



Letter

# Measurement of vector boson production cross sections and their ratios using $pp$ collisions at $\sqrt{s} = 13.6$ TeV with the ATLAS detector

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## ABSTRACT

Fiducial and total  $W^\pm$  and  $Z$  boson cross sections, their ratios and the ratio of top-antitop-quark pair and  $W$ -boson fiducial cross sections are measured in proton–proton collisions at a centre-of-mass energy of  $\sqrt{s} = 13.6$  TeV, corresponding to an integrated luminosity of  $29 \text{ fb}^{-1}$  of data collected in 2022 by the ATLAS experiment at the Large Hadron Collider. The measured fiducial cross-section values for  $W^+ \rightarrow \ell^+ \nu$ ,  $W^- \rightarrow \ell^- \bar{\nu}$ , and  $Z \rightarrow \ell^+ \ell^-$  ( $\ell = e$  or  $\mu$ ) boson productions are  $4250 \pm 150 \text{ pb}$ ,  $3310 \pm 120 \text{ pb}$ , and  $744 \pm 20 \text{ pb}$ , respectively, where the uncertainty is the total uncertainty, including that arising from the luminosity of about 2.2%. The measurements are in agreement with Standard-Model predictions calculated at next-to-next-to-leading-order in  $\alpha_s$ , next-to-next-to-leading logarithmic accuracy and next-to-leading-order electroweak accuracy.

## 1. Introduction

Precision measurements of the  $W^\pm$  and  $Z$  cross sections and their ratios at the Large Hadron Collider (LHC) provide an excellent probe of quantum chromodynamics (QCD) and of the proton structure. Measurements of  $W^\pm$  and  $Z$  cross sections have been performed by the ATLAS Collaboration [1] at centre-of-mass energies of 2.76 TeV [2], 5 TeV [3], 7 TeV [4], 8 TeV [5,6], and 13 TeV [7,8] and by the CMS [9] Collaboration at centre-of-mass energies of 7 TeV [10,11], 8 TeV [12,13], and 13 TeV [14]. The experimental precision of such measurements performed within the fiducial region defined by the detector acceptance has reached percent level, with sub-percent level precision for cross-section ratios.

In this letter, measurements of the inclusive fiducial and total cross sections of  $W^+ \rightarrow \ell^+ \nu$ ,  $W^- \rightarrow \ell^- \bar{\nu}$ , their ratio, and their ratios to the  $Z \rightarrow \ell^+ \ell^-$  cross section are presented. The measurements are made at an increased LHC centre-of-mass energy of 13.6 TeV, using a data sample corresponding to  $29 \text{ fb}^{-1}$ , with  $\ell$  referring to muons or electrons. The fiducial cross section for  $Z \rightarrow \ell^+ \ell^-$  production in the same data sample from this analysis has been published together with the top-antitop-quark pair  $t\bar{t}$  production cross section and their ratio in

Ref. [15]. Here, the first measurement of the ratios between  $t\bar{t}$  and  $W^\pm$ -boson fiducial cross sections in the same data sample is also presented to probe different parton densities of the proton.

The measurements are performed by using profile-likelihood (PLH) fits [16] to the inclusive data in the four fiducial single-lepton channels  $W^+ \rightarrow e^+ \nu$ ,  $W^+ \rightarrow \mu^+ \nu$ ,  $W^- \rightarrow e^- \bar{\nu}$ , and  $W^- \rightarrow \mu^- \bar{\nu}$ , and the two fiducial dilepton channels  $Z \rightarrow e^+ e^-$  and  $Z \rightarrow \mu^+ \mu^-$  to extract the  $W$  and  $Z$  boson cross sections, and their ratios  $\sigma_{W^+ \rightarrow \ell^+ \nu}$ ,  $\sigma_{W^- \rightarrow \ell^- \bar{\nu}}$ ,  $\sigma_{W^\pm \rightarrow \ell \nu}$ ,  $\sigma_{Z \rightarrow \ell^+ \ell^-}$ ,  $R_{W^\pm/Z}$ , and  $R_{W^+/W^-}$ . Similarly, combined fits of the four  $W$ -boson channels, the two  $Z$ -boson channels, and the two  $t\bar{t}$  channels from Ref. [15] are used to extract the cross-section ratios  $R_{t\bar{t}/W^\pm}$ ,  $R_{t\bar{t}/W^+}$ , and  $R_{t\bar{t}/W^-}$ .

The measurements are compared with theoretical predictions calculated at next-to-next-to-leading-order (NNLO). The predictions are supplemented by the resummation of logarithmically enhanced contributions in the low transverse-momentum region of the lepton pairs at next-to-next-to-leading-logarithmic (NNLL) accuracy in QCD, plus next-to-leading-order (NLO) electroweak (EW) accuracy, using various state-of-the-art parton distribution functions (PDFs). The dependence of the cross sections on the centre-of-mass energy is also tested.

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<sup>1</sup> ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the  $z$ -axis along the beam pipe. The  $x$ -axis points from the IP to the centre of the LHC ring, and the  $y$ -axis points upwards. Polar coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the  $z$ -axis. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$  and is equal to the rapidity  $y = \frac{1}{2} \ln \left( \frac{E+p_z c}{E-p_z c} \right)$  in the relativistic limit. Angular distance is measured in units of  $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$ .

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## 2. The ATLAS detector

The ATLAS experiment [1,17] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near  $4\pi$  coverage in solid angle.<sup>1</sup> It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range  $|\eta| < 2.5$ . It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAR) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity within the region  $|\eta| < 3.2$ . A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ( $|\eta| < 1.7$ ). The endcap and forward regions are instrumented with LAR calorimeters for EM and hadronic energy measurements up to  $|\eta| = 4.9$ . The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 Tm across most of the detector. The muon spectrometer includes a system of precision tracking chambers up to  $|\eta| = 2.7$  and fast detectors for triggering up to  $|\eta| = 2.4$ . The luminosity is measured mainly by the LUCID-2 detector [18] which is located close to the beampipe. A two-level trigger system is used to select events [19]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 3 kHz on average, depending on the data-taking conditions. A software suite [20] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

## 3. Data and MC samples

The analysis is performed using data collected in 2022, the first year of the Run 3 data taking period, by the ATLAS detector in  $pp$  collisions at  $\sqrt{s} = 13.6$  TeV, corresponding to an integrated luminosity of  $29.0 \pm 0.6 \text{ fb}^{-1}$  [21], after applying data-quality requirements [22].

Monte Carlo (MC) simulated events are used to optimise the selection, determine all backgrounds except for the multi-jet process, calculate the detector acceptance factor and to perform the final signal-extraction fit.

The production of  $Z$  and  $W$  bosons decaying to  $e$ ,  $\mu$  signal or  $\tau$  background final states was simulated with the SHERPA 2.2.12 generator [23] using NLO matrix elements (MEs) for up to two additional partons, and leading-order (LO) ME for up to five additional partons calculated with the COMIX [23] and OPENLOOPS [24–26] libraries. They were matched with the SHERPA parton shower (PS) [27] using the MEPS@NLO prescription [28] and the set of tuned parameters developed by the SHERPA authors. The NNPDF 3.0 NNLO PDF set [29] was used and the samples were normalised to a NNLO prediction [30].

Samples of diboson final states were simulated with SHERPA 2.2.12, including off-shell effects and Higgs boson contributions where appropriate. Fully leptonic final states and semi-leptonic final states were generated using MEs at NLO accuracy in QCD for up to one additional parton and at LO accuracy for up to three additional parton emissions.

The production of a top-quark pair  $t\bar{t}$  and the associated production of a single top-quark and a  $W$  boson ( $Wt$ ) were modelled using the POWHEGBOX v2 generator [31–34] interfaced to PYTHIA 8.307 [35] with the parton shower tune A14 [36]. The MEs were calculated at NLO precision in QCD using the NNPDF 3.0 NNLO PDF set. The  $t\bar{t}$  sample was normalised to the cross-section prediction at NNLO in perturbative QCD including the resummation of NNLL soft-gluon terms calculated using TOP++ 2.0 [37–43].

The effect of multiple interactions in the same and neighbouring bunch crossings (pile-up) was modelled by overlaying [44] the original hard-scattering event with simulated inelastic  $pp$  events generated by

EPOS 2.0.1.4 [45,46] and PYTHIA 8.307. The events generated with EPOS used the EPOS LHC tune, while the PYTHIA8 events used the NNPDF 2.3 LO PDF set [47] and the A3 tune [48]. The ATLAS detector response was simulated by the GEANT4 toolkit [49] with the full simulation of the ATLAS detector [50]. The simulated samples were then processed with the same software framework as the data.

## 4. Object definition and event selection

Events are selected if they include at least one lepton that is matched to an object identified by a single-lepton trigger. The lowest transverse momentum  $p_T$  threshold in the single-lepton triggers is 26 GeV for electrons and 24 GeV for muons [19,51,52]. Events are also required to have at least one reconstructed collision vertex with two or more associated tracks with  $p_T > 500$  MeV. The vertex with the highest  $\sum p_T^2$  of the associated tracks is taken as the primary vertex.

Electron candidates are reconstructed from clusters in the EM calorimeter matched to charged tracks measured in the ID. The electron candidates are required to satisfy *Tight* identification criteria [53], validated to be still working well for data taking at 13.6 TeV, and to have  $p_T > 27$  GeV and  $|\eta| < 2.47$ , excluding the transition region between the barrel and endcap calorimeters,  $1.37 < |\eta| < 1.52$ .

Muon candidates are reconstructed from tracks in the muon spectrometer matched to tracks from the ID. The muon candidates are required to satisfy *Medium* identification criteria [54], adapted for data taking at 13.6 TeV, with  $p_T > 27$  GeV and  $|\eta| < 2.5$ .

Leptons must originate from the primary vertex by requiring  $|z_0 \sin \theta| < 0.5$  mm, where  $z_0$  is the  $z$ -coordinate of the track at the point of closest approach to the  $z$ -axis. Furthermore, the significance of the transverse impact parameter, defined by the distance of closest approach of the track to the primary vertex point in the  $r - \phi$  projection  $|d_0|$ , divided by its estimated uncertainty  $\sigma(d_0)$ , is required to satisfy  $|d_0|/\sigma(d_0) < 5$  for electrons and  $|d_0|/\sigma(d_0) < 3$  for muons.

To select prompt leptons, tight isolation criteria are imposed on the charged leptons. Requirements are applied on the transverse momentum sum of all ID tracks within a variable cone around the lepton,  $p_T^{\text{varcone30}}$ , where the maximum cone size is  $\Delta R = 0.3$ , shrinking for larger  $p_T$  [53], and on the transverse energy  $E_T^{\text{cone20}}$  in a cone of  $\Delta R = 0.2$  around the lepton:  $p_T^{\text{varcone30}}/p_T < 0.06$  and  $E_T^{\text{cone20}}/p_T < 0.06$  for electrons and  $p_T^{\text{varcone30}}/p_T < 0.04$  and  $E_T^{\text{cone20}}/p_T < 0.15$  for muons.

Jets are used for the calculation of the missing transverse momentum (see below). They are reconstructed using a particle flow algorithm [55] that exploits both calorimeter and ID informations. The anti- $k_r$  algorithm [56,57] with a radius parameter  $R = 0.4$  is used. The jet energy calibration is based on Run 3 simulation and *in-situ* calibration [58], adapted for data taking at 13.6 TeV. Calibrated jet candidates are required to have  $p_T > 20$  GeV for  $|\eta| < 2.5$  and  $p_T > 30$  GeV for  $2.5 < |\eta| < 4.5$ . To suppress jets originating from pile-up, jets with  $p_T$  below 60 GeV are required to satisfy a neural-network-based jet vertex tagger (NNJVT) discriminant, a successor of the jet vertex tagger algorithm [59] used during the Run 2 data taking period in the years 2015 to 2018.

To remove the ambiguity when one physical object is reconstructed as multiple objects, the following algorithm is used, with each operation applied in the given order. If any electron candidate is found sharing a track with any other electron candidates, the candidate with smaller  $p_T$  is removed. Any electron candidate found to share a track with a muon is removed. The closest jet found within a  $\Delta R$  of 0.2 of an electron candidate is removed. Any electron candidate subsequently found within  $\Delta R$  of 0.4 of a jet is removed. Jets with less than three tracks associated to it found within  $\Delta R$  of 0.2 or with a muon inner-detector track ghost-associated to it are removed, then muon candidates found within  $\Delta R$  of 0.4 of a jet are removed.

The missing transverse momentum  $\vec{p}_T^{\text{miss}}$ , with magnitude  $E_T^{\text{miss}}$ , is defined as the negative of the sum of the transverse momenta of the reconstructed and calibrated physical objects, and a soft term built from

**Table 1**  
Summary of the event selection requirements.

Electron selections	$p_T > 27$ GeV $ \eta  < 2.47$ and veto of $1.37 <  \eta  < 1.52$
Muon selections	$p_T > 27$ GeV $ \eta  < 2.5$
$W$ -boson selections	Exactly one lepton $E_T^{\text{miss}} > 25$ GeV $m_T > 50$ GeV
$Z$ -boson selections	Exactly two same flavour opposite charged leptons $66 < m_{\ell\ell} < 116$ GeV

all tracks that are associated with the primary vertex, excluding those used in the physics objects, is also included [60].

The object reconstruction for the  $t\bar{t}$  analysis is described in detail in Ref. [15]. In addition to the objects defined above, jets containing  $b$ -hadrons are identified, using the 77% efficiency working point of the DL1d  $b$ -tagging algorithm [61,62].

The  $Z$ -boson decays into a pair of electrons or muons with opposite electric charge, thus two dilepton channels,  $ee$  and  $\mu\mu$ , are defined. In the case of the  $W$ -boson, the ones decaying into one lepton and a neutrino are considered, so four single lepton channels are defined according to the lepton flavour and electric charge:  $e^-\bar{\nu}$ ,  $e^+\nu$ ,  $\mu^-\bar{\nu}$ , and  $\mu^+\nu$ .

Events in the dilepton channels are required to have exactly two same-flavour leptons (electrons or muons) with opposite electric charge. The invariant mass of the dilepton pairs is required to be in the mass range  $66 < m_{\ell\ell} < 116$  GeV. In the single-lepton channels, events are required to have exactly one identified and isolated lepton,  $E_T^{\text{miss}}$  greater than 25 GeV, and a transverse mass  $m_T^W = \sqrt{2p_T^{\text{miss}}p_T^\ell(1 - \cos \Delta\phi_{\ell\nu})}$  greater than 50 GeV, where  $\Delta\phi_{\ell\nu}$  is the azimuthal angle between the charged lepton transverse momentum  $\vec{p}_T^\ell$  and  $\vec{p}_T^{\text{miss}}$ .

The event selections for the  $W$  and  $Z$  boson analysis are summarised in Table 1. The  $Z \rightarrow \ell\ell$  selection is the same as in Ref. [15] that also describes the event selection for the  $t\bar{t}$  analysis. Selected  $t\bar{t}$  candidates are required to have exactly one electron and one muon of opposite charge. No dilepton mass,  $E_T^{\text{miss}}$  or  $m_T^W$  requirements are imposed but the events are required to have one or two  $b$ -tagged jets.

## 5. Background estimation and yields

Background contributions to the  $W$  and  $Z$  boson final states correspond to two main categories: EW and top-quark processes, estimated by using MC simulations, and the multi-jet (MJ) background, estimated using a data-driven technique.

The EW background contributions include single-boson and diboson productions. The single-boson productions correspond to  $W^\pm \rightarrow \tau^\pm\nu$  and  $Z \rightarrow \tau^+\tau^-$  for both channels, where the subsequent leptonic decays of the  $\tau$  leptons are also treated as background,  $Z \rightarrow e^+e^-$  and  $Z \rightarrow \mu^+\mu^-$  for the  $W$  channels and  $W^\pm \rightarrow e^\pm\nu$  and  $W^\pm \rightarrow \mu^\pm\nu$  for the  $Z$ -boson channels. Diboson productions,  $WW$ ,  $WZ$ , and  $ZZ$  can have similar signatures to  $W$  or  $Z$  events if one of the bosons decays hadronically or invisibly or if leptonic decay products fail to satisfy the object selection. Likewise,  $t\bar{t}$  pair and  $Wt$  production can result in similar signatures to  $W$  or  $Z$  events, if one or two  $W$  bosons decay leptonically. For  $W$ -boson selections, the contribution of both the diboson and top-quark events to the background is small due to the lower production cross section. For  $Z$ -boson selections, all EW background contributions are at sub-percent level.

The MJ background stems from QCD jet production, where particles within the jets are mistakenly identified as prompt isolated leptons. It has major contributions from collimated charged and neutral pions and from non-prompt real leptons produced e.g. in semi-leptonic decays of heavy quarks or in-flight pion decays. Although this type of background

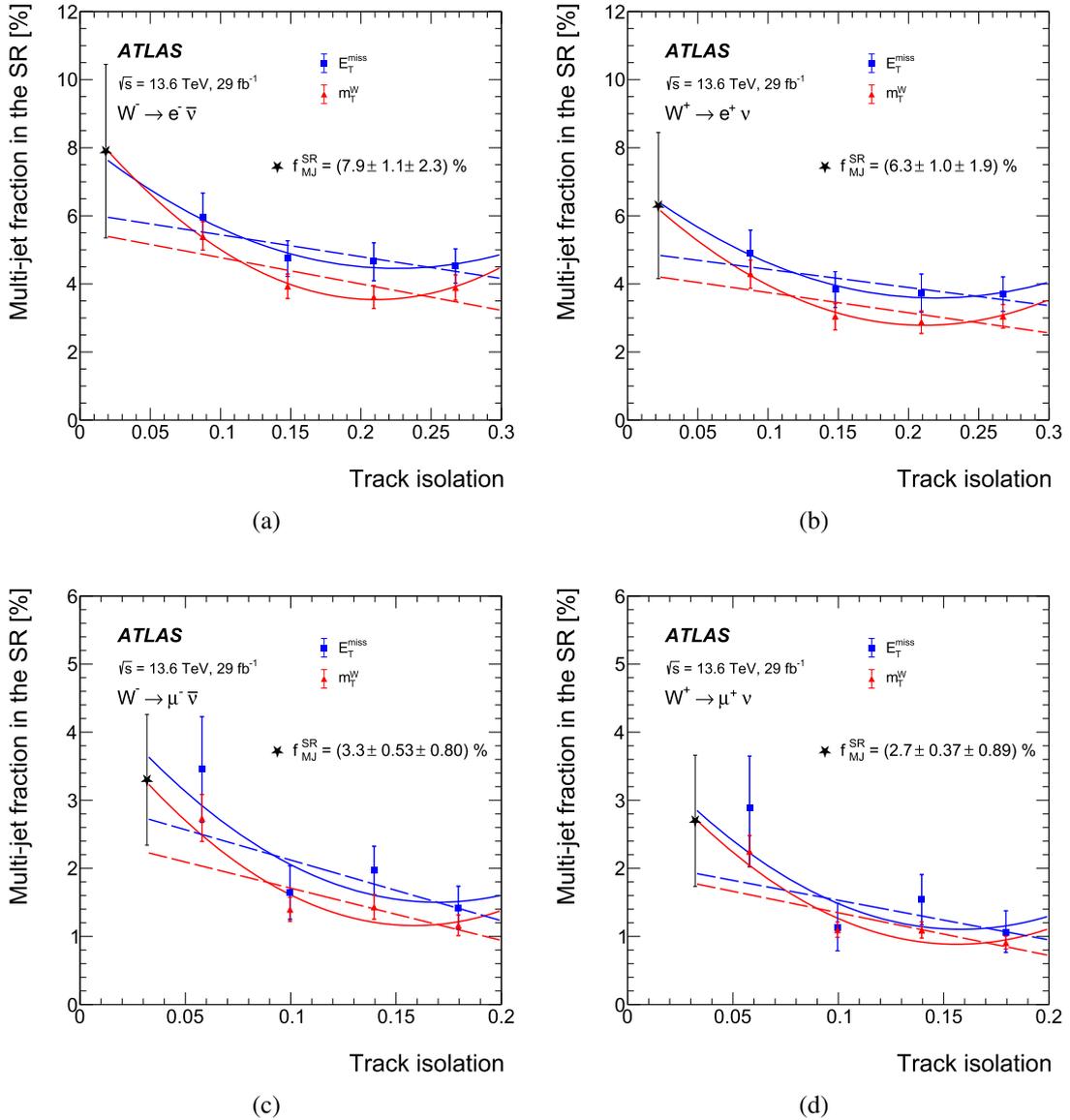
processes is efficiently rejected by the isolation selection and, in the  $W$ -boson case, by the lepton  $p_T$ ,  $E_T^{\text{miss}}$ , and  $m_T^W$  requirements, MJ processes still dominate the background in  $W$ -boson measurements at high pile-up due to the large production cross section and large  $E_T^{\text{miss}}$  generated through jet energy mis-measurements in the event, contributing to around 3–7% of data events. Because of the difficulties in the precise simulation of these processes, data-driven techniques are used for the estimation of the MJ background [7].

The MJ background in the four  $W$ -boson channels is estimated by performing PLH fits to the data in a fitting region enriched with MJ contribution, where the signal and background kinematic distributions have sufficient discriminating power. The discriminating variables used in these fits are  $E_T^{\text{miss}}$  and  $m_T^W$ . The signal region (SR) is defined by the full event selection, in particular,  $E_T^{\text{miss}} > 25$  GeV and  $m_T^W > 50$  GeV. The fitting region (FR) is defined similarly to the SR except that  $E_T^{\text{miss}} < 25$  GeV and  $m_T^W < 50$  GeV are required. The signal, EW, and top-quark background contributions in this region are estimated by using MC simulations, while the MJ distributions are derived in a control region (CR1) with similar kinematic selection as the FR, but where the lepton is required to fail to satisfy the track isolation requirement, denoted as anti-isolated. Similarly, another control region (CR2) is defined where the lepton is also required to fail isolation but has the same kinematic selection as the SR. The contamination from signal and other backgrounds in the CR1 and CR2 is estimated by using MC simulations and subtracted from the data to obtain the MJ templates in these regions. Pre-scaled supporting triggers with looser or without isolation requirements corresponding to a smaller integrated luminosity value than the nominal one are used to populate sufficiently the CR1 and CR2. These triggers have similar kinematic requirements to the nominal ones used to select events in the SR.

Several MJ templates are created for each  $W$ -boson decay channel by slicing the CR1 and CR2 as explained in the following. Four mutually exclusive isolation slices are defined by varying the track isolation variable progressively further from the signal region, while the calorimeter isolation is kept at the nominal value. The slices in the track isolation variable are equal in width and have an upper limit corresponding to 0.3 and 0.2 in the electron and muon channels, respectively. For each isolation slice, the normalisation of the corresponding MJ template in the FR is extracted using a PLH fit to the measured  $E_T^{\text{miss}}$  or  $m_T^W$  distribution. A transfer factor, calculated using the ratio of the MJ yields in the CR1 and CR2, is used to obtain the SR MJ yield from the FR fit result. This procedure leads to two sets of four SR MJ yields (two fit variables and four isolation slices) for each of the four  $W$ -boson channels. To reduce the bias due to the track isolation on the MJ yield in the SR, the MJ estimates obtained from each isolation slice are used to build an extrapolation to the track isolation selection used in the SR.

Fig. 1 shows the linear (dashed line) and quadratic (solid line) fits to the relative MJ yields as a function of the track isolation slice, where the average value of the track isolation of the events in the respective isolation slice is used as the central value. For each point, the uncertainty of the MJ fit in the FR is propagated into the MJ yield and enters the uncertainty of the final extrapolation. The quadratic fits are observed to have better performance than the linear fits in each channel, verified with a  $\chi^2$  criterion. The combined mean of the two quadratic extrapolations using the  $E_T^{\text{miss}}$  or  $m_T^W$  distribution is used as the central value for the final MJ yield in each channel, denoted  $f_{\text{MJ}}^{\text{SR}}$  in the figure. The first contribution to the uncertainty in the mean is calculated as the sum in quadrature between the combined error from the  $m_T^W$  and  $E_T^{\text{miss}}$  fits, and the difference between the  $m_T^W$  and  $E_T^{\text{miss}}$  fit results. The second contribution to the systematic uncertainty is derived from the difference between the linear and quadratic fit results, which constitutes the dominant contribution.

In the  $Z$ -boson channels, a conservative upper limit on the MJ background is estimated from the number of charge misidentified leptons, calculated using the  $m_{\ell\ell}$  sidebands from a same-sign lepton selection.



**Fig. 1.** Relative multi-jet yield in the SR as a function of the track isolation variable for the (a)  $W^- \rightarrow e^- \bar{\nu}$ , (b)  $W^+ \rightarrow e^+ \nu$ , (c)  $W^- \rightarrow \mu^- \bar{\nu}$ , and (d)  $W^+ \rightarrow \mu^+ \nu$  channels, shown with squares and triangles, respectively for the  $E_T^{\text{miss}}$  and  $m_T^W$  input measurements. The curves represent the extrapolation of the points to the SR using a quadratic function (solid curves) or a linear function (dashed lines). The  $x$ -axis corresponds to the position of the average of a track-isolation slice in the track isolation. The star represents the final MJ fraction ( $f_{\text{MJ}}^{\text{SR}}$ ) and is calculated using the combined average of the quadratic fits in each channel. The first uncertainty corresponds to the combined uncertainty including the difference between the  $m_T^W$  and  $E_T^{\text{miss}}$  quadratic fits, while the second uncertainty is due to the difference between linear and quadratic fit results.

In the case of the electron channel, this is found to be of sub-percent level, while the contribution in the muon channel is found to be even smaller. The systematic uncertainties are also negligible. The MJ contribution in the  $Z$ -boson channels is hence not considered in this analysis.

The event yields of background processes together with those from signal processes are shown in Table 2. Fig. 2 shows the  $m_T^W$  distributions in data and predictions for the four  $W$ -boson channels. The data agrees with the prediction within the uncertainties indicated by the hashed band. The  $m_{\ell\ell}$  distributions for the  $Z \rightarrow \ell\ell$  analysis are presented in Ref. [15].

## 6. Systematic uncertainties

The uncertainty of the integrated luminosity is 2.2%, based on the LUCID-2 detector [18] estimate, which is used for the primary luminosity measurements. For the electron efficiency corrections [53], extra systematic uncertainties are considered by comparing the simulations

between Run 2 and Run 3. The uncertainty of the muon efficiency corrections is obtained using the Run 3 data sample and simulations by independently varying the inner detector and muon spectrometer components, as determined from  $Z \rightarrow \mu^+ \mu^-$  events, following Ref. [54]. The electron energy calibration uncertainty is derived using Run 2 data sample and simulations, as described in Ref. [53], with dedicated uncertainties covering the difference between Run 2 and Run 3 simulations. The muon energy calibration uncertainty is obtained using Run 3 data, based on the approach described in Ref. [54]. The lepton trigger uncertainties are obtained by comparing the trigger efficiency results of Run 3 data with simulations. The jet energy scale and resolution uncertainties are estimated by using the Run 2 data sample, as described in Ref. [58], and an additional uncertainty is used to cover the difference between Run 2 and Run 3 by comparing simulations, as described in Ref. [15]. A conservative 10% uncertainty per jet is considered to cover the differences between data and simulations in the measured NNJVT efficiencies. Besides the propagation of systematic uncertainties of all

**Table 2**

Event yields of data and predictions after selections. Only MC statistical uncertainties are shown for the EW and top-quark processes. For the multi-jet process, the normalisation uncertainty is displayed instead. Rounding has been applied to all the yields except for those of the data.

	$W^- \rightarrow e^- \bar{\nu}$	$W^+ \rightarrow e^+ \nu$	$W^- \rightarrow \mu^- \bar{\nu}$	$W^+ \rightarrow \mu^+ \nu$
$W \rightarrow e\nu$	43,650,000 $\pm$ 70,000	55,370,000 $\pm$ 80,000	–	–
$W \rightarrow \mu\nu$	–	–	57,760,000 $\pm$ 80,000	74,900,000 $\pm$ 90,000
$W \rightarrow \tau\nu$	684,000 $\pm$ 8,000	819,000 $\pm$ 9,000	906,000 $\pm$ 10,000	1,120,000 $\pm$ 10,000
$Z \rightarrow ee/\mu\mu$	1,416,000 $\pm$ 4,000	1,459,000 $\pm$ 4,000	4,638,000 $\pm$ 8,000	4,903,000 $\pm$ 8,000
$Z \rightarrow \tau\tau$	88,000 $\pm$ 1,000	91,000 $\pm$ 1,000	107,000 $\pm$ 1,000	111,000 $\pm$ 1,000
$t\bar{t}$ +single-top	863,800 $\pm$ 400	905,400 $\pm$ 500	802,200 $\pm$ 400	843,400 $\pm$ 400
$VV$	93,500 $\pm$ 300	97,600 $\pm$ 300	98,500 $\pm$ 300	102,800 $\pm$ 300
Multi-jet	4,000,000 $\pm$ 1,000,000	4,000,000 $\pm$ 1,000,000	2,100,000 $\pm$ 700,000	2,200,000 $\pm$ 800,000
Total predicted	51,000,000 $\pm$ 1,000,000	63,000,000 $\pm$ 1,000,000	66,400,000 $\pm$ 700,000	84,200,000 $\pm$ 800,000
Data	50,748,537	62,610,338	65,053,470	82,360,980

	$Z \rightarrow e^+e^-$	$Z \rightarrow \mu^+\mu^-$
$Z \rightarrow ee$	7,710,000 $\pm$ 10,000	–
$Z \rightarrow \mu\mu$	–	13,961,000 $\pm$ 10,000
$Z \rightarrow \tau\tau$	2,500 $\pm$ 200	3,900 $\pm$ 200
$W \rightarrow \ell\nu$	139 $\pm$ 57	40 $\pm$ 27
$t\bar{t}$ +single-top	24,950 $\pm$ 50	37,000 $\pm$ 50
$VV$	14,960 $\pm$ 80	23,800 $\pm$ 100
Total predicted	7,750,000 $\pm$ 10,000	14,030,000 $\pm$ 10,000
Data	7,812,978	14,242,875

other physics objects, those of the track soft term are also considered for  $E_T^{\text{miss}}$  [60]. The uncertainty in the pile-up is determined by varying the average number of interactions per bunch-crossing by 4% in the simulation and it is accounted for with dedicated studies. The systematic uncertainties arising from normalisation of the multi-jet background are described in Section 5.

The theoretical uncertainties are categorised into two distinct components: the uncertainty  $\delta A$  on the *acceptance*  $A$ , the ratio of the number of events in the fiducial volume and the total phase space at the particle level, and the uncertainty  $\delta C$  on the *correction factor*  $C$ , the ratio of the expected signal events at the detector level and at the particle level in the fiducial volume, defined by lepton  $p_T^\ell > 27$  GeV, lepton  $|\eta^\ell| < 2.5$ ,  $E_T^{\text{miss}} > 25$  GeV and  $m_{T}^W > 50$  GeV for the  $W$ -boson processes and the same  $p_T^\ell$  and  $|\eta^\ell|$  selections and  $66 < m_{\ell\ell} < 116$  GeV for the  $Z$ -boson processes. For each theoretical uncertainty,  $\delta A$  is propagated into the measurement of the total cross section, whereas  $\delta C$  is included as a nuisance parameter in the PLH fit used to extract the fiducial cross section.

Various sources of the theoretical uncertainty are evaluated using the SHERPA signal samples. The QCD scale uncertainty is defined by the symmetrised envelope of seven-point variations of the renormalisation and factorisation scales, corresponding to varying  $\mu_R$  and  $\mu_F$  independently by factors of 1/2 and 2 to the combinations of  $(\mu_R, \mu_F) = (\mu_R/2, \mu_F/2), (2\mu_R, 2\mu_F), (\mu_R, 2\mu_F), (2\mu_R, \mu_F), (\mu_R, \mu_F/2)$ , and  $(\mu_R/2, \mu_F)$ . The PDF uncertainty is estimated based on the internal replicas of the NNPDF 3.0 NNLO set, which enter the fit as individual nuisance parameters. The PDF choice uncertainty is estimated by comparing the predictions calculated with NNPDF 3.0 NNLO and with PDF4LHC21 [63]. The  $\alpha_s$  uncertainty is calculated by comparing two different  $\alpha_s$  values used in PDF4LHC21.

The contribution of each of the background processes based on simulated samples is at percent level or smaller. A conservative modelling uncertainty of 5% covering the PDF input,  $\alpha_s$ , and QCD scale variations, is assigned for background processes from the  $W$  and  $Z$  bosons and the theoretical uncertainty is 10% for the diboson processes. The modelling uncertainties are 5.1% and 3.5% for the  $t\bar{t}$  and single-top processes, respectively, as evaluated in Ref. [15].

The results for the  $Z$  boson production are derived from fits to the two  $Z$ -boson channels as reported in Ref. [15]. The other results are derived from simultaneous fits of the four  $W$ -boson and the two  $Z$ -

boson channels. The lepton efficiency corrections, trigger efficiency and energy calibration uncertainties are treated as uncorrelated between electron and muon channels. The multi-jet background uncertainty is also considered to be uncorrelated. Other experimental uncertainties (uncertainty sources related to jet,  $E_T^{\text{miss}}$ , pile-up and luminosity) are considered to be fully correlated. The modelling uncertainties of electroweak and top-quark processes are regarded as fully uncorrelated. The uncertainties in signal modelling are fully correlated when combining electron and muon channels for the same boson. However, when combining channels of different bosons, these uncertainties are treated as uncorrelated sources due to the different production modes at the LHC.

The dominant uncertainty sources are channel dependent. The  $Z$ -boson cross sections are limited by the luminosity and lepton correction uncertainties. For the  $W$ -boson cross sections, the multi-jet background and jet-related uncertainties play important roles. However, for  $W^+/W^-$ -boson cross-section ratios, the dominant experimental uncertainty sources largely cancel out. The multi-jet background uncertainties become dominant sources for  $W^+/W^-$ -boson cross-section ratios since the multi-jet  $W^+$  and  $W^-$  boson uncertainties in each lepton channel are regarded as independent sources. Similarly, in the ratio of  $W^\pm$ -boson and  $Z$ -boson cross sections, the jet and multi-jet background uncertainties only affect the  $W$ -boson cross section but have no impact on the  $Z$ -boson cross section so they become dominant sources. In terms of the ratio of the  $t\bar{t}$  and  $W$  fiducial cross section, the  $t\bar{t}$  modelling and multi-jet background uncertainties are significant as they do not cancel out and, additionally, uncertainties stemming from jet and lepton trigger efficiency, as well as background modelling except the multi-jet, also do not fully cancel out and so they also play important roles.

## 7. Results

The cross sections  $\sigma_{W^+ \rightarrow e^+ \nu}$ ,  $\sigma_{W^- \rightarrow e^- \bar{\nu}}$ ,  $\sigma_{W^\pm \rightarrow \ell^\pm \nu}$ , and  $\sigma_{Z \rightarrow \ell^+ \ell^-}$  are extracted from PLH fits to the inclusive data in the four fiducial single-lepton channels  $W^+ \rightarrow e^+ \nu$ ,  $W^+ \rightarrow \mu^+ \nu$ ,  $W^- \rightarrow e^- \bar{\nu}$ , and  $W^- \rightarrow \mu^- \bar{\nu}$ , and the two fiducial dilepton channels  $Z \rightarrow e^+ e^-$  and  $Z \rightarrow \mu^+ \mu^-$ . The statistical model of the PLH fits is constructed in the following form:

$$L(\vec{n}; \mu_s, \vec{\theta}) = \prod_{c \in \text{channels}} \text{Pois}(n_{\text{data}} | \mu_{s,c} S_c(\vec{\theta}) + B_c(\vec{\theta})) \prod_{i \in \text{NPs}} G(\theta_i), \quad (1)$$

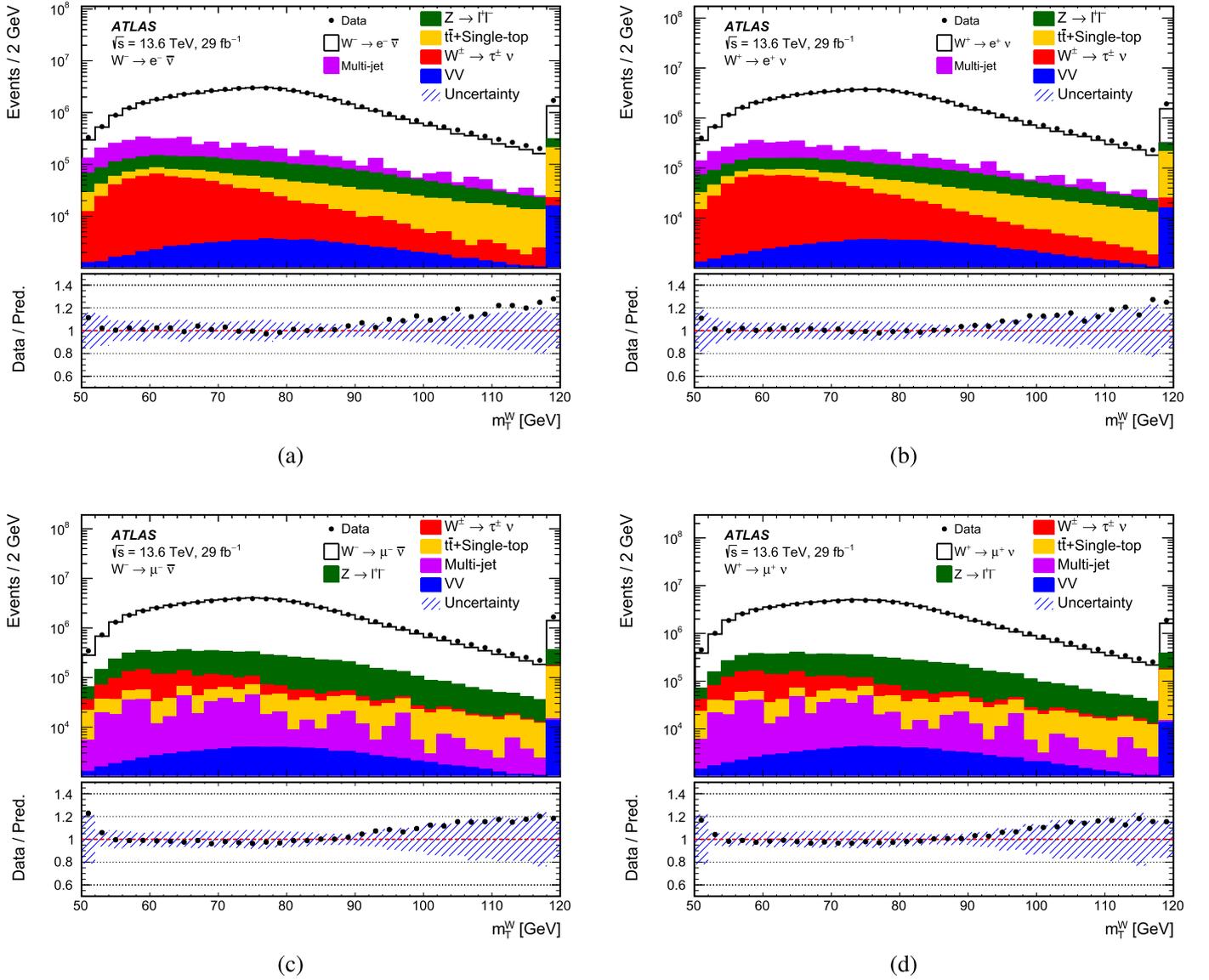


Fig. 2. Comparison of data (dots) and predictions (histograms) for the  $m_{W^W}$  distributions in the (a)  $W^- \rightarrow e^- \bar{\nu}$ , (b)  $W^+ \rightarrow e^+ \nu$ , (c)  $W^- \rightarrow \mu^- \bar{\nu}$ , and (d)  $W^+ \rightarrow \mu^+ \nu$  channels. The hashed band in the ratio plot denotes the total systematic uncertainty in the prediction. The rightmost bins contain the overflow events.

where  $\mu_s$  is the signal strength, which represents the ratio of the measured signal cross section over the predicted value,  $S_c$  is the expected number of signal events, and  $B_c$  is the expected background. The normalisation of the background contributions is determined by the fit and constrained by the background cross-section uncertainties. The quantity  $\theta_i$  is a nuisance parameter (see Section 6) which is constrained by a Gaussian term  $G(\theta_i)$ . The probability model is the product of the Poisson distributions (“Pois”) in each channel. The theoretical uncertainties of the  $W^-$  and  $Z$ -boson signal processes are incorporated into the fitting by introducing normalisation factors on the signal samples. The normalisation factors are calculated by comparing the correction factors of the nominal and theoretical variations, and taking the relative difference.

The ratios of the fiducial cross sections are extracted using fits as well. For the  $W^+/W^-$ -boson cross-section ratio,  $R_{W^+/W^-}$ , the  $W^+$ -boson signal strength  $\mu_{W^+}$  is expressed as the product  $R_{W^+/W^-} \mu_{W^-}$  in Eq. (1), thus the likelihood formula for the ratio is written as:

$$L(\vec{n}; \mu_s, \vec{\theta}) = \prod_{c \in W^+ \text{ channels}} \text{Pois}(n_{\text{data}} | R_{W^+/W^-} \mu_{W^-} S_c(\vec{\theta}) + B_c(\vec{\theta})) \times$$

$$\prod_{c \in W^- \text{ channels}} \text{Pois}(n_{\text{data}} | \mu_{W^-} S_c(\vec{\theta}) + B_c(\vec{\theta})) \times \prod_{c \in Z \text{ channels}} \text{Pois}(n_{\text{data}} | \mu_Z S_c(\vec{\theta}) + B_c(\vec{\theta})) \prod_{i \in \text{NPs}} G(\theta_i).$$

The ratios  $R_{W^\pm/Z}$ ,  $R_{\bar{t}t/W^\pm}$ ,  $R_{\bar{t}t/W^+}$ , and  $R_{\bar{t}t/W^-}$  are extracted in the same manner. In the latter cases, the  $\bar{t}t$  inputs and uncertainties are obtained from the  $\bar{t}t$  cross-section analysis at 13.6 TeV [15].

Fiducial cross sections,  $\sigma^{\text{fid}}$ , are calculated by multiplying the signal-strength parameter  $\mu$  with the nominal predicted fiducial cross section calculated with the SHERPA signal samples (see Section 3). Uncertainties in the signal-strength parameter  $\mu$  are propagated into  $\sigma^{\text{fid}}$ .

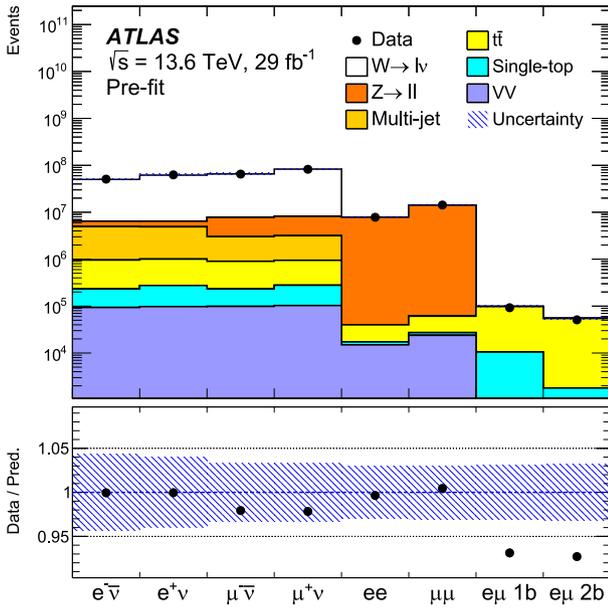
Total cross sections,  $\sigma^{\text{tot}}$ , are calculated by dividing  $\sigma^{\text{fid}}$  by the acceptance  $A$ . This correction is calculated with the SHERPA signal samples by dividing the predicted fiducial cross section by the predicted total cross section at the particle level, the latter derived without any kinematic cuts in the  $W$ -boson case and only with an invariant mass window  $66 < m_{\ell\ell} < 116$  GeV in the  $Z$ -boson case. The acceptance  $A$  includes theory uncertainties (Section 6), which are then propagated into  $\sigma^{\text{tot}}$ .

**Table 3**

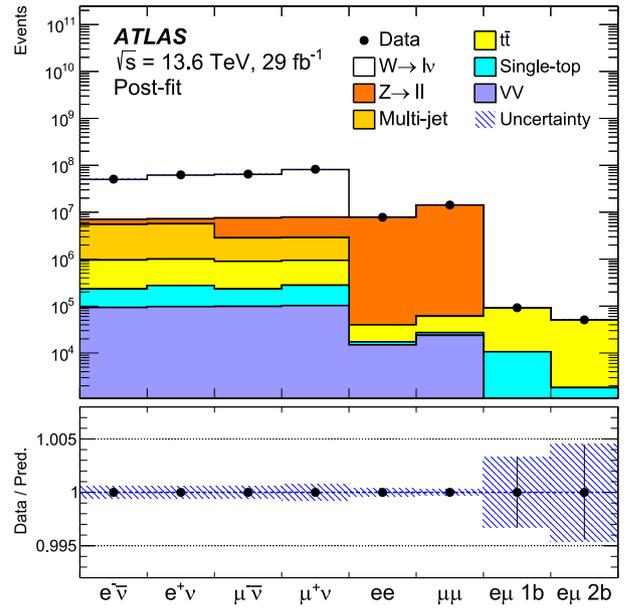
Observed impact (in %) of the different sources of uncertainty on the measured fiducial cross sections. Flavour-tagging uncertainties and top-quark modelling uncertainties are taken from Ref. [15].

Category	$\sigma(Z \rightarrow ee)$	$\sigma(Z \rightarrow \mu\mu)$	$\sigma(Z \rightarrow \ell\ell)$	$\sigma(W^- \rightarrow e^-\bar{\nu})$	$\sigma(W^+ \rightarrow e^+\nu)$	$\sigma(W^- \rightarrow \mu^-\bar{\nu})$	$\sigma(W^+ \rightarrow \mu^+\nu)$
Luminosity	2.2	2.2	2.2	2.5	2.5	2.5	2.4
Pile-up	1.2	0.3	0.8	1.1	1.1	0.3	0.4
MC statistics	<0.2	<0.2	<0.2	<0.2	0.4	<0.2	0.4
Lepton trigger	0.2	0.4	0.2	1.2	1.3	1.0	1.0
Electron reconstruction	1.4	-	0.9	0.7	0.8	-	-
Muon reconstruction	-	2.1	1.4	-	-	1.0	1.0
Multi-jet	-	-	-	2.9	2.4	1.3	1.1
Other background modelling	<0.2	<0.2	<0.2	<0.2	<0.2	0.5	0.4
Jet energy scale	-	-	-	1.4	1.4	1.3	1.4
Jet energy resolution	-	-	-	<0.2	0.3	0.2	0.2
NNJVT	-	-	-	1.6	1.5	1.3	1.3
$E_T^{\text{miss}}$ track soft term	-	-	-	<0.2	0.4	<0.2	<0.2
PDF	0.2	0.2	<0.2	0.8	0.8	0.6	0.5
QCD scale (ME and PS)	0.6	<0.2	0.3	1.3	1.2	0.6	0.6
Flavour tagging	-	-	-	-	-	-	-
$t\bar{t}$ modelling	-	-	-	-	-	-	-
Total systematic impact [%]	3.0	3.1	2.7	5.0	4.5	3.8	3.6
Statistical impact [%]	0.04	0.03	0.02	0.02	0.01	0.01	0.01

Category	$\sigma(W^- \rightarrow \ell^-\bar{\nu})$	$\sigma(W^+ \rightarrow \ell^+\nu)$	$\sigma(W^\pm \rightarrow \ell\nu)$	$R_{W^+/W^-}$	$R_{W^\pm/Z}$	$R_{t\bar{t}/W^\pm}$
Luminosity	2.5	2.4	2.4	<0.2	0.3	<0.2
Pile-up	0.5	0.7	0.6	<0.2	<0.2	<0.2
MC statistics	<0.2	0.2	<0.2	<0.2	<0.2	<0.2
Lepton trigger	1.0	0.9	0.9	<0.2	0.7	0.8
Electron reconstruction	0.4	0.5	0.4	<0.2	0.5	0.4
Muon reconstruction	0.6	0.6	0.6	0.2	0.8	0.6
Multi-jet	1.2	1.2	1.2	1.6	1.1	1.0
Other background modelling	0.4	0.4	0.4	<0.2	0.3	0.9
Jet energy scale	1.3	1.3	1.3	<0.2	1.3	1.3
Jet energy resolution	<0.2	0.2	<0.2	<0.2	<0.2	<0.2
NNJVT	1.4	1.3	1.3	<0.2	1.3	<0.2
$E_T^{\text{miss}}$ track soft term	<0.2	0.3	0.3	<0.2	0.3	0.3
PDF	0.5	0.5	0.3	0.5	0.2	0.4
QCD scale (ME and PS)	0.8	0.7	0.6	<0.2	0.7	0.7
Flavour tagging	-	-	-	-	-	<0.2
$t\bar{t}$ modelling	-	-	-	-	-	1.1
Total systematic impact [%]	3.7	3.5	3.5	1.7	2.4	2.5
Statistical impact [%]	0.01	0.01	0.01	0.01	0.02	0.32



(a)



(b)

**Fig. 3.** Comparison of the number of data events in each channel (dots) with the predictions (stacked histograms) shown (a) before and (b) after the fits. The dashed error band in the pre-fit figure gives the total systematic uncertainty before the fit, while in the post-fit figure, it represents the statistical uncertainty derived from the fit.

**Table 4**

The measured cross sections using the profile likelihood method. The quoted uncertainty corresponds to the total uncertainty (the statistical uncertainty is negligibly small). Rounding has been applied to all quoted numbers.

Channel	$\sigma^{\text{fid}} \pm \delta\sigma_{\text{stat} \oplus \text{syst}}$ [pb]	Acceptance $A$	$\sigma^{\text{tot}} \pm \delta\sigma_{\text{stat} \oplus \text{syst}}$ [pb]
$Z \rightarrow e^+e^-$	$740 \pm 22$	$0.374 \pm 0.011$	$1981 \pm 82$
$Z \rightarrow \mu^+\mu^-$	$747 \pm 23$	$0.374 \pm 0.011$	$1997 \pm 82$
$Z \rightarrow \ell^+\ell^-$	$744 \pm 20$	$0.374 \pm 0.011$	$1989 \pm 77$
$W^- \rightarrow e^-\bar{\nu}$	$3380 \pm 170$	$0.381 \pm 0.009$	$8880 \pm 490$
$W^- \rightarrow \mu^-\bar{\nu}$	$3310 \pm 130$	$0.381 \pm 0.009$	$8680 \pm 390$
$W^- \rightarrow \ell^-\bar{\nu}$	$3310 \pm 120$	$0.381 \pm 0.009$	$8690 \pm 390$
$W^+ \rightarrow e^+\nu$	$4350 \pm 200$	$0.366 \pm 0.009$	$11880 \pm 620$
$W^+ \rightarrow \mu^+\nu$	$4240 \pm 160$	$0.365 \pm 0.010$	$11620 \pm 530$
$W^+ \rightarrow \ell^+\nu$	$4250 \pm 150$	$0.366 \pm 0.009$	$11620 \pm 520$
$W^\pm \rightarrow \ell^\pm\nu$	$7560 \pm 270$	$0.372 \pm 0.009$	$20310 \pm 890$

Ratio	$R \pm \delta R_{\text{stat} \oplus \text{syst}}$
$W^+/W^-$	$1.286 \pm 0.022$
$W^\pm/Z$	$10.17 \pm 0.25$
$\bar{t}\bar{t}/W^-$	$0.256 \pm 0.008$
$\bar{t}\bar{t}/W^+$	$0.199 \pm 0.006$
$\bar{t}\bar{t}/W^\pm$	$0.112 \pm 0.003$

The impact of the uncertainties in the measured fiducial cross sections arising from different sources is summarised in Table 3. The uncertainties are grouped into distinct categories. To estimate the impact associated with each category, the nuisance parameters belonging to the category are fixed at the best-fit values and set as constants. Then a fitting process is performed again, resulting in a decreased uncertainty compared to the nominal uncertainty values. The difference in quadrature between the new and the nominal uncertainty is the impact of this category. The luminosity uncertainty values vary slightly from one channel to another due to different background contributions in each channel. The statistical impact is obtained by repeating the fit after having fixed all nuisance parameters to their fitted values.

The comparison of data and predictions before and after fits in all regions is shown in Fig. 3. Good agreement is observed in the single lepton and same flavour di-lepton regions while in the  $e\mu$  regions the data event yields are slightly lower than the predictions. The measured fiducial and total cross-section results and the corresponding acceptance with their respective uncertainties are summarised in Table 4. The  $Z$ -boson cross sections ( $\sigma_{Z \rightarrow e^+e^-}$ ,  $\sigma_{Z \rightarrow \mu^+\mu^-}$ , and  $\sigma_{Z \rightarrow \ell^+\ell^-}$ ) are obtained through individual fits to the two same flavour dilepton regions. The  $W$ -boson cross sections and the fiducial ratios ( $R_{W^+/W^-}$  and  $R_{W^\pm/Z}$ ) are fitted using the four single lepton and the two same flavour dilepton regions. Several fits are performed, using the same inputs but changing the parameters of interest each time. The  $W^+ \rightarrow e^+\nu$ ,  $W^+ \rightarrow \mu^+\nu$ ,  $W^- \rightarrow e^-\bar{\nu}$ , and  $W^- \rightarrow \mu^-\bar{\nu}$  cross sections are obtained simultaneously. The  $W^+$ - and  $W^-$ -boson cross sections are also derived in a simultaneous fit. The  $W^\pm$ -boson cross section, the  $R_{W^+/W^-}$  ratio, and the  $R_{W^\pm/Z}$  ratio are obtained in separate fits. The  $\bar{t}\bar{t}$  to  $W$ -boson cross-section ratios  $R_{\bar{t}\bar{t}/W^\pm}$ ,  $R_{\bar{t}\bar{t}/W^+}$ , and  $R_{\bar{t}\bar{t}/W^-}$  are derived in separate fits to the four  $W$ -boson channels, the two  $Z$ -boson channels, and the two  $\bar{t}\bar{t}$   $e\mu$  channels from Ref. [15].

Fig. 4 compares the measured results for the  $W^-$ ,  $W^+$ , and  $Z$  boson fiducial cross sections and  $R_{W^\pm/Z}$ ,  $R_{W^+/W^-}$ , and  $\bar{t}\bar{t}/W$  ratios to the Standard-Model (SM) theory predictions with different PDF sets: PDF4LHC21 [63], CT18, CT18A [64], MSHT20 [65–67], NNPDF4.0 [68], ABMP16 [69], and ATLASpdf21 [70]. The predictions are calculated at NNLO+NNLL QCD and NLO EW accuracy using DYTURBO-1.3.1 [71–74] and RENESANCE-1.3.3 [75,76], and combining them with an additive prescription, as used in Ref. [4]. The nominal  $\bar{t}\bar{t}$  predictions for all PDFs are calculated at NNLO in QCD including the resummation of NNLL soft-gluon terms calculated using TOP++ 2.0 [37–43] based on  $m_t = 172.5$  GeV. Theoretical uncertainties arising

from normalisation and factorisation scale variations for missing higher orders, the variation of the strong coupling constant  $\alpha_s$ , and variations of the input PDFs are evaluated. The latter source dominates in most cases as indicated with the inner error bars. Scale variations are taken as uncorrelated between different bosons and between bosons and  $\bar{t}\bar{t}$ , but the PDF variations are treated as correlated.

For the  $W^-$ ,  $W^+$ , and  $Z$  boson fiducial cross sections and their ratios, an overall good agreement is observed, while the  $\bar{t}\bar{t}/W$  ratio results are slightly lower than the predictions for most of the PDFs considered. This is consistent with the results of the Run 3  $\bar{t}\bar{t}$  cross-section measurement [15], where the measured  $\bar{t}\bar{t}$  cross-section is measured to be lower than the predicted value. The predictions based on the PDF4LHC21 set with  $m_t = 171.5$  GeV and  $m_t = 173.5$  GeV are also included in Fig. 4.

The measured total cross section is shown as a function of  $\sqrt{s}$ , together compared with the CT14NNLO predictions [77] in Fig. 5. Good agreement is observed between data and prediction.

## 8. Conclusion

A measurement of the inclusive  $W$ - and  $Z$ -boson production cross sections with decays into final states with electrons or muons, their ratios, and the ratios of  $\bar{t}\bar{t}$  to  $W$ -boson fiducial cross sections were performed using LHC  $pp$  collision data corresponding to  $29 \text{ fb}^{-1}$  collected by the ATLAS experiment at a new centre-of-mass energy of 13.6 TeV. The cross sections are measured for  $Z$ -boson production in a fiducial phase space corresponding to  $p_T^\ell > 27$  GeV,  $|\eta_\ell| < 2.5$ , and  $66 < m_{\ell\ell} < 116$  GeV and for  $W$ -boson production in a fiducial region corresponding to  $p_T^\ell > 27$  GeV,  $|\eta_\ell| < 2.5$ ,  $m_T^W > 50$  GeV, and  $E_T^{\text{miss}} > 25$  GeV. The measured fiducial cross-section values for  $W^+$ ,  $W^-$ , and  $Z$  boson productions are  $4250 \pm 150$  pb,  $3310 \pm 120$  pb, and  $744 \pm 20$  pb, respectively, where the uncertainty corresponds to the total uncertainty, including that arising from the luminosity, which amounts to about 2.2%. The measured values for the ratios of fiducial cross sections are:  $R_{W^+/W^-} = 1.286 \pm 0.022$ ,  $R_{W^\pm/Z} = 10.17 \pm 0.25$ , and  $R_{\bar{t}\bar{t}/W^\pm} = 0.112 \pm 0.003$ , where the uncertainty is the total uncertainty. The total cross sections are also measured in the mass range  $66 \text{ GeV} < m_{\ell\ell} < 116$  GeV for  $Z$ -boson production and in the full phase space for  $W$ -boson production. Measurements are performed on  $\sigma_{W^+}$ ,  $\sigma_{W^-}$ ,  $\sigma_{W^\pm}$ ,  $\sigma_Z$ ,  $R_{W^+/W^-}$ ,  $R_{W^\pm/Z}$ ,  $R_{\bar{t}\bar{t}/W^\pm}$ ,  $R_{\bar{t}\bar{t}/W^+}$ , and  $R_{\bar{t}\bar{t}/W^-}$ . The measured  $W$ - and  $Z$ -boson cross sections are in good agreement with the SM predictions whereas the  $\bar{t}\bar{t}$  over  $W$ -boson fiducial cross-section ratios are slightly overestimated by some of the theoretical predictions.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

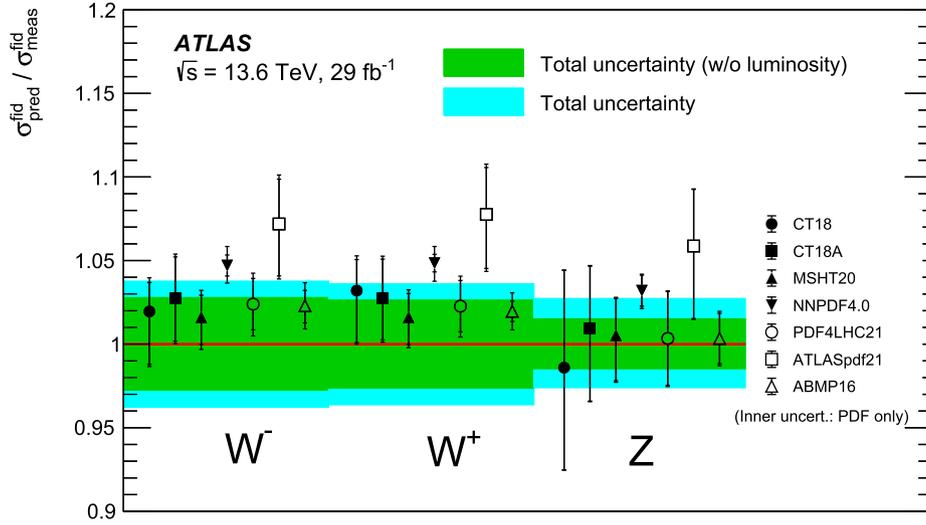
## Data availability

The data for this manuscript are not available. The values in the plots and tables associated to this article are stored in HEPDATA (<https://hepdata.cedar.ac.uk>).

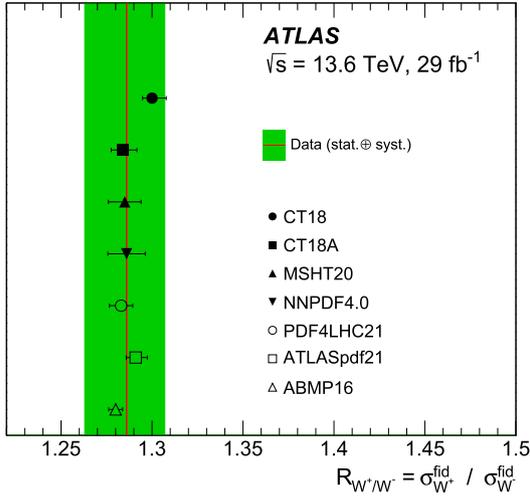
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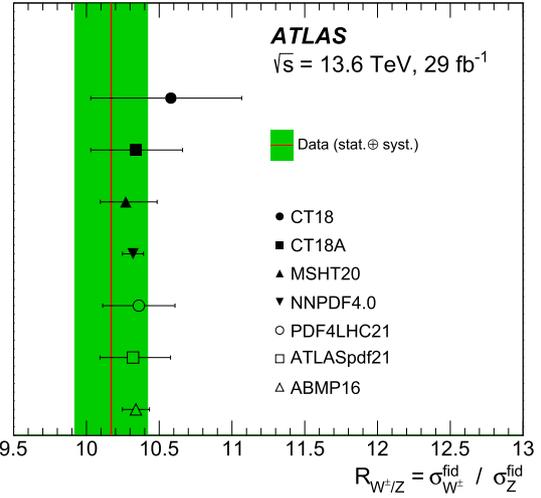
The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF/SFU (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), RAL (UK) and BNL (USA), the Tier-2 facilities



(a)



(b)



(c)

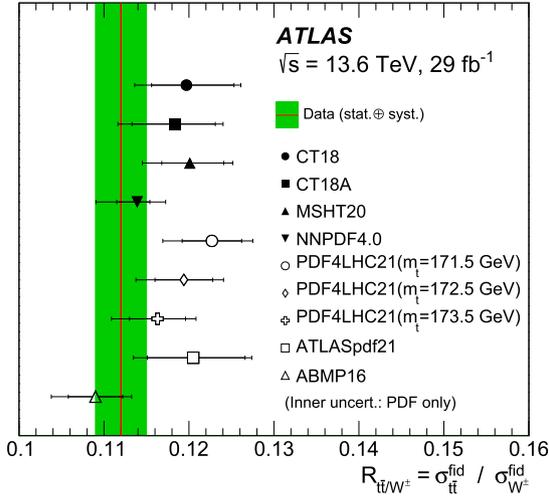
**Fig. 4.** The ratio of the predictions obtained with different PDF sets and the measured fiducial cross sections for (a)  $W^-$ ,  $W^+$ , and  $Z$  bosons, (b) and (c) their ratios  $R_{W^+/W^-}$  and  $R_{W^+/Z}$ , (d), (e) and (f) ratios of  $t\bar{t}$  over  $W$ -boson fiducial cross sections  $R_{t\bar{t}/W^\pm}$ ,  $R_{t\bar{t}/W^+}$ , and  $R_{t\bar{t}/W^-}$ . The outer (inner) band in (a) corresponds to the total uncertainty including (excluding) the luminosity uncertainty. The vertical band in the other plots shows the total (systematic and statistical) uncertainty in the data. The error bars on the predictions correspond to the theory uncertainties with the inner error bars (where available) representing the contributions from the PDF uncertainty.

worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [78].

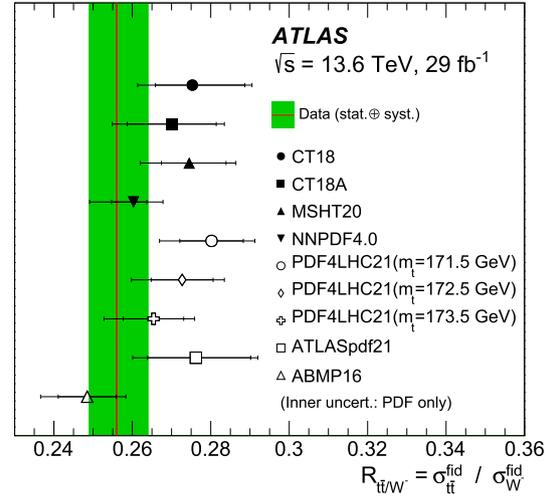
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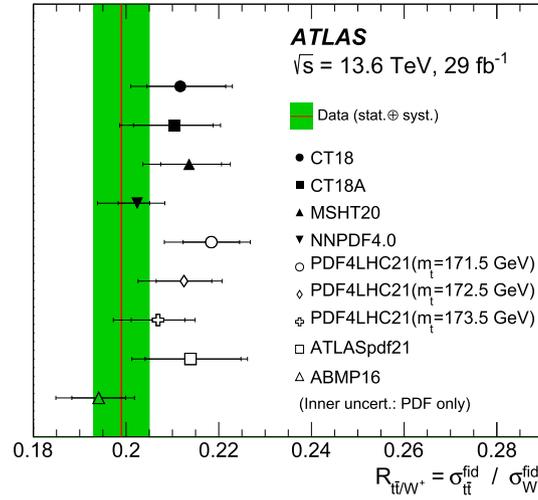
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(d)



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(f)

Fig. 4. (continued)

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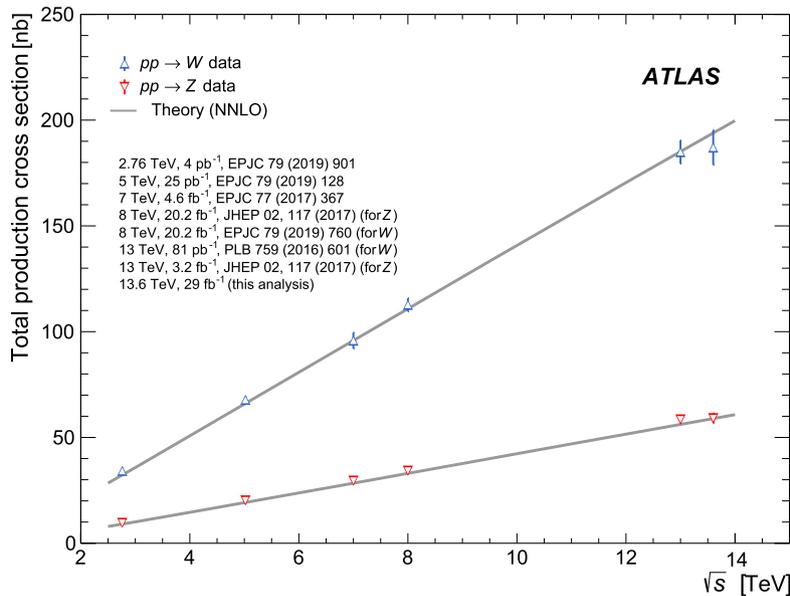


Fig. 5. The measured  $W$  and  $Z$  boson total production cross sections in the leptonic decay channel at different values of centre-of-mass energy. For comparison, the central values of the NNLO predictions based on the CT14NNLO PDF set are included.

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 K.J. Amirie <sup>156, [id](#)</sup>, S.P. Amor Dos Santos <sup>131a, [id](#)</sup>, K.R. Amos <sup>164, [id](#)</sup>, S. An <sup>84, [id](#)</sup>, V. Ananiev <sup>126, [id](#)</sup>,  
 C. Anastopoulos <sup>140, [id](#)</sup>, T. Andeen <sup>11, [id](#)</sup>, J.K. Anders <sup>36, [id](#)</sup>, S.Y. Andread <sup>47a,47b, [id](#)</sup>, A. Andreatza <sup>71a,71b, [id](#)</sup>,  
 S. Angelidakis <sup>9, [id](#)</sup>, A. Angerami <sup>41, [id](#)</sup>, A.V. Anisenkov <sup>37, [id](#)</sup>, A. Annovi <sup>74a, [id](#)</sup>, C. Antel <sup>56, [id](#)</sup>, E. Antipov <sup>146, [id](#)</sup>,  
 M. Antonelli <sup>53, [id](#)</sup>, F. Anulli <sup>75a, [id](#)</sup>, M. Aoki <sup>84, [id](#)</sup>, T. Aoki <sup>154, [id](#)</sup>, M.A. Aparo <sup>147, [id](#)</sup>, L. Aperio Bella <sup>48, [id](#)</sup>,  
 C. Appelt <sup>18, [id](#)</sup>, A. Apyan <sup>26, [id](#)</sup>, S.J. Arbiol Val <sup>87, [id](#)</sup>, C. Arcangeletti <sup>53, [id](#)</sup>, A.T.H. Arce <sup>51, [id](#)</sup>, E. Arena <sup>93, [id](#)</sup>,  
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 H. Asada <sup>112, [id](#)</sup>, K. Asai <sup>119, [id](#)</sup>, S. Asai <sup>154, [id](#)</sup>, N.A. Asbah <sup>36, [id](#)</sup>, K. Assamagan <sup>29, [id](#)</sup>, R. Astalos <sup>28a, [id](#)</sup>,  
 K.S.V. Astrand <sup>99, [id](#)</sup>, S. Atashi <sup>160, [id](#)</sup>, R.J. Atkin <sup>33a, [id](#)</sup>, M. Atkinson <sup>163, [id](#)</sup>, H. Atmani <sup>35f, [id](#)</sup>, P.A. Atmasiddha <sup>129, [id](#)</sup>,  
 K. Augsten <sup>133, [id](#)</sup>, S. Auricchio <sup>72a,72b, [id](#)</sup>, A.D. Auriol <sup>20, [id](#)</sup>, V.A. Austrup <sup>102, [id](#)</sup>, G. Avolio <sup>36, [id](#)</sup>, K. Axiotis <sup>56, [id](#)</sup>,  
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 A. Badea <sup>39, [id](#)</sup>, T.M. Baer <sup>107, [id](#)</sup>, P. Bagnaia <sup>75a,75b, [id](#)</sup>, M. Bahmani <sup>18, [id](#)</sup>, D. Bahner <sup>54, [id](#)</sup>, K. Bai <sup>124, [id](#)</sup>,  
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 L.T. Bazzano Hurrell <sup>30, [id](#)</sup>, J.B. Beacham <sup>51, [id](#)</sup>, T. Beau <sup>128, [id](#)</sup>, J.Y. Beaucamp <sup>91, [id](#)</sup>, P.H. Beauchemin <sup>159, [id](#)</sup>,  
 P. Bechtel <sup>24, [id](#)</sup>, H.P. Beck <sup>19, [id](#)</sup>, K. Becker <sup>168, [id](#)</sup>, A.J. Beddall <sup>82, [id](#)</sup>, V.A. Bednyakov <sup>38, [id](#)</sup>, C.P. Bee <sup>146, [id](#)</sup>,  
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 K.C. Benkendorfer <sup>61, [id](#)</sup>, L. Beresford <sup>48, [id](#)</sup>, M. Beretta <sup>53, [id](#)</sup>, E. Bergeaas Kuutmann <sup>162, [id](#)</sup>, N. Berger <sup>4, [id](#)</sup>,  
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 A. Berrocal Guardia <sup>13, [id](#)</sup>, T. Berry <sup>96, [id](#)</sup>, P. Berta <sup>134, [id](#)</sup>, A. Berthold <sup>50, [id](#)</sup>, S. Bethke <sup>111, [id](#)</sup>, A. Betti <sup>75a,75b, [id](#)</sup>,  
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 M. Birman <sup>170, [id](#)</sup>, M. Biros <sup>134, [id](#)</sup>, S. Biryukov <sup>147, [id](#)</sup>, T. Bisanz <sup>49, [id](#)</sup>, E. Bisceglie <sup>43b,43a, [id](#)</sup>, J.P. Biswal <sup>135, [id](#)</sup>,  
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 M. Boehler <sup>54, [id](#)</sup>, B. Boehm <sup>167, [id](#)</sup>, D. Bogavac <sup>36, [id](#)</sup>, A.G. Bogdanchikov <sup>37, [id](#)</sup>, C. Bohm <sup>47a, [id](#)</sup>, V. Boisvert <sup>96, [id](#)</sup>,  
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J. Boyd<sup>36, [id](#)</sup>, D. Boye<sup>29, [id](#)</sup>, I.R. Boyko<sup>38, [id](#)</sup>, L. Bozianu<sup>56, [id](#)</sup>, J. Bracinek<sup>20, [id](#)</sup>, N. Brahimi<sup>4, [id](#)</sup>, G. Brandt<sup>172, [id](#)</sup>,  
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S. Bressler<sup>170, [id](#)</sup>, D. Britton<sup>59, [id](#)</sup>, D. Britzger<sup>111, [id](#)</sup>, I. Brock<sup>24, [id](#)</sup>, G. Brooijmans<sup>41, [id](#)</sup>, E. Brost<sup>29, [id](#)</sup>,  
L.M. Brown<sup>166, [id](#)</sup>, L.E. Bruce<sup>61, [id](#)</sup>, T.L. Bruckler<sup>127, [id](#)</sup>, P.A. Bruckman de Renstrom<sup>87, [id](#)</sup>, B. Brüers<sup>48, [id](#)</sup>,  
A. Bruni<sup>23b, [id](#)</sup>, G. Bruni<sup>23b, [id](#)</sup>, M. Bruschi<sup>23b, [id](#)</sup>, N. Brusino<sup>75a,75b, [id](#)</sup>, T. Buanes<sup>16, [id](#)</sup>, Q. Buat<sup>139, [id](#)</sup>,  
D. Buchin<sup>111, [id](#)</sup>, A.G. Buckley<sup>59, [id](#)</sup>, O. Bulekov<sup>37, [id](#)</sup>, B.A. Bullard<sup>144, [id](#)</sup>, S. Burdin<sup>93, [id](#)</sup>, C.D. Burgard<sup>49, [id](#)</sup>,  
A.M. Burger<sup>36, [id](#)</sup>, B. Burghgrave<sup>8, [id](#)</sup>, O. Burlayenko<sup>54, [id](#)</sup>, J.T.P. Burr<sup>32, [id](#)</sup>, J.C. Burzynski<sup>143, [id](#)</sup>, E.L. Busch<sup>41, [id](#)</sup>,  
V. Büscher<sup>101, [id](#)</sup>, P.J. Bussey<sup>59, [id](#)</sup>, J.M. Butler<sup>25, [id](#)</sup>, C.M. Buttar<sup>59, [id](#)</sup>, J.M. Butterworth<sup>97, [id](#)</sup>, W. Buttinger<sup>135, [id](#)</sup>,  
C.J. Buxo Vazquez<sup>108, [id](#)</sup>, A.R. Buzykaev<sup>37, [id](#)</sup>, S. Cabrera Urbán<sup>164, [id](#)</sup>, L. Cadamuro<sup>66, [id](#)</sup>, D. Caforio<sup>58, [id](#)</sup>,  
H. Cai<sup>130, [id](#)</sup>, Y. Cai<sup>14a,14e, [id](#)</sup>, Y. Cai<sup>14c, [id](#)</sup>, V.M.M. Cairo<sup>36, [id](#)</sup>, O. Cakir<sup>3a, [id](#)</sup>, N. Calace<sup>36, [id](#)</sup>, P. Calafiura<sup>17a, [id](#)</sup>,  
G. Calderini<sup>128, [id](#)</sup>, P. Calfayan<sup>68, [id](#)</sup>, G. Callea<sup>59, [id](#)</sup>, L.P. Caloba<sup>83b, [id](#)</sup>, D. Calvet<sup>40, [id](#)</sup>, S. Calvet<sup>40, [id](#)</sup>,  
M. Calvetti<sup>74a,74b, [id](#)</sup>, R. Camacho Toro<sup>128, [id](#)</sup>, S. Camarda<sup>36, [id](#)</sup>, D. Camarero Munoz<sup>26, [id](#)</sup>, P. Camarri<sup>76a,76b, [id](#)</sup>,  
M.T. Camerlingo<sup>72a,72b, [id](#)</sup>, D. Cameron<sup>36, [id](#)</sup>, C. Camincher<sup>166, [id](#)</sup>, M. Campanelli<sup>97, [id](#)</sup>, A. Camplani<sup>42, [id](#)</sup>,  
V. Canale<sup>72a,72b, [id](#)</sup>, A.C. Canbay<sup>3a, [id](#)</sup>, E. Canonero<sup>96, [id](#)</sup>, J. Cantero<sup>164, [id](#)</sup>, Y. Cao<sup>163, [id](#)</sup>, F. Capocasa<sup>26, [id](#)</sup>,  
M. Capua<sup>43b,43a, [id](#)</sup>, A. Carbone<sup>71a,71b, [id](#)</sup>, R. Cardarelli<sup>76a, [id](#)</sup>, J.C.J. Cardenas<sup>8, [id](#)</sup>, G. Carducci<sup>43b,43a, [id](#)</sup>,  
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L. Carminati<sup>71a,71b, [id](#)</sup>, A. Carnelli<sup>136, [id](#)</sup>, M. Carnesale<sup>75a,75b, [id](#)</sup>, S. Caron<sup>114, [id](#)</sup>, E. Carquin<sup>138f, [id](#)</sup>, S. Carrá<sup>71a, [id](#)</sup>,  
G. Carratta<sup>23b,23a, [id](#)</sup>, A.M. Carroll<sup>124, [id](#)</sup>, T.M. Carter<sup>52, [id](#)</sup>, M.P. Casado<sup>13, [id](#)</sup>, M. Caspar<sup>48, [id](#)</sup>, F.L. Castillo<sup>4, [id](#)</sup>,  
L. Castillo Garcia<sup>13, [id](#)</sup>, V. Castillo Gimenez<sup>164, [id](#)</sup>, N.F. Castro<sup>131a,131e, [id](#)</sup>, A. Catinaccio<sup>36, [id](#)</sup>, J.R. Catmore<sup>126, [id](#)</sup>,  
T. Cavaliere<sup>4, [id](#)</sup>, V. Cavaliere<sup>29, [id](#)</sup>, N. Cavalli<sup>23b,23a, [id](#)</sup>, Y.C. Cekmecelioglu<sup>48, [id](#)</sup>, E. Celebi<sup>21a, [id](#)</sup>, S. Cella<sup>36, [id](#)</sup>,  
F. Celli<sup>127, [id](#)</sup>, M.S. Centonze<sup>70a,70b, [id](#)</sup>, V. Cepaitis<sup>56, [id](#)</sup>, K. Cerny<sup>123, [id](#)</sup>, A.S. Cerqueira<sup>83a, [id](#)</sup>, A. Cerri<sup>147, [id](#)</sup>,  
L. Cerrito<sup>76a,76b, [id](#)</sup>, F. Cerutti<sup>17a, [id](#)</sup>, B. Cervato<sup>142, [id](#)</sup>, A. Cervelli<sup>23b, [id](#)</sup>, G. Cesarini<sup>53, [id](#)</sup>, S.A. Cetin<sup>82, [id](#)</sup>,  
D. Chakraborty<sup>116, [id](#)</sup>, J. Chan<sup>17a, [id](#)</sup>, W.Y. Chan<sup>154, [id](#)</sup>, J.D. Chapman<sup>32, [id](#)</sup>, E. Chapon<sup>136, [id](#)</sup>,  
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A. Chitan<sup>27b, [id](#)</sup>, M. Chitishvili<sup>164, [id](#)</sup>, M.V. Chizhov<sup>38, [id](#)</sup>, K. Choi<sup>11, [id](#)</sup>, Y. Chou<sup>139, [id](#)</sup>, E.Y.S. Chow<sup>114, [id](#)</sup>,  
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K.M. Ciesla<sup>86a, [id](#)</sup>, V. Cindro<sup>94, [id](#)</sup>, A. Ciocio<sup>17a, [id](#)</sup>, F. Ciroto<sup>72a,72b, [id](#)</sup>, Z.H. Citron<sup>170, [id](#)</sup>, M. Citterio<sup>71a, [id](#)</sup>,  
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R.F. Coelho Barrue<sup>131a, [id](#)</sup>, R. Coelho Lopes De Sa<sup>104, [id](#)</sup>, S. Coelli<sup>71a, [id](#)</sup>, B. Cole<sup>41, [id](#)</sup>, J. Collot<sup>60, [id](#)</sup>,  
P. Conde Muño<sup>131a,131g, [id](#)</sup>, M.P. Connell<sup>33c, [id](#)</sup>, S.H. Connell<sup>33c, [id](#)</sup>, E.I. Conroy<sup>127, [id](#)</sup>, F. Conventi<sup>72a, [id](#)</sup>,  
H.G. Cooke<sup>20, [id](#)</sup>, A.M. Cooper-Sarkar<sup>127, [id](#)</sup>, F.A. Corchia<sup>23b,23a, [id](#)</sup>, A. Cordeiro Oudot Choi<sup>128, [id](#)</sup>, L.D. Corpe<sup>40, [id](#)</sup>,  
M. Corradi<sup>75a,75b, [id](#)</sup>, F. Corriveau<sup>105, [id](#)</sup>, A. Cortes-Gonzalez<sup>18, [id](#)</sup>, M.J. Costa<sup>164, [id](#)</sup>, F. Costanza<sup>4, [id](#)</sup>,  
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## Letter

# Measurement of the $t\bar{t}$ cross section and its ratio to the $Z$ production cross section using $pp$ collisions at $\sqrt{s} = 13.6$ TeV with the ATLAS detector

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## ABSTRACT

The inclusive top-quark-pair production cross section  $\sigma_{t\bar{t}}$  and its ratio to the  $Z$ -boson production cross section have been measured in proton–proton collisions at  $\sqrt{s} = 13.6$  TeV, using  $29 \text{ fb}^{-1}$  of data collected in 2022 with the ATLAS experiment at the Large Hadron Collider. Using events with an opposite-charge electron-muon pair and  $b$ -tagged jets, and assuming Standard Model decays, the top-quark-pair production cross section is measured to be  $\sigma_{t\bar{t}} = 850 \pm 3(\text{stat.}) \pm 18(\text{syst.}) \pm 20(\text{lumi.})$  pb. The ratio of the  $t\bar{t}$  and the  $Z$ -boson production cross sections is also measured, where the  $Z$ -boson contribution is determined for inclusive  $e^+e^-$  and  $\mu^+\mu^-$  events in a fiducial phase space. The relative uncertainty on the ratio is reduced compared to the  $t\bar{t}$  cross section, thanks to the cancellation of several systematic uncertainties. The result for the ratio,  $R_{t\bar{t}/Z} = 1.145 \pm 0.003(\text{stat.}) \pm 0.021(\text{syst.}) \pm 0.002(\text{lumi.})$  is consistent with the Standard Model prediction using the PDF4LHC21 PDF set.

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## 1. Introduction

Measurements of the top-quark production cross section in hadron-hadron collisions at the LHC provide essential tests of Quantum Chromodynamics (QCD) and parton distributions functions (PDFs). This quantity has been measured by ATLAS [1–4] and CMS [5–9] at energies between 5 and 13 TeV, and by LHCb [10,11] at energies between 7 and 13 TeV, with percent-level precision. Theory calculations with similar precision are available [12–17] and are found to be in good agreement with the measurements.

In the ratio of the  $t\bar{t}$  to the  $Z$ -boson production cross section, several experimental uncertainties cancel, so that it can be obtained very precisely. Since  $t\bar{t}$  production proceeds preferentially via a gluon-gluon initial state while  $Z$ -boson production is dominated by  $q\bar{q}$ , the ratio of these cross sections at a given centre-of-mass energy has a significant sensitivity to the gluon-to-quark PDF ratio [18,19]. ATLAS published such ratios at various centre-of-mass energies in Ref. [20]. Predictions for the  $Z$ -boson production cross section are available at NNLO QCD plus next-to-leading-order (NLO) electroweak (EW) accuracy [21–25].

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The analysis uses proton–proton collision data delivered by the LHC at CERN in 2022 at a new centre-of-mass energy of  $\sqrt{s} = 13.6$  TeV and recorded with the ATLAS detector, representing an integrated luminosity of  $29 \text{ fb}^{-1}$ . Due to the steep rise of the PDFs towards lower Bjorken- $x$ , a 12% increase of the  $t\bar{t}$  cross section at 13.6 TeV is expected with respect to 13 TeV, which should be visible already with the present precision on the detector calibration.

This letter reports the measurement of the  $t\bar{t}$  cross section in the full phase-space and of the ratio of the  $t\bar{t}$  and  $Z$ -boson cross sections. The CMS experiment has published a measurement of the  $t\bar{t}$  cross section at  $\sqrt{s} = 13.6$  TeV [26] using an integrated luminosity of  $1.21 \text{ fb}^{-1}$ , without including the ratio to the  $Z$ -boson cross section.

## 2. Analysis strategy

Top-quark pair production is analysed in the channel in which one top-quark decays into an electron, a neutrino and a  $b$ -quark, and the other top-quark into a muon, a neutrino and a  $b$ -quark. For  $Z$ -bosons, decays to a pair of electrons or muons are considered. Three channels are thus defined using electrons and muons of opposite electric charge:  $ee$ ,  $\mu\mu$  and  $e\mu$ .

In the  $e\mu$  channel, the presence of additional  $b$ -tagged jets is required. The analysis uses the method already employed in Ref. [2,27], where the numbers of events with one and two  $b$ -tagged jets are counted separately, allowing the  $t\bar{t}$  cross section to be extracted together with the efficiency to identify a  $b$ -tagged jet. Opposite-sign electron-muon pairs are selected and the numbers of events that have one  $b$ -tagged jet ( $N_1$ ) and two  $b$ -tagged jets ( $N_2$ ) are counted. The event yields are given by

$$N_1 = L\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\text{bkg}}, \quad (1)$$

$$N_2 = L\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{\text{bkg}}, \quad (2)$$

where  $L$  is the integrated luminosity,  $\sigma_{t\bar{t}}$  is the measured  $t\bar{t}$  cross section,  $\epsilon_b$  is the combined probability to reconstruct and  $b$ -tag a  $b$ -jet after the selection, and  $\epsilon_{e\mu}$  is the efficiency for a  $t\bar{t}$  event to pass the opposite-sign  $e\mu$  selection. The tagging correlation coefficient  $C_b = \epsilon_{bb}/\epsilon_b^2$ , where  $\epsilon_{bb}$  represents the probability to reconstruct and tag both  $b$ -jets, may deviate slightly from unity due to kinematic correlations of the  $b$ -jets produced in a  $t\bar{t}$  event and is estimated from simulation. The nominal value for  $C_b$  is found to be 1.0068.

For the same-flavour channels ( $ee$ ,  $\mu\mu$ ), the reconstructed invariant mass of the lepton pair,  $m_{\ell\ell}$ , is required to be  $66 < m_{\ell\ell} < 116$  GeV. These channels are then used to extract the cross section for  $Z$ -boson production

$$N_{ee} = L\sigma_Z\epsilon_{ee} + N_{ee}^{\text{bkg}}, \quad (3)$$

$$N_{\mu\mu} = L\sigma_Z\epsilon_{\mu\mu} + N_{\mu\mu}^{\text{bkg}}, \quad (4)$$

where  $N_{ee}$  ( $N_{\mu\mu}$ ) is the selected number of events passing the  $ee$  ( $\mu\mu$ ) selection. Parameters  $\epsilon_{ee}$  and  $\epsilon_{\mu\mu}$  are the efficiencies for a  $Z$ -boson event to pass the opposite-sign  $ee$  and  $\mu\mu$  selection, respectively.

The fiducial phase-space for  $Z$ -boson production is defined by the transverse momentum of the leptons  $p_T > 27$  GeV, the absolute value of the leptons' pseudorapidity  $|\eta| < 2.5$  and the invariant mass of  $66 < m_{\ell\ell} < 116$  GeV for  $\ell = e, \mu$ .<sup>1</sup> Within this phase space, an almost pure  $Z$ -boson contribution is obtained, with about 99.5% of events in the simulation originating from  $Z$ -boson production.

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

The total  $t\bar{t}$  production cross section and the ratio of the cross sections,  $R_{t\bar{t}/Z}$ , are measured in a common fit to the same- and different-flavour channels, using a binned profile-likelihood technique. To understand the cancellation of uncertainties in the cross section ratio, the fiducial  $Z$ -boson production cross section  $\sigma_{Z \rightarrow \ell\ell}^{\text{fid}}$  is measured in a separate fit using same-flavour dilepton events only, within the same phase space as used for the ratio measurement.

## 3. ATLAS detector

The ATLAS experiment [28,29] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near  $4\pi$  coverage in solid angle. It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer (MS). The inner tracking detector covers the pseudorapidity range  $|\eta| < 2.5$ . It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel/scintillator-tile hadron calorimeter covers the central pseudorapidity range ( $|\eta| < 1.7$ ). The endcap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to  $|\eta| = 4.9$ . The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 Tm across most of the detector. The muon spectrometer includes a system of precision tracking chambers and fast detectors for triggering. A two-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 3 kHz on average, depending on the data-taking conditions. An extensive software suite [30] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

## 4. Data and MC samples

The analysis is performed using the data collected between August and October 2022 with the ATLAS detector, in  $pp$  collisions at  $\sqrt{s} = 13.6$  TeV. After applying data-quality requirements [31], the data sample corresponds to an integrated luminosity of  $29 \text{ fb}^{-1}$ . The average number of inelastic  $pp$  collisions in the dataset is about 42. MC simulated samples are used in the analysis to optimise the event selection, estimate the selection efficiencies and correlation for the efficiencies of identifying and reconstructing two  $b$ -tagged jets, represented by the  $C_b$  parameter, and predict contributions from various background processes. If not stated otherwise, a top-quark mass of  $m_t = 172.5$  GeV is used, in the MC simulated samples and cross-section calculations.

The production of  $t\bar{t}$  events was simulated using the POWHEG BOX v2 [32–35] generator at next-to-leading-order (NLO) with the NNPDF3.0NLO [36] PDF set and the  $h_{\text{damp}}$  parameter set to  $1.5 m_t$  [37].<sup>2</sup> The events were interfaced to PYTHIA 8.307 [38] to model the parton shower, hadronisation, and underlying event, with parameters set according to the A14 tune [39] and using the NNPDF2.3LO set of PDFs [40]. The decays of bottom and charm hadrons were performed with EVTGEN 2.1.1 [41]. The  $t\bar{t}$  sample was normalised to the cross-section prediction at next-to-next-to-leading-order (NNLO) in QCD including the resummation of next-to-next-to-leading-logarithm (NNLL)

<sup>2</sup> The  $h_{\text{damp}}$  parameter is a resummation damping factor and one of the parameters that controls the matching of POWHEG matrix elements to the parton shower and thus effectively regulates the high- $p_T$  radiation against which the  $t\bar{t}$  system recoils.

soft-gluon terms calculated using TOP++ 2.0 [12–17,42]. For proton–proton collisions at a centre-of-mass energy of  $\sqrt{s} = 13.6$  TeV, this cross-section corresponds to  $\sigma(t\bar{t})_{\text{NNLO+NNLL}} = 924^{+32}_{-40}$  pb, including all  $t\bar{t}$  decay channels, using the PDF4LHC21 PDF set [43]. The uncertainty includes variations in the renormalisation and factorisation scale,  $\alpha_s$  and PDFs. For the nominal prediction, the renormalisation and factorisation scales were set equal to the top-quark mass, and the strong coupling constant was set to  $\alpha_s(m_Z) = 0.118$ . Samples of  $t\bar{t}$  and  $tW$  events with a different top-quark mass have been simulated to estimate the variation of the reconstruction efficiency as a function of this mass.

Events of  $Z/\gamma^* \rightarrow \ell^+\ell^-$  production were simulated with the SHERPA 2.2.12 [44] generator using NLO matrix elements (ME) for up to two partons, and up to five partons at leading-order (LO) calculated with the Comix [45] and OPENLOOPS [46–48] libraries. They were matched with the SHERPA parton shower [49] using the MEPS@NLO prescription [50–53] using the set of tuned parameters developed by the SHERPA authors. The NNPDF3.0NNLO set of PDFs was used. Decays of  $Z/\gamma^* \rightarrow e^+e^-$ ,  $Z/\gamma^* \rightarrow \mu^+\mu^-$  and  $Z/\gamma^* \rightarrow \tau^+\tau^-$  were simulated. The inclusive cross sections of the MC samples are normalised to NNLO in QCD and NLO in EW predictions, calculated using the MATRIX [54] program with the PDF4LHC21 PDF set. In both the MC generator requirement and in the MATRIX calculation, leptons before QED radiation are used. In the fiducial phase-space defined with lepton  $p_T > 27$  GeV,  $|\eta| < 2.5$  and  $66 < m_{\ell\ell} < 116$  GeV, the predicted cross-section at NNLO in QCD and NLO in EW is  $\sigma(Z)^{\text{fid.}} = 746 \pm 0.7(\text{integration})_{-5}^{+3}(\text{scale}) \pm 21(\text{PDF})$  pb for the  $Z$ -boson decaying into a single lepton flavour and leptons before QED radiation.<sup>3</sup>

For the calculation of the  $t\bar{t}$  to the  $Z$ -boson production cross-section ratio, several PDF sets are considered: PDF4LHC21, CT18 [55], CT18A [55], MSHT20 [56], NNPDF4.0 [57], ABMP16 [58] and ATLASpdf21 [59]. The uncertainties from the QCD scale variations are assumed to be uncorrelated between the processes, while the PDF variations are fully correlated in the calculation of the uncertainty. The QCD scale uncertainty is evaluated by restricting the variations of the renormalisation and factorisation scales, where  $\mu_r$  and  $\mu_f$  are independently varied by a factor of two while meeting the requirement that they never differ from each other by more than a factor of two. The predicted central values for the ratios for the different PDF sets vary between about 1.13 for the ABMP16 and 1.27 for the CT18 PDF set. The uncertainties on the predictions range from about 4.5% up to 9%.

The associated production of single top quarks with  $W$  bosons ( $tW$ ) was modelled with the POWHEG BOX v2 generator at NLO in QCD using the five-flavour scheme and the NNPDF3.0NNLO set of PDFs [36]. The diagram-removal scheme [60] was used to remove interference and overlap with  $t\bar{t}$  production. The events were interfaced to PYTHIA 8.307 using the A14 tune and the NNPDF2.3LO set of PDFs. The inclusive cross-section was corrected to the theory prediction calculated at approximate  $\text{N}^3\text{LO}$  in QCD using the PDF4LHC21 PDF set [61]. The cross-section corresponds to  $\sigma(tW)_{\text{aN}^3\text{LO}} = 87.9^{+2.0}_{-1.9}(\text{scale}) \pm 2.4(\text{PDF})$  pb.

Single-top-quark  $t$ -channel production was modelled with the POWHEG BOX v2 generator at NLO in QCD using the four-flavour scheme and the corresponding NNPDF3.0NNLO set of PDFs. The events were interfaced with PYTHIA 8.307 using the A14 tune and the NNPDF2.3LO set of PDFs. Single-top-quark  $s$ -channel production was modelled using the POWHEG BOX v2 [33–35,62] generator at NLO in QCD in the five-flavour scheme with the NNPDF3.0NNLO [36] PDF set. The events were interfaced with PYTHIA 8.307 using the A14 tune [39] and the NNPDF2.3LO PDF set. However,  $t$ -channel and  $s$ -channel productions contribute only via fake and non-prompt leptons.

The production of  $W$ +jets was simulated with the SHERPA 2.2.12 generator with the same settings as the  $Z$ -boson sample. The events

were normalised to NNLO in QCD with NLO EW corrections calculated using the MATRIX software with the PDF4LHC21 PDF set.

Samples of diboson final states ( $VV$ ) were simulated with the SHERPA 2.2.12 generator, including off-shell effects and Higgs boson contributions where appropriate. Fully-leptonic final states and semileptonic final states, where one boson decays leptonically and the other hadronically, were generated using matrix elements at NLO accuracy in QCD for up to one additional parton and at LO accuracy for up to three additional parton emissions.

Samples of associated production of top-quark pairs with a  $Z$ -boson or a  $W$ -boson are simulated using the SHERPA 2.2.12 generator. Events with at least two leptons in the final state are considered.

The effect of multiple interactions in the same and neighbouring bunch crossings (pile-up) was modelled by overlaying [63] the original hard-scattering event with simulated inelastic  $pp$  events generated by EPOS 2.0.1.4 [64,65] and PYTHIA 8.307. The events generated with EPOS used the EPOS LHC tune, while the PYTHIA 8 events used the NNPDF2.3 LO set of PDFs and parameter values set according to the A3 tune [66]. PYTHIA simulates events that contain at least one high transverse momentum ( $p_T$ ) jet, isolated photon or lepton from the decay of  $b$ -hadrons, while EPOS simulates all remaining events in the sample. The events are generated independently and a filter is applied to EPOS generated events to veto the events simulated by PYTHIA. The simulation has been reweighted to match the distribution of the number of primary vertices seen in data.

After the event generation, the ATLAS detector response is simulated by the toolkit GEANT4 [67] with the full simulation of the ATLAS detector [68]. The simulated samples are processed with the same software framework as the real data.

## 5. Object definitions and event selection

Events are selected if they include at least one lepton that is matched to a lepton identified by a single-lepton trigger. The lowest  $p_T$  threshold in the single-lepton triggers is 26 GeV for electrons and 24 GeV for muons. Events are also required to have at least one reconstructed collision vertex with two or more associated tracks with  $p_T$  greater than 500 MeV. The vertex with the highest  $\sum p_T^2$  of the associated tracks is taken as the primary vertex.

Electron candidates are reconstructed from clusters of energy deposits in the electromagnetic calorimeter which are matched to particle tracks inside the ID. The candidates need to pass the *Tight* likelihood-based identification criteria [69]. Furthermore, they should pass the kinematic requirements  $p_T > 27$  GeV and  $|\eta| < 2.47$ , with the transition region between the barrel and the endcap calorimeters at  $1.37 < |\eta| < 1.52$  excluded. Additionally, electron candidates need to fulfil impact parameter selection criteria:  $|z_0 \sin \theta| < 0.5$  mm and  $|d_0/\sigma(d_0)| < 5$ .<sup>4</sup>

Muon candidates are reconstructed from tracks from the MS matched to tracks from the ID. The candidates are required to pass *Medium* identification criteria [70] as well as  $p_T > 27$  GeV and  $|\eta| < 2.5$ . Additionally, muon candidates need to pass the selection of  $|z_0 \sin \theta| < 0.5$  mm and  $|d_0/\sigma(d_0)| < 3$ .

To suppress non-prompt electrons or muons, isolation criteria are imposed. The isolation is imposed by requiring the energy deposited in the calorimeter in a cone  $\Delta R < 0.2$  around the object, divided by the object  $p_T$ , to be smaller than 0.15 and the momentum, reconstructed by the ID, in a cone  $\Delta R < 0.3$  around the object, divided by the object  $p_T$ , to be smaller than 0.04.

Dedicated scale factors (SFs) are used to correct the identification, reconstruction, isolation and trigger efficiencies to match the efficiencies in data. For electrons, the identification SFs are calculated by

<sup>3</sup> The integration uncertainty represents the uncertainty due to the finite number of points used in the MC integration of the phase-space integrals.

<sup>4</sup>  $d_0$  is the distance of closest approach of the track to the primary vertex point, in the  $r$ - $\phi$  projection and  $|z_0|$  is the  $z$ -coordinate of the track at the point of closest approach to the global  $z$ -axis.

reconstructing Run 2 data using the same software as used for Run 3 and following the methodology described in Refs. [69,71]. The nominal reconstruction and isolation SFs are assumed to be one, with the differences observed between data and MC efficiencies being covered by the uncertainties in the SFs. For muons, the reconstruction, identification, isolation and track-to-vertex-association (*i.e.* impact parameter requirements) efficiency SFs have been measured using the Run 3 data, using the methodology described in Ref. [72]. The electron (muon) momentum is corrected using calibrations obtained from Run 2 (Run 3) with conservative uncertainties. Trigger SFs for both electron and muon triggers are measured in Run 3 in various data-taking periods and are applied to the simulation reflecting the relative luminosity of the individual periods.

Jets are reconstructed using a Particle Flow algorithm [73] that exploits both the calorimeter and ID information. The anti- $k_r$  [74] jet algorithm is used with radius parameter  $R = 0.4$  implemented in the FastJet [75] software. The calibration of jets uses simulation, representing the Run 3 conditions, to correct the jet-energy scale in both simulation and data. Furthermore, the jet-energy scale in data is corrected using the *in-situ* calibration measured in Run 2 [76]. Any residual difference between Run 2 and Run 3 conditions after applying the calibration is considered as a systematic uncertainty estimated from the simulation. After the calibration, jet candidates are required to have  $p_T > 30$  GeV and  $|\eta| < 2.5$ . To suppress jets originating from pile-up, jets need to pass a neural-network-based Jet Vertex Tagger (NNJVT) discriminant for jets with  $p_T$  below 60 GeV. This is a successor of the Jet Vertex Tagger [77].

Jets containing  $b$ -hadrons are identified ( $b$ -tagged) using the DL1d algorithm. The DL1d tagger uses a similar architecture as its predecessor DL1r, described in Ref. [78], but employs DeepSets [79] instead of a recurrent neural network for the processing of the track impact parameters. The DL1d algorithm returns the probability of a jet being light-flavour,  $c$ -jet and  $b$ -jet, which is then combined into a single discriminant. The jets are considered as  $b$ -tagged if the value of the discriminant passes the requirement corresponding to a 77% efficiency for tagging a true  $b$ -jet. The charm-jet (light-flavour-jet) rejection factor for jets with  $p_T > 20$  GeV is about 6 (260) in  $t\bar{t}$  events. Dedicated SFs are applied to the simulation to correct for the efficiency of tagging a true  $b$ -jet as a function of jet  $p_T$ . No SFs are applied for the mis-tagging of  $c$  and light-flavour jets, but their uncertainty is still considered. To remove the ambiguity when one physical object is reconstructed as multiple objects, the overlap-removal algorithm used in Ref. [80] is employed.

Selected events are required to have exactly two leptons (electrons or muons) of opposite electric charge. In the same-flavour channels, events are required to have  $66 < m_{\ell\ell} < 116$  GeV. No dilepton mass criteria are imposed on the  $e\mu$  channel, but the events are required to have one or two  $b$ -tagged jets, as described in Section 2.

Hadrons mis-identified as electrons as well as electrons from photon conversions and leptons from heavy flavour decays can be identified as prompt leptons. These contributions are collectively referred to as fake or non-prompt leptons. To estimate the contribution of fake or non-prompt leptons, for each simulated event, the MC particle-level information is checked to determine if the event that passed the selection contains a fake lepton or non-prompt lepton. Based on this particle-level information, the events are split into real and fake or non-prompt lepton contributions. The events classified as containing at least one fake or non-prompt lepton are combined into a single distribution, representing the estimate of this lepton contribution in data. In the  $e\mu$  channel, the expected contribution from the events with fake or non-prompt leptons accounts for about 1% of all events, while in the same-flavour channels the contribution is below 0.1% in both channels.

Fig. 1(a) compares the multiplicity of  $b$ -tagged jets for data and prediction in the inclusive  $e\mu$  channel. The distribution of the leading lepton  $p_T$  in the  $e\mu$  channel with at least one  $b$ -tagged jet, which is dominated by  $t\bar{t}$  production, is shown in Fig. 1(b). Figs. 1(c) and (d) compare the data and prediction for the leading lepton  $p_T$  distribution in the  $ee$

channel and  $\mu\mu$  channel, respectively, dominated by  $Z$ -boson production. Figs. 1(e) and (f) show the comparison of data and prediction for the invariant mass of the dilepton system in the  $ee$  and  $\mu\mu$  channel, respectively. The observed  $p_T$  distribution of the selected leptons with the highest  $p_T$  in an event is harder than expected in the same-flavour channels and softer in the  $e\mu$  channel. However, in both cases the data agree with the prediction within the uncertainties indicated by the hashed band for the low- $p_T$  regions that are relevant for this measurement as the lepton uncertainties impact the fitted cross section only via acceptance.

Table 1 shows the predicted and measured event yields in the different dilepton categories. The  $e\mu$  inclusive region is only used in the simulation to calculate  $C_b$ .

## 6. Systematic uncertainties

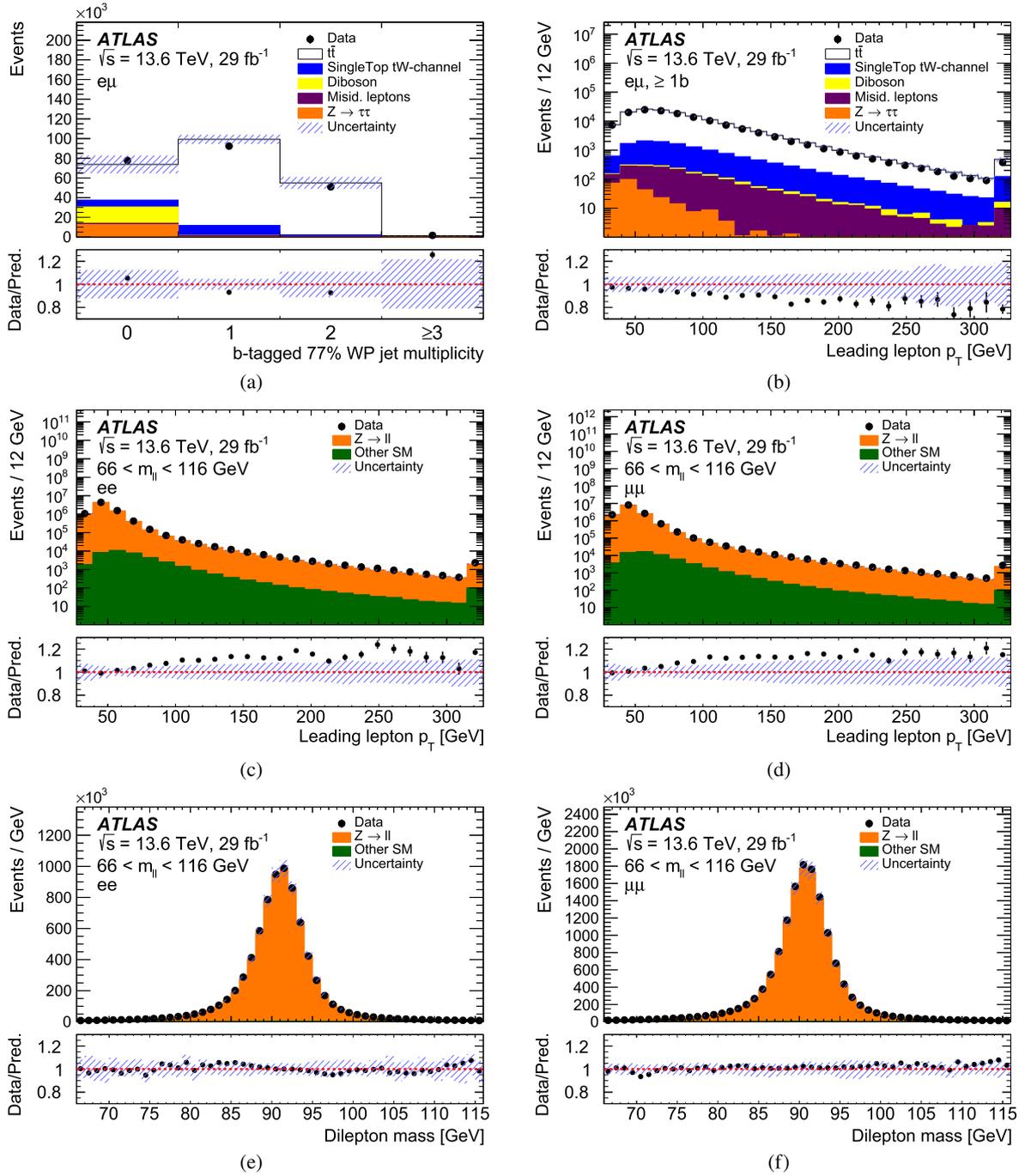
The uncertainty in the integrated luminosity for data recorded in 2022 is 2.2% [81], following the methodology discussed in Ref. [82], using the LUCID-2 detector [83] for the primary luminosity measurements, complemented by measurements using the inner detector and calorimeters. The uncertainty is dominated by effects from horizontal-vertical correlations, known as non-factorisation, in the bunch-density distributions during the beam-separation scans used to determine the absolute luminosity scale, as well as by uncertainties in transferring this calibration from the data-taking conditions of the absolute luminosity calibration to the conditions of routine physics data-taking. Various beam-, calibration-method-, consistency-, reproducibility- and stability-related effects provide smaller contributions to the overall uncertainty. The uncertainty in the pile-up modelling is estimated by varying the average number of interactions per bunch-crossing by 4% in the simulation.

For the electron energy corrections, uncertainties obtained from the Run 2 calibrations using  $Z \rightarrow ee$ , as described in Ref. [69], are increased, covering the differences in the reconstruction between Run 2 and Run 3 of the LHC as estimated from the simulation. The uncertainty in the muon momentum correction is estimated by separately varying the ID and MS components as estimated from  $Z \rightarrow \mu\mu$  events, similarly to Ref. [70]. The uncertainties in the corrections are split into several components both for electrons and muons.

The uncertainties in the electron identification SFs are computed comparing simulation between Run 2 and Run 3. It was checked that the SFs in Run 3 are within the estimated uncertainties in Run 2. The uncertainties on the muon SFs have been calculated using the methods described in Ref. [72]. The trigger efficiencies with their uncertainties are measured using the Run 3 data. Most events can be triggered by either lepton, reducing the systematic uncertainty from the modelling of the trigger efficiencies.

The lepton efficiencies (trigger, identification, reconstruction and isolation) are generally the dominant detector uncertainties on the measurements. They depend on the lepton  $p_T$ ,  $\eta$  and  $\phi$ . In the calculation of the uncertainty in  $R_{t\bar{t}/Z}$ , the nuisance parameters (NPs) corresponding to each systematic uncertainty for the detector related uncertainties are taken to be fully correlated between the  $t\bar{t}$  and  $Z$ -boson processes. Correlating or treating the lepton isolation uncertainties separately between the  $t\bar{t}$  and  $Z$ -boson processes has no significant impact on the central value nor the total uncertainty in the  $R_{t\bar{t}/Z}$  fit.

The uncertainties in the jet-energy scale (JES) [84] and jet-energy resolution (JER) [85] are considered, as estimated in Run 2. Additionally, dedicated uncertainties due to the differences in reconstruction between Run 2 and Run 3 are considered; these are estimated from simulation. A 10% uncertainty per  $b$ -tagged jet is considered for events in the  $e\mu$  channel to cover the discrepancies between data and simulation for the NNJVT discriminant. The uncertainty is not applied to simulated  $t\bar{t}$  events, as the jet reconstruction and tagging probability is eventually determined in data as the  $\epsilon_b$  parameter.



**Fig. 1.** Comparison of observed data and predictions for (a) the distribution of the number of  $b$ -tagged jets in the inclusive  $e\mu$  channel, (b) the  $p_T$  of the leading lepton in the  $e\mu$  channel with at least one  $b$ -tagged jet, (c) the leading lepton  $p_T$  in the  $ee$  channel, (d) the leading lepton  $p_T$  in the  $\mu\mu$  channel, the invariant mass of the dilepton system in (e) the  $ee$  channel and (f) the  $\mu\mu$  channel. The expected yields are calculated by normalising the MC prediction to the product of integrated luminosity and predicted cross section for each process. The “Other SM” represents all non- $Z$ -boson SM processes merged into a single distribution. The “Misid. leptons” label represents fake or non-prompt leptons. The hashed band represents the total uncertainty. The bottom panel shows the ratio of data to the prediction. The rightmost bins contain the overflow events.

The  $b$ -tagging efficiencies for the  $t\bar{t}W$  process and other backgrounds are estimated from the simulation. The uncertainty in the  $b$ -jet efficiency, binned in jet  $p_T$ , is estimated using dilepton  $t\bar{t}$  events, employing a simplified version of the method described in Ref. [86]. Separate,  $p_T$ -independent uncertainties are assigned to the charm- and light-flavours for the efficiency of (mis)-tagging. These are 20% for the  $c$ -mis-tag efficiency and 40% for the light-flavour-mis-tag efficiency. The uncertainties cover the differences in the modelling of the discriminant between data and simulation in  $t\bar{t}$  lepton+jets events for the charm mis-tag rate

and in events with a  $Z$ -boson and at least one jet for the light-flavour mis-tag rate.

The impact of using a different parton shower and hadronisation model is evaluated by comparing the nominal  $t\bar{t}$  sample with another sample produced by interfacing the POWHEG BOX v2 [32–35] generator using the NNPDF3.0NLO [36] PDF set with HERWIG 7.2.3 [87–89]. Uncertainties due to the modelling of the  $t\bar{t}$  signal are estimated considering independent variations of the renormalisation and factorisation scales in the ME of the nominal  $t\bar{t}$  sample by factors of 0.5 and 2, excluding variations that differ by a factor of four, but normalising the signal

**Table 1**

Predicted and observed event yields in the different dilepton regions after event selection. Systematic uncertainties, representing all considered sources, are shown for the predicted yields.

Process	Region				
	$e\mu$ inclusive	$e\mu$ 1 $b$	$e\mu$ 2 $b$	$ee$	$\mu\mu$
$t\bar{t}$	$177\,000 \pm 5\,000$	$87\,400 \pm 2\,600$	$52\,700 \pm 1\,600$	$22\,300 \pm 1\,200$	$33\,500 \pm 1\,900$
$Z \rightarrow ll$	$13\,100 \pm 600$	$270 \pm 70$	$14.2 \pm 3.0$	$7\,749\,000 \pm 230\,000$	$14\,100\,000 \pm 400\,000$
Single-top $tW$ -channel	$19\,000 \pm 9\,000$	$10\,200 \pm 700$	$1\,720 \pm 290$	$2\,250 \pm 120$	$3\,410 \pm 200$
Diboson	$17\,000 \pm 8\,000$	$230 \pm 120$	$5.3 \pm 3.0$	$9\,000 \pm 5\,000$	$18\,000 \pm 9\,000$
$t\bar{t}V$	$220 \pm 110$	$100 \pm 50$	$69 \pm 35$	$240 \pm 120$	$250 \pm 130$
Fake/non-prompt leptons	$2\,800 \pm 1\,400$	$1\,100 \pm 500$	$500 \pm 500$	$6\,000 \pm 6\,000$	$6\,000 \pm 6\,000$
Total prediction	$229\,000 \pm 14\,000$	$99\,200 \pm 3\,000$	$55\,000 \pm 1\,700$	$7\,780\,000 \pm 230\,000$	$14\,100\,000 \pm 400\,000$
Data	222 711	92 385	50 956	7 812 978	14 242 875

to the nominal cross section. Additionally, variations of the renormalisation and factorisation scales are considered for the parton shower simulation affecting the initial- and final-state radiation, where the former is represented by the variation of the Var3c parameter of the A14 tune [90]. The uncertainty due to the choice of the  $h_{\text{damp}}$  parameter is estimated by increasing it by a factor of two. To account for the uncertainty due to the top-quark  $p_T$  distribution mismodelling [27], the nominal  $t\bar{t}$  sample is compared with the same sample reweighted to match the top-quark  $p_T$  distribution computed at NNLO in QCD precision using the MATRIX program.

Several sources of systematic uncertainties in the modelling of the  $Z$ -boson events are considered. Independent renormalisation and factorisation scale variations in the ME as well as the simultaneous variations of the ME and the parton shower by a factor of 0.5 and 2, excluding variations that differ by a factor of four, are tested. The variation with the maximum impact on the yields is symmetrised and used to estimate the uncertainty in the analysis. This variation originates from the simultaneous variation of the renormalisation and factorisation scale by a factor of 0.5 in the ME and the parton shower. For all modelling uncertainties in the  $Z$ -boson production, the systematic variation is rescaled to have the same cross section in the fiducial phase-space.

A normalisation uncertainty of 3.5% is assigned to the  $tW$  process, reflecting the theoretical uncertainty in the cross section. Similarly to  $t\bar{t}$  uncertainties, scale variations in the ME, Var3c and for the final-state radiation of the parton shower are considered for the single-top quark processes. Furthermore, an uncertainty due to the interference between the  $tW$  and  $t\bar{t}$  processes is obtained by comparing the diagram-removal scheme with the diagram-subtraction scheme [60]. Scale variations between the  $t\bar{t}$  and  $tW$  production processes are assumed to be uncorrelated, but this assumption is found to have no significant impact on the total expected uncertainty.

The PDF uncertainty for  $t\bar{t}$  and  $Z$  modelling is estimated by considering the internal variations of the PDF4LHC21 PDF set [43]. This uncertainty is correlated between processes. Only the acceptance effects are considered for the PDF and the modelling uncertainties.

A normalisation uncertainty of 50 (100)% is assigned for the fake and non-prompt lepton background in the  $e\mu$  channel for events with 1 (2)  $b$ -tagged jets as estimated from the simulation, similarly to Ref. [91]. An uncertainty of 100% is assigned on the normalisation of the fake and non-prompt lepton background in the  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  events. A 50% uncertainty is considered for the normalisation of the diboson processes and processes with associated production of the top-quark pairs with a  $Z$ -boson or a  $W$ -boson. These normalisation uncertainties have no significant impact on the total uncertainty of the measurement.

## 7. Results

Fig. 2 shows the distributions used in the fit to extract the  $t\bar{t}$  cross section and the ratio of the cross sections. A profile-likelihood fit is used

to extract  $\sigma_{t\bar{t}}$  and  $R_{t\bar{t}/Z}$  together with the  $b$ -tagging efficiency  $\epsilon_b$ . The results of the fit are:

$$\sigma_{t\bar{t}} = 850 \pm 3(\text{stat.}) \pm 18(\text{syst.}) \pm 20(\text{lumi.}) \text{ pb},$$

$$R_{t\bar{t}/Z} = 1.145 \pm 0.003(\text{stat.}) \pm 0.021(\text{syst.}) \pm 0.002(\text{lumi.}),$$

$$\epsilon_b = 0.544 \pm 0.001(\text{stat.}) \pm 0.004(\text{syst.}) \pm 0.001(\text{lumi.}),$$

where the  $Z$ -boson cross section in  $R_{t\bar{t}/Z}$  is measured in a fiducial phase-space defined by lepton  $p_T > 27$  GeV, lepton  $|\eta| < 2.5$  and an invariant mass of  $66 < m_{\ell\ell} < 116$  GeV for  $\ell = e, \mu$ .

This procedure takes into account all correlations among systematic uncertainties in the  $t\bar{t}$  and  $Z$ -boson cross section measurements. The obtained values for the parameters  $\sigma_{t\bar{t}}$  and  $R_{t\bar{t}/Z}$  have a positive correlation of about 0.6. The result for  $\sigma_{t\bar{t}}$  is reported for a fixed top quark mass of  $m_t = 172.5$  GeV, and depends on the assumed value according to  $(1/\sigma_{t\bar{t}})d\sigma_{t\bar{t}}/dm_t = -0.36\%/GeV$ , as estimated from a variation of the top-quark mass in the  $t\bar{t}$  and  $tW$  samples to 171.5 GeV and 173.5 GeV.

The predicted values for the  $t\bar{t}$  cross section and the ratio  $R_{t\bar{t}/Z}$  extrapolated to the full phase assuming a top-quark mass of 172.5 GeV and using the PDF4LHC21 PDF set are:

$$\sigma_{t\bar{t}}^{\text{theory}} = 924^{+32}_{-40} (\text{scale} + \text{PDF} + \alpha_s) \text{ pb},$$

$$R_{t\bar{t}/Z}^{\text{theory}} = 1.238^{+0.063}_{-0.071} (\text{scale} + \text{PDF} + \alpha_s).$$

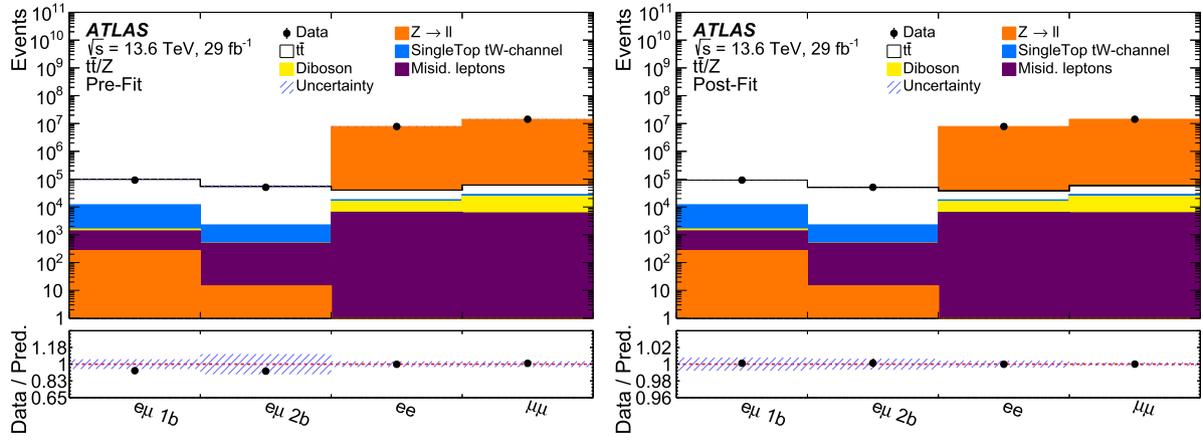
The  $\epsilon_b$  value in the  $t\bar{t}$  simulation is  $0.5431 \pm 0.0003$  (MC stat.), compatible within the per mille uncertainty with the fitted value. No significant pulls or constrains of the NPs are present, with the exception of a NP for the uncertainty in the isolation of muons, that is constrained to about 75% of its pre-fit uncertainty. The low constraining power in the fit is due to the presence of three unconstrained parameters in the likelihood.

Fig. 3 shows the measured  $t\bar{t}$  cross section as a function of the centre-of-mass energy compared to the theory prediction using the PDF4LHC21 PDF set. The 13.6 TeV measurement is slightly lower than the prediction but compatible within 1.5 standard deviations, when adding the downward uncertainty on the prediction and upward measurement uncertainties in quadrature. In Fig. 4, the ratio of the  $t\bar{t}$  and  $Z$ -boson production cross sections is compared to the prediction for several PDF sets. The measured ratio is compatible with the SM prediction based on the PDF4LHC21 set at 1.3 standard deviations assuming a top-quark mass of 172.5 GeV.

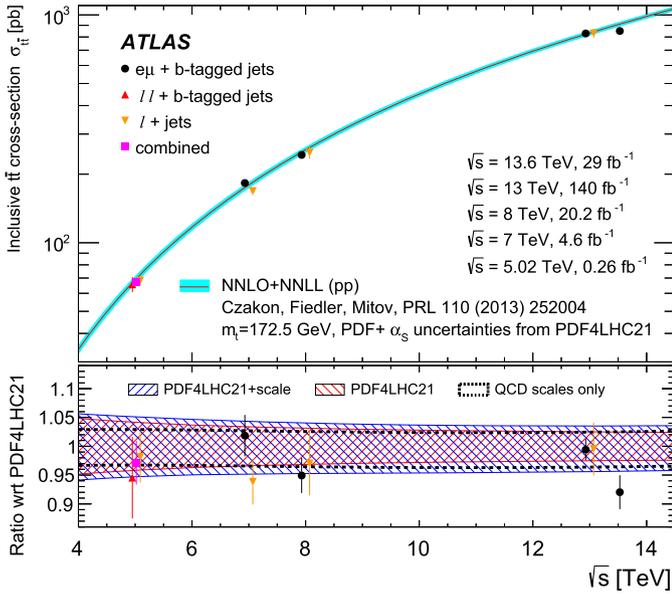
To understand the cancellation of the systematic uncertainties, the  $Z$ -boson cross section has been obtained from a fit to same-flavour events only. The result of the fit is:

$$\sigma_{Z \rightarrow \ell\ell}^{\text{fid.}} = 744 \pm 11 (\text{stat.} + \text{syst.}) \pm 16 (\text{lumi.}) \text{ pb},$$

using the same fiducial phase-space as was used for  $R_{t\bar{t}/Z}$ . The statistical uncertainty is negligible compared to the systematic uncertainty.



**Fig. 2.** Comparison of data and prediction for the event yields before (left) and after the fit (right) in the regions used in the  $t\bar{t}$  fit. The bottom panel shows the ratio of data over the prediction. The hashed bands represent the total uncertainty. Correlations of the NPs as obtained from the fit are used to build the uncertainty band in the post-fit distribution. The error bars on the data points are smaller than the displayed points.



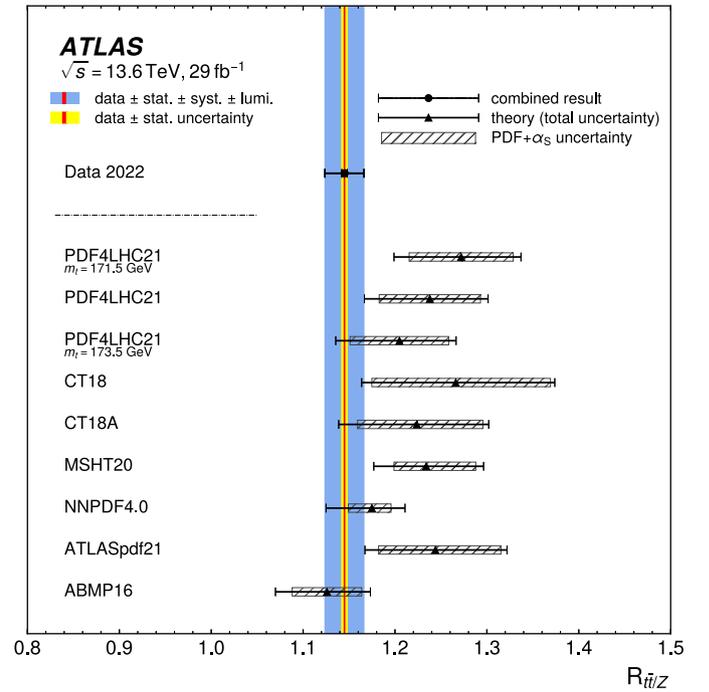
**Fig. 3.** Comparison of the measured  $t\bar{t}$  cross sections at various centre-of-mass energies and the theory predictions using the PDF4LHC21 PDF set. Measurements using the  $e\mu$  final state ( $e\mu + b$ -tagged jets);  $ee$ ,  $\mu\mu$  and  $e\mu$  final states ( $ll + b$ -tagged jets); single lepton final states ( $l +$  jets); as well as combinations of final states (combined) are compared. The bottom panel shows the ratio of the measured values and three predictions that either contain only the uncertainties originating from the QCD scale variations (black), only the variations in the PDF uncertainties (red) or the total uncertainty in the prediction (blue).

In the  $Z$ -boson cross section fit, a supplementary normalisation uncertainty of 5.1% is applied on the  $t\bar{t}$  sample, according to the theoretical uncertainty on the predicted cross section value. The only pull and constraint on nuisance parameters can come from the requirement that the  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  cross sections are equal. Since these two cross section measurements agree to better than 0.5 standard deviations, no pulls are observed.

The theory prediction for the fiducial  $Z \rightarrow \ell\ell$  cross section is

$$\sigma_{Z \rightarrow \ell\ell}^{\text{fid., theory}} = 746_{-22}^{+21} \text{ (scale + PDF + } \alpha_s) \text{ pb,}$$

agreeing with the measurement within 1 standard deviation. Table 2 shows the impact of the systematic uncertainties grouped by their origin. The largest source of systematic uncertainty in the individual cross sections originates from the uncertainty in the luminosity estimation, followed by electron and muon reconstruction. For the  $t\bar{t}$  cross section,



**Fig. 4.** Ratio of the  $t\bar{t}$  to the  $Z$ -boson cross section compared to the predictions for several sets of parton distribution functions. The total cross section for  $t\bar{t}$  production and the fiducial cross section for  $Z$ -boson production are used. If not explicitly mentioned, a top-quark mass of 172.5 GeV is assumed. The hatched box represents the PDF +  $\alpha_s$  component of the uncertainty on the prediction. For the PDF4LHC21 PDF set, predictions for different assumptions about the top-quark mass are also displayed.

the uncertainty in the parton shower and hadronisation modelling also has a significant impact on the precision. For the cross section ratio, several sources of the systematic uncertainties partially cancel out. The dominant uncertainty for the cross section ratio originates from  $t\bar{t}$  modelling, as it does not cancel out. Other significant uncertainties on the ratio include uncertainty in the trigger efficiencies and lepton reconstruction efficiencies. The trigger efficiency uncertainty does not fully cancel out as there are different  $\eta$  and  $p_T$  distributions in  $t\bar{t}$  and  $Z$ -boson events, and different combinations of triggers employed.

The simulated distribution of the  $p_T$  of the dilepton pair is known to not be accurately modelled by the MC simulation [92]. As a cross check, the simulated distribution of the  $p_T$  of the dilepton pair has been reweighted to match the data in  $ee$  and  $\mu\mu$  events, assuming that only

**Table 2**

Observed impact of the different sources of uncertainty on the  $t\bar{t}$  and  $Z$ -boson cross sections and their ratio  $R$ , grouped by category. The  $t\bar{t}$  cross section and  $R$  are obtained in a simultaneous fit to the four regions shown in Fig. 2, while the  $Z$ -boson cross section is obtained from a fit to same-flavour events only. The impact of each category is obtained by repeating the fit after having fixed the set of nuisance parameters corresponding to that category, and subtracting that uncertainty in quadrature from the uncertainty found in the full fit. The statistical uncertainty is obtained by repeating the fit after having fixed all nuisance parameters to their fitted values. Only the acceptance effects are considered for the PDF and the modelling uncertainties.

Category		Uncertainty [%]		
		$\sigma_{t\bar{t}}$	$\sigma_{Z \rightarrow \ell\ell}^{\text{fid.}}$	$R_{t\bar{t}/Z}$
$t\bar{t}$	$t\bar{t}$ parton shower/hadronisation	0.9	< 0.2	0.9
	$t\bar{t}$ scale variations	0.4	< 0.2	0.4
	$t\bar{t}$ normalisation	-	< 0.2	-
$Z$	Top quark $p_T$ reweighting	0.6	< 0.2	0.6
	$Z$ scale variations	< 0.2	0.4	0.3
Bkg.	Single top modelling	0.6	< 0.2	0.6
	Diboson modelling	< 0.2	< 0.2	0.2
Lept.	$t\bar{t}V$ modelling	< 0.2	< 0.2	< 0.2
	Fake and non-prompt leptons	0.6	< 0.2	0.6
	Electron reconstruction	1.2	1.0	0.4
	Muon reconstruction	1.4	1.4	0.3
Jets/tagging	Lepton trigger	0.4	0.4	0.4
	Jet reconstruction	0.4	-	0.4
PDFs	Flavour tagging	0.4	-	0.3
	PDFs	0.5	< 0.2	0.5
Luminosity	Pileup	0.7	0.8	< 0.2
	Luminosity	2.3	2.2	0.3
Systematic uncertainty	Systematic uncertainty	3.2	2.8	1.8
	Statistical uncertainty	0.3	0.02	0.3
Total uncertainty		3.2	2.8	1.9

$Z$ -boson events contribute. After the reweighting, the impact on the total predicted yields was found to be below 0.13%, thus negligible.

## 8. Conclusions

The first ATLAS measurements of the inclusive  $t\bar{t}$  production cross section and the ratio of the  $t\bar{t}$  to the  $Z$ -boson cross section at the new LHC centre-of-mass energy of 13.6 TeV are presented, using 29 fb<sup>-1</sup> of data collected in 2022. The  $t\bar{t}$  cross section is measured to be  $\sigma_{t\bar{t}} = 850 \pm 3(\text{stat.}) \pm 18(\text{syst.}) \pm 20(\text{lumi.})$  pb. The measured value for the ratio is  $R_{t\bar{t}/Z} = 1.145 \pm 0.003(\text{stat.}) \pm 0.021(\text{syst.}) \pm 0.002(\text{lumi.})$ . Both measurements agree with the Standard Model predictions of  $924^{+32}_{-40}(\text{scale} + \text{PDF} + \alpha_s)$  pb for the  $t\bar{t}$  cross section and of  $R_{t\bar{t}/Z}^{\text{theory}} = 1.238^{+0.063}_{-0.071}(\text{scale} + \text{PDF} + \alpha_s)$  for the ratio, using the PDF4LHC21 PDF set. The absolute cross section measurement is limited by the uncertainty in the luminosity measurement as well as the lepton efficiency uncertainties. In the ratio of the  $t\bar{t}$  and  $Z$  cross sections, however, the luminosity uncertainty and lepton uncertainties cancel out to a large extent resulting in the total uncertainty of about 1.9%. A top-quark mass of 172.5 GeV is assumed for the prediction and for the simulation used to correct data. The dependence on the Monte Carlo top-quark mass parameter on the cross section is provided.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data for this manuscript are not available. The values in the plots and tables associated to this article are stored in HEPDATA (<https://hepdata.cedar.ac.uk>).

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 L.T. Bazzano Hurrell <sup>30, [id](#)</sup>, J.B. Beacham <sup>51, [id](#)</sup>, T. Beau <sup>127, [id](#)</sup>, J.Y. Beaucamp <sup>90, [id](#)</sup>, P.H. Beauchemin <sup>158, [id](#)</sup>,  
 F. Becherer <sup>54, [id](#)</sup>, P. Bechtel <sup>24, [id](#)</sup>, H.P. Beck <sup>19, [id](#), [u](#)</sup>, K. Becker <sup>167, [id](#)</sup>, A.J. Beddall <sup>82, [id](#)</sup>, V.A. Bednyakov <sup>38, [id](#)</sup>,  
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 J.K. Behr <sup>48, [id](#)</sup>, J.F. Beirer <sup>36, [id](#)</sup>, F. Beisiegel <sup>24, [id](#)</sup>, M. Belfkir <sup>159, [id](#)</sup>, G. Bella <sup>151, [id](#)</sup>, L. Bellagamba <sup>23b, [id](#)</sup>,  
 A. Bellerive <sup>34, [id](#)</sup>, P. Bellos <sup>20, [id](#)</sup>, K. Beloborodov <sup>37, [id](#)</sup>, D. Benchebkroun <sup>35a, [id](#)</sup>, F. Bendecca <sup>35a, [id](#)</sup>,  
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 E. Bergeaas Kuutmann <sup>161, [id](#)</sup>, N. Berger <sup>4, [id](#)</sup>, B. Bergmann <sup>132, [id](#)</sup>, J. Beringer <sup>17a, [id](#)</sup>, G. Bernardi <sup>5, [id](#)</sup>,  
 C. Bernius <sup>143, [id](#)</sup>, F.U. Bernlochner <sup>24, [id](#)</sup>, F. Bernon <sup>36,102, [id](#)</sup>, A. Berrocal Guardia <sup>13, [id](#)</sup>, T. Berry <sup>95, [id](#)</sup>, P. Berta <sup>133, [id](#)</sup>,  
 A. Berthold <sup>50, [id](#)</sup>, I.A. Bertram <sup>91, [id](#)</sup>, S. Bethke <sup>110, [id](#)</sup>, A. Betti <sup>75a,75b, [id](#)</sup>, A.J. Bevan <sup>94, [id](#)</sup>, N.K. Bhalla <sup>54, [id](#)</sup>,  
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 R.M. Bianchi <sup>129, [id](#)</sup>, G. Bianco <sup>23b,23a, [id](#)</sup>, O. Biebel <sup>109, [id](#)</sup>, R. Bielski <sup>123, [id](#)</sup>, M. Biglietti <sup>77a, [id](#)</sup>, M. Bindi <sup>55, [id](#)</sup>,  
 A. Bingul <sup>21b, [id](#)</sup>, C. Bini <sup>75a,75b, [id](#)</sup>, A. Biondini <sup>92, [id](#)</sup>, C.J. Birch-sykes <sup>101, [id](#)</sup>, G.A. Bird <sup>20,134, [id](#)</sup>, M. Birman <sup>169, [id](#)</sup>,  
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 A. Bitadze <sup>101, [id](#)</sup>, K. Bjørke <sup>125, [id](#)</sup>, I. Bloch <sup>48, [id](#)</sup>, A. Blue <sup>59, [id](#)</sup>, U. Blumenschein <sup>94, [id](#)</sup>, J. Blumenthal <sup>100, [id](#)</sup>,  
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 M. Bona <sup>94, [id](#)</sup>, M. Boonekamp <sup>135, [id](#)</sup>, C.D. Booth <sup>95, [id](#)</sup>, A.G. Borbély <sup>59, [id](#), [as](#)</sup>, I.S. Bordulev <sup>37, [id](#)</sup>,  
 H.M. Borecka-Bielska <sup>108, [id](#)</sup>, G. Borissov <sup>91, [id](#)</sup>, D. Bortoletto <sup>126, [id](#)</sup>, D. Boscherini <sup>23b, [id](#)</sup>, M. Bosman <sup>13, [id](#)</sup>,  
 J.D. Bossio Sola <sup>36, [id](#)</sup>, K. Bouaouda <sup>35a, [id](#)</sup>, N. Bouchhar <sup>163, [id](#)</sup>, J. Boudreau <sup>129, [id](#)</sup>, E.V. Bouhova-Thacker <sup>91, [id](#)</sup>,  
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 J. Bracinik <sup>20, [id](#)</sup>, N. Brahimi <sup>62d, [id](#)</sup>, G. Brandt <sup>171, [id](#)</sup>, O. Brandt <sup>32, [id](#)</sup>, F. Braren <sup>48, [id](#)</sup>, B. Brau <sup>103, [id](#)</sup>, J.E. Brau <sup>123, [id](#)</sup>,  
 R. Brenner <sup>169, [id](#)</sup>, L. Brenner <sup>114, [id](#)</sup>, R. Brenner <sup>161, [id](#)</sup>, S. Bressler <sup>169, [id](#)</sup>, D. Britton <sup>59, [id](#)</sup>, D. Britzger <sup>110, [id](#)</sup>,  
 I. Brock <sup>24, [id](#)</sup>, G. Brooijmans <sup>41, [id](#)</sup>, W.K. Brooks <sup>137f, [id](#)</sup>, E. Brost <sup>29, [id](#)</sup>, L.M. Brown <sup>165, [id](#), [n](#)</sup>, L.E. Bruce <sup>61, [id](#)</sup>,  
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 M. Bruschi <sup>23b, [id](#)</sup>, N. Bruscino <sup>75a,75b, [id](#)</sup>, T. Buanes <sup>16, [id](#)</sup>, Q. Buat <sup>138, [id](#)</sup>, D. Buchin <sup>110, [id](#)</sup>, A.G. Buckley <sup>59, [id](#)</sup>,  
 O. Bulekov <sup>37, [id](#)</sup>, B.A. Bullard <sup>143, [id](#)</sup>, S. Burdin <sup>92, [id](#)</sup>, C.D. Burgard <sup>49, [id](#)</sup>, A.M. Burger <sup>40, [id](#)</sup>, B. Burghgrave <sup>8, [id](#)</sup>,  
 O. Burlayenko <sup>54, [id](#)</sup>, J.T.P. Burr <sup>32, [id](#)</sup>, C.D. Burton <sup>11, [id](#)</sup>, J.C. Burzynski <sup>142, [id](#)</sup>, E.L. Busch <sup>41, [id](#)</sup>, V. Büscher <sup>100, [id](#)</sup>,  
 P.J. Bussey <sup>59, [id](#)</sup>, J.M. Butler <sup>25, [id](#)</sup>, C.M. Buttar <sup>59, [id](#)</sup>, J.M. Butterworth <sup>96, [id](#)</sup>, W. Buttinger <sup>134, [id](#)</sup>,  
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G. Calderini <sup>127, [id](#)</sup>, P. Calfayan <sup>68, [id](#)</sup>, G. Callea <sup>59, [id](#)</sup>, L.P. Caloba <sup>83b</sup>, D. Calvet <sup>40, [id](#)</sup>, S. Calvet <sup>40, [id](#)</sup>,  
T.P. Calvet <sup>102, [id](#)</sup>, M. Calvetti <sup>74a,74b, [id](#)</sup>, R. Camacho Toro <sup>127, [id](#)</sup>, S. Camarda <sup>36, [id](#)</sup>, D. Camarero Munoz <sup>26, [id](#)</sup>,  
P. Camarri <sup>76a,76b, [id](#)</sup>, M.T. Camerlingo <sup>72a,72b, [id](#)</sup>, D. Cameron <sup>36, [id](#), [jh](#)</sup>, C. Camincher <sup>165, [id](#)</sup>, M. Campanelli <sup>96, [id](#)</sup>,  
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M. Capua <sup>43b,43a, [id](#)</sup>, A. Carbone <sup>71a,71b, [id](#)</sup>, R. Cardarelli <sup>76a, [id](#)</sup>, J.C.J. Cardenas <sup>8, [id](#)</sup>, F. Cardillo <sup>163, [id](#)</sup>,  
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L. Carminati <sup>71a,71b, [id](#)</sup>, A. Carnelli <sup>135, [id](#)</sup>, M. Carnesale <sup>75a,75b, [id](#)</sup>, S. Caron <sup>113, [id](#)</sup>, E. Carquin <sup>137f, [id](#)</sup>, S. Carrá <sup>71a,71b, [id](#)</sup>,  
G. Carratta <sup>23b,23a, [id](#)</sup>, F. Carrio Argos <sup>33g, [id](#)</sup>, J.W.S. Carter <sup>155, [id](#)</sup>, T.M. Carter <sup>52, [id](#)</sup>, M.P. Casado <sup>13, [id](#), [k](#)</sup>,  
M. Caspar <sup>48, [id](#)</sup>, F.L. Castillo <sup>4, [id](#)</sup>, L. Castillo Garcia <sup>13, [id](#)</sup>, V. Castillo Gimenez <sup>163, [id](#)</sup>, N.F. Castro <sup>130a,130e, [id](#)</sup>,  
A. Catinaccio <sup>36, [id](#)</sup>, J.R. Catmore <sup>125, [id](#)</sup>, V. Cavaliere <sup>29, [id](#)</sup>, N. Cavalli <sup>23b,23a, [id](#)</sup>, V. Cavasinni <sup>74a,74b, [id](#)</sup>,  
Y.C. Cekmecelioglu <sup>48, [id](#)</sup>, E. Celebi <sup>21a, [id](#)</sup>, F. Celli <sup>126, [id](#)</sup>, M.S. Centonze <sup>70a,70b, [id](#)</sup>, V. Cepaitis <sup>56, [id](#)</sup>, K. Cerny <sup>122, [id](#)</sup>,  
A.S. Cerqueira <sup>83a, [id](#)</sup>, A. Cerri <sup>146, [id](#)</sup>, L. Cerrito <sup>76a,76b, [id](#)</sup>, F. Cerutti <sup>17a, [id](#)</sup>, B. Cervato <sup>141, [id](#)</sup>, A. Cervelli <sup>23b, [id](#)</sup>,  
G. Cesarini <sup>53, [id](#)</sup>, S.A. Cetin <sup>82, [id](#)</sup>, D. Chakraborty <sup>115, [id](#)</sup>, J. Chan <sup>170, [id](#)</sup>, W.Y. Chan <sup>153, [id](#)</sup>, J.D. Chapman <sup>32, [id](#)</sup>,  
E. Chapon <sup>135, [id](#)</sup>, B. Chargeishvili <sup>149b, [id](#)</sup>, D.G. Charlton <sup>20, [id](#)</sup>, M. Chatterjee <sup>19, [id](#)</sup>, C. Chauhan <sup>133, [id](#)</sup>,  
S. Chekanov <sup>6, [id](#)</sup>, S.V. Chekulaev <sup>156a, [id](#)</sup>, G.A. Chelkov <sup>38, [id](#), [a](#)</sup>, A. Chen <sup>106, [id](#)</sup>, B. Chen <sup>151, [id](#)</sup>, B. Chen <sup>165, [id](#)</sup>,  
H. Chen <sup>14c, [id](#)</sup>, H. Chen <sup>29, [id](#)</sup>, J. Chen <sup>62c, [id](#)</sup>, J. Chen <sup>142, [id](#)</sup>, M. Chen <sup>126, [id](#)</sup>, S. Chen <sup>153, [id](#)</sup>, S.J. Chen <sup>14c, [id](#)</sup>,  
X. Chen <sup>62c,135, [id](#)</sup>, X. Chen <sup>14b, [id](#), [au](#)</sup>, Y. Chen <sup>62a, [id](#)</sup>, C.L. Cheng <sup>170, [id](#)</sup>, H.C. Cheng <sup>64a, [id](#)</sup>, S. Cheong <sup>143, [id](#)</sup>,  
A. Cheplakov <sup>38, [id](#)</sup>, E. Cheremushkina <sup>48, [id](#)</sup>, E. Cherepanova <sup>114, [id](#)</sup>, R. Cherkaoui El Moursli <sup>35e, [id](#)</sup>, E. Cheu <sup>7, [id](#)</sup>,  
K. Cheung <sup>65, [id](#)</sup>, L. Chevalier <sup>135, [id](#)</sup>, V. Chiarella <sup>53, [id](#)</sup>, G. Chiarelli <sup>74a, [id](#)</sup>, N. Chiedde <sup>102, [id](#)</sup>, G. Chiodini <sup>70a, [id](#)</sup>,  
A.S. Chisholm <sup>20, [id](#)</sup>, A. Chitan <sup>27b, [id](#)</sup>, M. Chitishvili <sup>163, [id](#)</sup>, M.V. Chizhov <sup>38, [id](#)</sup>, K. Choi <sup>11, [id](#)</sup>,  
A.R. Chomont <sup>75a,75b, [id](#)</sup>, Y. Chou <sup>103, [id](#)</sup>, E.Y.S. Chow <sup>113, [id](#)</sup>, T. Chowdhury <sup>33g, [id](#)</sup>, K.L. Chu <sup>169</sup>, M.C. Chu <sup>64a, [id](#)</sup>,  
X. Chu <sup>14a,14e, [id](#)</sup>, J. Chudoba <sup>131, [id](#)</sup>, J.J. Chwastowski <sup>87, [id](#)</sup>, D. Cieri <sup>110, [id](#)</sup>, K.M. Ciesla <sup>86a, [id](#)</sup>, V. Cindro <sup>93, [id](#)</sup>,  
A. Ciocio <sup>17a, [id](#)</sup>, F. Ciotto <sup>72a,72b, [id](#)</sup>, Z.H. Citron <sup>169, [id](#), [o](#)</sup>, M. Citterio <sup>71a, [id](#)</sup>, D.A. Ciubotaru <sup>27b</sup>, A. Clark <sup>56, [id](#)</sup>,  
P.J. Clark <sup>52, [id](#)</sup>, C. Clarry <sup>155, [id](#)</sup>, J.M. Clavijo Columbie <sup>48, [id](#)</sup>, S.E. Clawson <sup>48, [id](#)</sup>, C. Clement <sup>47a,47b, [id](#)</sup>,  
J. Clercx <sup>48, [id](#)</sup>, Y. Coadou <sup>102, [id](#)</sup>, M. Cobal <sup>69a,69c, [id](#)</sup>, A. Coccaro <sup>57b, [id](#)</sup>, R.F. Coelho Barrue <sup>130a, [id](#)</sup>,  
R. Coelho Lopes De Sa <sup>103, [id](#)</sup>, S. Coelli <sup>71a, [id](#)</sup>, A.E.C. Coimbra <sup>71a,71b, [id](#)</sup>, B. Cole <sup>41, [id](#)</sup>, J. Collot <sup>60, [id](#)</sup>,  
P. Conde Muiño <sup>130a,130g, [id](#)</sup>, M.P. Connell <sup>33c, [id](#)</sup>, S.H. Connell <sup>33c, [id](#)</sup>, I.A. Connelly <sup>59, [id](#)</sup>, E.I. Conroy <sup>126, [id](#)</sup>,  
F. Conventi <sup>72a, [id](#), [aw](#)</sup>, H.G. Cooke <sup>20, [id](#)</sup>, A.M. Cooper-Sarkar <sup>126, [id](#)</sup>, A. Cordeiro Oudot Choi <sup>127, [id](#)</sup>, L.D. Corpe <sup>40, [id](#)</sup>,  
M. Corradi <sup>75a,75b, [id](#)</sup>, F. Corriveau <sup>104, [id](#), [ai](#)</sup>, A. Cortes-Gonzalez <sup>18, [id](#)</sup>, M.J. Costa <sup>163, [id](#)</sup>, F. Costanza <sup>4, [id](#)</sup>,  
D. Costanzo <sup>139, [id](#)</sup>, B.M. Cote <sup>119, [id](#)</sup>, G. Cowan <sup>95, [id](#)</sup>, K. Cranmer <sup>170, [id](#)</sup>, D. Cremonini <sup>23b,23a, [id](#)</sup>,  
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J.E. Crosby <sup>121, [id](#)</sup>, G. Crosetti <sup>43b,43a, [id](#)</sup>, A. Cueto <sup>99, [id](#)</sup>, T. Cuhadar Donszelmann <sup>160, [id](#)</sup>, H. Cui <sup>14a,14e, [id](#)</sup>, Z. Cui <sup>7, [id](#)</sup>,  
W.R. Cunningham <sup>59, [id](#)</sup>, F. Curcio <sup>43b,43a, [id](#)</sup>, P. Czodrowski <sup>36, [id](#)</sup>, M.M. Czurylo <sup>63b, [id](#)</sup>,  
M.J. Da Cunha Sargedas De Sousa <sup>57b,57a, [id](#)</sup>, J.V. Da Fonseca Pinto <sup>83b, [id](#)</sup>, C. Da Via <sup>101, [id](#)</sup>, W. Dabrowski <sup>86a, [id](#)</sup>,  
T. Dado <sup>49, [id](#)</sup>, S. Dahbi <sup>33g, [id](#)</sup>, T. Dai <sup>106, [id](#)</sup>, D. Dal Santo <sup>19, [id](#)</sup>, C. Dallapiccola <sup>103, [id](#)</sup>, M. Dam <sup>42, [id](#)</sup>, G. D'amen <sup>29, [id](#)</sup>,  
V. D'Amico <sup>109, [id](#)</sup>, J. Damp <sup>100, [id](#)</sup>, J.R. Dandoy <sup>34, [id](#)</sup>, M.F. Daneri <sup>30, [id](#)</sup>, M. Danninger <sup>142, [id](#)</sup>, V. Dao <sup>36, [id](#)</sup>,  
G. Darbo <sup>57b, [id](#)</sup>, S. Darmora <sup>6, [id](#)</sup>, S.J. Das <sup>29, [id](#), [ay](#)</sup>, S. D'Auria <sup>71a,71b, [id](#)</sup>, C. David <sup>156b, [id](#)</sup>, T. Davidek <sup>133, [id](#)</sup>,  
B. Davis-Purcell <sup>34, [id](#)</sup>, I. Dawson <sup>94, [id](#)</sup>, H.A. Day-hall <sup>132, [id](#)</sup>, K. De <sup>8, [id](#)</sup>, R. De Asmundis <sup>72a, [id](#)</sup>, N. De Biase <sup>48, [id](#)</sup>,  
S. De Castro <sup>23b,23a, [id](#)</sup>, N. De Groot <sup>113, [id](#)</sup>, P. de Jong <sup>114, [id](#)</sup>, H. De la Torre <sup>115, [id](#)</sup>, A. De Maria <sup>14c, [id](#)</sup>,  
A. De Salvo <sup>75a, [id](#)</sup>, U. De Sanctis <sup>76a,76b, [id](#)</sup>, F. De Santis <sup>70a,70b, [id](#)</sup>, A. De Santo <sup>146, [id](#)</sup>, J.B. De Vivie De Regie <sup>60, [id](#)</sup>,  
D.V. Dedovich <sup>38</sup>, J. Degens <sup>114, [id](#)</sup>, A.M. Deiana <sup>44, [id](#)</sup>, F. Del Corso <sup>23b,23a, [id](#)</sup>, J. Del Peso <sup>99, [id](#)</sup>, F. Del Rio <sup>63a, [id](#)</sup>,  
L. Delagrangé <sup>127, [id](#)</sup>, F. Deliot <sup>135, [id](#)</sup>, C.M. Delitzsch <sup>49, [id](#)</sup>, M. Della Pietra <sup>72a,72b, [id](#)</sup>, D. Della Volpe <sup>56, [id](#)</sup>,  
A. Dell'Acqua <sup>36, [id](#)</sup>, L. Dell'Asta <sup>71a,71b, [id](#)</sup>, M. Delmastro <sup>4, [id](#)</sup>, P.A. Delsart <sup>60, [id](#)</sup>, S. Demers <sup>172, [id](#)</sup>, M. Demichev <sup>38, [id](#)</sup>,

S.P. Denisov <sup>37, [id](#)</sup>, L. D’Eramo <sup>40, [id](#)</sup>, D. Derendarz <sup>87, [id](#)</sup>, F. Derue <sup>127, [id](#)</sup>, P. Dervan <sup>92, [id](#)</sup>, K. Desch <sup>24, [id](#)</sup>,  
C. Deutsch <sup>24, [id](#)</sup>, F.A. Di Bello <sup>57b,57a, [id](#)</sup>, A. Di Ciaccio <sup>76a,76b, [id](#)</sup>, L. Di Ciaccio <sup>4, [id](#)</sup>, A. Di Domenico <sup>75a,75b, [id](#)</sup>,  
C. Di Donato <sup>72a,72b, [id](#)</sup>, A. Di Girolamo <sup>36, [id](#)</sup>, G. Di Gregorio <sup>36, [id](#)</sup>, A. Di Luca <sup>78a,78b, [id](#)</sup>, B. Di Micco <sup>77a,77b, [id](#)</sup>,  
R. Di Nardo <sup>77a,77b, [id](#)</sup>, C. Diaconu <sup>102, [id](#)</sup>, M. Diamantopoulou <sup>34, [id](#)</sup>, F.A. Dias <sup>114, [id](#)</sup>, T. Dias Do Vale <sup>142, [id](#)</sup>,  
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E. Dreyer <sup>169, [id](#)</sup>, I. Drivas-koulouris <sup>10, [id](#)</sup>, M. Drnevich <sup>117, [id](#)</sup>, A.S. Drobac <sup>158, [id](#)</sup>, M. Drozdova <sup>56, [id](#)</sup>, D. Du <sup>62a, [id](#)</sup>,  
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C. Dülsen <sup>171, [id](#)</sup>, A.E. Dumitriu <sup>27b, [id](#)</sup>, M. Dunford <sup>63a, [id](#)</sup>, S. Dungs <sup>49, [id](#)</sup>, K. Dunne <sup>47a,47b, [id](#)</sup>, A. Duperrin <sup>102, [id](#)</sup>,  
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 L. Iconomidou-Fayard <sup>66, [id](#)</sup>, P. Iengo <sup>72a,72b, [id](#)</sup>, R. Iguchi <sup>153, [id](#)</sup>, T. Iizawa <sup>126, [id](#)</sup>, Y. Ikegami <sup>84, [id](#)</sup>, N. Ilic <sup>155, [id](#)</sup>,  
 H. Imam <sup>35a, [id](#)</sup>, M. Ince Lezki <sup>56, [id](#)</sup>, T. Ingebretsen Carlson <sup>47a,47b, [id](#)</sup>, G. Introzzi <sup>73a,73b, [id](#)</sup>, M. Iodice <sup>77a, [id](#)</sup>,  
 V. Ippolito <sup>75a,75b, [id](#)</sup>, R.K. Irwin <sup>92, [id](#)</sup>, M. Ishino <sup>153, [id](#)</sup>, W. Islam <sup>170, [id](#)</sup>, C. Issever <sup>18,48, [id](#)</sup>, S. Istin <sup>21a, [id](#)</sup>,  
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A. Kourkoumeli-Charalampidi<sup>73a,73b, [id](#)</sup>, C. Kourkoumelis<sup>9, [id](#)</sup>, E. Kourlitis<sup>110, [id](#), [at](#)</sup>, O. Kovanda<sup>146, [id](#)</sup>,  
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M. Lassnig<sup>36, [id](#)</sup>, V. Latonova<sup>131, [id](#)</sup>, A. Laudrain<sup>100, [id](#)</sup>, A. Laurier<sup>150, [id](#)</sup>, S.D. Lawlor<sup>139, [id](#)</sup>, Z. Lawrence<sup>101, [id](#)</sup>,  
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