the E_T^{miss} calculation consistently with the definitions and uncertainties stated above.

Table 1

Number of observed events in the data in the electron and muon channels after the selection cuts as a function of the jet multiplicity. The expected signal and background contributions are also given. All simulated processes are normalised to theoretical SM predictions, except the multijet background which uses the normalisation presented in Section 6. The quoted uncertainties include statistical, systematic and theoretical components, except for the multijet background. All numbers correspond to an integrated luminosity of 35 pb^{-1}.

Electron channel	3 jets	4 jets	$\geqslant$ 5 jets
$t\bar{t}$	117 ± 16	109 ± 15	76 ± 19
$W +$ jets	524 ± 225	124 ± 77	35 ± 23
Multijet	64 ± 32	12 ± 6	8 ± 4
Single top	21 ± 5	7 ± 3	3 ± 2
$Z +$ jets	60 ± 28	21 ± 15	8 ± 6
Diboson	9 ± 3	1.9 ± 1.5	0.4 ± 0.8
Predicted	795 ± 236	275 ± 84	130 ± 35
Observed	755	261	123

Muon channel	3 jets	4 jets	$\geqslant$ 5 jets
$t\bar{t}$	165 ± 22	156 ± 18	108 ± 27
$W +$ jets	976 ± 414	222 ± 139	58 ± 38
Multijet	79 ± 24	18 ± 6	11 ± 3
Single top	31 ± 7	10 ± 4	4 ± 2
$Z +$ jets	58 ± 26	14 ± 10	5 ± 4
Diboson	16 ± 4	3 ± 2	0.6 ± 0.8
Predicted	1325 ± 422	423 ± 143	186 ± 51
Observed	1289	436	190

5. Event selection

Events that passed the trigger selection were required to contain exactly one reconstructed lepton with $p_T > 20$ GeV, matching the corresponding event filter object. Selected events were required to have at least one reconstructed primary vertex with at least five tracks. Events were discarded if any jet with $p_T > 20$ GeV was identified to be due to calorimeter noise or activity out of time with respect to the LHC beam crossings. The E_T^{miss} was required to be greater than 35 (20) GeV in the electron (muon) channel and the transverse mass constructed from the lepton and E_T^{miss} transverse momentum vectors was required to be greater than 25 GeV ($60 \text{ GeV} - E_T^{\text{miss}}$) in the electron (muon) channel. The muon requirement is referred to as the 'triangular cut'. The requirements were stronger in the electron channel to suppress the larger multijet background. Finally, events were required to have three or more jets with $p_T > 25$ GeV and $|\eta| < 2.5$. The selected events were then classified by the number of jets fulfilling these requirements and by the lepton flavour. Table 1 shows the number of selected events in the data in the electron and muon channels, together with the SM expectations for the signal and the different backgrounds. All predictions were obtained from MC simulation except the multijet background estimate which was obtained from data as described in the next section.

6. Background evaluation

The main backgrounds to $t\bar{t}$ signal events in the single lepton plus jets channel arise from W-boson production in association with jets, in which the W decays leptonically, and from multijet production. Smaller backgrounds arise from $Z +$ jets, diboson and single-top production. These smaller backgrounds have been estimated from MC simulation and normalised to the latest theoretical predictions, as discussed in Section 3.

The $W +$ jets background is difficult to predict from theory, particularly in the high jet-multiplicity bins. A data-driven cross-check following methods similar to those described in Ref. [8] was therefore performed. The results obtained with data were found to agree with the MC predictions within the uncertainties. Both analyses presented here rely on the assumption that the MC simulation correctly describes the kinematic properties of the $W+\text{jets}$ events, whereas the normalisation of the $W+\text{jets}$ cross-section was fitted from the data, as described in Section 7. In the analysis using b-tagging the theoretical uncertainty on the normalisation was used as a constraint in the fit, whereas in the other analysis it was allowed to vary freely.

The multijet background was measured with a data-driven approach. In the muon channel, the background from multijet events is dominated by 'non-prompt' muons arising from the decay of heavy-flavour hadrons, in contrast to the $t\bar{t}$ signal where muons arise from the 'prompt' decays of W-bosons. The multijet background can be estimated by defining two samples of muons, 'loose' and 'tight'. The tight sample is the one defined in the event selection described above, whilst the loose sample satisfies the same criteria *except* the muon isolation requirements. Since the reconstructed muons from background are associated with jets, they tend to be much less isolated than the leptons in $t\bar{t}$ decays. Any sample of muons is composed of prompt and non-prompt muons and it is assumed that the tight muon sample is a subsample of the loose sample:

$$N^{\text{loose}} = N^{\text{loose}}_{\text{prompt}} + N^{\text{loose}}_{\text{non-prompt}},$$

$$N^{\text{tight}} = \epsilon_{\text{prompt}} N^{\text{loose}}_{\text{prompt}} + \epsilon_{\text{non-prompt}} N^{\text{loose}}_{\text{non-prompt}}, \qquad (1)$$

where $N^{\text{loose}}_{\text{non-prompt}}$ is the number of loose, non-prompt muons (with the other N^x_y's defined similarly) and ϵ_{prompt} ($\epsilon_{\text{non-prompt}}$) represents the probability for a prompt (non-prompt) muon that satisfies the loose criteria to also satisfy the tight ones. The probability ϵ_{prompt} was measured from the data using high-purity samples dominated by Z-bosons decaying into muons. The probability $\epsilon_{\text{non-prompt}}$ for a non-isolated lepton to pass the isolation cuts was measured by defining control samples dominated by multijet events. Two different control samples were defined to have at least one jet plus a muon (i) with high impact parameter significance or (ii) with low transverse mass of the muon-E_T^{miss} system plus reversed triangular cut. These control samples gave consistent results. Contamination of the multijet control samples by muons from W and Z events was determined from MC simulation. The results of these studies are $\epsilon_{\text{non-prompt}}$ and ϵ_{prompt} as a function of the muon η, from which the multijet background expectations can be obtained as a function of any variable. A 30% systematic uncertainty was assigned to this estimate based on the observation that the method gives agreement to within 30% across the different jet multiplicities.

In the electron channel, the multijet background also includes photons inside jets undergoing conversions into electron–positron pairs and jets with high electromagnetic fractions. A different method was used, based on a binned likelihood fit of the E_T^{miss} distribution in the region $E_T^{\text{miss}} < 35$ GeV. The data was fitted to the sum of four templates: multijet, $t\bar{t}$, $W+\text{jets}$ and $Z+\text{jets}$. The templates for the latter three processes were obtained from MC simulation whereas the multijet template was obtained from the data in a control region defined by the full event selection criteria except that the electron candidate fails one or more of the identification cuts. The multijet background was obtained by extrapolating the fraction of multijet events from the fit at low E_T^{miss} to the signal region at high E_T^{miss}. Several choices of electron identification cuts were considered and the largest relative uncertainty among these (50%) was used as a conservative estimate of the systematic uncertainty of this background evaluation.

7. Cross-section extraction

The $t\bar{t}$ production cross-section was extracted by exploiting the kinematical properties of $t\bar{t}$ events compared to those from the dominant background ($W+\text{jets}$) by means of likelihood discriminants (D) constructed from several variables. Templates of the distributions D for signal and all background samples were created using the TMVA package [40]. The variables were selected for their good discriminating power, small correlation with each other, and low sensitivity to potentially large uncertainties such as jet energy calibration. The variables are:

- The pseudorapidity η of the lepton, since leptons produced in $t\bar{t}$ events are more central than those in $W+\text{jet}$ events.
- The aplanarity $\mathcal{A}$, defined as 3/2 times the smallest eigenvalue of the momentum tensor $M_{ij} = \sum_{k=1}^{N_{\text{objects}}} p_{ik} p_{jk} / \sum_{k=1}^{N_{\text{objects}}} p_k^2$, where p_{ik} is the i-th momentum component of the k-th object and p_k is the modulus of its momentum. The lepton and the four leading jets are the objects included in the sum. To increase the separation power of the aplanarity distribution, the transformed variable $\exp(-8 \times \mathcal{A})$ was used. This variable exploits the fact that $t\bar{t}$ events are more isotropic than $W+\text{jets}$ events.
- The charge of the lepton q_{lepton}, which uses the fact that a sample of $t\bar{t}$ events should contain the same number of positively and negatively charged leptons, while $W+\text{jet}$ events produce an excess of positively charged leptons in pp collisions.
- $H_{\text{T},3p}$, defined as the sum of the transverse energies of the third and fourth leading jets normalised to the sum of the absolute values of the longitudinal momenta of the four leading jets, the lepton and the neutrino, $H_{\text{T},3p} = \sum_{i=3}^{4} |p_{\text{T},i}^{\text{jet}}| / \sum_{j=1}^{N_{\text{objects}}} |p_{z,j}|$, where p_T is the transverse momentum and p_z the longitudinal momentum. The longitudinal momentum of the neutrino was obtained using the quadratic W mass constraint and taking the solution with the smaller neutrino p_z value. To increase the separation power of the $H_{\text{T},3p}$ distribution, the transformed variable $\exp(-4 \times H_{\text{T},3p})$ was used.
- The average $\overline{w}_{\text{JP}}$ of $w_{\text{JP}} = -\log_{10} P_l$ for the two jets with lowest P_l in the event. P_l is the probability for a jet to be a light jet from the JetProb b-tagging algorithm. These correspond to the jets that have the highest probability to be heavy-flavour jets.

Two complementary analyses were performed, one which relied upon the use of b-tagging information (i.e. the variable $\overline{w}_{\text{JP}}$) and one which did not. We refer to the analyses as 'tagged' and 'untagged', respectively. The untagged analysis employed the first three variables, whereas the tagged analysis did not consider the lepton charge but used $H_{T,3p}$ and $\overline{w}_{\text{JP}}$. $\overline{w}_{\text{JP}}$ was not included in the three-jet bin. Figs. 1 to 4 show the distributions of the discriminating variables for the selected data superimposed on the signal and background SM predictions for the different jet multiplicities.

The $t\bar{t}$ cross-section was extracted by means of a likelihood fit of the signal and background discriminant distributions to those of the data. The fit yields the fractions of $t\bar{t}$ signal and backgrounds in the data sample. The fit was performed simultaneously to four samples (three-jet exclusive and four-jet inclusive, electron and muon) in the untagged analysis and six samples (three-jet exclusive, four-jet exclusive and five-jet inclusive, electron and muon) in the tagged analysis, as these were the combinations that provided maximum sensitivity. The discriminants were built separately for each jet multiplicity and lepton flavour subsample, and the different channels were combined in the likelihood fit by multiplying the individual likelihood functions.

The normalisation of the $t\bar{t}$ signal templates is the parameter of interest in the fit and was allowed to vary freely in both analyses. The $t\bar{t}$ cross-section was assumed to be common to all channels and the number of $t\bar{t}$ events in each subsample returned by the fit was related to the $t\bar{t}$ cross-section by the expression $\sigma_{t\bar{t}} = N_{\mathrm{sig}}/(\int \mathcal{L}\,dt \times \epsilon_{\mathrm{sig}})$, where N_{sig} is the number of $t\bar{t}$ events, $\int \mathcal{L}\,dt$ is the integrated luminosity and ϵ_{sig} is the product of the signal acceptance, selection efficiency and branching ratio, obtained from $t\bar{t}$ simulation. The normalisation of the backgrounds was treated differently in the two analyses. In the untagged analysis the multijet and small backgrounds (single-top, diboson and $Z+$jets production) were fixed in the fit to their expected contributions, whereas the $W+$jets background was allowed to vary freely in each channel. In the tagged analysis all backgrounds were allowed to vary within the uncertainties of their assumed cross-sections, described in Sections 3 and 6. These uncertainties were used as Gaussian constraints on the cross-section normalisation. The robustness of this fitting approach was checked with ensemble tests. The central value and uncertainties returned by the fit were shown to be unbiased for a wide range of input cross-sections.

8. Systematic uncertainties

The evaluation of the systematic uncertainties was performed differently in the two analyses. The untagged analysis performed pseudo-experiments (PEs) with simulated samples which included the various sources of uncertainty. For example, for the JES uncertainty, PEs were performed with jet energies scaled up and down according to their uncertainties and the impact on the cross-section was evaluated. The tagged analysis, on the other hand, accounted for most of the changes in the normalisation and shape of the templates due to systematic uncertainties by adding ‘nuisance’ terms to the fit [41]. Templates of the samples with one standard deviation ’up’ and ’down’ variations of the systematic uncertainty source under study were generated in addition to the nominal templates. The fit interpolated between these templates with a continuous parameter by means of a Gaussian constraint. Before the fit, the constraint was such that the mean value was zero and the width was one; a fitted width less than one means that the data were able to constrain that particular source of uncertainty. The effects due to the modelling of the $W+$jets and multijet background shapes, initial and final state radiation, parton density function of the $t\bar{t}$ signal, NLO generator, hadronisation and template statistics cannot be fully described by a simple linear parameter controlling the template interpolation. As a consequence, they were not treated as nuisance terms but obtained by performing PEs with modified simulated samples, as was done in the untagged analysis.

The nuisance parameters of the systematic uncertainties were all fitted together taking into account the correlations among them in the minimisation process. As a consequence, the uncertainties on the fitted quantities obtained from the fit include both the statistical and the total systematic components. Therefore, to obtain an estimation of the individual contributions to the total uncertainty in the tagged analysis, each individual systematic uncertainty was obtained as the difference in quadrature between the total uncertainty and the uncertainty obtained after having fixed the corresponding nuisance parameter to its fitted value. The central values of the nuisance parameters after the fit agreed with their input values. The fit was cross-checked using PEs where the starting value of the nuisance parameters was different than the nominal value. The result was found to be unbiased. In addition, large variations of the kinematic dependence of the nuisance parameters (e.g. the JES as a function of the jet p_T) were considered and resulted in a negligible impact on the result of the fit.

Table 2

Statistical and systematic uncertainties on the measured $t\bar{t}$ cross-section in the untagged and tagged analyses. Multijet and small backgrounds normalisation uncertainties are already included in the statistical uncertainty (a/i) in the tagged analysis. $W+$jets heavy-flavour content and b-tagging calibration do not apply (n/a) to the untagged analysis. The luminosity uncertainty is not included in the table.

Method	Untagged		Tagged	
Statistical Error (%)	+10.1	−10.1	+5.8	−5.7
Object selection (%)				
JES and jet energy resolution	+4.1	−5.4	+3.9	−2.9
Lepton reconstruction, identification and trigger	+1.7	−1.6	+2.1	−1.8
Background modelling (%)				
Multijet shape	+3.5	−3.5	+0.8	−0.8
Multijet normalisation	+1.1	−1.2	a/i	
Small backgrounds norm.	+0.6	−0.6	a/i	
$W+$jets shape	+3.9	−3.9	+1.0	−1.0
$W+$jets heavy-flavour content	n/a		+2.7	−2.4
b-tagging calibration	n/a		+4.1	−3.8
$t\bar{t}$ signal modelling (%)				
ISR/FSR	+6.3	−2.1	+5.2	−5.2
NLO generator	+3.3	−3.3	+4.2	−4.2
Hadronisation	+2.1	−2.1	+0.4	−0.4
PDF	+1.8	−1.8	+1.5	−1.5
Others (%)				
Simulation of pile-up	+1.2	−1.2	< 0.1	
Template statistics	+1.3	−1.3	+1.1	−1.1
Systematic Error (%)	+10.5	−9.4	+9.7	−9.0

The systematic uncertainties on the cross-section for both methods are summarised in Table 2. The dominant effects in the untagged analysis were JES, multijet and $W+$jets backgrounds shape and ISR/FSR. The latter was also important in the tagged analysis, together with the uncertainty related to the signal MC generator. In addition, this analysis was sensitive to effects related to b-tagging, specifically the determination of the heavy-flavour content of the $W+$jets background and the calibration of the b-tagging algorithm itself. The luminosity uncertainty was 3.4% [42,43].

Several cross-checks of the cross-section measurements were performed. These included the results of the likelihoods applied to individual lepton channels and $t\bar{t}$ cross-section measurements done with simpler and complementary approaches, including cut-and-count methods and fits to kinematic variables such as the reconstructed top mass. These cross-checks gave consistent results within the uncertainties.

9. Results and conclusions

The results of the likelihood fits applied to the data are shown in Figs. 5 and 6, where the distributions of the discriminants in data are overlaid on the fitted discriminant distributions of the signal and backgrounds. The final measured cross-section results are: $\sigma_{t\bar{t}} = 173 \pm 17(\text{stat.})^{+18}_{-16}(\text{syst.}) \pm 6(\text{lumi.})\ \text{pb} = 173^{+25}_{-24}$ pb in the untagged analysis and $\sigma_{t\bar{t}} = 187 \pm 11(\text{stat.})^{+18}_{-17}(\text{syst.}) \pm 6(\text{lumi.})\ \text{pb} = 187^{+22}_{-21}$ pb in the tagged analysis. The two measurements are in agreement with each other. The latter has a better a priori sensitivity and thus constitutes the main result of this Letter. It is the most precise $t\bar{t}$ cross-section measurement at the LHC published to date and is in good agreement with the SM prediction calculated at NLO plus next-to-leading-log order 165^{+11}_{-16} pb [1–3].

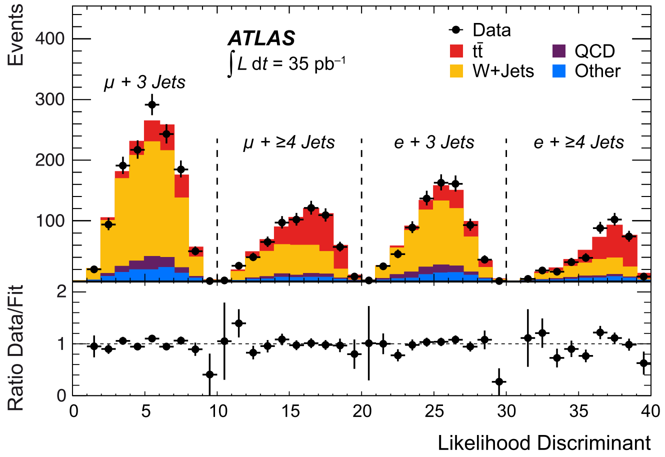

Fig. 5. Untagged analysis: (Top) The distribution of the likelihood discriminant for data superimposed on expectations for signal and backgrounds, scaled to the results of the fit. The left bins correspond to the muon channel and the right bins to the electron channel. (Bottom) The ratio of data to fit result.

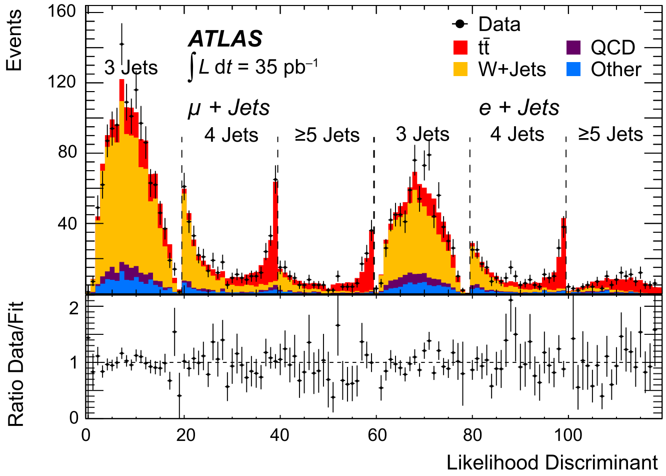

Fig. 6. Tagged analysis: (Top) The distribution of the likelihood discriminant for data superimposed on expectations for signal and backgrounds, scaled to the results of the fit. The left bins correspond to the muon channel and the right bins to the electron channel. (Bottom) The ratio of data to fit result.

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M. zur Nedden [15], V. Zutshi [105], 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 Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain*
[12] *(a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, 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) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de 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) School of Physics, 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] *AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, 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] *(a) E. Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, 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 Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*
[60] *Department of Physics, Indiana University, Bloomington, IN, United States*
[61] *Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
[62] *University of Iowa, Iowa City, IA, United States*
[63] *Department of Physics and Astronomy, Iowa State University, Ames, IA, United States*
[64] *Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia*
[65] *KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
[66] *Graduate School of Science, Kobe University, Kobe, Japan*
[67] *Faculty of Science, Kyoto University, Kyoto, Japan*
[68] *Kyoto University of Education, Kyoto, Japan*
[69] *Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
[70] *Physics Department, Lancaster University, Lancaster, United Kingdom*
[71] *(a) INFN Sezione di Lecce; (b) Dipartimento di Fisica, Università del Salento, Lecce, Italy*
[72] *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[73] *Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia*
[74] *School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*

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

[150] *Institute of Physics, Academia Sinica, Taipei, Taiwan*
[151] *Department of Physics, Technion - Israel Inst. of Technology, Haifa, Israel*
[152] *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
[153] *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
[154] *International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan*
[155] *Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
[156] *Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
[157] *Department of Physics, University of Toronto, Toronto, ON, Canada*
[158] *(a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto, ON, Canada*
[159] *Institute of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan*
[160] *Science and Technology Center, Tufts University, Medford, MA, United States*
[161] *Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia*
[162] *Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States*
[163] *(a) INFN Gruppo Collegato di Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy*
[164] *Department of Physics, University of Illinois, Urbana, IL, United States*
[165] *Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
[166] *Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain*
[167] *Department of Physics, University of British Columbia, Vancouver, BC, Canada*
[168] *Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada*
[169] *Waseda University, Tokyo, Japan*
[170] *Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel*
[171] *Department of Physics, University of Wisconsin, Madison, WI, United States*
[172] *Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*
[173] *Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
[174] *Department of Physics, Yale University, New Haven, CT, United States*
[175] *Yerevan Physics Institute, Yerevan, Armenia*
[176] *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 TRIUMF, Vancouver, BC, Canada.
[e] Also at Department of Physics, California State University, Fresno, CA, United States.
[f] Also at Novosibirsk State University, Novosibirsk, Russia.
[g] Also at Fermilab, Batavia, IL, United States.
[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 Department of Physics and Astronomy, University College London, London, United Kingdom.
[n] Also at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.
[o] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[p] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[q] Also at Manhattan College, New York, NY, United States.
[r] Also at School of Physics, Shandong University, Shandong, China.
[s] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
[t] Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
[u] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
[v] Also at Section de Physique, Université de Genève, Geneva, Switzerland.
[w] Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
[x] Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
[y] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
[z] Also at California Institute of Technology, Pasadena, CA, United States.
[aa] Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
[ab] Also at Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China.
[ac] Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
[ad] Also at Department of Physics, Oxford University, Oxford, United Kingdom.
[ae] Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
[af] Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.
[ag] 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.
[ah] Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
[*] Deceased.