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Observation of $t\bar{t}$ production in the lepton+jets and dilepton channels in p+Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV with the ATLAS detector

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Abstract: This paper reports the observation of top-quark pair production in proton-lead collisions in the ATLAS experiment at the Large Hadron Collider. The measurement is performed using 165 nb^{-1} of p+Pb data collected at $\sqrt{s_{\text{NN}}} = 8.16$ TeV in 2016. Events are categorised in two analysis channels, consisting of either events with exactly one lepton (electron or muon) and at least four jets, or events with two opposite-charge leptons and at least two jets. In both channels at least one b-tagged jet is also required. Top-quark pair production is observed with a significance over five standard deviations in each channel. The top-quark pair production cross-section is measured to be $\sigma_{t\bar{t}} = 58.1 \pm 2.0\,(\text{stat.})\,^{+4.8}_{-4.4}\,(\text{syst.})$ nb, with a total uncertainty of 9%. In addition, the nuclear modification factor is measured to be $R_{p\text{A}} = 1.090 \pm 0.039$ (stat.) $^{+0.094}_{-0.087}$ (syst.). The measurements are found to be in good agreement with theory predictions involving nuclear parton distribution functions.

Keywords: Heavy Ion Experiments, Top Physics

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Contents

1 Introduction

The heavy-ion (HI) collisions produced at the TeV-scale energies of the Large Hadron Collider (LHC) at CERN opened up the possibility to measure various elementary particle production for the first time in lead-lead (Pb+Pb) and proton-lead (p+Pb) systems. With the first observations of the $W^{\pm}$ boson [1, 2], the Z boson [3–5], bottom-quark jets (b-quark jets) [6, 7] and the τ-lepton [8, 9], only two Standard Model (SM) particles remain to be directly observed in Pb+Pb collisions: the Higgs boson and the top quark. While the Higgs boson production cross-section is too low to establish its observation in Pb+Pb collisions at the LHC, the observation of top-quark production is within reach.

In ultra-relativistic Pb+Pb collisions at the LHC, top quarks are expected to provide a unique tool to measure properties of the strongly interacting quark-gluon plasma (QGP) [10]. These properties may be inferred from modifications of various observables in Pb+Pb collisions in comparison to reference measurements in the proton-proton (pp) system. Often, modifications of event yields in Pb+Pb collisions relative to reference yields in pp collisions can be attributed to both initial-state effects (e.g., different parton distribution functions for heavy nuclei than for free nucleons) and final-state effects due to the creation of the QGP. Therefore, precise knowledge of the initial-state effects is crucial in anticipation of extracting QGP properties precisely from experimental data. This knowledge may be gained using measurements done in p+Pb collisions.

In p+Pb collisions, top quarks provide novel probes of nuclear parton distribution functions (nPDFs) [11–13], especially the gluon nPDF, which is particularly important for perturbative calculations in Quantum Chromodynamics (QCD) at the LHC energies [13–15]. The top-quark yields, measured using kinematics of electrons and muons originating from top-quark decays, provide precise information [11] in the kinematic region of Bjorken-$x \sim 3 \cdot 10^{-3}$–0.5 and $Q^2 \sim m_t^2 \sim 3 \cdot 10^4\,\text{GeV}^2$ (m_t stands for the top-quark mass), which is poorly constrained by other measurements. In this region, anti-shadowing and EMC effects [13] are supposed to modify the gluon nPDF shape compared with the free proton case. This might result in enhancements as large as 10% in the $t\bar{t}$ production cross-section compared with the same process measured in pp collisions.

The top quark, the heaviest elementary particle, is short-lived and decays through $t \to Wb$ with a branching ratio of almost 100%. The subsequent W boson decay may proceed leptonically ($W \to \ell\nu_\ell$, $\ell = e, \mu$) or hadronically ($W \to q\bar{q}'$) [16]. At the LHC, top quarks are preferentially produced in top quark-antiquark ($t\bar{t}$) pairs via gluon-gluon fusion and their production dominates over single-top-quark production [17]. With large integrated luminosities of p+Pb and Pb+Pb datasets recorded between 2015 and 2018 (Run 2), the observation of the $t\bar{t}$ process becomes accessible in HI collisions for the first time at the LHC. In particular, $t\bar{t}$ events reconstructed in the ℓ+jets ($t\bar{t} \to WbW\bar{b} \to \bar{\ell}\nu_\ell bq\bar{q}'\bar{b}$) and dilepton ($t\bar{t} \to WbW\bar{b} \to \bar{\ell}\nu_\ell b\ell'\bar{\nu_{\ell'}}\bar{b}$) channels, with relatively low expected background contributions, can be examined experimentally [18]. The CMS experiment observed $t\bar{t}$ production using the ℓ+jets decay channel in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV [19]. Also, evidence of $t\bar{t}$ production in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV was reported by the CMS collaboration with 4.0σ significance using the dilepton channel [20].

In this paper, a measurement of $t\bar{t}$ production in p+Pb collision data collected at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV with the ATLAS experiment is presented. Top-quark pairs are reconstructed in the ℓ+jets and dilepton channels using final states with electrons, muons and jets. The dilepton mode is less abundant than the ℓ+jets channels but has a significantly higher purity. The lower transverse-momentum requirements imposed on individual leptons and jets and more precise detector calibration studies considered in the data analysis lead to a significant improvement in the measurement precision compared with the result from ref. [19]. Also a nuclear modification factor for $t\bar{t}$ production in p+Pb is measured for the first time at the LHC. The results are compared with calculations at next-to-next-to-leading-order (NNLO) in the strong coupling constant α_s involving the most up-to-date nPDF sets.

2 ATLAS detector

The ATLAS experiment [21] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[1] It consists of an inner tracking detector 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

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[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. Polar 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 $\eta = -\ln\tan(\theta/2)$ 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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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 T m 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 [22] detector, which is located close to the beampipe. A two-level trigger system is used to select events [23]. 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 1 kHz on average depending on the data-taking conditions. A software suite [24] 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 simulated event samples

The data used in this measurement were collected with the ATLAS detector during p+Pb collisions in 2016, and correspond to an integrated luminosity of 165 nb^{-1}. The proton and Pb beams had an energy of 6.5 TeV and 2.56 TeV per nucleon, respectively, resulting in a nucleon-nucleon centre-of-mass collision energy of 8.16 TeV and a rapidity boost of this frame of ±0.465 units relative to the ATLAS laboratory frame, depending on the direction of the p beam. Two beam-direction configurations were provided with p+Pb and Pb+p collisions with about a factor of two more integrated luminosity in the latter configuration where the Pb beam goes in the $+z$ direction. The average number of hadronic interactions per bunch crossing was 0.18.

Samples of Monte Carlo (MC) simulated events are used to develop the analysis procedures, evaluate signal and background contributions, estimate signal efficiencies, and provide predictions for comparison with data. All samples are processed using the full ATLAS detector simulation [25] based on the GEANT4 4 framework [26]. All signal and simulated background samples are produced separately for two isospin (proton-proton and proton-neutron) configurations and then embedded into real p+Pb or Pb+p data events for accurate UE modelling. These 'data overlay events' are then processed using the same reconstruction and analysis chain as the data. Since the cross-section differences between the two isospin combinations are below 0.1%, rates of simulated events are scaled by the mass number $A_{\mathrm{Pb}} = 208$ of the Pb nucleus and a ratio of integrated luminosities in the data and MC simulation. The top-quark mass is set to 172.5 GeV in all top-quark samples. The EVTGEN program [27] is used to treat the decays of b- and c-flavoured hadrons in samples simulated using POWHEG BOX v2 [28] and MADGRAPH5_aMC@NLO 2.3.3 [29] MC generators.

The nominal simulated $t\bar{t}$ sample is produced using the next-to-leading-order (NLO) event generator POWHEG BOX v2 with the NNPDF3.0NLO parton distribution function (PDF) set [30]. It is interfaced with the PYTHIA 8.243 generator [31] using the NNPDF2.3LO PDF set [32] and the A14 tune [33] for the parton-shower and hadronisation modelling. The POWHEG resummation damping parameter h_{damp}, which controls matrix element to parton-shower matching and effectively regulates the high-p_{T} radiation, is set to 1.5 times the top-quark mass. All signal samples are normalised using the NNLO+next-to-next-to-leading logarithmic (NNLL) $t\bar{t}$ cross-section prediction from the TOP++ v2 program [34].

Alternative $t\bar{t}$ simulation samples are generated to assess systematic uncertainties related to the signal modelling. One sample uses the POWHEG BOX v2 MC generator with the HERWIG v7.2 parton-shower and hadronisation model [35] employing the H7.2-Default tune [35, 36]. Another sample is generated by employing the MADGRAPH5_aMC@NLO 2.3.3 generator in combination with the NNPDF3.0NLO PDF set, while using the PYTHIA 8 parton-shower and hadronisation model. Uncertainties in the amount of parton-shower radiation are evaluated by generating POWHEG BOX v2+PYTHIA 8 samples with an increased cut-off scale for the first gluon emission, represented by the h_{damp} parameter, which is set to three times the top-quark mass [37].

The backgrounds that are evaluated with MC simulation arise from W and Z bosons produced in association with jets, from single top-quark production and diboson production. The Z+jets, and W+jets events are simulated with the SHERPA v2.2.10 generator [38] in combination with the NNPDF3.0NNLO PDF set [30], using NLO matrix elements for up to two partons, and LO matrix elements for up to four partons, as discussed in ref. [39]. The V+jets ($V = W, Z$) samples are normalised to NNLO cross-sections [40] and are further filtered for the content of light, c- and b-quarks forming samples labelled as W+light/Z+light, W+c/Z+c and W+b/Z+b in the following.

The t-channel and tW associated production processes for single-top-quarks are simulated using the POWHEG BOX v2 [41, 42] generator with the NNPDF3.04fNLO [30] and NNPDF3.0NLO PDF sets, employing PYTHIA 8 with the A14 tune as the parton-shower and hadronisation model. The diagram removal scheme [43] is used to treat the interference between the $t\bar{t}$ and tW final states. Smaller backgrounds from diboson production (WW, WZ, and ZZ) with additional jets are simulated using the SHERPA v2.2.11 generator with the NNPDF3.0NNLO PDF set.

4 Event selection and background estimation

The events are selected using single-lepton electron or muon triggers with a minimum transverse momentum (p_{T}) threshold of 15 GeV [44, 45]. They are required to have at least one reconstructed vertex built from at least two good-quality charged-particle tracks with $p_{\mathrm{T}} > 0.1$ GeV.

Electron candidates are reconstructed from a localised cluster of energy deposits in the EM calorimeter matched to a track in the inner detector. They are further required to satisfy the 'Medium' likelihood-based requirements [46] and to have $p_{\mathrm{T}} > 18$ GeV and $|\eta_{\mathrm{cluster}}| < 2.47$. The electron candidates are required to be isolated using varying requirements on track- and calorimeter-based isolation [46].

Muon candidates are reconstructed by combining matching tracks reconstructed in the inner detector and the muon spectrometer, and are required to satisfy the 'Medium' quality requirements [47]. The muon candidates are also required to have $p_{\mathrm{T}} > 18$ GeV and $|\eta| < 2.5$, and to be isolated using fixed criteria for calorimeter-based isolation and varying requirements on track-based isolation [47]. Lepton tracks have to fulfil further requirements described in ref. [48].

Jets are reconstructed from calorimeter energy deposits [49], using the anti-k_t algorithm [50, 51] with a radius parameter $R = 0.4$. The jet kinematics are corrected event-by-event for the contribution from underlying event (UE), and are calibrated using simulations of the calorimeter response and in situ measurements of the absolute energy scale [52]. In-situ measurements are carried out in pp collisions and cross-calibrated to the p+Pb system. Jets reconstructed this way are referred to as HI jets. The kinematic variables are calculated using these jets. However, the b-tagging information is not available for HI jets. For this reason, a second type of jets is also used in the analysis.

The second type of jets is reconstructed from particle-flow (PF) objects that combine information from topological clusters of calorimeter energy deposits and nner-detector tracks [53]. The PF jets are built with the anti-k_t algorithm with a radius parameter $R = 0.4$ and calibrated in the same way as in high pile-up pp collisions at $\sqrt{s} = 13\,\text{TeV}$ [54]. PF jets containing b-hadrons are tagged using the DL1r algorithm [55], a multivariate discriminant based on deep-learning techniques making use of track impact parameters and reconstructed secondary vertices. A tagger working point with 85% efficiency (evaluated in simulated $t\bar{t}$ events) in pp collisions for tagging b-quark jets from top-quark decays is used, corresponding to rejection factors of about three against c-quark jets and 40 against light-quark and gluon jets.

HI jets with $p_{\text{T}} > 20$ GeV and $|\eta| < 2.5$ are matched to PF jets in the same event using a geometric criterion of minimal ΔR. The b-tagging information is inherited from matched PF jets if $\Delta R < 0.3$ between a HI and a PF jet. HI jets lacking a PF counterpart are considered as non-b-tagged. This mismatch arises predominantly from differences in energy calibration as HI jets have a dedicated calibration optimised for the low pile-up environment.

To prevent the double-counting of electron energy deposits as jets, the closest jet to an electron candidate is removed if it is within $\Delta R \leq 0.2$ of the electron. Furthermore, to reduce the contribution of leptons from heavy-flavour hadron decays inside jets, leptons within $\Delta R \leq 0.4$ of selected jets are discarded, unless the lepton is a muon and the jet has fewer than three associated tracks, in which case the jet is discarded. This approach is applied separately to both jet types prior to the HI-PF jet matching.

The missing transverse momentum, with magnitude $E_{\text{T}}^{\text{miss}}$, is computed using momenta of fully calibrated leptons, photons, and PF jets, combined with the soft hadronic activity measured by reconstructed charged-particle tracks not associated with the hard objects [56]. No requirement on $E_{\text{T}}^{\text{miss}}$ is imposed in the final event selections used for this measurement.

Events with exactly two opposite-sign leptons form the dilepton channel. Events with same-flavour lepton pairs (e^+e^- or $\mu^+\mu^-$) with the invariant mass ($m_{\ell\ell}$) within a Z boson mass window ($80 < m_{\ell\ell} < 100$ GeV) are discarded, and $m_{\ell\ell}$ must be greater than 15 (45) GeV in the $e\mu$ (ee and $\mu\mu$) channel. The latter condition is imposed to match the phase space of the Z+jets simulation sample and does not have a significant impact on the results. Events are further required to have at least two HI jets including at least one b-tagged jet. Such events form the signal region (SR) of the dilepton channel. The regions with two leptons and exactly one or at least two b-tagged jets are labelled as $2\ell1b$ and $2\ell2b$incl, respectively.

Events with exactly one lepton and at least four HI jets including at least one b-tagged jet form the SR of the ℓ+jets channel. Based on the lepton flavour, the ℓ+jets SR is further split into four regions with one electron or muon and exactly one or at least two b-tagged jets, labelled as $1\ell1b$ e+jets, $1\ell2b$incl e+jets, $1\ell1b$ μ+jets and $1\ell2b$incl μ+jets.

Non-prompt leptons, hadrons and photons that meet the lepton selection criteria are sources of the non-prompt and misidentified lepton background, commonly referred to as fake-lepton background. In this measurement, the normalisation and shape of the fake-lepton background are estimated from data using a technique called the Matrix Method (MM) [57]. The MM technique exploits differences for lepton-identification-related characteristics between prompt, isolated leptons originating from W and Z boson decays (referred to as real leptons), and leptons that are either non-isolated or result from the misidentification of photons or jets (referred to as fake leptons). The method expresses the number of selected events in each sample as a linear combination of the numbers of events with real and fake leptons, where the coefficients are determined using 'Tight' and 'Loose' lepton selections and are related to the probabilities (efficiencies) for 'Loose' leptons to also satisfy the 'Tight' selection criteria. 'Tight' and 'Loose' selections are used to measure both the real- and fake-lepton efficiencies. The 'Tight' selection employs the complete set of high-quality lepton identification criteria. The 'Loose' lepton selection is obtained from the 'Tight' selection by relaxing the identification requirements and dropping the lepton isolation requirements [46, 47]. The real-lepton efficiencies are evaluated in MC samples (Z+jets, $t\bar{t}$) as the ratio of the numbers of simulated prompt leptons passing the 'Tight' requirements and simulated prompt leptons passing the 'Loose' requirements. The fake-lepton efficiencies are estimated using dedicated control regions (CR) with one lepton passing 'Loose' identification and isolation requirements, and missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}} < 20$ GeV. Due to limited statistical precision in the CR with two leptons, the one-lepton CR is also used to evaluate the fake-lepton contribution for the SR in the dilepton channel. Both the real- and fake-lepton efficiencies are evaluated for electrons and muons in p_{T} and $|\eta|$ bins in event categories with zero, one and at least two b-tagged jets.

Fake-lepton efficiencies vary between 15%–22% for electrons and 0.5%–10% for muons, and are larger at lower lepton p_{T}. Data events which satisfy the baseline analysis selection imposed on 'Loose' leptons are weighted according to the efficiencies for both the prompt and fake leptons. To validate the method, the predictions are compared with data in a CR with a larger fraction of fake-lepton candidates than expected in the analysis SR and a satisfactory agreement is found. This CR, which is defined by imposing the dilepton and ℓ+jets selection and requiring no b-tagged jets, is dominated by W/Z+jets processes.

The main background contribution in the dilepton channel includes the Z+jets and single-top tW processes. Up to 5% of Z+jets events originate from the $Z \to \tau^+\tau^-$ process. This fraction rises to about 99% in selected events in the $e\mu$ channel. The background in ℓ+jets channel is formed mainly by W+jets events and the fake-lepton contribution. The expected signal fractions in the SRs are 21% and 73% in the ℓ+jets 1b and $\geq 2b$ regions, respectively; and 53%, and 91% in the dilepton 1b and $\geq 2b$ regions, respectively.

5 Systematic uncertainties

Systematic uncertainties affecting the measurement arise from the reconstruction of leptons and jets, b-tagging, fake-lepton background, the signal and background modelling, and integrated luminosity.

Uncertainties in the muon momentum scale and resolution follow those in ref. [47]. The analysis includes uncertainties in the data-to-MC correction factors applied to simulated samples for the muon reconstruction, isolation, track-to-vertex-association, and the trigger efficiencies, evaluated using $Z \to \mu^+\mu^-$ events in p+Pb collisions. Uncertainties in the electron reconstruction, identification, isolation and trigger are derived using $Z \to e^+e^-$ events in p+Pb collisions and the uncertainty in the low pile-up energy calibration is evaluated in accordance with ref. [46]. The jet-related uncertainties are derived from in situ studies of the calorimeter response [52] and their application to the jets used in HI data [58], and from comparisons of the simulated response in samples from different generators. The b-tagging systematic uncertainties are computed by varying the data-to-MC correction factors within their uncertainties [59–61]. To assess uncertainties in the HI-PF jet matching, two systematic variations are introduced. The first uncertainty adjusts the matching distance ΔR to ± 0.1 from the default $\Delta R = 0.3$ for matching b-tagged jets. The second accounts for events where HI jets lack a PF counterpart (18% of jets in data and 15% in the signal and background MC samples), in which case HI jets are randomly considered as b-tagged based on the light-flavour jet mistag rate [61]. The resulting systematic variation has a negligible effect on the final result.

Additional systematic uncertainties related to the normalisation of the V+jets samples are determined using the Berends scaling technique [62–64]. Single-top-quark diagram removal and diagram subtraction variation samples are used to assess the uncertainties from the interference between the $t\bar{t}$ and tW processes [42]. A conservative uncertainty of 9.5% is considered for the normalisation of both the tW and t-channel single-top-quark processes [48]. The diboson background normalisation is allowed to vary by 50% [65].

Systematic uncertainties of the fake-lepton background estimate in both ℓ+jets and dilepton channels arise from statistical and systematic variations of the real- and fake-lepton efficiencies, and are evaluated using the MM technique. Additional conservative uncertainties of 100% of the normalisation in the μ+jets and 50% of the normalisation in the e+jets and the dilepton SRs are imposed as uncorrelated uncertainties. The magnitudes of the systematic variations in the normalisation of the fake-lepton background are inferred from the agreement of the data to prediction in a zero b-tagged jets ($0b$) CR. Additional shape variations of this background in the ℓ+jets channel are evaluated also in the $0b$ CR. To derive the fake-lepton background shape variations, all background contributions except the fake-lepton events are subtracted from the data and the difference is normalised to the number of fake-lepton events. A ratio is constructed of such subtracted and scaled data to the fake-lepton contribution as a function of the azimuthal angle $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \ell)$ between the lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$. Values of this ratio vary from 0.5 to 3.5 in bins of $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \ell)$. The ratio is fit by a second-order polynomial. Shape variations of the fake-lepton background in $1b$ and $\geq 2b$ ℓ+jets SRs are defined as up and down fit shape variations using the fit parameter uncertainties.

The shape of the $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \ell)$ variable is not correlated to the shape of the fit variable described in section 6.

Uncertainties due to the choice of the parton-shower and hadronisation models in addition to the matrix-element matching to the parton shower are estimated by using the alternative $t\bar{t}$ MC samples. The uncertainty due to initial-state radiation (ISR) is estimated by variations of α_s for ISR in the A14 tune [33]. Further effects on the ISR are evaluated by varying the renormalisation (μ_r) and factorisation scales (μ_f) in the matrix-element calculation as well as the h_damp parameter. The μ_r and μ_f are varied independently by factors of 0.5 and 2.0 avoiding same side variations of the scales. The effect of final-state radiation (FSR) uncertainties is evaluated by modifying the μ_r for emissions from the parton shower by factors of 0.5 and 2.0. The PDF uncertainties affecting the $t\bar{t}$ signal are evaluated using the PDF4LHC15 Hessian uncertainties [66].

The uncertainty in the integrated luminosity of the combined data sample is 2.4%. It is derived from the calibration of the luminosity scale using x-y beam-separation scans, following a methodology similar to that detailed in ref. [67], and using the LUCID-2 detector for the baseline luminosity measurements [22].

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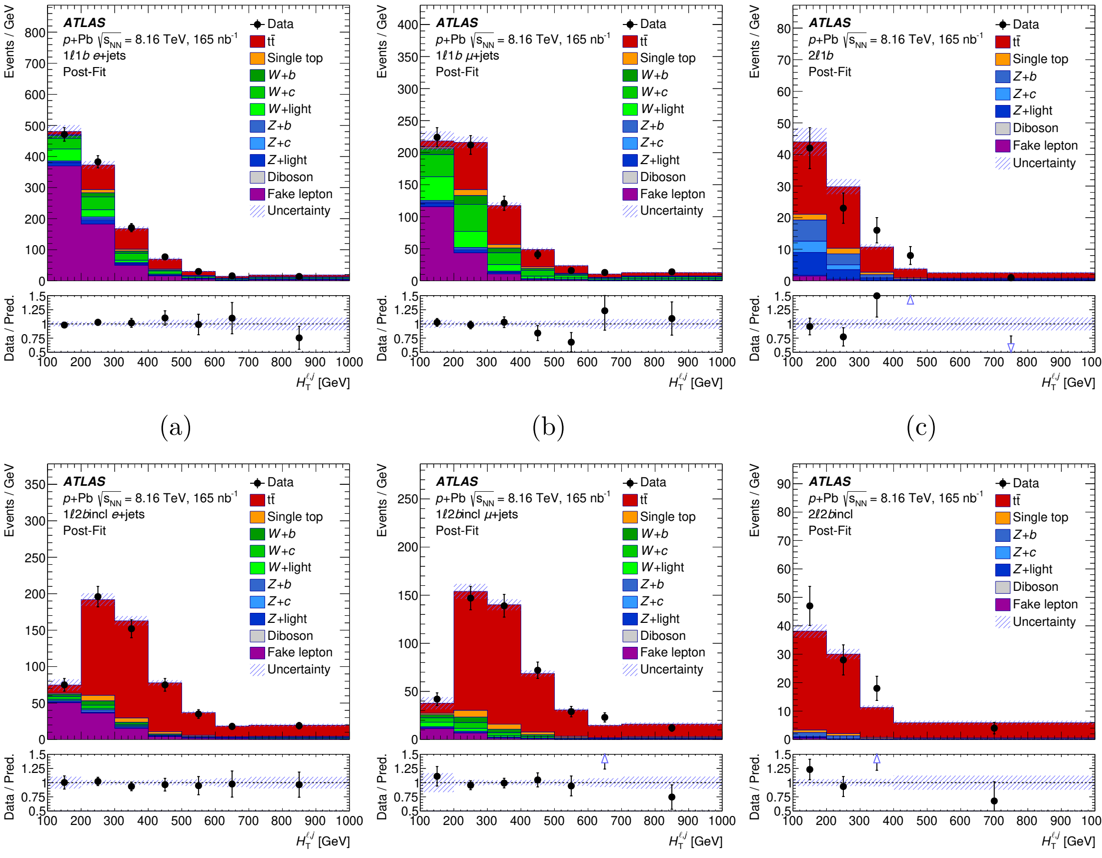
6 Results

The signal strength $\mu_{t\bar{t}}$, defined as the ratio of the observed signal for the combined ℓ+jets and dilepton final states to the SM expectation with no nPDF effects included, is measured using a binned profile-likelihood method [68]. The parameter $\mu_{t\bar{t}}$ is determined by the fit to the $H_\mathrm{T}^{\ell,j}$ data distributions in the six SRs, where the $H_\mathrm{T}^{\ell,j}$ variable is defined as the scalar sum of the transverse momenta of the leptons and HI jets. In the fit, systematic uncertainties are represented by nuisance parameters, which are additional fit parameters constrained by a Gaussian-distributed probability density. By allowing the nuisance parameters to shift from their expected values of zero, the best global fit to the data is achieved. This procedure permits an improved description of the data by combined signal and background contributions, considering their modelling in terms of shapes and normalisation, and the effects of experimental uncertainties, which leads to a reduction of the total systematic uncertainty in the parameter of interest. The $H_\mathrm{T}^{\ell,j}$ distributions predicted by the fit are shown in figure 1 for the six SRs. Distributions predicted by the fit and the observed distributions are in reasonable agreement.

All systematic uncertainties in the fit are treated as correlated over the SRs unless stated otherwise in section 5. The uncertainties associated with the fake-lepton background are notably constrained during the fitting process. The leading contributions to the total systematic uncertainty are the jet energy scale and signal modelling. Table 1 shows a breakdown of relative systematic uncertainties on the cross-section in data. The total relative systematic uncertainty amounts to 8%.

The background-only hypothesis is rejected with a significance of more than five standard deviations, establishing the observation of the $t\bar{t}$ process in p+Pb collisions by ATLAS. Figure 2 presents the signal strength $\mu_{t\bar{t}}$ obtained in each region separately and in the combined fit. The fitted $\mu_{t\bar{t}}$ values in individual channels are consistent within uncertainties and within the SM prediction. The precision of the $\mu_{t\bar{t}}$ value is limited by systematic uncertainties in the ℓ+jets SRs while the statistical uncertainties dominate in the dilepton SRs. The significance is extracted using separate fits of $\mu_{t\bar{t}}$ to the combined four ℓ+jets and combined two dilepton SRs, and exceeds in both cases by five standard deviations. This establishes the observation of $t\bar{t}$ production in the individual ℓ+jets and dilepton channels. The latter is reported for the first time in p+Pb collisions at the LHC.



(a) (b) (c)

(d) (e) (f)

Figure 1. Comparison of data and total post-fit prediction for the $H_{\mathrm{T}}^{\ell,j}$ distribution in each of the six SRs (e+jets: (a) $1\ell1b$ and (d) $1\ell2b$incl, μ+jets: (b) $1\ell1b$ and (e) $1\ell2b$incl, dilepton: (c) $2\ell1b$ and (f) $2\ell2b$incl), with uncertainties represented by the hatched area. The full markers in the bottom panels show a ratio of data and a sum of predictions. Open triangles indicate bins with entries which are outside the ratio range. The first and last bins include underflow and overflow events, respectively. The vertical order of the individual contributions forming the total prediction is the same as in the legend. The Z+jets contribution is negligible in the ℓ+jets $\geq 2b$ regions.

The measured $\mu_{t\bar{t}}$ value is translated to the inclusive $t\bar{t}$ production cross-section ($\sigma_{t\bar{t}}$) using the formula:

$$\sigma_{t\bar{t}} = \mu_{t\bar{t}} \cdot A_{\mathrm{Pb}} \cdot \sigma_{t\bar{t}}^{\mathrm{th}}, \tag{6.1}$$

where $A_{\mathrm{Pb}} = 208$ is the lead mass number and $\sigma_{t\bar{t}}^{\mathrm{th}}$ is the predicted $t\bar{t}$ production cross-section in nucleon-nucleon collisions derived at the NNLO precision used to normalise the signal $t\bar{t}$ samples in ℓ+jets and dilepton decay modes [28, 34]. The measured inclusive $t\bar{t}$ cross-section for p+Pb collisions is $\sigma_{t\bar{t}} = 58.1 \pm 2.0\ (\mathrm{stat.})\ ^{+4.8}_{-4.4}\ (\mathrm{syst.})\ \mathrm{nb} = 58.1\ ^{+5.2}_{-4.9}\ (\mathrm{tot.})\ \mathrm{nb}$. The combined relative uncertainty amounts to 9% and is dominated by the systematic contribution.

Figure 3(a) shows a comparison of the observed $\sigma_{t\bar{t}}$ with the measurement by CMS in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ [19]. The two results are in agreement within 1.4 standard deviations. Also the most precise measurement of the $t\bar{t}$ production cross-section

Source	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ unc. up [%]	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ unc. down [%]
Jet energy scale	+4.6	−4.1
$t\bar{t}$ generator	+4.5	−4.0
Fake-lepton background	+3.1	−2.8
Background	+3.1	−2.6
Luminosity	+2.8	−2.5
Muon uncertainties	+2.3	−2.0
W+jets	+2.2	−2.0
b-tagging	+2.1	−1.9
Electron uncertainties	+1.8	−1.5
MC statistical uncertainties	+1.1	−1.0
Jet energy resolution	+0.4	−0.4
$t\bar{t}$ PDF	+0.1	−0.1
Systematic uncertainty	+8.3	−7.6

Table 1. Summary of the impact of the systematic uncertainties on $t\bar{t}$ cross-section grouped into different categories. The quoted uncertainties are obtained by repeating the fit with a group of nuisance parameters fixed to their fitted values and subtracting in quadrature the resulting total uncertainty from the uncertainty of the complete fit. However, the total uncertainty is not the quadratic sum of the grouped impacts, as this approach neglects the correlation among the different groups.

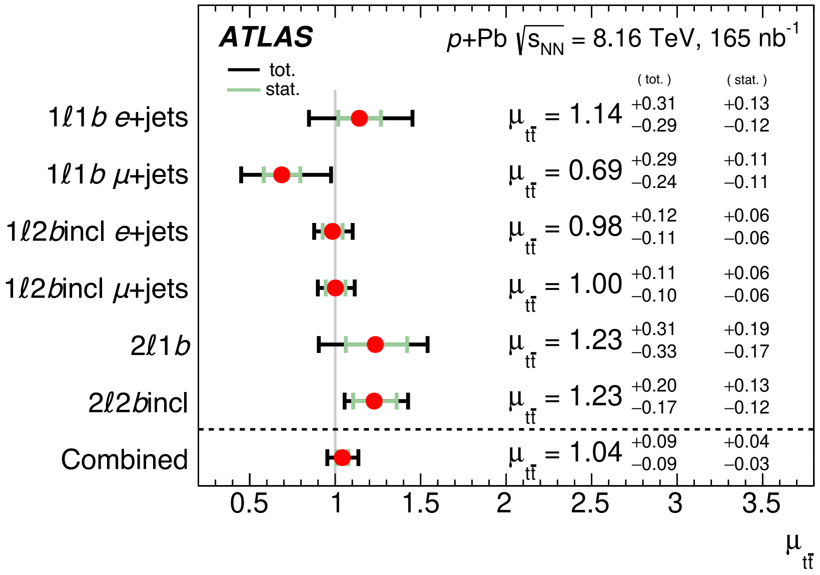
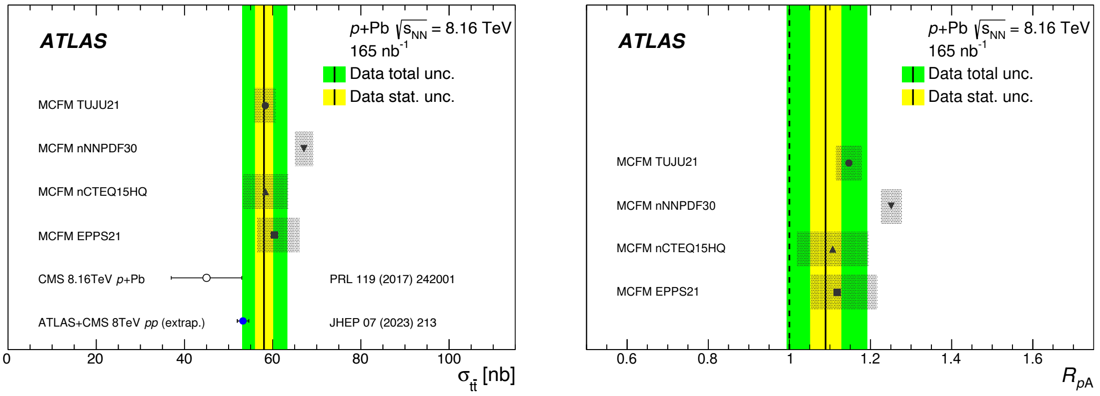


Figure 2. The observed best-fit values of the signal strength $\mu_{t\bar{t}}$ and their uncertainties by final-state category and combined. The individual $\mu_{t\bar{t}}$ values for the channels are obtained from a simultaneous fit with the signal-strength parameter for each channel floating independently. The SM prediction is $\mu_{t\bar{t}} = 1$.



(a) (b)

Figure 3. Comparison between measured and predicted values of (a) $\sigma_{t\bar{t}}$ and (b) R_{pA}. $\sigma_{t\bar{t}}$ is also compared with the existing measurement in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ [19], and the combined measurement of $t\bar{t}$ production cross-section in pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$ from ATLAS and CMS collaborations [69]. The latter is extrapolated to the centre-of-mass energy of this measurement and is using the A_{Pb} factor. Predictions are calculated at NNLO precision using the MCFM code [70] scaled to the p+Pb system and given for different nPDF sets. The uncertainty in the predictions represents the internal PDF uncertainty. The solid black line indicates the measured value. The combined statistical and systematic uncertainty of the measurement is represented by the outer band around the central value, while the statistical component is depicted as the inner band.

in pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$ from the ATLAS and CMS combination [69] is shown. The cross-section value is extrapolated to the centre-of-mass energy of this measurement using the Top++ v2 prediction and scaled by A_{Pb} to the p+Pb system. The extrapolated cross-section has a 2.5% relative uncertainty and does not involve any dependence on nPDF. The extrapolation factor amounts to 1.0528 ± 0.0005 (PDF) $^{+0.0001}_{-0.0013}$ (scale). The measured cross-section is also compared with NLO calculations obtained with the MCFM generator [70] scaled to the NNLO precision in QCD using the K-factor ($K = 1.139$) derived using the Top++ v2 generator. Four nPDF sets are used as input to the MCFM calculations: EPPS21 [71], nCTEQ15HQ [72, 73], nNNPDF30 [74, 75] and TUJU21 [76]. The largest discrepancy is found for the nNNPDF30 nPDF set which does not include the recent Run 2 LHC data for heavy-flavour production from p+Pb collisions [77]. The remaining nPDF sets are in good agreement with the measured cross-section value.

A nuclear modification factor defined as

$$R_{pA} = \frac{\sigma_{t\bar{t}}^{p+\mathrm{Pb}}}{A_{\mathrm{Pb}} \cdot \sigma_{t\bar{t}}^{pp}} \tag{6.2}$$

is extracted using the measured $t\bar{t}$ cross-sections in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ and pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$ [69]. The latter is extrapolated to the centre-of-mass energy of the p+Pb system. All uncertainties are assumed to be uncorrelated in the cross-section measurements in p+Pb and pp.

The nuclear modification factor is measured to be $R_{pA} = 1.090 \pm 0.039\,(\mathrm{stat.})\,^{+0.094}_{-0.087}\,(\mathrm{syst.}) = 1.090 \pm 0.100\,(\mathrm{tot.})$. A comparison between the measured R_{pA} in data and theory is shown in figure 3(b). The measured value is found to be consistent with unity within the uncertainty.

R_{pA} is also calculated at NNLO precision using the MCFM code [70] scaled to the p+Pb system for four different nPDF sets. The uncertainty associated with the baseline PDF for pp interactions is considered fully correlated in the predictions and cancels out in the ratio. The resulting uncertainty represents the uncertainty on nPDF. All nPDF calculations result in R_{pA} values above unity. A good agreement is found between the measured and predicted R_{pA}. The largest difference of more than one standard deviation above the measured R_{pA} value is observed for the nNNPDF30 prediction.

7 Conclusion

This paper reports a measurement of top-quark pair production in p+Pb collisions at the centre-of-mass energy $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ per nucleon pair with the ATLAS experiment. Top-quark pairs are observed in the individual ℓ+jets and dilepton channels with electrons and muons in the final state. The top-quark pair production in the dilepton channel is observed with significance exceeding five standard deviations for the first time in the p+Pb system at the LHC. From the combination of both channels, the cross-section is measured with a relative uncertainty of 9%, which makes this measurement the most precise $t\bar{t}$ cross-section determination in nuclear collisions to date. The measured cross-section is found to be in good agreement with a previous measurement by the CMS Collaboration and with SM predictions. A measurement of the nuclear modification factor is reported using an extrapolation of the previously measured cross-section in pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$, based on a perturbative QCD calculation at NNLO. Good agreement is found between the measured and predicted R_{pA} values involving most of the state-of-the-art nPDF sets. The largest deviation, of more than one standard deviation, is found for the nNNPDF30 set. This measurement paves a new way to constrain nPDFs in the high Bjorken-x region. As such it is also an important input for upcoming measurements involving the extraction of QGP properties in Pb+Pb collisions at the LHC.

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