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Observation of Top Quark Production in Proton-Nucleus Collisions

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The first observation of top quark production in proton-nucleus collisions is reported using proton-lead data collected by the CMS experiment at the CERN LHC at a nucleon-nucleon center-of-mass energy of \( \sqrt{s_{\text{NN}}} = 8.16 \) TeV. The measurement is performed using events with exactly one isolated electron or muon candidate and at least four jets. The data sample corresponds to an integrated luminosity of 174 nb\(^{-1}\).

The measured cross section is \( \sigma_{\text{t}\bar{t}} = 45 \pm 8 \) nb, consistent with predictions from perturbative quantum chromodynamics.

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The top quark, the heaviest elementary particle in the standard model, has been the subject of numerous detailed studies based on data samples with large integrated luminosities in \( p\bar{p} \) and \( pp \) collisions [1] accumulated at the Fermilab Tevatron and the CERN LHC, respectively. Until recently, top quark studies remained inaccessible in nuclear collisions because of the small integrated luminosities of the first heavy ion runs at the LHC and the low nucleon-nucleon \( (NN) \) center-of-mass energies \( \sqrt{s_{\text{NN}}} \) available at the BNL RHIC. This situation changed when the 2016 LHC proton-lead \( (p\bar{Pb}) \) run at \( \sqrt{s_{\text{NN}}} = 8.16 \) TeV produced a data set corresponding to an integrated luminosity of 174 nb\(^{-1}\) (equivalent to 36 pb\(^{-1}\) of nucleon-nucleon collision data). Top quark cross sections at the LHC are dominated by pair production via gluon-gluon fusion processes \( (gg \rightarrow t\bar{t} + X) \), and are computable with great accuracy in perturbative quantum chromodynamics (QCD) [2,3]. In proton-nucleus collisions, the top quark is a novel and theoretically precise probe of the nuclear gluon density at high virtualities \( Q^2 \approx m_t^2 \) (where \( m_t \) is the top quark mass) in the unexplored high Bjorken-\( x \) region \( x \gtrsim 2m_t/\sqrt{s_{\text{NN}}} \approx 0.05 \) [4,5]. In this region, “antishadowing” and “EMC” effects [6] are expected to modify the gluon density with respect to that in the free-proton case [7,8]. The production of top quarks thus provides information on the nuclear parton distribution functions (nPDF) that is complementary to that obtained through studies of electroweak boson production. In comparison to the \( W \) and \( Z \) cases [9,10], top-pair cross sections are more sensitive to gluon (rather than quark) densities at Bjorken-\( x \) values about twice as large. Novel studies of parton energy loss using top quarks in the quark-gluon plasma formed in nucleus-nucleus collisions have also been proposed [4,11]. A good understanding of top quark production in proton-nucleus collisions is crucial as a baseline for these studies.

Once produced, the top quark decays promptly without hadronizing (lifetime \( \tau_t \approx 0.15 \) fm) into a \( W \) boson plus a bottom quark, and top quark pair events are commonly categorized according to the subsequent decay of the two \( W \) bosons. When one \( W \) boson decays leptonically \( (\ell v, \ell = e, \mu) \) and the other hadronically \( (q\bar{q}') \), the \( \ell + j \) final state presents a typical signature of one isolated charged lepton and momentum imbalance from the unobserved neutrino in one \( W \) decay, two light quark jets from the other \( W \) decay, and two \( b \) jets from the two original top quark decays. Such a final state features a large branching fraction \( (\approx 30\% \) for the \( e + \) jets and \( \mu + \) jets channels combined, and \( \approx 34\% \) adding also events from the \( t \rightarrow W \rightarrow \tau \rightarrow e, \mu \) decay chain) and moderate background contamination, and thereby provides favorable conditions for the detection of \( t\bar{t} \) production in proton-nucleus collisions.

This Letter describes the first observation of top quark production in nuclear collisions. The analysis is carried out with \( p\bar{Pb} \) collisions collected by the CMS experiment at the LHC at \( \sqrt{s_{\text{NN}}} = 8.16 \) TeV, using \( t\bar{t} \) candidates with the event topology described above. The \( t\bar{t} \) cross section is extracted from a combined maximum-likelihood fit of the invariant mass of the two light-quark jets from the \( W \)-boson decay, in different categories of events with zero, one, or at least two \( b \)-tagged jets.

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two end cap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and end cap detectors. Muons are detected in gas-ionization chambers.
Particle candidates are reconstructed off-line with the CMS particle-flow (PF) algorithm [19], which identifies and provides a list of particles using an optimized combination of information from the various elements of the CMS detector. Events are required to contain exactly one muon [20] or electron [21] candidate, with \( p_T > 30 \text{ GeV} \) and \( |\eta| < 2.1 \), excluding in the electron case the transition region \( 1.444 < |\eta| < 1.566 \) between the ECAL barrel and end cap, where the reconstruction of electron objects is less efficient. The muon and electron candidates are required to be isolated from nearby hadronic activity within a cone of \( \Delta R = 0.3 \) around the direction of the track at the primary event vertex.

The cone is defined as \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \), and \( \Delta \eta \) and \( \Delta \phi \) are the separations in pseudorapidity and azimuthal angle. The scalar \( p_T \) sum of all PF candidates consistent with arising from the primary event vertex and contained within the cone of radius \( \Delta R \), excluding the contribution from the lepton candidate, is used to define a relative isolation variable, \( I_{\text{rel}} \), through the ratio of this sum to the \( p_T \) of the lepton candidate. A charged lepton is selected if its relative isolation discriminant value satisfies \( I_{\text{rel}} < 0.15 \) (muon), 0.07 (electron in the barrel), or 0.08 (electron in one of the end caps). These thresholds have been optimized to reduce the contamination from nonprompt leptons. To remove the Drell-Yan background, events are rejected from the analysis if they contain extra electrons (muons) that are reconstructed using a looser set of identification criteria and have \( p_T > 20(15) \text{ GeV} \) within \( |\eta| < 2.5(2.4) \). The efficiency of the lepton selection is measured using a “tag-and-probe” method [22] in events enriched with \( Z \)-boson candidates and selected by the same trigger requirements as the signal candidate events. The combined reconstruction, lepton identification, and trigger efficiency is determined as a function of lepton \( p_T \) and \( \eta \).

Events are required to have at least four reconstructed jets with \( p_T > 25 \text{ GeV} \) and \( |\eta| < 2.5 \), that are separated by at least \( \Delta R = 0.3 \) from the selected muon or electron. Jets are reconstructed from the PF candidates using the anti-\( k_T \) clustering algorithm [23] with a distance parameter of 0.4. Jet energy corrections extracted from the full detector simulation are applied as functions of jet \( p_T \) and \( \eta \) [24,25] to both data and simulated samples. A residual correction to the data is applied to account for a small data-MC discrepancy in the jet energy response. Jets from \( b \) quarks are tagged based on the presence of a secondary vertex from \( B \)-hadron decays, identified using a multivariate algorithm combining tracking information [26]. The distinct \( \pi^0 \) signature of two \( b \) jets in the event, which rarely occurs in background processes such as \( W + \) jets and QCD multijet (collectively labeled as “nontop” background), is used to extract the signal. The number of jets passing a threshold on the \( b \)-jet identification discriminant, corresponding to a \( b \)-tagging efficiency of approximately 70% with a misidentification rate of less than 0.1% for light-flavor jets, as estimated in simulated \( p\Pb \) events, is used to
classify the selected events into no (0 b), exactly one (1 b), or at least two (2 b) tagged-jet categories. All three event categories are exploited in a maximum-likelihood fit in order to extract the signal cross section, and simultaneously constrain the background contamination and determine the efficiency of the b-jet identification.

In the ℓ + jets final state, two light-flavor jets (jj') are produced in the decay of one of the W bosons, and the resonant nature of their invariant mass provides a distinctive feature of the tt signal with respect to the main backgrounds. Given that these light-flavor jets are correlated at production, they are also closer in phase space relative to other dijet combinations in the event. In cases where more than two non-b-tagged jets are found, the jj' pair with smallest separation in the η-φ plane is used to form a W-boson candidate. The invariant mass of those two jets, m_{jj'}, is used as input for the maximum-likelihood fit.

The parametrization of the signal in the fit model is derived from the MC simulation, while that of the backgrounds is obtained from control regions in the data. In the MC simulation, pairs of jets that are geometrically grounds is obtained from control regions in the data. In derived from the MC simulation, while that of the back-
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The background from QCD multijet events due to mis-agreement observed between the MC simulation and a criteria is modeled with the help of dedicated background backgrounds. The free parameters of the fit are the normalization of the signal, QCD multijet, and transverse momentum (defined as the negative of the vectorial p_T sum of all identified particles) smaller than 20 GeV in magnitude. The initial normalization of the QCD multijet backgrounds in the other b-jet multiplicity categories is also determined from events with missing transverse momentum smaller than 20 GeV.

The number of events in each b-jet category is obtained by fitting the sum of the contributions for signal and backgrounds. The free parameters of the fit are the normalization of the signal, QCD multijet, and W + jets yields (as well as the parameters of their functional forms described above), the b-finding efficiency, i.e., the probability that a jet originating from the b quark from a top quark decay passes both the kinematic and the b-tagging selections, and an overall jet energy scale factor. Figure 1 shows the m_{jj'} distribution for events with zero, one, or at least two b-tagged jets, compared with the fit results.

To further examine the hypothesis that the selected data are consistent with the production of top quarks, we define a proxy of the top quark mass, m_{top}, as the invariant mass of a t → jj'b candidate formed by pairing the W candidate with a b-tagged jet. This pairing is chosen to minimize the absolute difference between the invariant masses of the t → jj'b and the t → ℓνb candidates. In the 0 b and 1 b categories, the jet(s) with the highest value(s) of the b-quark identification discriminator are considered for this purpose. Figure 2 shows the distribution of m_{top} reconstructed for events in the 0, 1, and 2 b-tagged jet categories, with all signal and background parameters kept fixed to those from the outcome of the m_{jj'} fit.

The total number of tt signal events obtained through the fit of the μ + jets and e + jets channels combined is 710. Sources of experimental uncertainty in the measurement include the uncertainty in the b-tagging efficiency, which is
measured \textit{in situ} and bears the largest effect of ±13% on the \( t\bar{t} \) cross section; and the jet energy scale [24], which takes into account a 3%-level difference between the reconstructed and generated jet energy in MC events and a 3% residual calibration uncertainty from data, that together propagate as an additional ±4% uncertainty in the final cross section. Background shape and normalization uncertainties are also determined in the fit procedure and have a ±7% effect on the extracted cross section. Uncertainties in the lepton trigger and reconstruction efficiencies, estimated with the tag-and-probe method, result in a ±4% effect on the measured cross section. The integrated luminosity calibration for \( p\Pb \) data taking conditions results in a ±5% uncertainty. The jet energy resolution [24], as estimated in proton-proton collision data, and the 0.1% uncertainty of the LHC beam energy [30], have a numerically insignificant effect on this measurement.

The compatibility of the data with a background-only hypothesis has been evaluated using a profile-likelihood ratio as a test statistic [31], including all systematic uncertainties as nuisance parameters with Gaussian priors. Several tests have been performed, varying the estimation method and the background modeling assumptions. Even with the most conservative assumptions, the background-only hypothesis is excluded with a significance above 5 standard deviations. The \( t\bar{t} \) production cross section is then obtained via

\[
\sigma_{\tilde{t}\bar{t}} = \frac{S}{A\varepsilon L},
\]

where \( S \) is the number of fitted signal events; \( A = 0.060 \pm 0.002 \) and \( 0.056 \pm 0.002 \) are the total acceptances in the \( \mu + \text{jets} \) and \( e + \text{jets} \) channels relative to all generated \( t\bar{t} \) events, including the branching fraction to leptons, as determined from simulation; \( \varepsilon = 0.91 \pm 0.04 \) and \( 0.63 \pm 0.03 \) are the \( \mu + \text{jets} \) and \( e + \text{jets} \) event selection efficiencies as estimated from data; and \( L \) is the total integrated luminosity. The 4% uncertainty in the acceptance correction \( A \), including its dependence on the proton and Pb PDFs, and on the values of theoretical scales and the QCD coupling (\( \alpha_s = 0.118 \pm 0.001 \) at the \( Z \)-boson mass), has been determined from a NLO \( p\Pb \to t\bar{t} + X \) sample generated with \textsc{powheg} (v.2) [32–34]. The total uncertainty on \( S \) is obtained from the covariance matrix of the fit. It is further split into a statistical part, by leaving \( \sigma_{\tilde{t}\bar{t}} \) to float in the fit and fixing all other parameters to their post-fit values, and a systematic part, by subtracting the square of the statistical uncertainty from the square of the total uncertainty. From Eq. (1), we measure

\[
\sigma_{\tilde{t}\bar{t}}^{\mu+\text{jets}} = 44 \pm 3(\text{stat}) \pm 8(\text{syst}) \text{ nb},
\]

\[
\sigma_{\tilde{t}\bar{t}}^{e+\text{jets}} = 56 \pm 4(\text{stat}) \pm 13(\text{syst}) \text{ nb},
\]

in the individual \( \mu + \text{jets} (S = 420) \) and \( e + \text{jets} (S = 348) \) channels, with relative total uncertainties of 18% and 23%, respectively. The combined fit to both channels yields

\[
\sigma_{\tilde{t}\bar{t}} = 45 \pm 8(\text{total}) \text{ nb}.
\]

The measured cross section is found to be consistent with the theoretical prediction [5] \( \sigma(p\Pb \to t\bar{t} + X) = 59.0 \pm 5.3(\text{PDF})^{+1.6}_{-2.1}(\text{scale}) \text{ nb} \), computed with \textsc{mcfm} (v.8) [35] using the CT14 proton PDF [36] and the EPPS16 nPDF for the lead ions [8], scaled to NNLO + NNLL accuracy with a \( K \) factor computed with \textsc{top++} (v.2.0) [2], and multiplied by \( A = 208 \). The PDF uncertainties are obtained from the corresponding 56 + 40 eigenvalues of the CT14 + EPPS16 sets (corresponding to a 90% confidence level) added in quadrature, while the theoretical scale uncertainty is estimated by modifying the factorization and renormalization scales within a factor of 2 with respect to their default value set at \( \mu_F = \mu_R = m_t \). The same calculation with the CT10 proton PDF [37] and EPS09 [7] nPDF yields \( \sigma(p\Pb \to t\bar{t} + X) = 57.5 \pm 4.3(\text{PDF})^{+1.5}_{-2.0}(\text{scale}) \text{ nb} \). The difference in the theoretical \( t\bar{t} \) cross section computed with the PDF for free protons and for bound nucleons is small. A net overall antishadowing effect increases the total top-quark pair cross section by only 4% for both the EPPS16 and EPS09 sets in \( p\Pb \) relative to \( pp \) collisions [5].
difference is too small to be observed in the data with the current experimental uncertainties. Figure 3 shows the measured and theoretical cross sections for $t\bar{t}$ production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV, compared with the results from $pp$ collisions at $\sqrt{s} = 8$ TeV [38,39] scaled by $A$ and by the ratio of 8.16 TeV over 8 TeV NNLO + NNLL cross sections.

In summary, the top pair production cross section has been measured for the first time in proton-nucleus collisions, using pPb data at $\sqrt{s_{NN}} = 8.16$ TeV with a total integrated luminosity of 174 nb$^{-1}$. The measurement is performed by analyzing events with exactly one isolated electron or muon and at least four jets. The significance of the $t\bar{t}$ signal against the background-only hypothesis is above 5 standard deviations. The measured cross section is $\sigma_{t\bar{t}} = 45 \pm 8$ nb, consistent with the expectations from scaled $pp$ data as well as perturbative quantum chromodynamics calculations. This first measurement paves the way for further detailed investigations of top-quark production in proton-nucleus and nucleus-nucleus collisions at LHC energies and beyond, Phys. Lett. B 746, 64 (2015).

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