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Observation of $t\bar{t}$ Production in Pb+Pb Collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with the ATLAS Detector

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Top-quark pair production is observed in lead–lead (Pb + Pb) collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV at the Large Hadron Collider with the ATLAS detector. The data sample was recorded in 2015 and 2018, amounting to an integrated luminosity of 1.9 nb^{-1}. Events with exactly one electron and one muon and at least two jets are selected. Top-quark pair production is measured with an observed (expected) significance of 5.0 (4.1) standard deviations. The measured top-quark pair production cross section is $\sigma_{t\bar{t}} = 3.6\,^{+1.0}_{-0.9}\,(\mathrm{stat})\,^{+0.8}_{-0.5}\,(\mathrm{syst})$ μb, with a total relative uncertainty of 31%, and is consistent with theoretical predictions using a range of different nuclear parton distribution functions. The observation of this process consolidates the evidence of the existence of all quark flavors in the preequilibrium stage of the quark-gluon plasma at very high energy densities, similar to the conditions present in the early Universe.

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Heavy-ion (HI) collisions at the Large Hadron Collider (LHC) recreate the quark-gluon plasma (QGP) in a laboratory setting. This exotic state of matter, consisting of deconfined quarks and gluons, is believed to have existed in the early Universe. However, the QGP is short-lived, with a lifetime of the order of 10 fm/c ($\approx 10^{-23}$ s), making direct measurement impossible [1]. Instead, particles produced in the collisions and passing through the QGP are used as probes, providing essential insights into QGP properties, and therefore improving our understanding of the development of the early Universe and Quantum Chromodynamics (QCD) [1–3] under extreme conditions.

Top quarks produced in HI collisions are expected to offer valuable new experimental insights [4]. Of particular interest, is the study of hadronically decaying W bosons from top-quark decays, which can yield unique information about the time structure of the QGP [5]. This is made possible by the time delay between the decay of the top quark and the subsequent decay of the W boson, offering insights unattainable by any other current experimental method. Additionally, top-quark measurements in HI collisions may provide constraints on nuclear modifications to the parton distribution functions (nPDFs) [6,7], especially in kinematic regions that are poorly constrained by other measurements.

At the LHC, top quarks are predominantly produced in top quark–antiquark ($t\bar{t}$) pairs, with pair production being more common than single top-quark production [8]. The top quark is highly unstable, almost always decaying into a W boson and a b quark. Its lifetime is shorter than the timescale to form hadrons, meaning it decays before hadrons can form. The W boson then decays either leptonically ($W \to \ell\nu$) or hadronically ($W \to q\bar{q}'$). In LHC collisions, top-quark production is primarily the result of gluon-gluon fusion. The $t\bar{t}$ production cross section is calculated at next-to-next-to-leading-order (NNLO) and next-to-next-to-leading-logarithmic (NNLL) precision in QCD [9]. With large integrated luminosity data samples from proton–lead (p + Pb) and lead–lead (Pb + Pb) collisions, it becomes experimentally feasible to reconstruct $t\bar{t}$ events in the ℓ + jets ($t\bar{t} \to WbW\bar{b} \to \ell\nu_{\ell}bq\bar{q}'\bar{b}$) and dilepton ($t\bar{t} \to WbW\bar{b} \to \ell\nu_{\ell}b\ell\bar{\nu}\ell\bar{b}$) channels [10]. The ATLAS and CMS Collaborations have observed $t\bar{t}$ production in the ℓ + jets and dilepton channels in p + Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV [11,12], and CMS has provided evidence of $t\bar{t}$ production in the dilepton channel with a significance of 4.0σ using Pb + Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [13].

The first observation is presented of $t\bar{t}$ production in Pb + Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV using data from the ATLAS experiment. Top-quark pair events are selected in the electron-muon ($e\mu$) decay channel, $t\bar{t} \to e\nu_e\mu\nu_{\mu}b\bar{b}$, as this channel has the least background contamination. The electron-electron (ee) and muon-muon ($\mu\mu$) channels, which are dominated by $Z \to \ell\ell$ production, are used to derive and validate detector response corrections. The data sample was collected in 2015 and 2018, corresponding to a total integrated luminosity of 1.9 nb^{-1}. No requirements

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are imposed on b-quark-initiated jets, allowing it to serve as a basis for calibrating heavy-flavor jets in HI collisions. As such, this work represents a significant milestone for future studies of hadronically decaying top quarks in a QGP.

The ATLAS experiment [14] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle [15]. 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 (MS). The ID covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. A 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 end cap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The MS 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 MS 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 [16] detector, which is located close to the beam pipe. A two-level trigger system is used to select events [17]. 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 [18] 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.

The centrality of Pb + Pb events characterizes the degree of geometric overlap of the colliding nuclei. It is defined using $\sum E_T$, the total transverse energy measured in the Forward Calorimeter (FCal) [19,20], which covers the $3.1 < |\eta| < 4.9$ range. Events are categorized into centrality intervals using a Glauber model [21] parametrization of the $\sum E_T$ distribution. Each interval represents a range in $\sum E_T$, starting at 0% for the most central collisions and ending at 100% for the most peripheral collisions.

Events are selected using single-electron or single-muon triggers with a minimum transverse momentum (p_T) threshold of 15 and 8 GeV, respectively [22–24]. The events are required to have exactly one reconstructed vertex built from at least two good-quality charged-particle tracks with $p_\mathrm{T} \geq 0.5$ GeV [25]. Events are selected in the 0%–80% centrality interval to avoid contributions from photon-induced processes. This requirement has a minimal effect on the signal yield as the contribution to the $t\bar{t}$ cross section from the 80%–100% centrality range is estimated to be below 1%. The average number of hadronic interactions per bunch crossing was 1.8×10^{-3} and 2.6×10^{-3} for 2015 and 2018, respectively.

Electron candidates are reconstructed from a localized cluster of energy deposits in the EM calorimeter, matched to a track in the ID. Candidates must originate from the primary vertex with the transverse impact parameter significance of $|d_0|/\sigma_{d_0} < 5$ and the longitudinal impact parameter of $|\Delta z_0 \sin\theta| < 0.5$ mm. They are further required to satisfy the "Loose" likelihood-based identification criteria [26] and must have $p_\mathrm{T} > 18$ GeV and $|\eta| < 2.47$. The electron candidates are required to be isolated using track- and calorimeter-based isolation requirements [27].

Muon candidates are reconstructed by matching tracks reconstructed in the ID and the MS. Candidates are required to originate from the primary vertex with $|d_0|/\sigma_{d_0} < 3$ and $|\Delta z_0 \sin\theta| < 0.5$ mm. They must satisfy "Loose" identification criteria [28] and are further required to have $p_\mathrm{T} > 15$ GeV and $|\eta| < 2.5$. The muon candidates must also satisfy track- and calorimeter-based isolation requirements [27,28].

Jets are reconstructed from calorimeter energy deposits [29] using the anti-k_t algorithm [30,31] with a radius parameter $R = 0.4$, and are required to have $p_\mathrm{T} > 35$ GeV and $|\eta| < 2.5$. Jet kinematics are corrected event by event for the contribution from underlying event (UE) particles, and are calibrated using simulations of the calorimeter response [32] and *in situ* measurements of the absolute energy scale. *In situ* measurements are carried out in proton–proton (pp) collisions and cross calibrated to the Pb + Pb data using the method described in Ref. [33], providing an initial jet calibration. Since jet modeling influences calculations of the missing transverse momentum ($\vec{p}_\mathrm{T}^\mathrm{miss}$, with magnitude $E_\mathrm{T}^\mathrm{miss}$), no requirement on $E_\mathrm{T}^\mathrm{miss}$ is imposed in the analysis. No b-tagging requirements are imposed on jets.

Samples of Monte Carlo (MC) simulated events are used to develop the analysis procedures, evaluate signal and background contributions, estimate signal efficiencies, and compare the predicted distributions with data. All samples are processed using the full ATLAS detector simulation [34] based on the Geant4 framework [35]. The simulation samples are produced using event-generator configurations similar to those developed for pp analyses [36,37]. The nominal simulated $t\bar{t}$ sample is produced using the next-to-leading-order (NLO) event generator Powheg Box v2[38] with the NNPDF3.0NLO parton distribution function (PDF) set [39], where the top-quark mass (m_t) is set to 172.5 GeV. It is interfaced with Pythia8 [40] with the NNPDF2.3LO PDF set [41] and the A14 set of tuned parameters [42] for the parton-shower and hadronization modeling.

Alternative $t\bar{t}$ simulation samples are generated to assess systematic uncertainties related to the signal modeling. In all the top-quark samples, m_t is set to 172.5 GeV, and the EvtGen program [43] is used for the decays of b- and c-flavored hadrons. One alternative sample uses the Powheg Box v2 MC generator with the Herwig v7.2 parton-shower and hadronization model [44,45], employing the H7.2-Default set of tuned parameters [45,46]. Another Powheg Box v2+ Pythia8 sample is used to assess the uncertainty in the matrix element and parton shower matching. Uncertainties in the amount of parton-shower radiation are evaluated by setting the h_{damp} parameter, which controls the p_{T} of the first additional gluon emission beyond the leading-order Feynman diagram in the parton shower, to $3m_t$ instead of the nominal value of $1.5m_t$. All signal samples are normalized using a K factor of $K = 1.149$ to the cross section calculated at NNLO + NNLL precision in QCD using the Top++ v2 program [47] with the NNPDF3.0NLO PDF set.

The background processes evaluated using MC simulation are from Z bosons produced with jets (Z + jets), single-top quark (tW) and diboson (VV) production. The Z + jets events are simulated at NLO precision in QCD, using the Powheg Box v1 [48] generator interfaced with Pythia8, using the AZNLO CTEQ6L1 set of tuned parameters. The tW associated production processes for single-top quarks are simulated at NLO precision in QCD, using the Powheg Box v2 [49,50] generator with the NNPDF3.0NLO PDF set, and using Pythia8 with the A14 NNPDF2.3LO set of tuned parameters. The diagram-removal scheme is used to treat the interference with $t\bar{t}$ production [51]. The VV backgrounds are simulated at NLO precision in QCD, using the Sherpa v2.2.14 generator [52] with the NNPDF3.0NNLO PDF set [39].

Simulated signal and background samples are produced separately for four isospin configurations (proton–proton, proton–neutron, neutron–proton, and neutron–neutron) and embedded into Hijing [53] minimum-bias Pb + Pb events for UE modeling. The Z + jets samples are produced only for the proton–proton configuration, as no significant differences between isospin combinations are expected in the cross section. The events are processed using the same reconstruction and analysis chain as the data. The samples are reweighted on an event-by-event basis to match the $\sum E_T$ distribution in Pb + Pb data with a looser selection of at least one lepton (electron or muon) with a p_{T} above 15 GeV (10 GeV) for electrons (muons).

To correct for residual differences between data and simulation in the detector response, dedicated corrections are applied accounting for energy and momentum scale and resolution, and lepton efficiencies. Corrections for electrons are based on the methods described in Ref. [26], while corrections for muons follow those in Ref. [28]. Scale factors corresponding to electron reconstruction, muon quality, and muon track-to-vertex-matching, derived in 13 TeV pp collisions, are applied. Additional correction factors for electron and muon identification, isolation and trigger requirements are estimated by using this Pb + Pb data sample and the tag-and-probe method in $Z \to \ell\ell$ events [26,28]. The detector response corrections are validated using the invariant mass spectrum of $Z \to \ell\ell$ candidate events in data and simulation. The events are selected by requiring same-flavor oppositely charged leptons with an invariant mass between 66 and 116 GeV.

Two signal regions (SR_1 and SR_2) are built from events with exactly one muon and one oppositely charged electron. The dilepton invariant mass ($m_{e\mu}$) is required to be $\geq$30 GeV to minimize the fake-lepton background contribution. At least two jets with $p_{\mathrm{T}} \geq 35$ GeV are required. SR_1 and SR_2 are defined with a selection on the dilepton transverse momentum $p_{\mathrm{T}}^{e\mu} > 40$ GeV and $\leq$40 GeV, respectively. Distributions of $m_{e\mu}$ and $p_{\mathrm{T}}^{e\mu}$ in the $e\mu$ channel can be found in the Supplemental Material [54]. Splitting events into two signal regions, where SR_1 is dominated by signal, improves the measurement sensitivity. The observed number of events in SR_1 and SR_2 is 22 and 10, respectively. The main background is the fake-lepton contribution, followed by Z + jets with $Z \to \tau\tau$ and leptonically decaying τ leptons.

Effects of jet quenching [55] are not modeled in MC simulation. Jet quenching is extensively explored at the LHC [56], typically reducing the energy scale and broadening the resolution between the final state parton kinematics and the reconstructed jet energy in a HI collision. Any modifications to the jet spectra may potentially affect the event yields in the signal regions. Therefore, the detector response and the jet modeling is studied using $Z \to \ell\ell$ events, with at least one reconstructed jet. Effective correction factors for the jet energy scale are derived separately for central and peripheral collisions to account for the remaining mismodeling of the detector response, jet-quenching effects, the description of jets from the UE, and random energy fluctuations that are reconstructed as jets. Moreover, the jet selection in the analysis is optimized such that the impact of the lack of jet-quenching modeling in MC simulation is minimized. Only a requirement on the number of jets is imposed and jet kinematics are not used in the discriminating variable for the cross-section measurement.

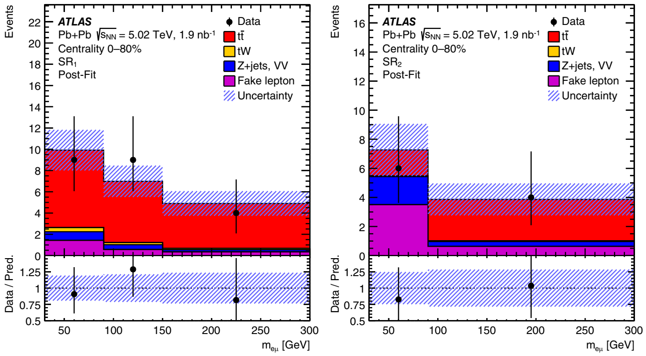
Fake-lepton backgrounds are from nonprompt leptons, hadrons, and photons that meet the lepton selection criteria. The main source of fake-lepton background in the dilepton channel is the W + jets process. The normalization and $m_{e\mu}$ distribution shape of the fake-lepton background, which are used in the fitting procedure, are directly estimated from data using the *ABCD* method. Four independent regions are defined: signal region A (corresponding to the combined SR_1 and SR_2), and background control region B which is defined using the same selection criteria as in the signal, but requiring two same-sign electrically charged leptons. Regions C and D are equivalent to the regions A

and B, respectively, but with inverted lepton isolation requirements. Regions $B-D$ are therefore enhanced with fake-lepton contributions. After subtracting potential signal and other background contributions in the regions $B-D$, and assuming no correlations between isolation and the charge requirements, the fake-background contribution in the signal region can be estimated as $N_B N_C / N_D$, where N_i denotes the number of events in the control region i. The shape of the $m_{e\mu}$ distribution of the fake-lepton contribution is estimated by using the region C. Due to the limited number of events in the regions $B-D$, the fake-lepton background is estimated inclusively for electrons and muons. Approximately 36% and 64% of the fake-lepton contribution originates from fake electrons and muons, respectively.

There are systematic uncertainties affecting the measurement from the reconstruction of leptons and jets, the fake-lepton background estimate, the signal and background modeling, and the luminosity measurement. The modeling systematic uncertainties are derived from one-sided variations and symmetrized. Differences between alternative signal MC samples and the nominal one are as much as 12%. Uncertainties due to initial-state radiation (ISR) and final-state radiation (FSR) are negligible [12]. Uncertainties in the electron and muon reconstruction performance are evaluated by varying the corresponding data-to-MC correction factors by their uncertainties. The jet-related uncertainties are derived from *in situ* studies of the calorimeter response [32], and from comparisons of the simulated response in samples from different generators. Uncertainties in the effective jet correction factors are derived from variations with no corrections applied, and symmetrized.

The VV background normalization is allowed to vary by 26%, which corresponds to the uncertainty in Sherpa generator predictions extrapolated to the center-of-mass energy of the Pb + Pb system [57,58]. The MC prediction of VV production is found to be consistent with the data in a control region, using events that satisfy the signal selection but with zero jets with $p_T > 35$ GeV. Therefore, no additional shape-related uncertainties are applied to the VV process. The normalization uncertainty of the $Z \to \tau\tau$ process is 10%, reflecting the measurement uncertainty of Z boson production in HI collisions [59]. An uncertainty of 9.5% is applied for the normalization of the tW process [37].

The fake-lepton background uncertainties include statistical and systematic variations in both the $m_{e\mu}$ distribution shape and normalization. Systematic variations in the normalization are evaluated by varying the isolation requirements in regions C and D. The $m_{e\mu}$ distribution shape variation is evaluated using the same-sign electrically charged selection, which corresponds to the combined region B and D. The nominal and the systematically varied fake-lepton $m_{e\mu}$ distribution shapes are smoothed using an exponential function because of the small number of events.



(a) (b)

FIG. 1. Postfit distributions of the $m_{e\mu}$ variable in (a) the SR_1 and (b) the SR_2, with total postfit uncertainties represented by the hatched area. The filled markers in the bottom panels show the ratio between data and the sum of predictions.

The uncertainty in the integrated luminosity of the combined data sample is 1.5%. It is derived following a method similar to the one given in Ref. [60], and using the LUCID-2 detector for the baseline luminosity measurements [16].

The signal strength $\mu_{t\bar{t}} \equiv \sigma_{t\bar{t}}/\sigma_{t\bar{t}}^{\mathrm{th}}$ is defined as the ratio of the observed $t\bar{t}$ cross section for the $e\mu$ final state to the SM expectation without any nuclear modifications to the PDFs. The parameter $\mu_{t\bar{t}}$ is determined by a combined fit to the $m_{e\mu}$ distribution in both the signal regions. The invariant mass distributions predicted by the fit (postfit) in both the signal regions are shown in Fig. 1. The fit favors smaller background contributions than predicted, leading to a higher signal yield after the fit. The distributions predicted by the fit and the observed distributions are in good agreement.

Systematic uncertainties are included in the fit via nuisance parameters (NPs), which are additional fit parameters constrained by a Gaussian-distributed probability density function. The breakdown of relative systematic uncertainties is provided in the Supplemental Material [54]. The leading contributions to the total systematic uncertainty are from the signal modeling, followed by the jet-related uncertainties. The total relative systematic uncertainty amounts to 18%, while the statistical uncertainty is 26%.

The measured $\mu_{t\bar{t}}$ value is translated to an inclusive $t\bar{t}$ production cross section using the theoretical prediction for $\sigma_{t\bar{t}}^{\mathrm{th}}$ derived in the 0%–100% centrality range at the NNLO + NNLL precision using the Top++ v2 program. The cross section in the 0%–100% centrality interval is predicted to be 0.19% higher compared to the 0%–80% range. The theoretical cross section in pp collisions at $\sqrt{s} = 5.02$ TeV, scaled by the lead mass number ($A_{\mathrm{Pb}} = 208$) squared, is $2.95^{+0.08}_{-0.10}(\mathrm{scale})^{+0.10}_{-0.09}(m_t)^{+0.21}_{-0.21}(\mathrm{PDF} + \alpha_s)$ μb [37]. The measured inclusive $t\bar{t}$

cross section in Pb + Pb collisions is $\sigma_{t\bar{t}} = 3.6\,^{+1.0}_{-0.9}\,(\mathrm{stat})\,^{+0.8}_{-0.5}\,(\mathrm{syst})\ \mu\mathrm{b} = 3.6\,^{+1.2}_{-1.0}\,(\mathrm{tot})\ \mu\mathrm{b}$. The total relative uncertainty is 31%. The probability for the background-only hypothesis to result in a signal-like excess at least as large as seen in data is derived using the profile-likelihood ratio following the CL_S procedure described in Ref. [61]. From this, the significance of the observed signal is 5.0 standard deviations, while 4.1 standard deviations are expected.

Figure 2 shows the measured $\sigma_{t\bar{t}}$ compared with the measurement in Pb + Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV by CMS [13] and the ATLAS measurement in pp collisions at $\sqrt{s} = 5.02$ TeV [37], scaled by A^2_{Pb}. Experimental results agree within their uncertainties. The measured cross section is also compared with NLO calculations obtained with the MCFM generator [62] scaled to the NNLO + NNLL precision in QCD using the K factor of $K = 1.149$, and scaled to the Pb + Pb system by A^2_{Pb}. Four state-of-the-art nPDF sets are used as input [63] to the MCFM calculations: EPPS21 [64], nCTEQ15HQ [65,66], nNNPDF30 [67] and TUJU21 [68]. Good agreement is found between the measurement of $\sigma_{t\bar{t}}$ and all predictions. Further improvement in the measurement precision is needed to constrain nPDFs.

In conclusion, top-quark pair production in Pb + Pb collisions is observed at the center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV per nucleon pair in the ATLAS experiment. The top-quark pairs are reconstructed using dilepton final states with electrons and muons. The top-quark pair production cross section is measured to be $\sigma_{t\bar{t}} = 3.6\,^{+1.0}_{-0.9}\,(\mathrm{stat})\,^{+0.8}_{-0.5}\,(\mathrm{syst})\ \mu\mathrm{b}$ with an observed (expected) significance of 5.0 (4.1) standard deviations. The total integrated cross section is measured with a total relative uncertainty of 31%, dominated by statistical uncertainties in the limited data sample size. A good agreement is found between the measurement and SM predictions with nuclear effects. The observation of this process consolidates the evidence of the presence of all quark flavors in the pre-equilibrium stage of the QGP, similar to conditions in the early Universe [69]. This result paves the way for further studies of the QGP and the physics of the early Universe with top quarks.

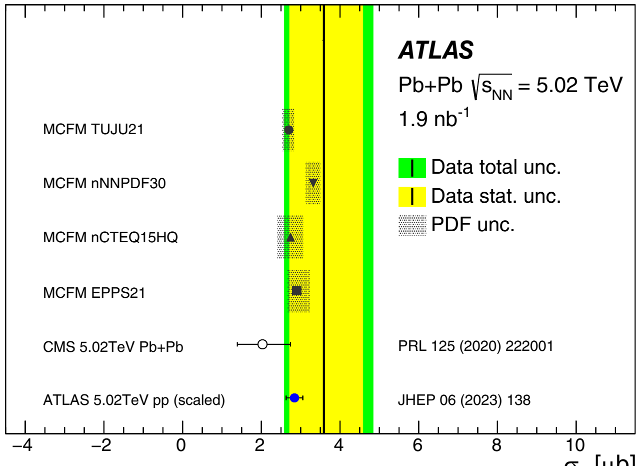


FIG. 2. Comparison between observed and predicted values of $\sigma_{t\bar{t}}$. This measurement is compared with the CMS Collaboration measurement of $\sigma_{t\bar{t}}$ in Pb + Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [13] and the ATLAS measurement in pp collisions at $\sqrt{s} = 5.02$ TeV [37]. The latter is scaled by A^2_{Pb}. The theoretical cross section is obtained from NLO calculations using the MCFM generator [62] scaled to the NNLO + NNLL precision by the K factor of $K = 1.149$. Predictions are scaled to the Pb + Pb system by A^2_{Pb} and given for different nPDF sets. The uncertainty in predictions represents the internal PDF uncertainty.

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