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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 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 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 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

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

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

where L is the integrated luminosity, $\sigma_{t\bar{t}}$ is the measured $t\bar{t}$ cross section, ϵ_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 ϵ_{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

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

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

where N_{ee} ($N_{\mu\mu}$) is the selected number of events passing the ee ($\mu\mu$) selection. Parameters ϵ_{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 $p_{\text{T}} > 27$ GeV, the absolute value of the leptons' pseudorapidity $|\eta| < 2.5$ and the invariant mass of $66 < m_{\ell\ell} < 116$ GeV for $\ell = e, \mu$.[1] 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.

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 $\sigma^{\text{fid.}}_{Z\to\ell\ell}$ 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 4π 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 T m 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 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_{damp} parameter set to $1.5\,m_t$ [37].[2] 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)

[1] 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, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

[2] The h_{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, α_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 $Z/\gamma^* \to \ell^+\ell^-$ 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 $Z/\gamma^* \to e^+e^-$, $Z/\gamma^* \to \mu^+\mu^-$ and $Z/\gamma^* \to \tau^+\tau^-$ 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 $\sigma(Z)^{\text{fid.}} = 746 \pm 0.7(\text{integration})^{+3}_{-5}(\text{scale}) \pm 21(\text{PDF})$ pb for the Z-boson decaying into a single lepton flavour and leptons before QED radiation.[3]

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 μ_r and μ_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 NNPDF3.0nlo 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 N^{3}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 NNPDF3.0nlo 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 NNPDF3.0nlo [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 $|d_0/\sigma(d_0)| < 5$.[4]

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

[3] The integration uncertainty represents the uncertainty due to the finite number of points used in the MC integration of the phase-space integrals.

[4] d_0 is the distance of closest approach of the track to the primary vertex point, in the r—ϕ 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_t [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 $p_{\mathrm{T}} > 30$ 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 $p_{\mathrm{T}} > 20$ 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 $Z \to ee$, 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 $Z \to \mu\mu$ 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}, η and ϕ. 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 ϵ_b parameter.

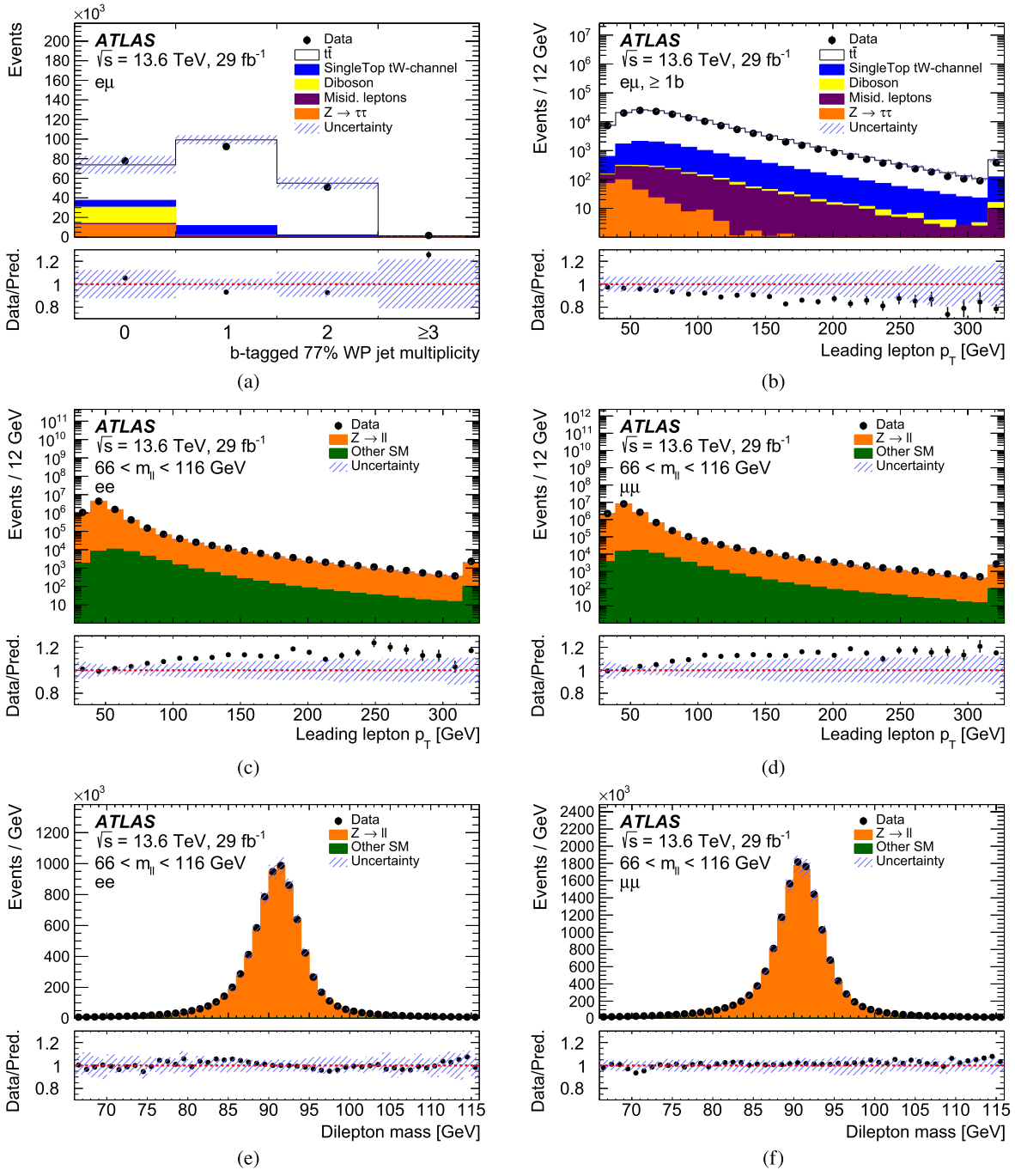


Fig. 1. Comparison of observed data and predictions for (a) the distribution of the number of b-tagged jets in the inclusive $e\mu$ channel, (b) the p_{T} of the leading lepton in the $e\mu$ channel with at least one b-tagged jet, (c) the leading lepton p_{T} in the ee channel, (d) the leading lepton 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 tW 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 ± 5 000	87 400 ± 2 600	52 700 ± 1 600	22 300 ± 1 200	33 500 ± 1 900
$Z \to ll$	13 100 ± 600	270 ± 70	14.2 ± 3.0	7 7490 000 ± 230 000	14 100 000 ± 400 000
SingleTop tW-channel	19 000 ± 9 000	10 200 ± 700	1 720 ± 290	2 250 ± 120	3 410 ± 200
Diboson	17 000 ± 8 000	230 ± 120	5.3 ± 3.0	9 000 ± 5 000	18 000 ± 9 000
$t\bar{t}V$	220 ± 110	100 ± 50	69 ± 35	240 ± 120	250 ± 130
Fake/non-prompt leptons	2 800 ± 1 400	1 100 ± 500	500 ± 500	6 000 ± 6 000	6 000 ± 6 000
Total prediction	229 000 ± 14 000	99 200 ± 3 000	55 000 ± 1 700	7 780 000 ± 230 000	14 100 000 ± 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_{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 $Z \to ee$ and $Z \to \mu\mu$ 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 ϵ_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 $p_{\text{T}} > 27$ 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 $(1/\sigma_{t\bar{t}})\mathrm{d}\sigma_{t\bar{t}}/\mathrm{d}m_t = -0.36\%/\text{GeV}$, 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 ϵ_b value in the $t\bar{t}$ simulation is 0.5431 ± 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:

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

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.

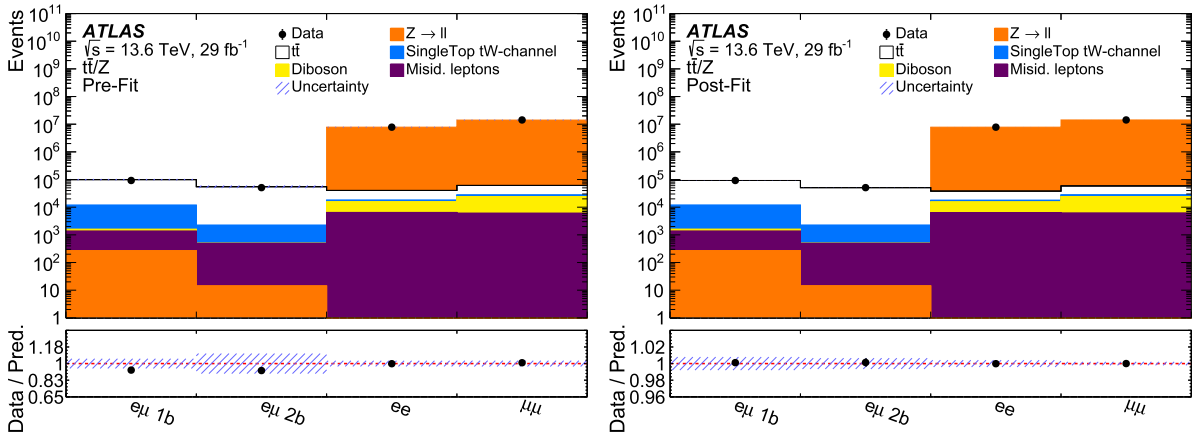


Fig. 2. Comparison of data and prediction for the event yields before (left) and after the fit (right) in the regions used in the $t\bar{t}$ fit. The bottom panel shows the ratio of data over the prediction. The hashed bands represent the total uncertainty. Correlations of the NPs as obtained from the 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.

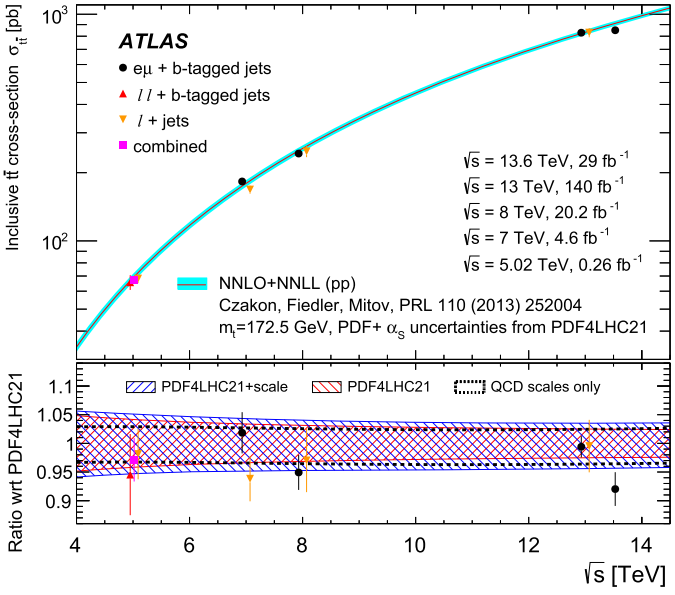


Fig. 3. Comparison of the measured $t\bar{t}$ cross sections at various centre-of-mass energies and the theory predictions using the PDF4LHC21 PDF set. Measurements using the $e\mu$ final state ($e\mu$ + b-tagged jets); ee, $\mu\mu$ and $e\mu$ final states (ll + b-tagged jets); single lepton final states (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).

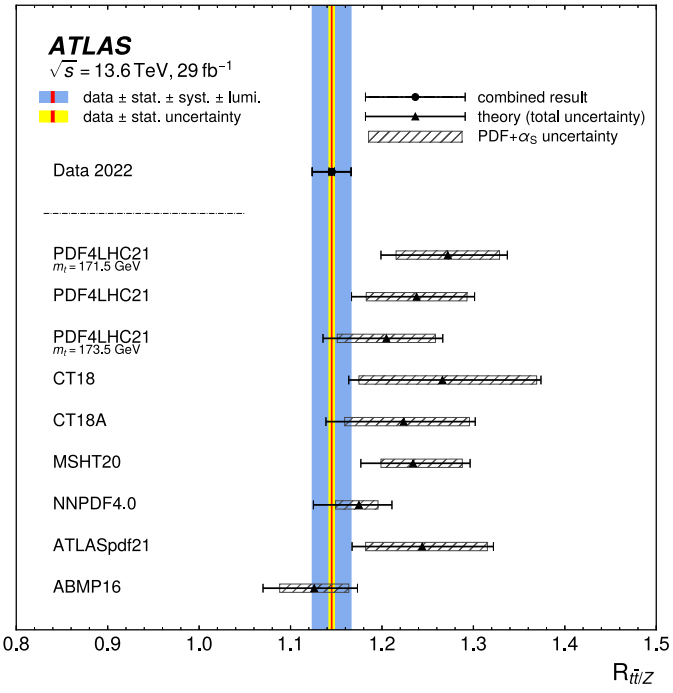


Fig. 4. Ratio of the $t\bar{t}$ to the Z-boson cross section compared to the predictions for several sets of parton distribution functions. The total cross section for $t\bar{t}$ production and the fiducial cross section for Z-boson production are used. If not explicitly mentioned, a top-quark mass of 172.5 GeV is assumed. The hatched box represents the PDF+α_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.

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 $Z \to ee$ and $Z \to \mu\mu$ 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 $Z \to \ell\ell$ cross section is

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

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, 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 η 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 [%]		
		$\sigma_{t\bar{t}}$	$\sigma^{\text{fid.}}_{Z\to\ell\ell}$	$R_{t\bar{t}/Z}$
$t\bar{t}$	$t\bar{t}$ 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	-
	Top quark p_{T} reweighting	0.6	< 0.2	0.6
Z	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
	$t\bar{t}V$ modelling	< 0.2	< 0.2	< 0.2
	Fake and non-prompt leptons	0.6	< 0.2	0.6
Lept.	Electron reconstruction	1.2	1.0	0.4
	Muon reconstruction	1.4	1.4	0.3
	Lepton trigger	0.4	0.4	0.4
Jets/tagging	Jet reconstruction	0.4	-	0.4
	Flavour tagging	0.4	-	0.3
	PDFs	0.5	< 0.2	0.5
	Pileup	0.7	0.8	< 0.2
	Luminosity	2.3	2.2	0.3
	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^{-1} 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 $924^{+32}_{-40}(\text{scale} + \text{PDF} + \alpha_{\text{s}})$ pb for the $t\bar{t}$ cross section and of $R^{\text{theory}}_{t\bar{t}/Z} = 1.238^{+0.063}_{-0.071}(\text{scale} + \text{PDF} + \alpha_{\text{s}})$ 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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