

Study of Nuclear Effects on Charm Production in Light-Ion Collisions

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The onset of nuclear effects in light-ion collisions is studied by measuring the ratio of D^0 meson production between NeNe and OO collisions at a center-of-mass energy per nucleon pair of 5.36 TeV recorded by the LHCb detector. The D^0 meson yields are measured differentially in transverse momentum (p_T) for $0.5 < p_T < 20$ GeV in the rapidity (y) region $2.0 < y < 4.5$, and are normalized to the total number of recorded inelastic nucleus-nucleus collisions in each data sample. The resulting production ratio shows evidence of variation as a function of p_T , which is inconsistent with predictions based on nuclear modification of nucleon structure alone. This measurement is consistent with the onset of quark-gluon plasma production with increasing nucleus size in high-energy nuclear collisions.

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The hot medium of deconfined quarks and gluons known as quark-gluon plasma (QGP) was first conclusively observed in high-energy collisions of heavy nuclei more than 20 years ago at the Relativistic Heavy Ion Collider (RHIC) [1–5]. Since the initial discovery of QGP in heavy-ion collisions, QGP-like signatures such as hydrodynamic flow, enhanced production of strange hadrons, and suppression of charmonium have been observed in small collision systems such as proton-proton and proton-nucleus collisions at the Large Hadron Collider (LHC) and proton-nucleus collisions at RHIC [6–17]. Evidence for parton energy loss in small collision systems, however, is notably absent [18–20]. Explaining the unexpected observation of QGP-like signatures in small collision systems has presented a major theoretical challenge, and the origins of these effects cannot be conclusively understood with current results.

Heavy-quark production is sensitive to a wide range of QGP properties [21]. Because of their large masses, bottom and charm quarks are produced in heavy-ion collisions via high-energy parton-parton interactions at early times before the formation of the QGP. The heavy quarks subsequently interact with the medium throughout its evolution, losing energy through radiation and elastic collisions with QGP constituents. Energy-loss effects are sensitive to both the microscopic interactions between the heavy quark and the QGP constituents and the path traveled by the heavy quark through the QGP. Consequently, studies of heavy-flavor

hadron production in nuclear collisions provide information about the universal transport properties of QGP and the size of the plasma produced [22]. Heavy-quark production in heavy-ion collisions has been studied extensively at both RHIC and LHC experiments [23–25].

In 2025, the LHC produced ^{16}O (OO) collisions and ^{20}Ne (NeNe) collisions for the first time at a center-of-mass energy per nucleon pair ($\sqrt{s_{\text{NN}}}$) of 5.36 TeV. The ATLAS, ALICE, and CMS collaborations have used these collisions to study the structure of ^{16}O and ^{20}Ne nuclei using anisotropic flow [26–28]. These light-ion collisions can also potentially create a volume of QGP large enough to produce observable parton energy loss [29,30]. Evidence for parton energy loss in OO collisions was recently observed by the CMS Collaboration [31]. Collisions of neon nuclei are expected to produce a slightly larger volume of QGP than those of oxygen nuclei, resulting in larger energy loss effects. The relative magnitude of energy loss in NeNe and OO collisions is sensitive to the transport properties of the QGP and the rate of onset of QGP production with increasing system size.

This Letter presents a measurement of the ratio of D^0 meson production rates in NeNe to OO collisions at $\sqrt{s_{\text{NN}}} = 5.36$ TeV with the LHCb detector (charge conjugate hadrons are included implicitly throughout this Letter). The production ratio is defined as

$$\mathcal{R}_{\text{NeNe/OO}}^{D^0} \equiv \frac{dN_{D^0}^{\text{NeNe}}/dp_T}{dN_{D^0}^{\text{OO}}/dp_T} \frac{N_{\text{inel}}^{\text{OO}}}{N_{\text{inel}}^{\text{NeNe}}}, \quad (1)$$

where $dN_{D^0}^{\text{AA}}/dp_T$ is the differential D^0 yield in AA collisions as a function of transverse momentum (p_T), $N_{\text{inel}}^{\text{AA}}$ is the number of inelastic collisions in the AA sample, and A denotes the colliding nuclei. The yields of D^0 mesons, reconstructed in the $D^0 \rightarrow K^-\pi^+$ decay, are

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measured differentially in p_T for $0.5 < p_T < 20$ GeV (natural units are used throughout this Letter) in the rapidity range $2.0 < y < 4.5$. The OO and NeNe datasets were collected in 2025 and correspond to integrated luminosities of 5.5 and 0.51 nb⁻¹, respectively.

The LHCb Run 3 detector [32] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. It was installed during LHC long-shutdown 2 to allow effective operation at about 5 times the luminosity with respect to the Run 1–2 detector [32,33]. The LHCb Run 3 detector keeps the general organization of subsystems of the original LHCb detector [32,33], though most subsystems were upgraded. The high-precision tracking system consists of a silicon-pixel vertex detector (VELO) surrounding the interaction region, a large-area silicon-strip detector located upstream of a dipole magnet, and three stations of scintillating-fiber detectors located downstream of the magnet [34]. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov (RICH) detectors [35].

Simulated samples are used to model the detector response to D^0 decays. In the simulation, D^0 mesons are generated using Pythia [36] with a specific LHCb configuration [37] and embedded into OO and NeNe events generated using EPOS-LHC [38]. Decays of unstable particles are described by EvtGen [39], and final-state radiation is generated using Photos [40]. The interaction of the generated particles with the detector, and its response, are implemented using the Geant4 toolkit [41,42] as described in Ref. [43].

The ratio $\mathcal{R}_{\text{NeNe/OO}}^{D^0}$ can be expressed in terms of experimental quantities,

$$\mathcal{R}_{\text{NeNe/OO}}^{D^0} = \frac{Y_{D^0}^{\text{NeNe}}}{Y_{D^0}^{\text{OO}}} \times \frac{\epsilon_{\text{OO}}}{\epsilon_{\text{NeNe}}} \times \frac{N_{\text{inel}}^{\text{OO}}}{N_{\text{inel}}^{\text{NeNe}}}, \quad (2)$$

where $Y_{D^0}^{\text{AA}}$ and ϵ_{AA} are the D^0 yields and detection efficiencies in each p_T region, respectively. All NeNe and OO collision events must have at least one reconstructed track in the VELO. Candidate D^0 mesons are reconstructed using the decay $D^0 \rightarrow K^- \pi^+$. The K^- and π^+ candidates consist of good-quality tracks that are inconsistent with originating from the collision vertex. They must have $p_T > 400$ MeV, $p > 5$ GeV, and $2 < \eta < 5$, and they must be identified as kaons and pions, respectively, using information from the RICH system. The final-state tracks must form a good-quality D^0 decay vertex, and the D^0 candidate's momentum must point from the collision vertex to the decay vertex.

The selected D^0 samples include prompt D^0 signal produced directly from the collision, nonprompt D^0 mesons produced in b -hadron decays, and combinatorial background. The combinatorial background contribution is

determined using a binned maximum-likelihood fit to the D^0 candidate mass distribution $m(K^- \pi^+)$ [44]. The D^0 signal is modeled using the sum of two Gaussian functions with a common mean, and the combinatorial background is modeled using a linear function. The prompt D^0 signal yield is then determined using a fit to the D^0 candidate $\ln \chi_{\text{IP}}^2$ distribution, where χ_{IP}^2 is defined as the difference in χ^2 of the collision vertex fit performed with and without the D^0 candidate. Since D^0 mesons from b -hadron decays do not originate from the collision vertex, they have larger average χ_{IP}^2 values than prompt D^0 mesons. The $\ln \chi_{\text{IP}}^2$ fit is performed for candidates in the signal mass region, defined as a ± 25 MeV window around the known D^0 mass [45]. The combinatorial background yield in the signal region is fixed using the results of the $m(K^- \pi^+)$ fit. Candidates outside the signal region are used to construct a combinatorial background template. The prompt and nonprompt D^0 contributions are modeled using bifurcated Gaussian functions, and the prompt model includes exponential tails as described in Ref. [46]. The prompt and nonprompt model parameters are constrained using fits to simulated prompt D^0 mesons and D^0 mesons from semi-leptonic b -hadron decays, respectively. The $m(K^- \pi^+)$ and $\ln \chi_{\text{IP}}^2$ fitting procedure is repeated in each p_T region. The sums of the fits over all p_T regions are shown in Fig. 1. Additional fit examples are shown in Supplemental Material [47].

The D^0 detection efficiency in Eq. (2) includes contributions from reconstruction, charged-particle identification (PID), and selection efficiencies. These efficiencies are similar in OO and NeNe collisions, but the difference in charged-particle multiplicities between the two systems leads to small differences, which are measured in data. Because of the high granularity of the VELO detector, the VELO track reconstruction efficiency does not vary significantly within the charged-particle multiplicities produced in OO and NeNe collisions. As a result, only the efficiency of reconstructing a charged particle traversing the full detector, given a reconstructed VELO track segment, is corrected. The charged-particle reconstruction efficiency is measured using $K_S^0 \rightarrow \pi^+ \pi^-$ decays. The K_S^0 travels a resolvable distance before decaying, creating a displaced decay vertex. Constraints from the collision and decay vertex positions allow for the determination of the final-state track momenta without fully reconstructing both tracks. One of the final-state pions is reconstructed as a track with signals in both the VELO and scintillating-fiber detectors (long track). Because this track includes signals both upstream and downstream of the dipole magnet, its momentum is measured precisely. The other “probe” pion is reconstructed using only signals from the VELO. The probe pion momentum is calculated by requiring that the total K_S^0 momentum points along its reconstructed flight direction. The flight direction is defined by the vector

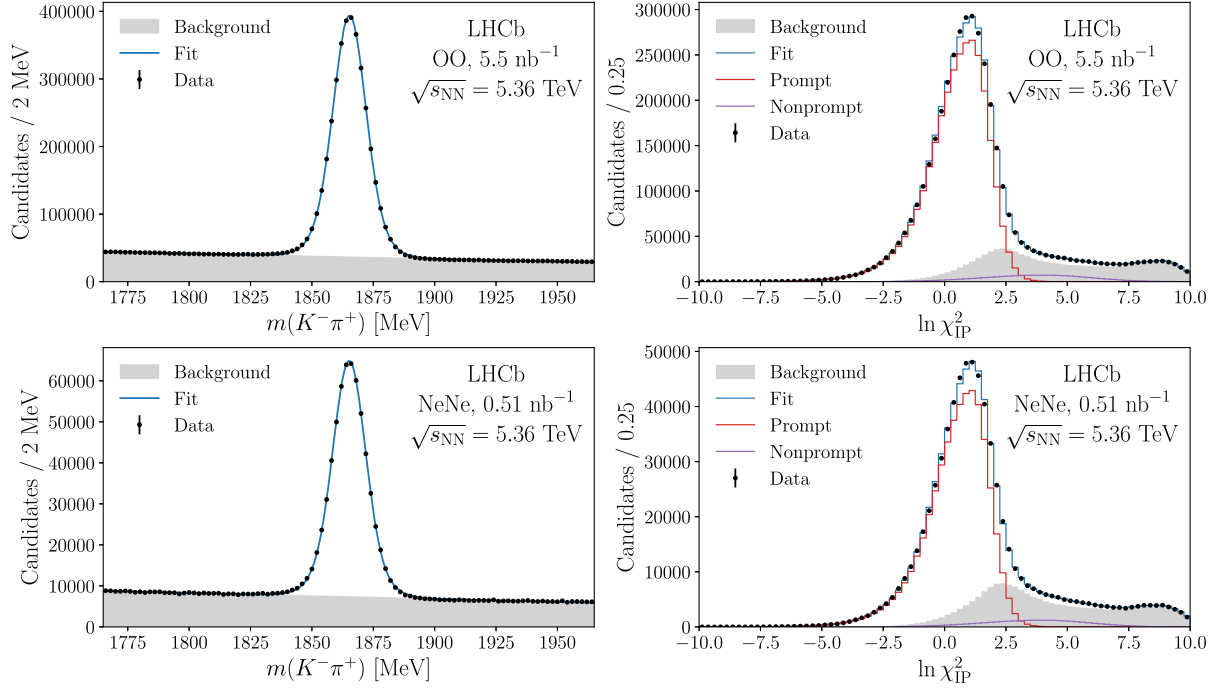


FIG. 1. Distributions for reconstructed and selected $D^0 \rightarrow K^- \pi^+$ candidates. Left: $K^- \pi^+$ mass distributions. Right: $\ln \chi_{\text{IP}}^2$ distributions in the $m(K^- \pi^+)$ signal window for (top) OO and (bottom) NeNe collisions. The sum of the fits in each p_T interval are also shown.

pointing from the collision vertex to the K_S^0 decay vertex. The track reconstruction efficiency is then the fraction of reconstructed K_S^0 mesons with probe tracks that have a corresponding reconstructed long track. This efficiency is measured as a function of charged-particle kinematics and the total number of activated VELO pixel clusters in the collision event (N_{VP}).

The PID efficiency is measured using the $D^0 \rightarrow K^- \pi^+$ decay products in $D^{*+} \rightarrow D^0 \pi^+$ decays. This decay mode provides a sample of identified kaons and pions without utilizing PID criteria. The reconstructed D^0 -meson candidate and its decay products must satisfy the same kinematic and reconstruction quality requirements as those used for determining the total D^0 yields, but no PID criteria are required. The accompanying pion is required to have $p > 1$ GeV, $p_T > 200$ MeV, $2 < \eta < 5$, and must be consistent with originating from the collision vertex. The PID efficiency is measured separately for kaons and pions and corresponds to the fraction of candidates for which the relevant hadron is correctly identified. This efficiency is also measured as a function of the hadron kinematics and N_{VP} .

The charged-particle reconstruction and identification efficiencies are used to estimate the total D^0 reconstruction and PID efficiencies. The D^0 efficiency is calculated by convolving the measured reconstruction and PID efficiency maps with the kinematic and multiplicity distributions from simulated D^0 decays. In order to accurately describe the OO and NeNe event multiplicities, the N_{VP} distributions in the simulated samples are corrected to match those in data.

The combined reconstruction and PID efficiency ratio varies between about 1.03 and 1.04 in all p_T intervals, except for the highest- p_T interval where the correction is 1.07 ± 0.03 .

Because quantities related to track and decay vertex quality do not depend on multiplicity, the efficiency of requirements based on these quantities will cancel in $\mathcal{R}_{\text{NeNe/OO}}^{D^0}$. However, due to their higher multiplicities NeNe collision vertices are reconstructed with better resolution than OO collision vertices, leading to better IP resolution for D^0 decay products. Given that χ_{IP}^2 is inversely proportional to the square of the IP resolution, this difference results in different efficiencies of the track χ_{IP}^2 requirement in the two samples. The magnitude of this effect is estimated by measuring the impact parameter (IP) resolution for charged particles in NeNe and OO collisions using $J/\psi \rightarrow \mu^+ \mu^-$ decays. The IP resolutions in NeNe and OO collisions are found to be compatible within an uncertainty of about 0.8%, and the resulting $\mathcal{R}_{\text{NeNe/OO}}^{D^0}$ uncertainty ranges between 0.4% and 1.0%. The difference in collision vertex reconstruction performance also affects the efficiency of the D^0 momentum pointing requirement. This efficiency difference is estimated by measuring the D^0 yield with and without the pointing requirement. The measured efficiency difference has a maximum of about 0.8% in the lowest p_T interval and is less than 0.5% in most other intervals.

The uncertainties are summarized in Table I and fall into three categories: uncorrelated between p_T intervals

TABLE I. Relative sources of uncertainties in percent. The ranges correspond to the minimum and maximum values of the associated uncertainties across all p_T intervals.

Source	Uncertainty [%]
Uncorrelated	
Statistical uncertainty	0.5–5.7
Simulation sample size	0.3–5.2
Pointing efficiency	0.2–0.8
Correlated	
Fit model	0.1–0.5
Rec. and PID efficiency	0.2–1.7
IP resolution	0.4–1.0
Global	
Normalization	4.1

(uncorrelated), correlated and p_T -dependent (correlated), and correlated and constant in p_T (global). The largest uncertainty in most p_T intervals is a global systematic uncertainty from the determination of $N_{\text{inel}}^{\text{OO}}/N_{\text{inel}}^{\text{NeNe}}$. The N_{inel} ratio is estimated using the ratio of visible collisions in the OO and NeNe samples. The uncertainty is estimated by varying the criteria used to define a visible collision. This uncertainty accounts for possible differences in the probabilities of inelastic NeNe and OO collisions producing visible activity in the detector. The baseline definition requires a reconstructed collision vertex in the interaction region, while the alternative requires two VELO tracks. The relative difference in $N_{\text{inel}}^{\text{OO}}/N_{\text{inel}}^{\text{NeNe}}$ between these two definitions is 4.1%.

Uncorrelated uncertainties arise from the finite size of the experimental and simulated datasets, as well as the statistical uncertainty associated with the efficiency of the D^0 pointing requirement. The largest correlated uncertainty in most p_T intervals arises from the uncertainty in the IP resolution difference between NeNe and OO collisions. This effect is estimated by scaling the minimum χ_{IP}^2 requirement in one sample at a time. The scaling factor is given by the square of the measured IP resolution ratio. This ratio is varied by its uncertainty, and the deviation from the baseline result is taken as a systematic uncertainty. An additional correlated systematic uncertainty arises from the choice of fit model for prompt D^0 yield determination. The measurement is repeated using alternative fit models, and the largest absolute deviation from the baseline in each p_T interval is taken as the systematic uncertainty, which is fully correlated across p_T intervals.

Correlated uncertainties also arise from the limited sample sizes of the tracking and PID efficiency calibration samples. These are estimated by repeating the measurement using bootstrapped calibration samples and taking the standard deviation of the resulting variations as the systematic uncertainty. The PID efficiency is also affected by

the choice of kinematic intervals used for the calibration, as the PID efficiency varies rapidly at low momentum near the threshold for producing Cherenkov radiation in the RICH detector. The measurement is repeated with finer momentum intervals, and the difference between this and the baseline measurement is taken as a systematic uncertainty. Kinematic differences between data and simulation can also result in an incorrect efficiency determination. This effect is studied by calculating the efficiency using the kinematic and N_{VP} distributions of reconstructed D^0 candidates in data. The difference between this and the baseline result is taken as a systematic uncertainty. This uncertainty is subdominant everywhere except the two lowest p_T intervals, where it is the largest correlated systematic uncertainty. All reconstruction and PID efficiency uncertainties are combined in Table I. A covariance matrix is calculated for each uncertainty source, and the total covariance matrix is the sum of these contributions.

The fully corrected $\mathcal{R}_{\text{NeNe/OO}}^{D^0}$ ratio is shown in Fig. 2. The significance of the deviation from the constant null hypothesis is determined using Wilks's theorem [48]. Using a linear model, the data prefer a nonzero slope with a significance of 4.3σ . The data are compared to a next-to-leading order perturbative QCD calculation of the D^0 cross section ratio using the EPPS21 nuclear parton distribution function (nPDF) set [49,50]. This calculation is scaled by the ratio of the average number of binary nucleon-nucleon collisions in a single nuclear collision ($\langle N_{\text{coll}}^{\text{OO}} \rangle / \langle N_{\text{coll}}^{\text{NeNe}} \rangle$) [51]. The perturbative QCD calculation accounts for differences in the partonic structure between nucleons in neon and oxygen nuclei. This calculation does not describe the shape of the measured ratio, indicating the presence of nuclear effects beyond the modification of nuclear parton densities. The data are also compared to calculations that include cold nuclear matter effects, such as parton distribution modification, as well as radiative and collisional energy loss in the QGP [52]. Only the calculation including both collisional and radiative energy loss in the QGP accurately reproduces the p_T dependence of the measured ratio. Consequently, these data suggest the presence of QGP-like effects in charm production in NeNe collisions. These QGP-like effects are stronger in NeNe collisions than in OO collisions, consistent with a gradual increase in QGP production with increasing collision size.

In conclusion, the D^0 -meson production ratio $\mathcal{R}_{\text{NeNe/OO}}^{D^0}$ is measured at forward rapidity. This is the first study of charm production in light-ion collisions at the LHC. The large light-ion datasets collected in 2025 and the excellent performance of the LHCb detector allow for precise measurements of this ratio over a wide kinematic range. The resulting measurement shows evidence for the gradual increase of QGP-like effects with collision size in light-ion collisions. Furthermore, the high precision of this measurement can provide constraints on heavy quark diffusion and energy loss in the produced medium.

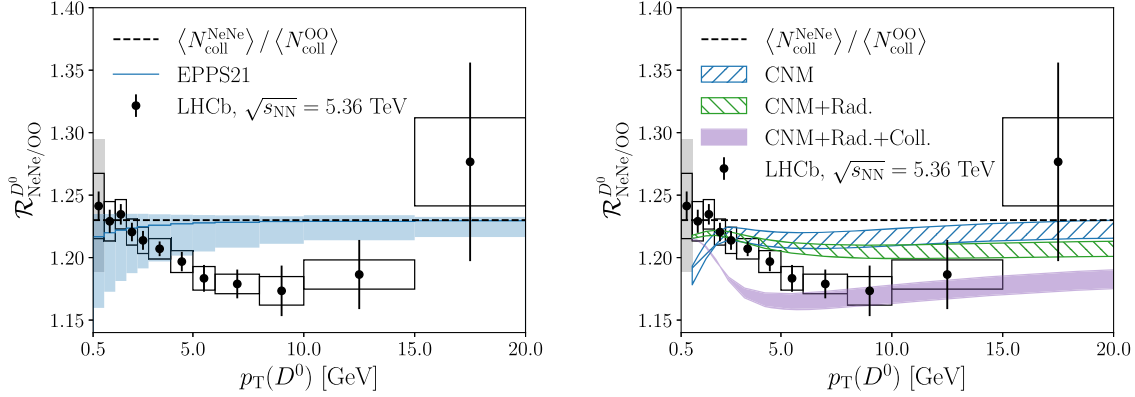


FIG. 2. Production ratio $\mathcal{R}_{\text{NeNe/OO}}^{D^0}$ in regions of D^0 transverse momentum. Uncorrelated uncertainties are shown as vertical bars, and correlated uncertainties are shown as boxes. The horizontal widths of the boxes correspond to the p_T interval. The global normalization uncertainty is shown as a gray band centered on the lowest p_T data point. The left panel shows a calculation using the EPPS21 nPDF set. The blue band shows the nPDF uncertainties for a 68% confidence interval. This calculation is scaled by the ratio of the average number of binary nucleon-nucleon collisions per nuclear collision, which is shown as a black dashed line [51]. No uncertainty from this scaling factor is shown, although this normalization uncertainty is expected to be large relative to both the measurement and nPDF uncertainties. The right panel shows calculations that include cold nuclear matter (CNM) effects, as well as radiative (Rad.) and collisional (Coll.) energy loss in the QGP [52].

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Data availability—There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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