# Centrality-Dependent Modification of Jet-Production Rates in Deuteron-Gold Collisions at sqrt[s_{NN}]=200 GeV

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Jet production rates are measured in $p$+$p$ and $d$+Au collisions at $\sqrt{s_{NN}}$=200 GeV recorded in 2008 with the PHENIX detector at the Relativistic Heavy Ion Collider. Jets are reconstructed using the $R = 0.3$ anti-$k_t$ algorithm from energy deposits in the electromagnetic calorimeter and charged tracks in multi-wire proportional chambers, and the jet transverse momentum ($p_T$) spectra are corrected for the detector response. Spectra are reported for jets with $12 < p_T < 50$ GeV/$c$, within a pseudorapidity acceptance of $|\eta| < 0.3$. The nuclear-modification factor ($R_{d\mathrm{Au}}$) values for 0%–100% $d$+Au events are found to be consistent with unity, constraining the role of initial state effects on jet production. However, the centrality-selected $R_{d\mathrm{Au}}$ values and central-to-peripheral ratios ($R_{\mathrm{CP}}$) show large, $p_T$-dependent deviations from unity, challenging the conventional models that relate hard-process rates and soft-particle production in collisions involving nuclei.

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Jet cross-section measurements in $d$+Au collisions at the Relativistic Heavy Ion Collider (RHIC) are crucial for benchmarking the effects of the so-called cold-nuclear-matter environment, where jet production rates are expected to be sensitive to the modification of the nuclear parton densities [1] or to the energy loss of fast partons in the nucleus [2–4]. Recent observations of collective behavior in small collision systems at the Large Hadron Collider (LHC) and RHIC [5–8] suggest that jet quenching in a possibly formed quark-gluon plasma [9] may play a role as well. Measurements of jet production as a function of centrality, an experimental proxy for the impact parameter of the deuteron with respect to the nucleus, are particularly important. They may reveal the impact parameter dependence of the nuclear parton densities [10], of nonlinear quantum chromodynamics (QCD) effects at very high parton densities [11, 12], or of energy loss. More generally, they test the applicability of geometric models that describe how soft observables and hard process rates in heavy ion collisions are related [13]. At RHIC energies, jet spectra have previously been reported only in $p$+$p$ collisions [14, 15].

Modifications to jet production rates from the vacuum expectation are quantified through the nuclear-modification factor $R_{d\mathrm{Au}} \equiv (\mathrm{d}N^{\mathrm{cent}}/\mathrm{d}p_T)/(T^{\mathrm{cent}}_{d\mathrm{Au}}\mathrm{d}\sigma/\mathrm{d}p_T)$, where the numerator is the per-event jet yield as a function of transverse momentum ($p_T$) in a given class of $d$+Au collisions ("cent"), and the denominator is the jet production cross section in $p$+$p$ collisions scaled by the corresponding mean value of the nuclear-overlap function $T_{d\mathrm{Au}}$. Because $T_{d\mathrm{Au}}$ cannot be directly determined experimentally, it is typically calculated within a Glauber model of relativistic nuclear collisions. $R_{d\mathrm{Au}}$ values of unity mean that the jet rate in $d$+Au collisions is consistent with that in $p$+$p$ collisions after correcting for the larger degree of partonic overlap. The double ratio of the $R_{d\mathrm{Au}}$ in central (large $T_{d\mathrm{Au}}$) events to that in peripheral (small $T_{d\mathrm{Au}}$) events, $R_{\mathrm{CP}}$, quantifies the relative modification between $d$+Au event classes.

Previous measurements of hadron production at midrapidity in $d$+Au collisions [16, 17] found that $R_{d\mathrm{Au}}$ is consistent with unity at $p_T$ =5–10 GeV/$c$ for all centralities, implying that hard-process yields scale with the overlap of the incoming partons and constraining the role of nuclear effects. The data further suggested that $R_{d\mathrm{Au}}$ for $p_T$ >10 GeV/$c$ deviates from unity [16], but with small statistical significance. Recent measurements of $p_T \gtrsim$100 GeV/$c$ jet and dijet production in $p$+Pb collisions at the LHC showed a large, unexpected sensitivity to the collision centrality [18, 19]. A number of novel explanations [20–22] have been proposed for these effects, which are generally expected to persist to RHIC energies, but at large $p_T$ where previous measurements have lacked statistical precision. This Letter presents the centrality dependence of jet production in an asymmetric collision system over a kinematic range previously not measured at RHIC.

Jets were measured in one of the PHENIX central spectrometers (the "East" arm) [23] during data taking in 2008. The spectrometer provides a pseudorapidity aperture of $|\eta| < 0.35$, $\pi/2$ coverage in azimuth, and is situated outside a 0.9 T axial magnetic field. Charged-particle tracks are measured by a set of multi-wire proportional chambers, including an inner drift chamber and multiple outer pad chambers that together provide a resolution of $\sigma_p/p = 0.7\% \oplus 1\% p$ where $p$ is in GeV/$c$. Energy deposits from neutral particles are measured by the finely segmented electromagnetic calorimeter, composed of two lead-glass Čerenkov and two lead-scintillator sectors, which have a resolution determined by beam tests [24] to be $\sigma_E/E = 5.9\%/\sqrt{E} \oplus 0.8\%$ and $8.1\%/\sqrt{E} \oplus 2.1\%$, respectively, where $E$ is in GeV. Calibration was performed through the reconstruction of neutral pion decays. The calorimeter further provides a trigger signal initiated by the presence of at least 1.6 or 2.1 GeV of energy deposited in one of the groups of overlapping $4 \times 4$ towers in the lead-glass or lead-scintillator modules, respectively. In addition to the spectrometer, a pair of beam–beam counter detectors situated along the beam line at $3.0 < |\eta| < 3.9$ provide the minimum-bias trigger signal and reconstruct the $z$ position of the primary vertex.

The analyzed $p$+$p$ and $d$+Au data sets were carefully chosen, and the single central arm was used, to ensure a large, stable and uniform acceptance for jets, and corresponded to 2.0 pb$^{-1}$ and 23 nb$^{-1}$ (equivalent to an integrated nucleon–nucleon luminosity of 9.1 pb$^{-1}$), respectively. The centrality of $d$+Au collisions was characterized using the total charge deposited in the Au-going beam-beam counter. A Glauber Monte Carlo [13, 25] description of $d$+Au collisions was used, along with the hypothesis that this charge increased linearly with the number of nucleon–nucleon collisions [26], to determine the fraction of $d$+Au collisions accepted by the minimum-bias trigger, $88 \pm 4\%$, and to estimate the mean value of the nuclear-overlap function $T^{\mathrm{cent}}_{d\mathrm{Au}}$ for 0%–100% centrality events, as well as those defined by the centrality intervals ("cent") of 0%–20%, 20%–40%, 40%–60%, and 60%–88%. The relationship between the Au-going charge and the collision geometry has been validated through, for example, an analysis of forward neutron production in $d$+Au collisions, and analyses of $p$+$p$ collisions indicate that it should hold for events that produce $p_T = 20$ GeV hadrons [26].

In this analysis, the final-state jet definition is specified by applying the anti-$k_t$ algorithm [27, 28] with radius parameter $R = 0.3$ to electromagnetic clusters (in the calorimeter) and charged-particle tracks (in the drift and pad chambers), each with a minimum $p_T$ of 0.4 GeV/$c$. The anti-$k_t$ algorithm clusters outward from the hard core of jets, reducing the sensitivity to detector edges. A detailed set of criteria designed to select charged particles with a well-measured momentum while ensuring a large and uniform acceptance were applied to candidate reconstructed tracks. Clusters consistent with arising from the same particle as a reconstructed track were rejected to avoid double counting jet constituent energy. Jets which are dominated by reconstructed tracks with a large, erroneously measured $p_T$ [29] were rejected by requiring at least three constituent particles and by requiring at least one quarter of the momentum to arise from clusters. To ensure that the core of the jet is fully contained within the detector, the jet axis was required to be separated from the edge of the acceptance by 0.05 units in pseudorapidity and azimuth.

Detector-level jets, defined as those passing the above criteria, were used to form a transverse momentum spectrum ($p_T^{\rm rec}$) in each event class. The contribution of the small underlying event background was not subtracted on a jet-by-jet basis, but was corrected for in the unfolding procedure described below. Jets were selected from the triggered data if a jet constituent fell into the same region of the calorimeter that provided the trigger signal. The trigger efficiency was estimated for each event class by checking this condition as a function of $p_T^{\rm rec}$ in minimum-bias events. The $p_T^{\rm rec}$-level spectra were corrected for this efficiency, which rose monotonically with $p_T^{\rm rec}$ and was approximately 70% (98%) at 10 GeV/$c$ (25 GeV/$c$).

Monte Carlo simulations were used to determine the response of the detector to jets and to correct the measured spectra. In simulation, jets are defined by applying the anti-$k_t$ algorithm to long-lived primary particles, resulting in jets with a particle-level transverse momentum ($p_T$). The PYTHIA 6.4 event generator [30] with the D6T tune [31] and CTEQL1 parton distribution function set [32] was used to generate hard scattering $p$+$p$ events with a jet within the acceptance of the East arm. Six separate samples with exclusive selections on the hard-scattering momentum transfer in PYTHIA, consisting of $10^5$ events each, were weighted according to their partial cross-section and combined to form a $p_T$ spectrum from 8 to 80 GeV/$c$. The response of the detector was simulated with GEANT3 [33] and the resulting events were analyzed identically to the data. To understand the effects of the underlying event in $d$+Au collisions, jet reconstruction was also performed on the simulated events after they were embedded into minimum-bias $d$+Au data events of each centrality. In each event class, particle-level jets were matched with detector-level jets and the correspondence between the true $p_T$ and the measured $p_T^{\rm rec}$ was collected into a response matrix $\mathcal{R}(p_T, p_T^{\rm rec})$.

The reconstruction and selection efficiency, $\epsilon(p_T)$, for particle-level jets within $|\eta| < 0.3$ rose with $p_T$ and was $\approx 35\%$ (50%) at 10 GeV/$c$ (25 GeV/$c$) in $p$+$p$ collisions. The inefficiency was dominated by the minimum requirement on the calorimetric fraction of the jet momentum. For a given selection on the particle-level jet $p_T$, the mean value of the $p_T^{\rm rec}/p_T$ distribution $\approx$ 0.65-0.70 resulted from missing neutral hadronic energy and tracking inefficiency. The width of this distribution was $\approx$20%–25%, rose slightly with $p_T$, and was driven by jet-by-jet fluctuations in the neutral hadronic momentum fraction and not by the resolution on the constituent momenta. In the $d$+Au event classes, the impact of the underlying event on the response decreased systematically with increasing jet $p_T$. For $p_T$ =20 GeV/$c$ jets in 0%–20% centrality $d$+Au events, the underlying event background increased the efficiency by 2%, the average $p_T^{\rm rec}$ by 0.1–0.2 GeV/$c$, and the $p_T^{\rm rec}$ resolution by 1%, relative to that in $p$+$p$ events.

The $p_T^{\rm rec}$-level spectra were corrected for the detector response and the presence of the underlying event in $d$+Au collisions through the singular-value-decomposition unfolding method [34, 35]. For an observed spectrum $\mathrm{d}N/\mathrm{d}p_T^{\rm rec}$, this method inverts the equation $\mathrm{d}N/\mathrm{d}p_T^{\rm rec} = \mathcal{R}\cdot \mathrm{d}N/\mathrm{d}p_T$ by expressing $\mathrm{d}N/\mathrm{d}p_T$ as a linear combination of the left singular vectors of $\mathcal{R}$, with coefficients determined by $\mathrm{d}N/\mathrm{d}p_T^{\rm rec}$. This inversion is regularized by keeping the contribution only from the $k$ vectors with the largest singular values. The contribution from the remaining vectors is truncated to ensure that $\mathrm{d}N/\mathrm{d}p_T$ is unaffected by statistical fluctuations.

Following standard techniques [34], $k$ was fixed at 5, and the results were validated by comparing $\mathrm{d}N/\mathrm{d}p_T$, propagated through $\mathcal{R}$, to $\mathrm{d}N/\mathrm{d}p_T^{\rm rec}$, and by examining the curvature of $\mathrm{d}N/\mathrm{d}p_T$ with respect to the simulated $p_T$ spectrum used to populate $\mathcal{R}$. The iterative Bayesian method [36] gave consistent results. The statistical uncertainties on $\mathrm{d}N/\mathrm{d}p_T$ were evaluated by resampling $\mathrm{d}N/\mathrm{d}p_T^{\rm rec}$ according to its uncertainties and observing the changes in $\mathrm{d}N/\mathrm{d}p_T$. Finally, the $\mathrm{d}N/\mathrm{d}p_T$ spectra were corrected for the reconstruction efficiency $\epsilon(p_T)$. At low $p_T$ in 0%–20% events, the $R_{d\mathrm{Au}}$ after unfolding was lower than the detector-level $R_{d\mathrm{Au}}$ by $\approx$20%, while the two are comparable at high $p_T$ or in peripheral events.

The $p$+$p$ differential cross section was constructed [16] via $2\pi\sigma^{pp}N^{\rm jet}(p_T)/\epsilon^{pp}N^{\rm evt}\epsilon(p_T)\Delta p_T\Delta\eta\Delta\phi$, where $\sigma^{pp} = 23.0 \pm 2.2$ mb is the minimum-bias cross section, $\epsilon^{pp} = 0.79 \pm 0.02$ is the fraction of jet events meeting the minimum-bias condition, and $2\pi/\Delta p_T\Delta\eta\Delta\phi$ are phase-space factors. Figure 1 shows the $d$+Au yields and the $p$+$p$ cross section, which compares well with a perturbative QCD calculation [37, 38].

The measured spectra and nuclear-modification factors are subject to systematic uncertainties from a variety of sources. For most sources, the effects on the results were determined by modifying the simulation sample, the event or jet-selection criteria, or the unfolding procedure itself, and repeating the analysis. The variations were applied simultaneously in the analyses of the $d$+Au and $p$+$p$ spectra to allow for their full or partial cancellation in the $R_{d\mathrm{Au}}$ and $R_{\rm CP}$ quantities, with the exception of the variation of $k$, described below.

The impact of uncertainties on the detector energy scales was determined by varying the momenta of the reconstructed tracks and clusters in simulation. The cluster energies were varied by 3%. The track momenta were varied

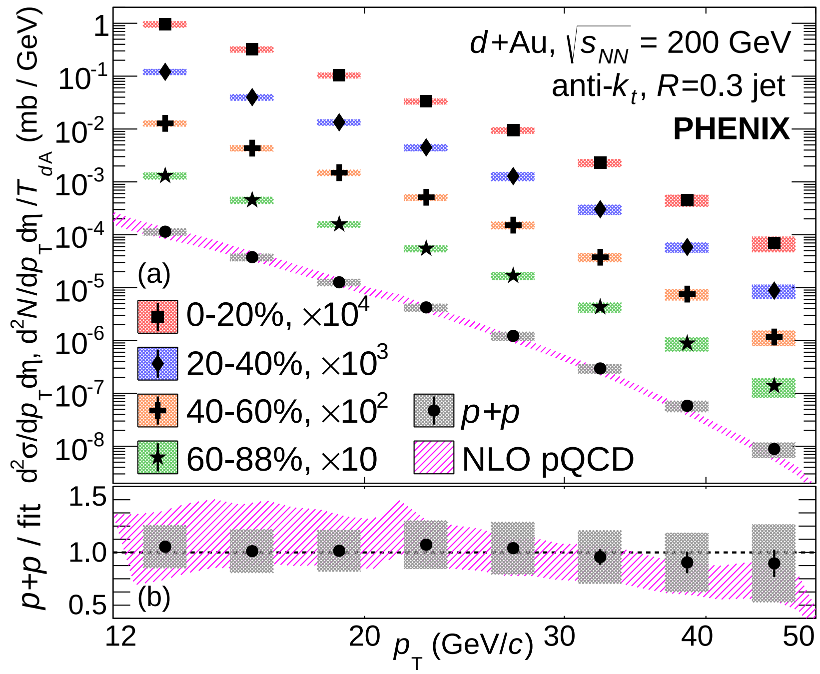


FIG. 1. (Color online) Measured anti-$k_t$, $R = 0.3$ jet yields in $d$+Au collisions, and the measured and calculated jet cross section in $p$+$p$ collisions, with the data series offset by multiplicative factors. Total systematic uncertainties, including overall normalization uncertainties, and statistical uncertainties are shown as shaded bands and vertical bars, respectively. In the bottom panel, the $p$+$p$ data and perturbative QCD calculation [37, 38] are divided by a fit to the data.

by a track $p_T$-dependent amount, which was 2% for $p_T \leq 10$ GeV/$c$ and increased linearly to 4% for $p_T = 30$ GeV/$c$. The sensitivity of the results to the jet selection was evaluated by varying the maximum and minimum requirement on the calorimetric content of the jet, and by raising the required number of jet constituents. The uncertainty in the jet acceptance was evaluated by doubling the fiducial distance between jets and the edges of the detector, and by restricting the vertex $z$ position to a narrower range. The uncertainties associated with the unfolding procedure were evaluated by changing the power law index of the simulated $p_T$ spectrum by $\pm 1$, and by increasing and decreasing the value of $k$. Because they are statistical in nature, the effects on the spectra from varying $k$ were treated as uncorrelated between the event classes. The sensitivity to the underlying physics model was evaluated by performing the corrections with a sample of PYTHIA events analogous to the nominal one but generated with TUNE A [39] and the CTEQ5L [40] set. A 2% uncertainty, uncorrelated between event classes, was assigned to the spectra below 25 GeV/$c$ to cover possible defects in modeling the trigger efficiency.

For each observable, the magnitudes of the resulting changes were added in quadrature to obtain a total systematic uncertainty. The total uncertainty on the spectra increased from 12% at $p_T = 12$ GeV/$c$ to 30% or higher at $p_T = 50$ GeV/$c$ and was dominated at all $p_T$ by the energy scale. Because the reconstruction procedure in $d$+Au and $p$+$p$ collisions was identical, and the performance, corrections and resulting spectra are very similar, the effects of the variations on $R_{d\mathrm{Au}}$ and $R_{\mathrm{CP}}$ canceled to a large degree. The uncertainties on this quantity ranged from 4% at $p_T = 12$ GeV/$c$ (with no single source dominating) to 15% or higher (dominated by unfolding and physics model) at $p_T = 50$ GeV/$c$.

Additional normalization uncertainties on the $p$+$p$ cross section of 10% arose from the uncertainty on $\sigma^{pp}/\epsilon^{pp}$. Uncertainties in the determination of $T_{d\mathrm{Au}}$ contributed to the $R_{d\mathrm{Au}}$ and $R_{\mathrm{CP}}$, such that the total uncertainty on these ranged from 3% to 13%.

Figure 2 summarizes the measured $R_{d\mathrm{Au}}$ and $R_{\mathrm{CP}}$ quantities. The 0%–100% $R_{d\mathrm{Au}}$ is consistent with unity at all $p_T$ values and is $p_T$-independent within uncertainties. The data are consistent with a next-to-leading order calculation [41–44] incorporating the EPS09 [1] nuclear-parton-density set, suggesting that nuclear effects are small at high-$Q^2$ in the nuclear Bjorken-$x$ range $\approx 0.1$–$0.5$. When compared to calculations over a range of energy loss rates in the cold nucleus [4], the data favor only small momentum transfers between the hard-scattered parton and nuclear material, providing constraints on initial-state, or any additional final-state, energy loss.

In contrast, the centrality-dependent $R_{d\mathrm{Au}}$ values strongly deviate from unity, manifesting as a suppression ($R_{d\mathrm{Au}} <$

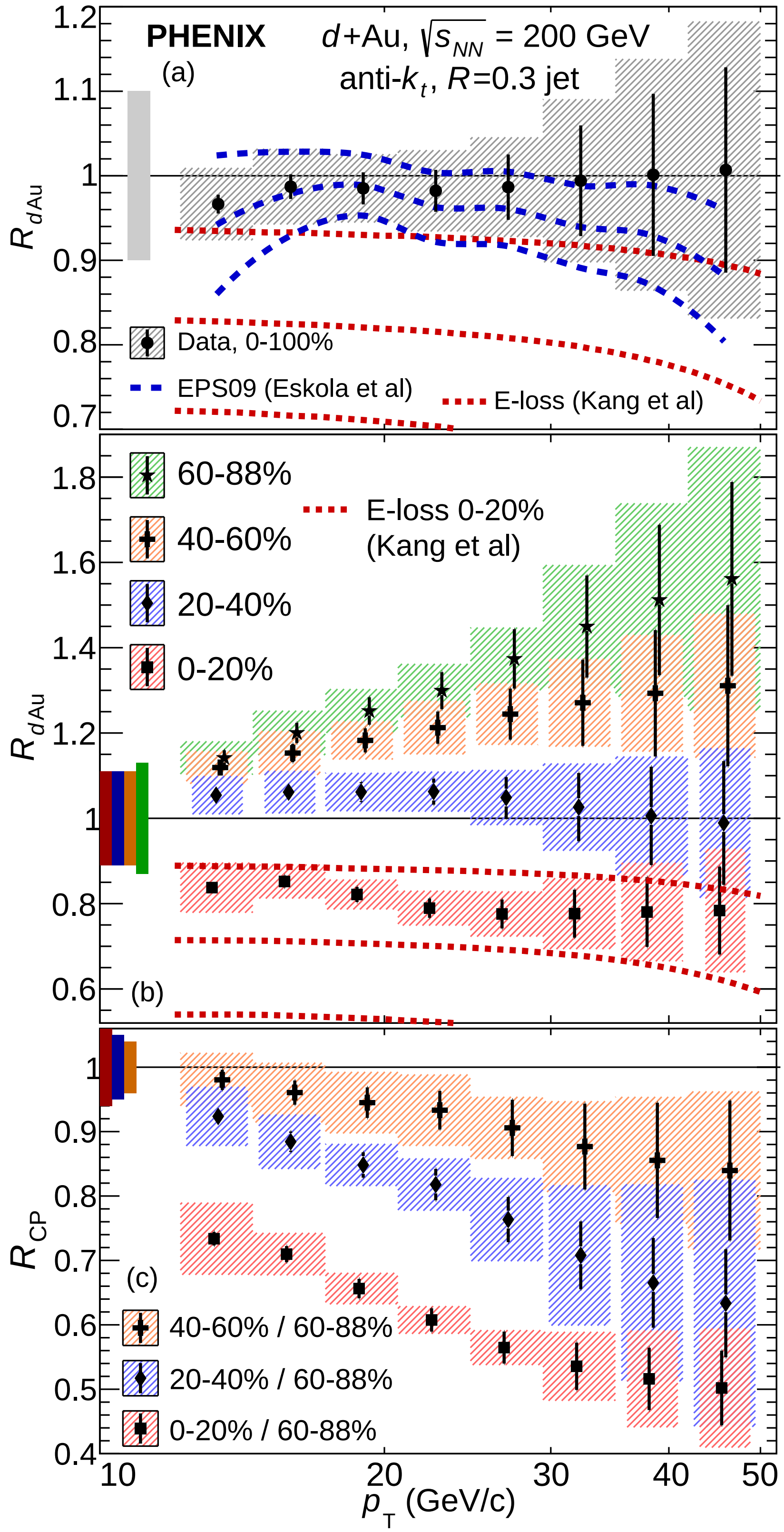


FIG. 2. (Color online) $R_{d\mathrm{Au}}$ for (a) 0%–100% and (b) centrality-selected collisions, and (c) $R_{\mathrm{CP}}$, as a function of $p_T$. Systematic, statistical and normalization uncertainties are shown as shaded bands, vertical bars, and the leftmost bands centered at 1, respectively. When error bands overlap vertically, their horizontal widths have been adjusted so that both are visible. Dashed lines show the uncertainty range of calculations incorporating nuclear parton densities [1] and energy loss [4].

1) and enhancement ($R_{d\mathrm{Au}} > 1$) in central and peripheral collisions respectively, which increase in magnitude with $p_T$. Accordingly, the $R_{\mathrm{CP}}$ is $< 1$ in most selections and decreases systematically with $p_T$ and in more central events. While the suppressed $R_{d\mathrm{Au}}$ in 0%–20% events is consistent with a calculation incorporating modest energy loss, an enhancement in 40%–88% events, which coincidentally cancels with the suppression to produce an unmodified minimum bias rate, is challenging to understand as a distinct physics effect.

If jet production is unmodified but a physics bias enters into the centrality classification, this could naturally explain the $R_{d\mathrm{Au}}$ results. In fact, measurements of centrality-dependent yields are understood to be biased by the increased multiplicity in hard-scattering nucleon-nucleon events [26, 45–47], which generally increases (decreases) the yield in central (peripheral) collisions. The results have been corrected for this bias following Ref. [26], thus slightly increasing the magnitude of the modifications. On the other hand, if the charged particle multiplicity several units of rapidity away in the Au-going direction were suppressed instead of enhanced in $p_T > 12$ GeV/$c$ jet events, this would reverse the sign of the correction and could result in the observed modifications. The jet $p_T$-dependence of this correlation has been studied in $p$+$p$ data and in HIJING [48], where it is well-reproduced. The decreased multiplicity results in modest changes ($< 5\%$) in the correction factors for events with $p_T = 20$ GeV/$c$ hadrons [26], a much smaller effect than what is needed to describe the $R_{d\mathrm{Au}}$ data. Thus, no feature of elemental $p$+$p$ collisions can explain the data alone, indicating the relevance of the large nucleus and the need for successful models to describe the correlation between soft and hard processes in $p$+$p$ and $d$+Au.

At midrapidity, jet production in $p$+Pb collisions at the LHC [18] follows a similar modification pattern in the Bjorken-$x$ range, $x_p \sim x_{\mathrm{Pb}} \gtrsim 0.1$. However, the $R_{p\mathrm{Pb}}$ in those results scales with proton-$x$, suggesting a scenario in which the modifications arise from a novel feature of the proton wavefunction at large $x$ [20–22]. For example, if high-$x$ deuteron configurations have a weaker than average interaction strength and strike fewer nucleons in the Au nucleus [21], this would result in the unmodified, suppressed and enhanced $R_{d\mathrm{Au}}$ in minimum-bias, central and peripheral events, respectively. If so, the observed centrality dependence of forward hadron production [49–52] in $d$+Au collisions may arise from the same mechanism as the results presented here, because both are kinematically associated with the scattering of a large-$x$ parton in the deuteron. Finally, using an alternate estimate of $T_{d\mathrm{Au}}$ provided by applying the Glauber–Gribov color fluctuation model [53, 54] to the data would increase the deviation of $R_{d\mathrm{Au}}$ in the most central and peripheral events from unity by 10% and 5%, respectively.

This Letter presents the first measurement of high-$p_T$ jet production in $d$+Au collisions at RHIC. The jet rate in inclusive collisions is broadly consistent with expectations, providing constraints in a new kinematic regime on modifications to the parton densities in nuclei and on the energy loss of fast partons in the nuclear medium. When compared to the expectation from geometric considerations, the rates in centrality-selected events strongly deviate from unity, featuring suppression and enhancement patterns in central and peripheral events, respectively. These deviations grow with increasing $p_T$, but cancel in the overall jet rate, and challenge the conventional pictures of how hard-process rates and soft-particle production are related in collisions involving nuclei.

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