Evidence for top quark production in nucleus-nucleus collisions

The CMS Collaboration

Abstract

Evidence for the production of top quarks in heavy ion collisions is reported in a data sample of lead-lead collisions recorded in 2018 by the CMS experiment at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{\text{NN}}} = 5.02$ TeV, corresponding to an integrated luminosity of $1.7 \pm 0.1 \text{nb}^{-1}$. Top quark pair ($t\bar{t}$) production is measured in events with two opposite-sign high-$p_T$ isolated leptons ($\ell^+\ell^- = e^+e^-, \mu^+\mu^-, \text{and } e^\pm\mu^\mp$). We test the sensitivity to the $t\bar{t}$ signal process by requiring or not the additional presence of b-tagged jets, and hence the feasibility to identify top quark decay products irrespective of interacting with the medium (bottom quarks) or not (leptonically decaying W bosons). To that end, the inclusive cross section ($\sigma_{t\bar{t}}$) is derived from likelihood fits to a multivariate discriminator, which includes different leptonic kinematic variables, with and without the b-tagged jet multiplicity information. The observed (expected) significance of the $t\bar{t}$ signal against the background-only hypothesis is 4.0 (6.0) and 3.8 (4.8) standard deviations, respectively, for the fits with and without the b-jet multiplicity input. After event reconstruction and background subtraction, the extracted cross sections are $\sigma_{t\bar{t}} = 2.02 \pm 0.69$ and $2.56 \pm 0.82 \mu\text{b}$, respectively, which are consistent with each other and lower than, but still compatible with, the expectations from scaled proton-proton data as well as from perturbative quantum chromodynamics predictions. This measurement constitutes the first step towards using the top quark as a novel tool for probing strongly interacting matter.
1 Introduction

The multi-TeV energies available at the CERN Large Hadron Collider (LHC) have opened up the possibility to measure for the first time various large-mass elementary particles in heavy-ion collisions. After the first observations of the W [1, 2] and Z [3–5] bosons, there remain only three standard model (SM) elementary particles without direct observation in nucleus-nucleus collisions: the $\tau$ lepton, the Higgs boson, and the top quark. Whereas the $\tau$ should be observable without much difficulty, but lacks so far a clear theoretical motivation for its measurement in the heavy-ion environment, that of the Higgs boson is beyond the center-of-mass and luminosity reach of the LHC [6]. The top quark, on the other hand, is expected to be accessible to experimental study in lead-lead (PbPb) collisions at the LHC [7], and constitutes a novel and theoretically precise probe of the nuclear gluon density in the poorly explored high Bjorken-$x$ region, as well as of the properties of the produced quark-gluon-plasma (QGP) [7, 8]. The study presented here shows for the first time evidence for the production of the top quark—the heaviest elementary particle known—in lead-lead (PbPb) collisions, after its previous observation in proton-lead (pPb) collisions [9] at the LHC.

The top quark is produced at hadron colliders predominantly in pairs (t$\bar{t}$) through quantum chromodynamics (QCD) processes, mostly gluon-gluon fusion, and is thereby a sensitive probe of the gluon parton distribution function (PDF) of the incoming hadrons [10]. Once produced, it decays very rapidly ($\tau_\ell \lesssim 0.1$ fm) with almost 100% probability into a W boson plus a b quark. Top quark pair production is thereby characterized by a final state comprising two b-jets plus the decay products of the two W bosons. Experimentally, the top quark decays with W bosons decaying hadronically have large branching fractions but are more difficult to identify due to the large background of multiple jets produced in other physics processes. On the other hand, the dilepton final states in which both W bosons decay into electrons or muons are the cleanest channels for a measurement, despite their relatively small branching fraction $B(t\bar{t} \to \ell^+\ell^-\nu_\ell\bar{\nu}_\ell b\bar{b}) \approx 5.25\%$, for $\ell^\pm = e^\pm, \mu^\pm$ [11]. In PbPb collisions, given the very large jet multiplicity hampering the measurement of the top quark in its multijet final state, and the availability of suitable triggers to collect events with high-$p_T$ leptons, a measurement of t$\bar{t}$ production in three dilepton final states, $e^+e^−, μ^+μ^−$, and $e^{±}μ^{∓}$ is possible.

Since its discovery at the Fermilab Tevatron more than twenty years ago [12, 13], top quark pairs have been measured at the LHC in final states with at least one lepton in proton-proton (pp) [14–18], as well as in proton-nucleus [9] collisions, but have so far not been observed in nucleus-nucleus collisions due to insufficient center-of-mass energies or integrated luminosities. Recently, during November and December 2018, PbPb collision data at a nucleon-nucleon (NN) center-of-mass energy of $\sqrt{s_{_{NN}}} = 5.02$ TeV were delivered by the LHC with a peak luminosity exceeding the design luminosity of $10^{32} \text{cm}^{-2}\text{s}^{-1}$ by a factor of more than six. The resulting total integrated luminosity of $1.7 \pm 0.1 \text{nb}^{-1}$ allows for a first attempt to observe the top quark and measure the t$\bar{t}$ cross section ($\sigma_{t\bar{t}}$) in nuclear collisions. The $\sigma_{t\bar{t}}$ is extracted in this work from two event selection categories: (i) making use of the final-state dilepton kinematics alone, and (ii) also adding extra requirements on the number of jets “tagged” as arising from b quarks (referred to as “b jets”) in the event. On the one hand, the former is of particular interest since leptons propagate through the produced medium regardless of its nature, thereby providing favorable conditions for the detection of t$\bar{t}$ production. On the other hand, since top quarks decay mostly within the strongly interacting medium, the latter establishes a new tool to study the mechanisms of medium-induced parton energy loss.
2 Experimental setup and event sample

The CMS apparatus surrounds the collision point with full azimuthal (φ) and extended polar (θ) angle coverage; the latter expressed in units of pseudorapidity η = −ln tan(θ/2). Its central feature is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T for accurate measurement of the transverse momentum p_{T} of charged particles. Charged particle trajectories are measured by a silicon pixel and strip tracker system within |η| < 2.5 [19]. The reconstructed tracks are used to estimate individual primary- and secondary-interaction vertices (denoted by PV and SV, respectively), and the three-dimensional LHC luminous region. Electrons and photons are reconstructed by their deposited transverse energy (E_{T}) in groups of crystals of the electromagnetic calorimeter (ECAL) [20]. Muons are detected over the pseudorapidity range |η| < 2.4 in gas-ionization detectors embedded in the steel flux-return yoke outside of the solenoid [21]. Hadronic jets are reconstructed from the tracker information as well as the energy deposits in the ECAL and brass and scintillator hadron calorimeters (HCAL) [22]. Both ECAL and HCAL detectors are organized in barrel (|η| < 1.5) and endcap (|η| = 1.5−3.0) sections, covering a total of six units of pseudorapidity.

Forward hadron (HF) calorimeters extend the pseudorapidity coverage up to |η| = 5.2. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [23].

The event sample of PbPb collisions recorded by the CMS detector corresponds to an integrated luminosity of 1.7 ± 0.1 nb^{-1} [24], equivalent to a NN integrated luminosity of ≈ 80 pb^{-1}. The absolute luminosity scale is derived following a methodology similar to that described in Ref. [24]; by transversely displacing one beam through the other, and measuring the interaction rate as a function of displacement, the size of the beams is determined. The number of simultaneous collisions per bunch crossing is on average ≲ 1 in the entire data set.

3 Monte Carlo event simulation and theory predictions

Monte Carlo (MC) signal samples for top quark pair production, NN → t¯t + X, are generated at next-to-leading-order (NLO) using the MADGRAPH\textunderscore AMC@NLO (v2.4.2) [25] and POWHEG (v2) [26, 27] codes, with a mixture of pp and pn interactions corresponding to their ratio in PbPb (A = 208 and Z = 82) [28]. The EPPS16 NLO nuclear PDF [28], with free-nucleon CT14 NLO PDF [29], strong coupling α_s(m_Z) = 0.118 ± 0.001 at the Z boson mass [11], and top quark mass m_t = 172.5 GeV [30], are consistently used in all calculations and simulated samples. The number of signal events is normalized to the cross section computed with the T\textsc{op}++ (v2.0) program [31] at next-to-next-to-leading-order (NNLO) in perturbative QCD, including soft-gluon resummation at next-to-next-to-leading-log (NNLL) accuracy [32], α_{NNLO+NNLL}^{tch+X} = 73.1^{+7.9}_{−7.3} (PDF + α_S(m_Z))^{+1.9}_{−2.4} (scale) pb, corresponding to σ_{PbPb→tch+X}^{NNLO+NNLL} = 3.16^{+0.34}_{−0.32} (PDF + α_S(m_Z))^{+0.08}_{−0.11} (scale) μb. The antishadowing of the nuclear gluon PDF [28] results in a few percent enhancement in the t¯t cross section in PbPb collisions compared to that of pp collisions simply scaled by A^2 [7]. The PDF+α_S(m_Z) uncertainties, amounting to +10.9%, −10.0%, are obtained from the 54 eigenvector sets of the EPPS16 set plus QCD coupling variations. The theoretical uncertainty due to missing higher-order corrections, amounting to +2.7%, −3.4%, is estimated by modifying the renormalization (μ_R) and factorization (μ_F) scales within a factor of two from their default values μ_R = μ_F = m_t.

A similar setup is used for the simulation of the backgrounds. Low- (m_Z/γ→ℓℓ ≈ 20–50 GeV) and high-mass (m_Z/γ→ℓℓ > 50 GeV), i.e., Drell–Yan (DY), and W boson production in association with jets (W+jets) events are generated with MADGRAPH\textunderscore AMC@NLO. They are normal-
ized to the NNLO cross sections from the FEWZ (v3.1.b2) program [33], and further corrected with scaling factors derived from data. The contributions from WW, WZ, and ZZ production (collectively referred to as “VV”) are simulated with POWHEG, and normalized to the NLO cross sections calculated with MCFM (v8.0) [34]. Single top quark plus W boson events (tW) are simulated using the NLO POWHEG [35] MC generator, and normalized to the approximate NNLO cross sections [36].

All samples are generated with final states restricted to electron muon decay modes, including final $\mu$ and $e$ from tau lepton decays (in the case of the $t\bar{t}$ signal these combined channels have a total branching fraction of $B = 0.0639$). The parton-level results from the matrix-elements calculators are then interfaced to the PYTHIA8 (v2.3.0) [37, 38] MC event generator to simulate parton showering and hadronization with the “CMS PYTHIA8” [39] set of parameters (“tune”). All generated samples are then embedded (at the step of detector digitization) in PbPb events, at the same PV location, using the HYDJET (v1.9) [40] MC generator in order to mimic the effects of the heavy-ion underlying event (UE), without any medium-induced modification of the signal final-state particles (which anyway is expected not to affect in any way the top decay leptons). This embedding is applied with an event-by-event weight factor, based on the average number of NN collisions calculated with a Glauber model [41] for each PbPb centrality interval; the latter defined as the degree of the overlap of the two colliding nuclei. Simulated samples finally include an emulation of the full detector response, based on GEANT4 [42], and a realistic description of the luminous region produced by the collisions.

4 Event selection and physics-object reconstruction

The event sample is filtered in real time (“online”) using a two-tier trigger system [43] composed of the so-called Level-1 (L1) and High Level Trigger (HLT) subsystems. The L1 muon triggers are hardware-based flags signaled by primordial candidates in the muon detectors. The HLT system reconstructs the full muon candidate tracks by combining the L1 information with inner tracker hits, keeping single muon objects above a threshold of $p_T = 12$ GeV. For electrons, electromagnetic energy deposits are reconstructed at L1 through the sum of the $E_T$ deposited in two neighboring groups of $5 \times 5$ ECAL crystals (trigger towers), and events with at least one such reconstructed deposit with $E_T > 15$ GeV are then selected by the system. At the HLT, the energy deposits in the ECAL are reconstructed using the hybrid- and island-clustering algorithms in the barrel and endcaps, respectively. After cleaning for spurious signals, the HLT keeps single electron objects above a threshold of 20 GeV. In all cases, the coincidence with beam monitoring triggers [44] is required to remove noncollision sources, such as from cosmic rays.

Offline, particles are reconstructed with the particle-flow (PF) algorithm [45], which identifies and provides a list of particle candidates using an optimized combination of information from the various elements of the CMS detector. Events are required to contain at least one pair of opposite-sign (OS) leptons, with $p_T > 20$ GeV and $|\eta| < 2.4$ (2.1) for the muon (electron) candidates. For the electron case, we additionally exclude the regions $1.444 < |\eta| < 1.566$ (barrel-to-endcap transition in ECAL), and $-3.000 < \eta < -1.392$ and $-1.57 < \phi < -0.87$ (specific to the 2018 data-taking period), where the reconstruction of electron objects is less efficient. The muon [21] and electron [20] candidates are required to satisfy stringent quality requirements and to be well separated (“isolated”) from nearby hadronic activity. For that purpose, a cone of radius $\Delta R \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ around the direction of the lepton candidate is defined, together with the isolation variable given by the scalar $p_T$ sum, $I = \sum_i p_{Ti}$, of PF candidates within $\Delta R = 0.2$ of the lepton candidate. Charged PF candidates are considered if
their trajectory is consistent with the PV position, which must lie within 20 cm along the beam direction of the geometrical center of the detector [46]. To remove the UE background from the cone around the lepton, we estimate the median of the energy-density $\rho$ in the event, clustering particles in pseudojets [47] and making use of the FASTJET technique [48, 49]. The final relative isolation variable is defined as $I_{\text{rel}} = [I - \text{UE}(\rho)] / p_T$, where $\text{UE}(\rho)$ is a parametrization of the observed $\rho$ distribution, accounting for the residual $\eta$-dependence of the average energy deposition. The muon (electron) candidates are selected if the discriminant value satisfies $I_{\text{rel}} < -0.06 (+0.08)$.

In events with more than one pair of OS leptons passing the above selection, we select the two leptons that yield the highest scalar $p_T$ sum. Events with dilepton invariant mass of $m(\ell^+\ell^-) < 20$ GeV and $1 - |\Delta\phi(\ell)|/\pi > 0.01$ are removed to suppress decays of heavy-flavor resonances, low-mass $Z/\gamma^*$, and photon-photon ($\gamma\gamma \rightarrow \ell^+\ell^-$) processes. Dilepton events in the $\mu^+\mu^-$ and $e^+e^-$ final states are still swamped by the $Z/\gamma^*$ background. To further suppress this contribution, we discard events around $m_Z$, i.e. $76 < m(\ell^+\ell^-) < 106$ GeV. Events with $\tau$ leptons are included in the simulation and considered as part of the $t\bar{t}$ signal if they further decay into muons or electrons that satisfy the selection requirements. The efficiency of the lepton selection is measured applying a data-based method [50] to events in a control region enriched with $Z \rightarrow \ell^+\ell^-$ boson candidates selected by the same trigger requirements as the $t\bar{t}$ signal candidate events. We then use the combined reconstruction, lepton identification and isolation, and trigger efficiencies as determined from this Z data set to correct, via a tag-and-probe method [51], the lepton $p_T$ and $\eta$ in the MC event generation as a function of the global PbPb event properties.

The distinct presence of two b jets in the $t\bar{t}$ final state is used to enhance the sensitivity to the top quark signal. To that end, jets are reconstructed from the PF candidates using the anti-$k_T$ clustering algorithm [47, 49] with a distance parameter of 0.4. The jet constituents are further corrected for the UE contribution on a particle-by-particle basis using the “constituent subtraction” method [52, 53]. We require jets to have $p_T > 30$ GeV and $|\eta| < 2.0$, and to be separated by at least $\Delta R = 0.4$ from the selected leptons. Using a multivariate algorithm that combines tracking and SV information (Combined Secondary Vertex, CSVv2) [54], b quark jets are identified. A jet is considered as b tagged if the associated CSVv2 discriminator value is higher than the optimized b tagging working point. After all selection criteria, the b tagging efficiency in our $t\bar{t}$-enriched samples is of approximately 60 (70)%, with a misidentification rate of 5 (2)% for light-flavor jets, as estimated in the 0–30 (30–100)% most central PbPb events. The two jets with the highest CSVv2 discriminator value are used to count the b tagging multiplicity $N_{b\text{tag}}$. We then classify the selected events into the “0b” ($N_{b\text{tag}} = 0$), “1b” ($N_{b\text{tag}} = 1$), or “2b” ($N_{b\text{tag}} = 2$) tagged-jet categories.

Jet energy scale and resolution corrections extracted from the full detector simulation are applied as functions of jet $p_T$ and $\eta$ [22] to both data and simulated samples. A residual correction to the data is applied to account for a small data-simulation discrepancy in the jet energy response. The difference in b tagging and misidentification efficiencies between data and simulation is also studied as functions of jet $p_T$ and $\eta$, and PbPb event centrality.

5 Backgrounds and $t\bar{t}$ signal extraction

The main background contaminating the dilepton (plus b-jets) signal selection is DY (plus b-jets) production, and it is modeled from simulation with corrections obtained from data, as detailed below. In the cross-flavor final states, in particular, there is an additional contamination...
5. Backgrounds and t\(\bar{t}\) signal extraction

from W+jets and QCD multijet events, where the produced jets are mainly from heavy quarks eventually decaying into secondary (i.e., nonprompt) high-\(p_T\) leptons. These latter processes, referred to in what follows as “combinatorial” or “nonprompt” backgrounds, are directly derived from control regions in the data as explained next. Smaller background contributions from tW and VV production are directly estimated from the MC simulations.

Drell–Yan production of dilepton pairs contaminates the same-flavor channels mainly from off-shell \(Z/\gamma^*\) decays. In the \(e\mu\) channel, the contamination is due to \(Z/\gamma^* \rightarrow \tau^+\tau^- \rightarrow e^\pm\mu^\mp + X\) events. The simulation provides a good modeling of the kinematics of the dilepton pair, except for the low-\(p_T\) region where gluon resummation dominates and the agreement is less good. We thus derive a data/MC scale factor using \(Z \rightarrow \mu^+\mu^-\) events that is applied to correct the DY simulation. The difference between the unweighted and MC-weighted spectrum is taken as the DY \(p_T\) uncertainty. The scale factor for the \(Z/\gamma^*\) background normalization is measured, as in Ref. [55], from the number of events within the Z boson mass window, extrapolated to the number of events outside the window.

The combinatorial background has contributions from W+jets, DY with one lost lepton, and heavy-flavor jet events with nonisolated or nongenuine lepton candidates. The relative contribution and kinematics of each process are expected to depend strongly on the centrality of the collision, in a way not reliably modeled by the MC event generation. To estimate the shape of the nonprompt distributions, an event mixing technique is employed. The nonprompt-e/\(\mu\) control region is formed applying the same criteria as to the signal selection, except for requiring dilepton pairs with same sign (SS). The SS dilepton events predominantly contain at least one misidentified lepton. The scaling from the SS control to the signal region is performed assuming the ratio of the number of OS to SS events with misidentified leptons to be unity. This approach is validated using a mixed-event technique: first, each lepton is substituted randomly by a same-flavor lepton from a pool of events that share very similar centrality, energy density \(p, I_{\text{rel}},\) and (di)lepton \(p_T\); the kinematic variables are then recomputed; last, the mixed dilepton hypothesis is accepted according to the nearest-neighbors algorithm [56].

The extraction of the \(t\bar{t}\) cross section and its significance is based on a combined fit to the kinematical properties of several event categories based, first, on the three dilepton flavor combinations and, secondly, adding to the latter also the number of b-tagged jets \((N_{\text{b tag}} = 0, 1,\) or 2). Events in which the b-tagged jet multiplicity is greater or equal to one are expected to be very pure in the signal process. However, since b jets, unlike leptons, are affected by final-state energy loss in the medium [57], one needs to take into account the modified efficiency to identify them as b jets, with respect to the one expected in simulation, as discussed below.

In both (leptonic-only, and dilepton plus b jet) analyses, a Boosted Decision Tree (BDT) classifier is trained to maximize the sensitivity to the signal and extract the most accurate \(t\bar{t}\) cross section possible. The BDT classifier is trained on the signal versus the largest overall background of DY production, based on leptonic quantities only in order to minimize effects from the imprecise knowledge of the jet quantities in the heavy-ion environment. The BDTs exploit the properties of the leading- (“\(\ell_1\)””) and subleading-\(p_T\) (“\(\ell_2\)””) leptons and their correlations.

To form the BDT discriminator distributions, the following variables are used in descending order of importance: (i) the \(p_T\) of leading lepton, \(p_T(\ell_1)\), (ii) the (normalized) momentum imbalance between leptons, \(A_{p_T} = \frac{p_T(\ell_1) - p_T(\ell_2)}{p_T(\ell_1) + p_T(\ell_2)}\), (iii) the \(p_T\) of the dilepton system, \(p_T(\ell^+\ell^-)\), (iv) the absolute \(\eta\) value of the dilepton system, \(|\eta(\ell^+\ell^-)|\), (v) the absolute azimuthal separation of the leptons, \(|\Delta\phi(\ell^+\ell^-)|\), and (vi) the scalar sum of the absolute \(\eta\) of the two leptons, \(\sum_{i=1,2}|\eta_i|\).

Using the TMVA framework [58] and events fulfilling the dilepton selection criteria, we train
BDTs separately in the $\mu^+\mu^-$ and $e^+e^-$ background-dominated final states. The selected configuration for the multivariate analysis is a BDT with gradient boosting, and whose expected performance is evaluated with “the area under the curve” metric, yielding a value of 0.9 (an algorithm with ideal discrimination would yield 1.0, whereas with no discrimination would yield 0.5). Cross validation with different tuned parameters was performed, but no significant gain was observed. While the training of the BDT was done solely against same-flavor off-shell Z boson events, the BDT classifier manages to capture the main features of the signal and background processes, and therefore it can also be used for the most sensitive cross-flavor (on- and off-shell Z) channel.

Figure 1 shows the observed BDT discriminator distributions for the three dilepton flavor combinations. Also shown are the expected, prefit, values of $t\bar{t}$ signal and the various sources of background. The classifier separates well the $t\bar{t}$ signal from the $Z/\gamma^*$ background in the $\mu^+\mu^-$ and $e^+e^-$ final states. The $t\bar{t}$ signal (red histogram) populates the high-BDT discriminator values in all cases. The uncertainties in the data are statistical only, while the uncertainties in the backgrounds include a prefit expectation of the systematic uncertainties. In general, the data tend to be slightly above (below) the expectations for the sum of signal and backgrounds in the same- (opposite-) flavor categories, although both are consistent accounting for the statistical uncertainties.

The distributions of the BDT in the three b-tagged categories are shown in Fig. 2 for $e^+e^-$ (left), $\mu^+\mu^-$ (middle), and $e^\pm\mu^\mp$ (right) events, respectively. Due to the limited sample size (both in data and MC simulations), only three bins in the BDT classifier are used for 0b- and 1b-tagged categories, while a single bin is used for the case of 2b-tagged jets. The spectrum of the BDT classifier for the DY sample is taken from the MC simulation, after having reweighted the counts in each $N_{b\text{ tag}}$ bin to the $N_{b\text{ tag}}$ spectrum underneath the Z boson peak, as described before.

6 Results

The signal strength is defined as the ratio of the observed $\sigma_{t\bar{t}}$ to the expectation from theory, $\mu = \sigma_{t\bar{t}}/\sigma_{t\bar{t}}^{\text{th}}$ with $\sigma_{t\bar{t}}^{\text{th}} = 3.16 \mu b$. Two independent profile likelihood fits of the binned BDT dis-
6. Results

Figure 2: Observed (markers) and prefit expected (filled histograms) BDT discriminator distributions in the $e^+e^-$ (left), $\mu^+\mu^-$ (middle), and $e^\pm\mu^\mp$ (right) channels separately for the 0b-, 1b-, and 2b-jet multiplicity categories. The data are shown with markers, and the signal and background processes with filled histograms. The vertical bars on the markers represent the statistical uncertainties in data. The hatched regions show the prefit uncertainties in the sum of $t\bar{t}$ signal and backgrounds. The lower panels display the ratio of the data to the predictions, including the $t\bar{t}$ signal, with bands representing the prefit uncertainties in the predictions.

criminator distributions shown in Figs. 1 and 2 are used to extract $\mu$ and the significance of the $t\bar{t}$ process against the background-only hypothesis in terms of standard deviations (s.d.). The implementation of the fit is done using the RooFit/ROOTS package [59, 60] through the Higgs combination tool [61], accounting for all sources of uncertainty, statistical and systematic, and their correlations. Sources of systematic uncertainty are incorporated into the analysis via nuisance parameters [62] that are treated according to the frequentist paradigm. The best fit value of $\mu$ and its uncertainty $\Delta\mu$ (corresponding to a 68% confidence level) are extracted, following the procedure described in Section 3.2 of Ref. [62] and implemented in Ref. [63].

In the dilepton-alone categories, it can be seen from the prefit distributions of Fig. 2, that the observed data lies somewhat below the expectation, especially in the higher sensitivity $e^\pm\mu^\mp$ phase space region at high-BDT discriminator values. This is reflected in the extracted values of the observed (expected) signal strengths, $\mu = 0.81^{+0.26}_{-0.23} (1.00^{+0.23}_{-0.22})$, and significances 3.8 (4.8) s.d. This result constitutes the first evidence of the $t\bar{t}$ process in heavy ion collisions. Figure 3 compares the data to the postfit predictions in the three dilepton categories.

The 0b, 1b, and 2b tagged-jet categories are exploited in a second maximum-likelihood fit to control better the background contamination, to determine the efficiency of the b jet identification, $\varepsilon_b$, and to extract $\mu$ independently. To that end, we correlate the number of $t\bar{t}$ signal events in the three tagged-jet categories based on multinomial probabilities [64], using $\varepsilon_b$ and a parameter ($\delta_{QGIP}$) accounting for medium-induced suppression of $\varepsilon_b$ following a jet quenching model [65, 66]. The best fit value of $\mu$ is obtained after “profiling” [55] $\varepsilon_b$, separately in the three tagged-jet categories. The extracted values of the observed (expected) are $\mu = 0.64^{+0.22}_{-0.20} (1.00^{+0.23}_{-0.21})$ for the signal strength, and 4.0 (6.0) s.d. for the significances. The results are similar to those of the purely leptonic, although the signal strength $\mu$ is somewhat smaller. Figure 4 compares the data to the postfit predictions in the categories that use the b-jet multiplicity information.

The expected number of signal and background events in each final state after all selection criteria and the signal extraction fit have been applied, is given in Table 1 (for the dilepton plus b jet categories), along with the observed yields.
Figure 3: Observed (markers) and postfit predicted (filled histograms) BDT discriminator distributions in the $e^+e^-$ (left), $\mu^+\mu^-$ (middle), and $e^+\mu^\mp$ (right) channels. The data are shown with markers, and the signal and background processes with filled histograms. The vertical bars on the markers represent the statistical uncertainties in data. The hatched regions show the postfit uncertainties in the sum of $t\bar{t}$ signal and backgrounds. The lower panels display the ratio of the data to the predictions, including the $t\bar{t}$ signal, with bands representing the postfit uncertainties in the predictions.

Figure 4: Observed (markers) and postfit predicted (filled histograms) BDT discriminator distributions in the $e^+e^-$ (left), $\mu^+\mu^-$ (middle), and $e^+\mu^\mp$ (right) channels separately for the 0b-, 1b-, and 2b-jet multiplicity categories. The data are shown with markers, and the signal and background processes with filled histograms. The vertical bars on the markers represent the statistical uncertainties in data. The hatched regions show the postfit uncertainties in the sum of $t\bar{t}$ signal and backgrounds. The lower panels display the ratio of the data to the predictions, including the $t\bar{t}$ signal, with bands representing the postfit uncertainties in the predictions.
Table 1: Number of expected background and signal events, and observed event yields in the $e^+e^-$, $\mu^+\mu^-$, and $e^\pm\mu^\mp$ event categories for the three b jet multiplicities (0b, 1b, 2b) after all selection criteria and the signal extraction fit.

<table>
<thead>
<tr>
<th>Process</th>
<th>$e^+e^-$</th>
<th>$\mu^+\mu^-$</th>
<th>$e^\pm\mu^\mp$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z/\gamma^*$</td>
<td>$410.2\pm15.4$</td>
<td>$40.4\pm2.7$</td>
<td>$44.0\pm0.8$</td>
</tr>
<tr>
<td>Nonprompt</td>
<td>$1.9\pm0.3$</td>
<td>$0.2\pm0.1$</td>
<td>$3.3\pm0.6$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$2.8\pm0.8$</td>
<td>$3.2\pm0.8$</td>
<td>$4.5\pm1.2$</td>
</tr>
<tr>
<td>Total background</td>
<td>$410.2\pm15.1$</td>
<td>$42.8\pm2.7$</td>
<td>$45.0\pm0.8$</td>
</tr>
</tbody>
</table>

The impact from individual sources of systematic uncertainty is obtained by repeating the fits after fixing one nuisance parameter at a time at its postfit uncertainty ($\pm1\sigma$) value. The impact from the statistical uncertainty is evaluated leaving $\mu$ to float in the fits and fixing all other parameters at their postfit values. The observed (expected) shift in the signal strength, $\Delta\mu$, is used as the estimate of the observed (expected) uncertainty. Nuisance parameters that affect the normalization (distribution) are modeled by log-normal (Gaussian) probability distribution functions. Common sources of experimental uncertainty at the $2\ell_{\text{OS}}$ and $2\ell_{\text{OS}} + \text{jets}$ levels include the lepton selection efficiency, integrated luminosity, and the data-based normalization of the background. The statistical uncertainties in the $t\bar{t}$ signal and background distributions are estimated separately. The $2\ell_{\text{OS}} + \text{jets}$ selection is also impacted by the jet energy scale and resolution, and the uncertainty in $\epsilon_{\text{iso}}$, considering maximum and no b-quark energy loss.

Sources of theory uncertainty mainly affect the relative number of accepted to generated $t\bar{t}$ signal events, referred to as the “analysis acceptance” ($A$). The values of $A$ are measured relative to all generated $t\bar{t}$ signal events, including the branching fraction to leptons, as determined from the simulation. The effects of the nPDF parametrization, the choice of $\mu_R$ and $\mu_F$ scales, and $a_5(m_Z)$ are included. We additionally take into account the $p_T$ modeling of the $t\bar{t}$ signal and $Z/\gamma^*$ background distributions, and the uncertainty due to $m_t$ in the $t\bar{t}$ signal hadronization. The 0.1% uncertainty in the LHC beam energy [67] has a numerically insignificant effect on the measurement. The summary of all sources of systematic uncertainty and their observed impact $\Delta\mu/\mu$ are given in Table 2. The precision of the measurements is dominated by the statistical uncertainties.

The inclusive $t\bar{t}$ production cross section is finally obtained from the $2\ell_{\text{OS}}$ and $2\ell_{\text{OS}} + \text{jets}$ analyses multiplying the best-fit $\mu$ values of $0.81^{+0.26}_{-0.23}$ and $0.64^{+0.22}_{-0.20}$ respectively, by the theoretical expectation. Accounting for the acceptance corrections of $A = 3.55 \pm 0.03$ and $3.41 \pm 0.03$, we measure $\sigma_{t\bar{t}} = 2.56 \pm 0.82$ (tot) and $2.02 \pm 0.69$ (tot) $\mu$b, respectively, in the combined $e^+e^-$, $\mu^+\mu^-$, and $e^\pm\mu^\mp$ final states, with a relative total uncertainty of 32 and 34% for the $2\ell_{\text{OS}}$ and $2\ell_{\text{OS}} + \text{jets}$ analyses, respectively. The total uncertainty in $\mu$ is obtained from the covariance matrix of the fits. It is further split into a statistical part leaving $\mu$ to float in the fits and fixing all other parameters to their postfit values. The measured $\sigma_{t\bar{t}}$ is found to be smaller than, but still consistent with, the theoretical NNLO+NNLL prediction, computed with the EPPS16+CT14 NLO parton densities. The same calculation with the NNPDF30 NNLO [68] PDF yields $\sigma_{t\bar{t}}^{\text{NNLO+NNLL}} = 2.98 \pm 0.14$ (PDF $\oplus a_5(m_Z)\uparrow^{0.08}_{-0.08}$ (scale)) $\mu$b. Although a net overall anti-shadowing effect [28] is expected to increase $\sigma_{t\bar{t}}$ in PbPb relative to pp collisions [7], the data appear below the theoretical expectations with and without nuclear PDF effects. Figure 5 presents a summary of the extracted cross sections, including the measurement at $\sqrt{s} = 5.02$ TeV [17] in proton-proton collisions, compared to the corresponding NNLO+NNLL predictions [32].
Table 2: Observed impact of each source of uncertainty in the signal strength $\mu$, for the leptonic-only and leptonic+b-tagged analyses. The total uncertainty is obtained from the covariance matrix of the fits. The values quoted are symmetrized.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta \mu / \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>leptonic-only</td>
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<tr>
<td>Total statistical uncertainty</td>
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</tr>
<tr>
<td>Total systematic experimental uncertainty</td>
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<tr>
<td>Background normalization</td>
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<td>Lepton selection efficiency</td>
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<tr>
<td>Jet energy scale and resolution</td>
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<tr>
<td>$b$ tagging efficiency</td>
<td>—</td>
</tr>
<tr>
<td>Integrated luminosity</td>
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</tr>
<tr>
<td>Total theoretical uncertainty</td>
<td>0.05</td>
</tr>
<tr>
<td>$nPDF, \mu_R, \mu_F$ scales, and $\alpha_S(m_Z)$</td>
<td>$&lt;0.01$</td>
</tr>
<tr>
<td>Top quark and $Z$ boson $p_T$ modeling</td>
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</tr>
<tr>
<td>Top quark mass</td>
<td>$&lt;0.01$</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Figure 5: Inclusive $t\bar{t}$ cross sections measured in the combined $e^+e^-$, $\mu^+\mu^-$, and $e^\pm\mu^\mp$ final states in PbPb collisions (divided by the mass number squared, $A^2$), compared to theoretical NNLO+NNLL predictions [32], and pp results at $\sqrt{s_{NN}} = 5.02$ TeV [17]. The total experimental error bars (theoretical error bands) include statistical and systematic (PDF and scale) uncertainties added in quadrature.
7 Summary

In summary, evidence for top quark pair production in nucleus-nucleus collisions has been presented for the first time, using lead-lead data at $\sqrt{s_{_{NN}}} = 5.02$ TeV with a total integrated luminosity of $1.7 \pm 0.1$ nb$^{-1}$. The measurement is performed analyzing events with at least one pair of isolated and oppositely charged leptons ($\ell^+\ell^-$, $\mu^+\mu^-$, and $e^\pm\mu^\mp$) with large transverse momenta, as well as adding the information on the number of jets tagged as originating from the hadronization of bottom quarks. The inclusive cross section ($\sigma_{_{T\bar{T}}}$) is derived from likelihood fits to a multivariate discriminator, which includes different leptonic kinematic variables. Using the dilepton categories with and without the b-tagged jet multiplicity information, we demonstrate that top quark decay products are identified, irrespective of whether interacting with the medium or not. The measured cross sections are $\sigma_{_{T\bar{T}}} = 2.02 \pm 0.69$ (tot) and $2.56 \pm 0.82$ (tot) $\mu$b, respectively. These values are consistent with each other and lower, but still compatible, with respect to the expectations from scaled pp data as well as from perturbative quantum chromodynamics calculations. The observed (expected) significance of the $t\bar{t}$ signal against the background-only hypothesis are 4.0 (6.0) and 3.8 (4.8) standard deviations in the two cases, respectively. This first measurement paves the way for further detailed investigations of top quark production in nuclear interactions, providing, in particular, a new tool for studies of the strongly interacting matter created in nucleus-nucleus collisions.

References


