Evidence for top quark production in nucleus-nucleus collisions

The CMS Collaboration

Abstract

Ultrarelativistic heavy ion collisions recreate in the laboratory the thermodynamical conditions prevailing in the early universe up to $10^{-6}$ seconds, thereby allowing the study of the quark-gluon plasma (QGP), a state of quantum chromodynamics (QCD) matter with deconfined partons. The top quark, the heaviest elementary particle known, is accessible in nucleus-nucleus collisions at the CERN LHC, and constitutes a novel probe of the QGP. Here, we report the first-ever evidence for the production of top quarks in nucleus-nucleus collisions, using lead-lead collision data at a nucleon-nucleon centre-of-mass energy of 5.02 TeV recorded by the CMS experiment. Two methods are used to measure the cross section for top quark pair production ($\sigma_{tt}$) via the decay into charged leptons (electrons or muons) and bottom quarks. One method relies on the leptonic information alone, and the second one exploits, in addition, the presence of bottom quarks. The measured cross sections, $\sigma_{tt} = 2.54^{+0.84}_{-0.74}$ and $2.03^{+0.71}_{-0.64}$ $\mu$b, respectively, are compatible with expectations from scaled proton-proton data and QCD predictions.

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The multi-TeV energies available at the CERN LHC have opened up the possibility to measure, for the first time, various high-mass elementary particles produced in heavy ion collisions. After the observation of the W \cite{1,2} and Z \cite{3-5} bosons, there remained two heavier elementary particles in the standard model without direct observation in nucleus-nucleus collisions: the Higgs boson \cite{6,7} and top quark. Whereas the Higgs boson lies beyond the reach of heavy ion collisions at the LHC \cite{8,9}, the top quark is accessible for experimental study in lead-lead (PbPb) collisions \cite{10}. More specifically, the top quark constitutes a novel and theoretically precise probe of the nuclear parton distribution functions (nPDFs) in the poorly explored region where partons have a large fraction of the nucleon momentum, as well as of the properties of the produced quark-gluon plasma (QGP) \cite{10,11}. First, precise knowledge of nPDFs is a key prerequisite to extract detailed information on the QGP properties from the experimental data. Second, top quarks, on average, decay on a timescale similar to the formation of the QGP, hence offering a unique opportunity to study its time evolution \cite{11}. The study presented here shows evidence for the production of the top quark in PbPb collisions as measured by the CMS detector \cite{12}.

The top quark is produced at hadron colliders predominantly in pairs (t\bar{t}) through quantum chromodynamics (QCD) processes, mostly gluon-gluon fusion at the LHC, and is thereby a sensitive probe of the gluon PDF of the incoming nucleons \cite{13}. Once produced, it decays very rapidly (within an average distance of \(~0.15\) fm) with almost 100\% probability into a W boson and a bottom (b) quark. Top quark pair production is thereby characterized by final states comprising the decay products of the two W bosons, and two b jets, resulting from the hadronization products of b quarks. Experimentally, W bosons decaying hadronically, i.e. to a quark-antiquark pair, have large branching fractions but are more difficult to identify because of the large QCD multijet background. The dilepton final states, in which both W bosons decay into electrons (e) or muons (\(\mu\)) and the corresponding neutrinos (\(\nu\)), are the cleanest final states for the t\bar{t} signal measurement, despite their relatively small branching fraction \(B(t\bar{t} \rightarrow \ell^+ \ell^- \nu_\ell \bar{\nu}_\ell \, b \bar{b}) = 5.25\%\) \cite{14}, with \(\ell^\pm = e^\pm, \mu^\pm\). Dedicated algorithms deployed in real time \cite{15} allow the CMS detector to collect events with high transverse momentum (\(p_T\)) leptons, hence making the measurement of t\bar{t} production in PbPb collisions possible in three dilepton final states, i.e. \(e^+e^-, \mu^+\mu^-, \) and \(e^\pm\mu^\mp\). Figure 1 displays a candidate t\bar{t} event in the \(e^\pm\mu^\mp\) final state in the PbPb data sample.

Since the t\bar{t} production discovery at the Fermilab Tevatron more than twenty years ago \cite{16,17},

\[t\bar{t} \rightarrow (bW^+) (\bar{b}W^-) \rightarrow (b e^+\nu_e) (\bar{b} \mu^-\bar{\nu}_\mu).\]
top quark pairs have been measured at the LHC in proton-proton (pp) [18–22] as well as proton-nucleus [23] collisions, but so far have not been observed in nucleus-nucleus collisions because of insufficient centre-of-mass energies or integrated luminosities. During November–December 2018, PbPb collision data at a nucleon-nucleon (NN) centre-of-mass energy of \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \) were delivered by the LHC with a peak luminosity exceeding the design luminosity of \( 10^{27} \text{ cm}^{-2} \text{ s}^{-1} \) by a factor of more than six. The data sample, recorded by the CMS experiment and corresponding to an integrated luminosity of \( (1.7 \pm 0.1) \text{ nb}^{-1} \) [24], allows for the first measurement of the \( \tau \tau \) cross section (\( \sigma_{\tau \tau} \)) in PbPb collisions.

The cross section \( \sigma_{\tau \tau} \) was extracted by employing two methods according to the following criteria: (i) making use of the final-state dilepton kinematic properties alone, and (ii) imposing extra requirements on the number of jets “tagged” as originating from b quarks (referred to as “b-tagged jets”) in the event. The first method is motivated by the fact that leptons propagate unscathed through the QGP, thereby providing favourable conditions for the detection of \( \tau \tau \) production. The second method, which enhances the signal over background in standard pp analyses, is applied with realistic estimates of the impact of b quark energy loss, also known as “jet quenching”, in the QGP [25].

As a result of the smallness of the signal, the large background, and the corresponding complexity of the measurement, the analysis is designed with a few unique features. First, this is the only \( \tau \tau \) measurement so far where kinematic information of the decay dilepton system alone is used to extract the signal. Second, a novel event-by-event mixing technique, including global-event and lepton information, is implemented to carefully constrain the background. Third, to avoid any bias, the top quark search is designed following a “blind” analysis procedure [26], whereby the selection criteria were optimized and fixed first using about one third of the data sample, before being applied to the full data set. The analysis demonstrates the feasibility of measuring the top quark—the heaviest elementary particle known—in nucleus-nucleus collisions, and using it as a novel probe of the strongly interacting matter produced in such collisions.

1 Event selection, background and \( \tau \tau \) signal estimation

The data sample is filtered to favour events with two opposite-sign (OS) high-\( p_T \) leptons that do not belong to jets and are thus isolated from nearby hadronic activity. The characteristic additional presence of two b-tagged jets in the \( \tau \tau \) decay chain is then used, in our second method only, to enhance the sensitivity to the top quark signal. Jets are considered as b tagged if an optimized “combined secondary vertex” (CSV) discriminator [27] produces a value for the probability of the jet to stem from the hadronization of the b quark above a certain threshold. The b tagging efficiency depends upon the overlap of the two colliding nuclei. This geometrical factor depends on the centrality percentile, where the percentages are fractions of the total inelastic hadronic cross section, with 0% corresponding to full overlap of the two colliding nuclei.

After the selection criteria, the b tagging efficiency in \( \tau \tau \) Monte Carlo (MC) simulation samples is approximately 60 (70)%, with a misidentification rate of 5 (2)%, in the 0–30 (30–100)% centrality interval. The two jets with the highest CSV discriminator values are used to count the b-tagged jet multiplicity, \( N_{b\text{-tag}} \), and classify the selected events into the “0b” (\( N_{b\text{-tag}} = 0 \)), “1b” (\( N_{b\text{-tag}} = 1 \)), and “2b” (\( N_{b\text{-tag}} = 2 \)) jet categories.

The main background contaminating the \( \tau \tau \) signal selection is Drell–Yan (DY) quark-antiquark annihilation into lepton-antilepton pairs through Z bosons or virtual photons (a process referred to as “Z/\( \gamma^* \)”) modelled from simulation with corrections obtained from data, as de-
tailed below. In the $e^\pm \mu^\mp$ final state, in particular, there are additional contaminations from $W$ boson production in association with jets ("$W+$jets"), $Z/\gamma^*$ with one nonreconstructed lepton, and QCD multijet events, where the produced jets are mainly from heavy quarks eventually decaying into high-$p_T$ leptons that are erroneously identified as being isolated. These latter processes, referred to in what follows as "nonprompt" background, are directly derived from control regions in the data, as explained next. Smaller background contributions from single top quark and $W$ boson ("$tW$"), and WW, WZ, and ZZ (collectively referred to as "VV") production, are directly estimated from MC simulations.

Drell–Yan production contaminates the $e^+e^-$ and $\mu^+\mu^-$ final states mainly with offshell $Z/\gamma^*$ decays. In the $e^\pm \mu^\mp$ final state, the contamination is due to $Z\text{gstar} \rightarrow \tau^+\tau^- \rightarrow e^\pm \mu^\mp + X$ events, where "$X$" represents other particles. The simulation provides a good modelling of the dilepton kinematic properties, except for the low-$p_T$ region where multiple soft-gluon emission dominates and the agreement is slightly worse. We thus apply correction ("scale") factors to the MC simulation using events in data enriched with $Z\text{gstar} \rightarrow e^+e^- +$ boson candidates. The scale factors are measured as a function of centrality, but no particular dependence is seen. The difference between the corrected and uncorrected MC distributions is considered as the $Z/\gamma^*$ $p_T$ modelling uncertainty. Events in the $e^+e^-$ and $\mu^+\mu^-$ final states with dilepton invariant mass $m(\ell^+ \ell^-)$ in the proximity of the $Z$ boson mass $m_Z$ [14] ($76 < m(\ell^+ \ell^-) < 106$ GeV) are rejected, and their number is used to control the normalization of the corrected MC distributions outside the $m_Z$ region.

The relative contribution and kinematic properties of each nonprompt-background process are expected to depend strongly on centrality, in a way not reliably modelled by the MC simulation. The overall normalization of the nonprompt background is thus estimated by forming a "same-sign" (SS) control region, i.e. applying the same criteria as to the signal selection, but requiring SS lepton pairs. The SS dilepton events predominantly contain at least one misidentified lepton. The scaling from the SS control to the signal regions is performed assuming the ratio of the number of OS to SS events containing misidentified leptons to be unity. To estimate the distribution of the nonprompt background, an event mixing technique is developed. The mixing is performed for each lepton in a pool of 100 different events sharing the same features (i.e. lepton charge and flavour, and whether originating from onshell or offshell $Z$ bosons). Each lepton is randomly substituted, and the kinematic variables are recomputed with this new dilepton hypothesis. A multidimensional distance is calculated with respect to the original event using a nearest-neighbour algorithm [28]. The variables entering the algorithm are the centrality, energy density, lepton $p_T$ and isolation, and dilepton $p_T$. The highest ranked mixed events are chosen as the nominal distribution. Differences with respect to the distributions obtained using events further apart in this multidimensional distance, i.e. lower ranked hypotheses, are considered as a source of systematic uncertainty.

For both the dilepton-only and dilepton plus $b$-tagged jets methods, 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 simulated $t\bar{t}$ signal versus the overall largest $Z/\gamma^*$ background. This classifier is based exclusively on leptonic quantities to minimize effects from the imprecise knowledge of the jet properties in the heavy ion environment. The BDT exploits the properties of the leading- and subleading-$p_T$ leptons, denoted by "$\ell_1$" and "$\ell_2$", respectively, and their correlations. As input to the BDT classifier, the following variables are used in descending order of importance: (i) the $p_T$ of the leading lepton, $p_T(\ell_1)$, (ii) the normalized momentum imbalance between $\ell_1$ and $\ell_2$, $A_{\rho_1} = (p_T(\ell_1) - p_T(\ell_2)) / (p_T(\ell_1) + p_T(\ell_2))$, (iii) the dilepton $p_T$, (iv) the dilepton absolute pseudorapidity ($|\eta|$), (v) the absolute azimuthal separation between $\ell_1$ and $\ell_2$, and (vi) the sum of the
absolute $\eta$ of $\ell_1$ and $\ell_2$.

Using the TMVA framework \cite{tmva} and events fulfilling the selection criteria, we train our BDT classifier simultaneously in the $e^+e^-$ and $\mu^+\mu^-$ background-dominated final states. The selected configuration for the multivariate analysis is a BDT with gradient boosting. The classification probabilities for individual events are derived using a transformation of the background and signal distributions, in which background events are uniformly distributed between 0 and 1, whereas signal events cluster towards 1. The expected BDT performance is evaluated computing the area under the “receiver operating characteristics” curve, 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 differently tuned parameters was performed, but no significant gain was observed. While the training of the BDT was done solely against $Z/\gamma^* \rightarrow e^+e^-$, $\mu^+\mu^-$ events, the BDT classifier captures the main features of the signal and background processes, therefore it can be used for the $e^\pm\mu^\mp$ final state.

Figure 2 shows the observed BDT discriminator distributions for the dilepton-only method. The $t\bar{t}$ signal and various sources of background are also shown, indicated as “prefit expected” as they are not adjusted according to the statistical treatment (“fit”) of Section 2. The classifier separates well the $t\bar{t}$ signal from the $Z/\gamma^*$ background in all 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 uncertainty, described in the next section.

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) final states. 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 expectations, including the $t\bar{t}$ signal, with bands representing the prefit uncertainties in the expectations.

2 Results

Profile likelihood fits to binned BDT discriminator distributions are used to extract the “signal strength” ($\mu$) and the significance (in units of standard deviations) of the $t\bar{t}$ process against the background-only hypothesis. These fits were preformed separately for the dilepton-only and dilepton plus b-tagged jets methods. The value of $\mu$ is defined as the ratio of the observed $\sigma_{t\bar{t}}$ to the expectation from theory, i.e. $\mu = \sigma_{t\bar{t}} / \sigma_{t\bar{t}}^{\text{th}}$. The theoretical cross section $\sigma_{t\bar{t}}^{\text{th}} = \sigma_{\text{NNLO}+\text{NLL}}^{\text{PbPb}\rightarrow t\bar{t}+X} = 3.22^{+0.38}_{-0.35}$ (nPDF + PDF) $\pm 0.09$ (scale) $\mu$b, calculated with the TOP++ (v2.0) pro-
gram [30] at next-to-next-to-leading order (NNLO) in QCD, including soft-gluon resummation at next-to-next-to-leading logarithmic (NNLL) accuracy. The ratio of the EPPS16 [31] nuclear to CT14 [32] free-nucleon next-to-leading order (NLO) PDFs is used to scale the cross section obtained with CT14 NNLO PDFs. The same calculation but with the free-nucleon CT14 and NNPDF30 [33] NNLO PDFs yields $c_{NN+NNLL}^{NLO+NLO} = 3.04_{-0.14}^{+0.18} \text{(PDF)} + 0.08^{+0.08} \sqrt{-0.10} \text{(scale)}$ and $2.98 \pm 0.14 \text{(PDF) + 0.08} \pm 0.10 \text{(scale)} \mu b$, respectively. The small difference between the PbPb and pp theoretical cross sections arises from the nPDF “antishadowing” effect [10].

In the dilepton-only method, it is already seen from the prefit distributions of Fig. 2 that the data are somewhat below the expectation at the high-BDT discriminator values in the higher sensitivity $e^\pm \mu^\mp$ phase space region. This is also reflected in the extracted value of the observed (expected) $\mu = 0.79_{-0.23}^{+0.26} (1.00_{-0.25}^{+0.25})$, where contributions to the uncertainties are statistical and systematic in nature, and the significance of 3.8 (4.8) standard deviations. This result constitutes the first evidence of $t\bar{t}$ production in nucleus-nucleus collisions.

Events in which $N_{b\text{-tag}} \geq 1$ are expected to be very pure in the $t\bar{t}$ signal process. Since $b$ quarks are affected by final-state energy loss in the QGP, we take into account the centrality-dependent impact from jet quenching on $N_{b\text{-tag}}$. We make use of a jet quenching model [34, 35], that is consistent with the CMS b jet data [25], estimating the expected migration of $t\bar{t}$ signal events among the 0b-, 1b-, or 2b-tagged jet categories. A combined profile likelihood fit, introducing a parameter $\epsilon_b$, that correlates the number of $t\bar{t}$ signal events in the three b-tagged jet categories based on multinomial probabilities [20], is thus expected to control better the background contamination. We include in the likelihood the effects on $\epsilon_b$ from jet quenching (comparing the maximum with no b quark energy loss scenarios), and the intrinsic uncertainties in the b tagging efficiency and misidentification rate. The values of the observed (expected) signal strength and significance are $\mu = 0.63_{-0.20}^{+0.22} (1.00_{-0.21}^{+0.23})$ and 4.0 (5.8) standard deviations, respectively. These results are similar to those from the dilepton-only method, although $\mu$ is somewhat smaller. Figure 3 compares the data to the $t\bar{t}$ signal and various sources of background adjusted according to the fit procedure (“postfit predicted”) for the dilepton plus b-tagged jets method. The BDT distribution for the $Z/\gamma^*$ background is taken from the MC simulation, after scaling the event yield in each $N_{b\text{-tag}}$ bin to the corresponding $N_{b\text{-tag}}$ distribution observed in data within the $m_\gamma$ region.

Common sources of experimental uncertainties in the two methods include the lepton selection efficiency, integrated luminosity, and the normalization of the background based on control samples in data. The statistical uncertainties in the $t\bar{t}$ signal and background distributions are estimated separately. The dilepton plus b-tagged jets method is, in addition, affected by the uncertainty in $\epsilon_b$, and the jet energy scale and resolution. Sources of theoretical uncertainty affect the relative number of selected over generated $t\bar{t}$ signal events. The effects of the nPDF parametrization, the choice of renormalization and factorization scales, and the strong coupling constant at the Z boson mass, $\alpha_S(m_Z)$, are included. We also take into account the uncertainties in the $p_T$ modelling of the $t\bar{t}$ signal and $Z/\gamma^*$ background distributions as well as in the top quark mass. The precision of the two methods is dominated by the statistical uncertainty ($\approx 28\%$).

The inclusive $t\bar{t}$ production cross sections (for the dilepton-only and dilepton plus b-tagged jets methods) are finally obtained in the combined $e^+e^-$, $\mu^+\mu^-$, and $e^\pm\mu^\mp$ final states multiplying the best fit $\mu$ values of $0.79_{-0.23}^{+0.26}$ and $0.63_{-0.21}^{+0.22}$ by the theoretical expectation. We measure $\sigma_{t\bar{t}} = 2.54_{-0.74}^{+0.84}$ and $2.03_{-0.64}^{+0.71} \mu b$ for the two cross section extractions. The measured $\sigma_{t\bar{t}}$ are found to be smaller than, but still consistent with, the theoretical predictions at NNLO+NNLL accuracy in QCD that incorporate nuclear modifications via the EPPS16 or nCTEQ15 [36] nPDFs. Despite
Evidence for top quark pair (t\bar{t}) production in nucleus-nucleus collisions is presented for the first time, using lead-lead collision data at a nucleon-nucleon centre-of-mass energy of 5.02 TeV with a total integrated luminosity of (1.7 ± 0.1) nb\(^{-1}\). The measurement utilises events with at least one pair of isolated and oppositely charged leptons (electrons or muons) with large transverse momenta, and is performed twice, with and without adding the information on the number of jets “tagged” as originating from the hadronization of bottom (b) quarks (“b-tagged jets”). The inclusive cross section (\(\sigma_{t\bar{t}}\)) is derived from likelihood fits to a multivariate t\bar{t} signal and backgrounds. The lower panels display the ratio of the data to predictions, including the b\textsuperscript{−} signal, with bands representing the postfit uncertainties in the predictions.

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The measured cross sections are \(\sigma_{t\bar{t}} = 5.8 \pm 0.74 \) (right) final states separately for the 0b-, 1b-, and 2b-tagged 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 predictions, including the b\textsuperscript{−} signal, with bands representing the postfit uncertainties in the predictions.

The expected antishadowing effect, the data appear below the theoretical expectations with or without nPDF effects. Figure 3 presents a summary of the extracted cross sections, including the measurement in pp collisions at \(\sqrt{s} = 5.02\) TeV scaled by the Pb mass number squared, \(A^2\), compared with the corresponding theoretical predictions [37].

### 3 Summary

Evidence for top quark pair (t\bar{t}) production in nucleus-nucleus collisions is presented for the first time, using lead-lead collision data at a nucleon-nucleon centre-of-mass energy of 5.02 TeV with a total integrated luminosity of (1.7 ± 0.1) nb\(^{-1}\). The measurement utilises events with at least one pair of isolated and oppositely charged leptons (electrons or muons) with large transverse momenta, and is performed twice, with and without adding the information on the number of jets “tagged” as originating from the hadronization of bottom (b) quarks (“b-tagged jets”). The inclusive cross section (\(\sigma_{t\bar{t}}\)) is derived from likelihood fits to a multivariate t\bar{t} signal and backgrounds, which includes different leptonic kinematic variables. Using the dilepton-only and dilepton plus b-tagged jets methods, we demonstrate that top quark decay products can be identified irrespective of any possible final-state interactions with the quark-gluon plasma. The measured cross sections are \(\sigma_{t\bar{t}} = 2.54^{+0.84}_{-0.74}\) and \(2.03^{+0.71}_{-0.64}\) nb, respectively. These values are compatible with, though somewhat lower than, the expectations from scaled proton-proton data and perturbative quantum chromodynamics calculations. The observed (expected) significance of the t\bar{t} signal against the background-only hypothesis amounts to 3.8 (4.8) and 4.0 (5.8) standard deviations in the two methods. This measurement is a milestone for the heavy ion and top quark physics programs at the LHC, and demonstrates the versatility of the CMS detector to extract such a complex signal in a very intricate environment. This is just the first step in using the top quark as a novel and powerful probe of the quark-gluon plasma.

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References


A Methods

A.1 Experimental setup and event sample

The CMS apparatus surrounds the collision point with full azimuthal ($\phi$) and extended polar ($\theta$) angle coverage; the latter is expressed as $\eta = -\ln\tan(\theta/2)$. 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 $p_T$ of charged particles. Charged particle trajectories are measured by a silicon pixel and strip tracker system within $|\eta| < 2.5$ [38]. 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) [39]. Muons are detected over the range $|\eta| < 2.4$ in gas-ionization detectors embedded in the steel flux-return yoke outside of the solenoid [40]. Hadronic jets are reconstructed from the tracker information as well as the energy deposits in the ECAL, and brass and scintillator hadron calorimeters (HCAL) [41]. Both ECAL and HCAL are organized in barrel ($|\eta| < 1.5$) and endcap ($|\eta| = 1.5–3.0$) sections. Forward hadron (HF) calorimeters extend the coverage up to $|\eta| = 5.2$, and using the $E_T$ sum deposited in them we estimate the centrality [42]. 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. [12].

The event sample of $(1.7 \pm 0.1) \text{pb}^{-1}$ [24] of PbPb collisions is equivalent to an NN integrated luminosity of $\approx 80 \text{pb}^{-1}$, considering the approximate scaling by $A^2$. The absolute luminosity scale is derived following a methodology similar to that described in Ref. [24], whereby the size of the beams is determined by transversely displacing one beam through the other, and measuring the interaction rate as a function of displacement. The number of simultaneous collisions per bunch crossing is on average $\ll 1$ in the entire data set.

A.2 Monte Carlo event simulation and theoretical predictions

Two Monte Carlo signal samples for top quark pair production, $\text{NN} \rightarrow t\bar{t} + X$, are generated at NLO in QCD using the MadGraph5_aMC@NLO (v2.4.2) [43] and POWHEG (v2) [44,45] codes, with a mixture of proton-proton, proton-neutron, and neutron-neutron collisions corresponding to their ratio in PbPb. The EPPS16 NLO nPDF [31], with CT14 NLO free-nucleon PDF [32], is 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) [39]. Muons are detected over the range $|\eta| < 2.4$ in gas-ionization detectors embedded in the steel flux-return yoke outside of the solenoid [40]. Hadronic jets are reconstructed from the tracker information as well as the energy deposits in the ECAL, and brass and scintillator hadron calorimeters (HCAL) [41]. Both ECAL and HCAL are organized in barrel ($|\eta| < 1.5$) and endcap ($|\eta| = 1.5–3.0$) sections. Forward hadron (HF) calorimeters extend the coverage up to $|\eta| = 5.2$, and using the $E_T$ sum deposited in them we estimate the centrality [42]. 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. [12].

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A.2 Monte Carlo event simulation and theoretical predictions

Two Monte Carlo signal samples for top quark pair production, $\text{NN} \rightarrow t\bar{t} + X$, are generated at NLO in QCD using the MadGraph5_aMC@NLO (v2.4.2) [43] and POWHEG (v2) [44,45] codes, with a mixture of proton-proton, proton-neutron, and neutron-neutron collisions corresponding to their ratio in PbPb. The EPPS16 NLO nPDF [31], with CT14 NLO free-nucleon PDF [32], is 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) [39]. Muons are detected over the range $|\eta| < 2.4$ in gas-ionization detectors embedded in the steel flux-return yoke outside of the solenoid [40]. Hadronic jets are reconstructed from the tracker information as well as the energy deposits in the ECAL, and brass and scintillator hadron calorimeters (HCAL) [41]. Both ECAL and HCAL are organized in barrel ($|\eta| < 1.5$) and endcap ($|\eta| = 1.5–3.0$) sections. Forward hadron (HF) calorimeters extend the coverage up to $|\eta| = 5.2$, and using the $E_T$ sum deposited in them we estimate the centrality [42]. 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. [12].

The event sample of $(1.7 \pm 0.1) \text{pb}^{-1}$ [24] of PbPb collisions is equivalent to an NN integrated luminosity of $\approx 80 \text{pb}^{-1}$, considering the approximate scaling by $A^2$. The absolute luminosity scale is derived following a methodology similar to that described in Ref. [24], whereby the size of the beams is determined by transversely displacing one beam through the other, and measuring the interaction rate as a function of displacement. The number of simultaneous collisions per bunch crossing is on average $\ll 1$ in the entire data set.
MCFM (v8.0) [49]. Events from tW production are simulated also at NLO using POWHEG [50], and normalized to the approximate NNLO cross sections [51].

The parton-level results from the above matrix-elements calculators are then interfaced to the PYTHIA8 (v2.3.0) [52] MC event generator to simulate parton showering and hadronization with a set of parameters (“tune”) derived from CMS pp data [53]. All MC generated NN events are given an event-by-event weighting factor to replicate the centrality distribution in data, based on the average number of NN collisions calculated with a Glauber model [54] for each PbPb centrality interval. At the step of detector digitization, they are placed at the same PV location as a heavy ion background event, part of a MC sample generated using HYDJET (v1.9) [55], to mimic the effects of the underlying event (UE) without any QGP-induced modifications of the final-state particles from the top quark decay. Finally, all simulated samples include an emulation of the full CMS detector response, based on GEANT4 [56], and a realistic description of the luminous region produced by the collisions.

A.3 Event selection and physics-object reconstruction

The event sample is filtered in real time (“online”) using a two-tier trigger system [15] composed of the so-called Level-1 (L1) and high-level trigger (HLT) subsystems. For electrons, electromagnetic energy deposits are reconstructed at L1 in two neighbouring groups of ECAL crystals, and events with \( E_T > 15 \text{ GeV} \) are selected. At the HLT, the energy deposits in the ECAL are reconstructed using the particle-flow (PF) algorithm [57] in the barrel and endcaps. After suppression of spurious signals, the HLT keeps single electron objects above the \( E_T \) threshold of 20 GeV. The L1 muon triggers are hardware-based flags signalled by primitive 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 the \( p_T \) threshold of 12 GeV. For both cases, the coincidence with beam monitoring triggers [15] is required to remove noncollision sources, such as cosmic rays.

Offline, particle candidates are reconstructed with the PF algorithm using an optimized combination of information from the various elements of the CMS detector. Events are required to contain at least one pair of OS leptons, with \( p_T > 25 \) (20)\,GeV and \( |\eta| < 2.1 \) (2.4) for the electron (muon) candidates. For the electron case, we additionally exclude the regions \( 1.444 < |\eta| < 1.566 \) (barrel-to-endcap transition in ECAL), and for the 2018 data the rectangular region \(-3.000 < \eta < -1.392, -1.57 < \phi < -0.87 \) radians, where the reconstruction of electron objects is less efficient. The electron [39] and muon [40] 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 centre of the detector [58]. 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 [59] and making use of the FASTJET technique [60] [61]. The final relative isolation variable is defined as \( I_{\text{rel}} = \left| I - \text{UE}(\rho) \right| / p_T \), where \( \text{UE}(\rho) \) is a parametrization of the observed \( \rho \) distribution, accounting for the residual \( \eta \)-dependence of the average energy deposition. The electron (muon) candidates are selected if the discriminant value satisfies \( I_{\text{rel}} < +0.08 \) (−0.06).

In cases where more than one pair of OS leptons satisfying the above selection is found, we select the two leptons that yield the highest scalar \( p_T \) sum. Dilepton events in the \( e^+e^- \) and
A.4 Extracting the signal strength parameter

In the first step, we discard events around $m_Z$, i.e. $76 < m(\ell^+\ell^-) < 106$ GeV. 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 [63], the MC event generation as a function of the lepton $p_T$ and $\eta$, and event centrality.

Jets are reconstructed from the PF candidates using the anti-$k_T$ clustering algorithm [59, 61] 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 [64, 65]. 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 [27], b quark jets are identified. Jet energy scale and resolution corrections extracted from the full detector simulation are applied as functions of jet $p_T$ and $\eta$ [41] 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.

A.4 Extracting the signal strength parameter

The implementation of the $t\bar{t}$ signal-strength fits are performed in the ROOFIT/ROOSTATS package [66, 67] through the tool developed in the course of the Higgs boson discovery [6, 7], accounting for sources of uncertainty, statistical and systematic, and their correlations. We extract the significance based on the frequentist paradigm using a “profile” likelihood ratio as a test statistic [68], in which sources of systematic uncertainty are incorporated into the likelihood via “nuisance parameters” that are profiled from (i.e. fitted to) the data. The best fit value of $\mu$ and its uncertainty $\Delta \mu$ (corresponding to a 68% confidence level) are thus obtained after profiling (e.g. $\epsilon_b$), and following the procedure described in Section 3.2 of Ref. [69]. The total uncertainty in $\mu$ is obtained from the covariance matrix of the fits. 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 ($\pm 1\sigma$) value. The impact from the statistical uncertainty is evaluated leaving $\mu$ to float in the fits and fixing all other parameters to 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 modelled by log-normal (Gaussian) probability distribution functions. The summary of all sources of uncertainty and their observed impact $\Delta \mu / \mu$ are given in Table [1].
Table 1: Observed impact of each source of uncertainty on the signal strength $\mu$, for the dilepton-only and dilepton plus b-tagged jets methods. 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>
<th>Dilepton only</th>
<th>Dilepton plus b-tagged jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total statistical uncertainty</td>
<td>0.27</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>Total systematic experimental uncertainty</td>
<td>0.17</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>Background normalization</td>
<td>0.12</td>
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<td></td>
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<tr>
<td>Background and tf signal distribution</td>
<td>0.07</td>
<td>0.08</td>
<td></td>
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<tr>
<td>Lepton selection efficiency</td>
<td>0.06</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
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<td>0.02</td>
<td></td>
</tr>
<tr>
<td>$b$ jet identification ($\epsilon_b$)</td>
<td>—</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>0.05</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Total theoretical uncertainty</td>
<td>0.05</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>$n$PDF, $\mu_R, \mu_F$ scales, and $\alpha_S(m_Z)$</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
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<tr>
<td>Top quark and Z boson $p_T$ modelling</td>
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<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Top quark mass</td>
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<td>&lt;0.01</td>
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<tr>
<td>Total uncertainty</td>
<td>0.32</td>
<td>0.34</td>
<td></td>
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</tbody>
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