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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 evidence for the production of top quarks in nucleus-nucleus collisions, using lead-lead collision data at a nucleon-nucleon center-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 ($\sigma_{\mathrm{t\bar{t}}}$) via the selection of 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, $\sigma_{\mathrm{t\bar{t}}} = 2.54^{+0.84}_{-0.74}$ 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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*See Appendix B for the list of collaboration members

Since the top quark discovery at the Fermilab Tevatron more than twenty years ago [1, 2], top quarks have been measured at the LHC in proton-proton (pp) [3–7] as well as proton-nucleus [8] collisions, but so far have not been observed in nucleus-nucleus collisions because of insufficient nucleon-nucleon (NN) center-of-mass energies ($\sqrt{s_{_{\mathrm{NN}}}}$) or integrated luminosities. The multi-TeV energies available at the CERN LHC have opened up the possibility to measure, for the first time, the top quark in lead-lead (PbPb) collisions [9]. More specifically, the top quark constitutes a novel and theoretically precise probe of the nuclear parton distribution functions (nuclear PDFs, or 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) [9, 10]. 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 [10]. The study presented here shows evidence for the production of the top quark in PbPb collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ with an integrated luminosity of $(1.7 \pm 0.1)\,\mathrm{nb}^{-1}$ [11] as recorded by the CMS detector [12].

The top quark—the heaviest elementary particle known—is produced at hadron colliders predominantly in pairs ($\mathrm{t\bar{t}}$) 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 [13]. Once produced, it decays 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. The dilepton final states, in which both W bosons decay into electrons (e) or muons (μ) and the corresponding neutrinos (ν), are the cleanest final states for the $\mathrm{t\bar{t}}$ signal measurement, despite their relatively small branching fraction $\mathcal{B}(\mathrm{t\bar{t}} \to \ell^+\ell^-\,\nu_\ell\bar{\nu}_\ell\,\mathrm{b\bar{b}}) = 5.25\%$ [14], with $\ell^\pm = \mathrm{e}^\pm, \mu^\pm$. See Appendix A for a candidate $\mathrm{t\bar{t}}$ event.

In this letter, the measurement of the $\mathrm{t\bar{t}}$ cross section ($\sigma_{\mathrm{t\bar{t}}}$) in three dilepton final states, i.e., $\mathrm{e^+e^-}$, $\mu^+\mu^-$, and $\mathrm{e}^\pm\mu^\mp$, is performed by (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"). The first method is motivated by the fact that leptons propagate unscathed through the QGP, thereby providing favorable conditions for the detection of $\mathrm{t\bar{t}}$ 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 [15].

The main feature of the CMS detector is a superconducting solenoid, providing a magnetic field of 3.8 T. Within the solenoid volume is a silicon pixel and strip tracker, which is used to detect charged particles, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. Hadron forward calorimeters extend the pseudorapidity coverage up to $|\eta| = 5.2$. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system, the relevant kinematic variables (e.g., the transverse momentum p_{T}), and the physics-object reconstruction, can be found in Ref. [12]. The data sample is collected with a two-level trigger system [16]: at level-1 events are selected by custom hardware processors while the high-level trigger uses fast versions of the offline software. All particle candidates are reconstructed with the particle-flow algorithm [17] using an optimized combination of information from the various elements of the CMS detector.

The data sample is filtered to favor events with two opposite-sign (OS) high-p_{T} leptons, with $p_{\mathrm{T}} > 25$ (20) GeV and $|\eta| < 2.1$ (2.4) for the electron [18] (muon [19]) candidates, that do not belong to jets reconstructed using a distance parameter of 0.4 [20, 21] and are thus isolated from nearby hadronic activity. The correction for the underlying event (UE) formed from soft processes is done on a particle-by-particle basis using an estimation of the median of the energy density ρ [20–22] in the event for the lepton isolation, and the "constituent subtraction" method [23, 24] for the jet constituents. The characteristic additional presence of two b-tagged jets in the $\mathrm{t\bar{t}}$ decay chain is then used, in our second method only, to enhance the sensitivity to the top quark signal. Jets must have $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.0$, and are considered as b tagged if an optimized "combined secondary vertex" (CSV) discriminator [25] produces a value above a certain threshold for the probability of the jet to stem from the hadronization of the b quark. The b tagging efficiency depends on the geometric overlap of the two colliding nuclei as given by the centrality percentile [26]. This percentile is defined from percentages corresponding to fractions of the total inelastic hadronic cross section, e.g., with 0% denoting the full overlap of the two colliding nuclei. After the selection criteria, the b tagging efficiency in a $\mathrm{NN} \to \mathrm{t\bar{t}}$ Monte Carlo (MC) simulation sample, generated at next-to-leading order (NLO) in QCD using the MADGRAPH5_aMC@NLO (v2.4.2) [27] program and interfaced to the "tuned" [28] PYTHIA8 (v2.3.0) [29] MC event generator, 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, $N_{\text{b-tag}}$, and classify the selected events into the "0b" ($N_{\text{b-tag}} = 0$), "1b" ($N_{\text{b-tag}} = 1$), and "2b" ($N_{\text{b-tag}} = 2$) jet categories.

The main background is Drell–Yan quark-antiquark annihilation into lepton-antilepton pairs through Z bosons or virtual photons (a process referred to as "Z/γ^*"). It contaminates all final states with either offshell (in $\mathrm{e^+e^-}$and $\mu^+\mu^-$) or $\mathrm{Z}/\gamma^* \to \tau^+\tau^- \to \mathrm{e}^\pm\mu^\mp + X$ (in $\mathrm{e}^\pm\mu^\mp$) decays, where "X" represents other particles. The Z/γ^* process is modeled at NLO using the MADGRAPH5_aMC@NLO simulation with corrections obtained from data, as detailed below. In the $\mathrm{e}^\pm\mu^\mp$ final state, in particular, there are additional contaminations from W boson production in association with jets ("W+jets"), Z/γ^* with one unreconstructed lepton, and QCD multijet events. In these cases, 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 simulation with POWHEG [30, 31]. In all simulated samples, the EPPS16 NLO nPDF [32], with CT14 NLO free-nucleon PDF [33], the strong coupling constant at the Z boson mass $\alpha_{\mathrm{S}}(m_{\mathrm{Z}}) = 0.118 \pm 0.001$ [14], and the top quark mass $m_{\mathrm{t}} = 172.5\,\mathrm{GeV}$ [34] are used as input. At the step of detector digitization, each hard scattering event is placed at the same primary-vertex [35] location as a heavy ion background event generated with HYDJET (v1.9) [36], to mimic the effects of the 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 [37], and a realistic description of the luminous region produced by the collisions.

The Z/γ^* simulation provides a good modeling 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 $\mathrm{Z}/\gamma^* \to \ell^+\ell^-$ candidates. The scale factors are measured as a function of centrality, but no particular centrality dependence is seen. The difference between the corrected and uncorrected MC distributions is considered as the Z/γ^* p_{T} modeling uncertainty. Events in the $\mathrm{e^+e^-}$ and $\mu^+\mu^-$ final states with dilepton invariant mass $m(\ell^+\ell^-)$ in the proximity of the Z boson mass m_Z [14] ($76 < m(\ell^+\ell^-) < 106\,\mathrm{GeV}$) are rejected, and their number is used to control the normalization of the corrected MC distributions outside the m_Z region. The overall normalization of the nonprompt background is 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 flavor, 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-neighbor algorithm [38]. The variables entering the algorithm are the centrality, ρ, lepton p_T and isolation, and the magnitude of the p_T of the dilepton system ("dilepton p_T"). The highest ranked mixed events, corresponding to the smallest multidimensional distance, 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 [39]) classifier is trained on the simulated $\mathrm{t\bar{t}}$ signal versus the overall $\mathrm{Z}/\gamma^* \to \mathrm{e^+e^-},\mu^+\mu^-$ 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 "ℓ_1" and "ℓ_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, $p_\mathrm{T}(\ell_1)$, (ii) the normalized momentum imbalance between ℓ_1 and ℓ_2, $A_{p_\mathrm{T}} = (p_\mathrm{T}(\ell_1) - p_\mathrm{T}(\ell_2))\ /\ (p_\mathrm{T}(\ell_1) + p_\mathrm{T}(\ell_2))$, (iii) the dilepton p_T, (iv) the absolute pseudorapidity of the dilepton system, (v) the absolute azimuthal separation between ℓ_1 and ℓ_2, and (vi) the sum of the absolute η of ℓ_1 and ℓ_2.

Figure 1 (left) shows the observed BDT discriminator distribution for the dilepton-only method in the higher sensitivity $\mathrm{e}^\pm\mu^\mp$ final state (see Appendix A for the $\mathrm{e^+e^-}$and $\mu^+\mu^-$ final states). The $\mathrm{t\bar{t}}$ signal and various sources of background are also shown, indicated as "prefit expected" as they are not adjusted according to any statistical treatment ("fit"). The Z/γ^*background is normalized to the next-to-next-to-leading order (NNLO) cross section from the FEWZ (v3.1.rc) program [40], and the VV and tW contributions are normalized to the NLO and the approximate NNLO cross sections calculated with MCFM (v8.0) [41] and from Ref. [42], respectively. The classifier separates well the $\mathrm{t\bar{t}}$ signal from the Z/γ^* background in all final states. The $\mathrm{t\bar{t}}$ signal (red histogram) populates the high-BDT discriminator values. The uncertainties in the data are statistical only, while the uncertainties in the backgrounds include a prefit expectation of the systematic uncertainty.

Profile likelihood fits [43, 44] to binned BDT discriminator distributions are performed separately for the dilepton-only and dilepton plus b-tagged jets methods. The best fit values of "signal strength" (μ), their uncertainty $\Delta\mu$ (corresponding to a 68% confidence level), and the significance (in units of standard deviations) of the $\mathrm{t\bar{t}}$ process against the background-only hypothesis, are obtained following the procedure described in Section 3.2 of Ref. [45] and the frequentist paradigm using the profile likelihood ratio as a test statistic [46], accordingly. The value of μ is defined as the ratio of the observed $\sigma_{\mathrm{t\bar{t}}}$ to the expectation from theory, i.e., $\mu = \sigma_{\mathrm{t\bar{t}}}/\sigma^{\mathrm{th}}_{\mathrm{t\bar{t}}}$. The theoretical cross section $\sigma^{\mathrm{th}}_{\mathrm{t\bar{t}}} = \sigma^{\mathrm{NNLO+NNLL}}_{\mathrm{PbPb}\to\mathrm{t\bar{t}}+X} = 3.22\,^{+0.38}_{-0.35}$ (nPDF $\oplus$

PDF) $^{+0.09}_{-0.10}$ (scale) μb, calculated with the Top++ (v2.0) program [47, 48] at NNLO in QCD, including soft-gluon resummation at next-to-next-to-leading logarithmic (NNLL) accuracy, with the nuclear EPPS16 [32] and free-nucleon CT14 [33] PDFs. The same calculation but with the free-nucleon CT14 and NNPDF30 [49] NNLO PDFs (scaled by the square of the number of nucleons in the Pb nucleus, $A^2 = 208^2$) yields $\sigma^{\text{NNLO+NNLL}}_{\text{PbPb}\to\mathrm{t\bar{t}}+X} = 3.04\,^{+0.18}_{-0.14}\,(\text{PDF})\,^{+0.08}_{-0.10}\,(\text{scale})$ and $2.98 \pm 0.14\,(\text{PDF} \oplus \alpha_S(m_Z))\,^{+0.08}_{-0.10}\,(\text{scale})\,\mu$b, respectively. The small difference between the cross sections obtained with nuclear and free-nucleon PDFs arises from the nPDF "antishadowing" effect, which is only mildly dependent on $\sqrt{s_{_{\text{NN}}}}$ [9].

In the dilepton-only method, the extracted values of $\mu = 0.79^{+0.26}_{-0.23}$ (where contributions to $\Delta\mu$ are statistical and systematic in nature) and significance of 3.8 standard deviations constitute the first evidence of $\mathrm{t\bar{t}}$ production in nucleus-nucleus collisions. As can be seen in the prefit distribution of Fig. 1 (left), the data are somewhat below the expectation at the high-BDT discriminator values. This is also reflected in differences in μ and significance, where the expected values are $\mu = 1.00^{+0.25}_{-0.23}$ and 4.8 standard deviations, respectively.

Events in which $N_{\text{b-tag}} \geq 1$ are expected to be very pure in the $\mathrm{t\bar{t}}$ 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 $N_{\text{b-tag}}$. We make use of a jet quenching model [50, 51] that is consistent with the CMS b jet data [15], estimating the expected migration of $\mathrm{t\bar{t}}$ signal events among the 0b-, 1b-, or 2b-tagged jet categories. A combined profile likelihood fit, introducing a parameter ε_{b} that correlates the number of $\mathrm{t\bar{t}}$ signal events in the three b-tagged jet categories based on multinomial probabilities [5], is thus expected to control better the background contamination. We include in the likelihood the effects on ε_{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 $\mu = 0.63^{+0.22}_{-0.20}$ ($1.00^{+0.23}_{-0.21}$) and 4.0 (5.8) standard deviations, respectively. Figure 1 (right) compares the data to the $\mathrm{t\bar{t}}$ signal and various sources of background adjusted according to the fit procedure ("postfit predicted") for the dilepton plus b-tagged jets method in the $\mathrm{e}^{\pm}\mu^{\mp}$ final state (see Appendix A for the $\mathrm{e}^{+}\mathrm{e}^{-}$and $\mu^{+}\mu^{-}$ final states). The BDT distribution for the Z/γ^{*} background is taken from the MC simulation, after scaling the event yield in each $N_{\text{b-tag}}$ bin to the corresponding $N_{\text{b-tag}}$ distribution observed in data within the m_{Z} region.

Sources of experimental uncertainties, incorporated into the likelihoods via "nuisance parameters", include the lepton selection efficiency found using a "tag-and-probe" method [52] (6%), integrated luminosity [11] (5%), and the normalization of the background based on control samples in data (12%). The statistical uncertainties in the $\mathrm{t\bar{t}}$ signal and background distributions (7%) are estimated separately. The dilepton plus b-tagged jets method is, in addition, affected by the uncertainty in ε_{b} (6%), and the jet energy scale and resolution (2%) estimated following the methodology of Ref. [53]. Sources of theoretical uncertainty included in the likelihoods are the nPDF parametrization (derived from the 54+40 eigenvalues of the EPPS16+CT14 sets), the choice of renormalization and factorization scales (within a factor of two from their default values of $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = m_{\mathrm{t}}$), and $\alpha_S(m_{\mathrm{Z}})$ are included (<1%). We also take into account the uncertainties in the p_{T} modeling of the $\mathrm{t\bar{t}}$ signal and Z/γ^{*} background distributions (5%) as well as in the top quark mass (<1%). The precision of the two methods is dominated by the statistical uncertainty (≈28%).

The inclusive $\mathrm{t\bar{t}}$ production cross sections (for the dilepton-only and dilepton plus b-tagged jets methods) are finally obtained in the combined $\mathrm{e}^{+}\mathrm{e}^{-}$, $\mu^{+}\mu^{-}$, and $\mathrm{e}^{\pm}\mu^{\mp}$ final states multiplying the best fit μ values of $0.79^{+0.26}_{-0.23}$ and $0.63^{+0.22}_{-0.20}$ by the theoretical expectation. We measure $\sigma_{\mathrm{t\bar{t}}} =$

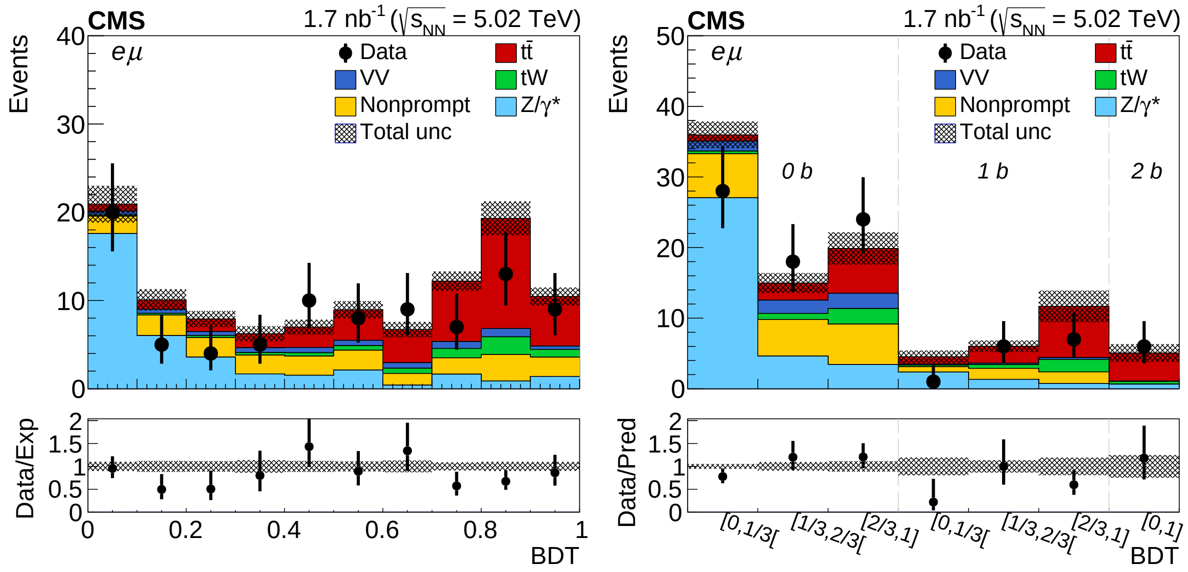

Figure 1: Observed and prefit expected (left) or postfit predicted (right) BDT discriminator distributions in the e$^{\pm}\mu^{\mp}$ final state either inclusively (left) or separately in the 0b-, 1b-, and 2b-tagged jet multiplicity categories (right). The data are shown with markers, and the signal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

$2.54^{+0.84}_{-0.74}$ and $2.03^{+0.71}_{-0.64}\,\mu$b for the two methods, i.e., smaller than, but still consistent with, the theoretical predictions at NNLO+NNLL accuracy in QCD. Despite the expected antishadowing effect, the data appear below the theoretical expectations with or without nPDF effects. Figure 2 presents a summary of the extracted cross sections, including the measurement in pp collisions at $\sqrt{s} = 5.02\,\mathrm{TeV}$ [6] scaled by A^2, compared with the corresponding theoretical predictions.

In summary, evidence for top quark pair ($\mathrm{t\bar{t}}$) production is presented for the first time in nucleus-nucleus collisions, irrespective of any possible final-state interactions of the studied top quark decay products (charged leptons and bottom quarks) with the quark-gluon plasma (QGP). Using lead-lead collisions with a total integrated luminosity of $(1.7 \pm 0.1)\,\mathrm{nb}^{-1}$ at a nucleon-nucleon center-of-mass energy of 5.02 TeV, we measure the inclusive $\mathrm{t\bar{t}}$ cross section ($\sigma_{\mathrm{t\bar{t}}}$) utilizing the leptons only, and in a second method, in addition, the bottom quarks. The extracted $\sigma_{\mathrm{t\bar{t}}} = 2.54^{+0.84}_{-0.74}$ and $2.03^{+0.71}_{-0.64}\,\mu$b in the two methods, respectively, are compatible with, though somewhat lower than, the expectations from scaled proton-proton data and perturbative quantum chromodynamics calculations. This measurement is just the first step in using the top quark as a novel and powerful probe of the QGP.

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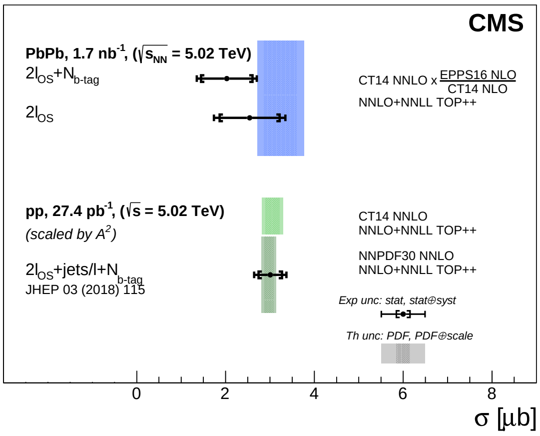

Figure 2: Inclusive $t\bar{t}$ cross sections measured with two methods in the combined e^+e^-, $\mu^+\mu^-$, and $e^\pm\mu^\mp$ final states in PbPb collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$, and pp results at $\sqrt{s} = 5.02\,\text{TeV}$ (scaled by A^2) from Ref. [6]. The measurements are compared with theoretical predictions at NNLO+NNLL accuracy in QCD [47, 48]. The inner (outer) experimental uncertainty bars include statistical (statistical and systematic, added in quadrature) uncertainties. The inner (outer) theoretical uncertainty bands correspond to nuclear [32, 54] or free-nucleon [33, 49] PDF (PDF and scale, added in quadrature) uncertainties.

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A $t\bar{t}$ event display and BDT distributions in the e^+e^- and $\mu^+\mu^-$ final states

Dedicated algorithms deployed in real time allow the CMS detector to collect events with high-p_T leptons, hence making the measurement of $t\bar{t}$ production in PbPb collisions possible in the e^+e^-, $\mu^+\mu^-$, and $e^\pm\mu^\mp$ final states. Figure A.1 displays a candidate $t\bar{t}$ event in the $e^\pm\mu^\mp$ final state in the PbPb data sample.

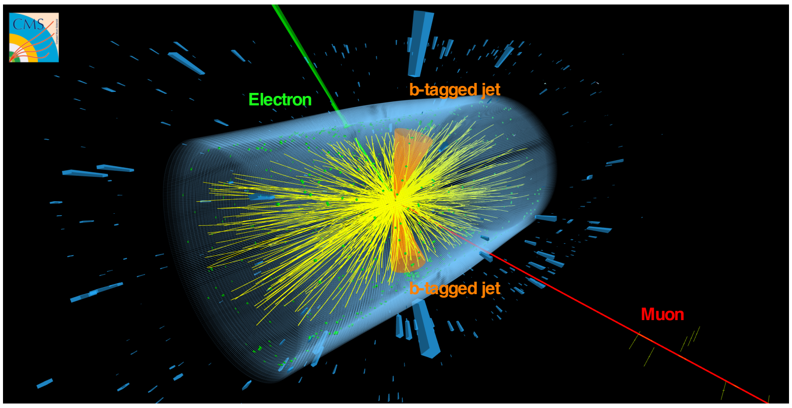

Figure A.1: Event display of a candidate $t\bar{t}$ event measured in PbPb collisions where each top quark decays into a bottom quark and a W boson. The b quarks and W bosons, in turn, produce jets and leptons, respectively. The event is interpreted as originating from the dilepton decay chain $t\bar{t} \to (bW^+)(\bar{b}W^-) \to (b\,e^+\nu_e)(\bar{b}\,\mu^-\bar{\nu}_\mu)$.

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 by 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. Figures A.2 and A.3 show the observed BDT discriminator distributions for the dilepton-only (as prefit expected) and dilepton plus b-tagged jets (as postfit predicted) methods, respectively, in the e^+e^-(left) and $\mu^+\mu^-$ (right) final states.

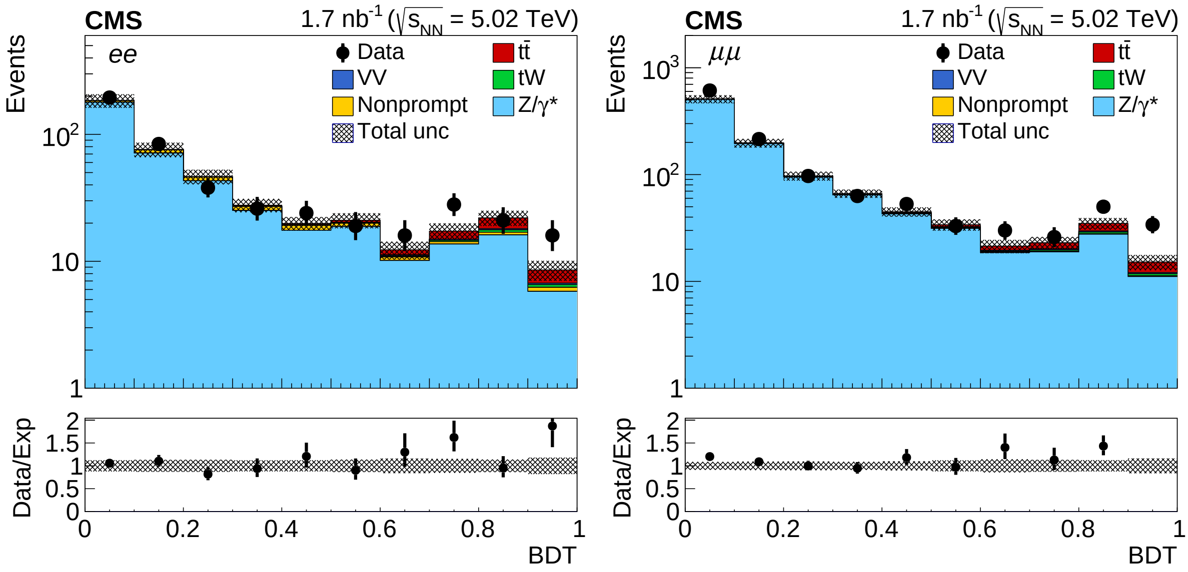

Figure A.2: Observed (markers) and prefit expected (filled histograms) BDT discriminator distributions in the e^+e^- (left) and $\mu^+\mu^-$ (right) final states. The data are shown with markers, and the signal and background processes with filled histograms. The vertical bars on the markers represent 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.

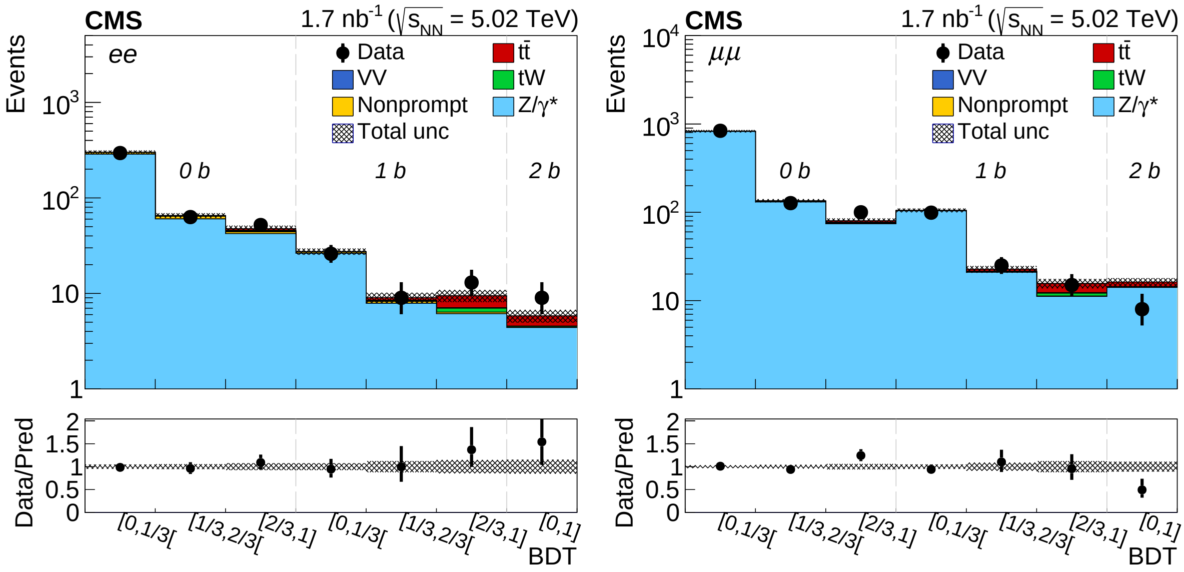

Figure A.3: Observed (markers) and postfit predicted (filled histograms) BDT discriminator distributions in the e^+e^- (left) and $\mu^+\mu^-$ (right) final states separately for the 0b-, 1b-, and 2b-tagged jet multiplicity categories. The data are shown with markers, and the signal and background processes 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 $t\bar{t}$ signal, with bands representing the postfit uncertainties in the predictions.

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60: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
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62: Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey
63: Also at Mersin University, Mersin, Turkey
64: Also at Piri Reis University, Istanbul, Turkey
65: Also at Adiyaman University, Adiyaman, Turkey
66: Also at Ozyegin University, Istanbul, Turkey
67: Also at Izmir Institute of Technology, Izmir, Turkey
68: Also at Necmettin Erbakan University, Konya, Turkey
69: Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
70: Also at Marmara University, Istanbul, Turkey
71: Also at Milli Savunma University, Istanbul, Turkey
72: Also at Kafkas University, Kars, Turkey
73: Also at Istanbul Bilgi University, Istanbul, Turkey
74: Also at Hacettepe University, Ankara, Turkey
75: Also at Vrije Universiteit Brussel, Brussel, Belgium
76: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
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78: Also at Monash University, Faculty of Science, Clayton, Australia
79: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
80: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
81: Also at California Institute of Technology, Pasadena, USA

82: Also at Bingol University, Bingol, Turkey
83: Also at Georgian Technical University, Tbilisi, Georgia
84: Also at Sinop University, Sinop, Turkey
85: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
86: Also at Nanjing Normal University Department of Physics, Nanjing, China
87: Also at Texas A&M University at Qatar, Doha, Qatar
88: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea