Cold-Nuclear-Matter Effects on Heavy-Quark Production at Forward and Backward Rapidity in $d + \mathrm{Au}$ Collisions at $\sqrt{s_{NN}} = 200$ GeV

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The PHENIX experiment has measured open heavy-flavor production via semileptonic decay over the transverse momentum range $1 < p_T < 6$ GeV/c at forward and backward rapidity ($1.4 < |y| < 2.0$) in $d+\mathrm{Au}$ and $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV. In central $d+\mathrm{Au}$ collisions, relative to the yield in $p+p$ collisions scaled by the number of binary nucleon-nucleon collisions, a suppression is observed at forward rapidity (in the d-going direction) and an enhancement at backward rapidity (in the Au-going direction). Predictions using nuclear-modified-parton-distribution functions, even with additional nuclear-p_T broadening, cannot simultaneously reproduce the data at both rapidity ranges, which implies that these models are incomplete and suggests the possible importance of final-state interactions in the asymmetric $d+\mathrm{Au}$ collision system. These results can be used to probe cold-nuclear-matter effects, which may significantly affect heavy-quark production, in addition to helping constrain the magnitude of charmonia-breakup effects in nuclear matter.

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Heavy quarks are essential probes of the evolution of the medium created in heavy-ion collisions, because they are produced in the early stages of nuclear collisions. Heavy-quark production has been studied via semileptonic-decay electrons and muons, as well as fully reconstructed D mesons, at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider [1,2]. In $p+p$ collisions, heavy-quark production tests perturbative quantum chromodynamics and provides a baseline for the results from heavy-ion collisions [3–5]. In central $\mathrm{Au}+\mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV, strong suppression of high-transverse-momentum (p_T) electrons from semileptonic decay of open heavy-flavor hadrons has been observed at midrapidity [6,7]. At forward rapidity, a similar level of suppression has been measured for the production of heavy-flavor muons in central $\mathrm{Cu}+\mathrm{Cu}$ collisions [8]. Although suppression of high-p_T particles was predicted as an effect of partonic energy loss in the dense medium created in heavy-ion collisions [9–11], the observed suppression is difficult to explain solely with hot-nuclear-matter effects [8,12]. To interpret such measurements, it is essential to probe the underlying cold-nuclear-matter (CNM) effects, which may also be present.

Control experiments with $d+\mathrm{Au}$ collisions allow us to probe those CNM effects, including modifications of the parton distribution functions (PDF) and nuclear-p_T broadening, with minimal impact from the hot nuclear medium. Because heavy quarks are produced primarily by gluon fusion at RHIC, modification of the gluon density in the nucleus can be observed in the charm and bottom production rates [13,14]. Based on PYTHIA [15] calculations, the average parton momentum fraction x in the Au nucleus leading to heavy-flavor muons with $1 < p_T^{\mu} < 6$ GeV/c at backward rapidity ($-2.0 < y < -1.4$, Au-going direction) and forward rapidity ($1.4 < y < 2.0$, d-going direction) is $\approx 8 \times 10^{-2}$ and $\approx 5 \times 10^{-3}$, respectively. Parton energy loss and multiple scattering in the nucleus can change the resulting heavy-flavor hadron momentum spectrum [16]. Previous results in $d+\mathrm{Au}$ collisions at midrapidity show a significant enhancement of heavy-flavor electrons at moderate p_T [17]. In this Letter, we present measurements of the p_T spectra and the nuclear-modification factor (R_{dA}) of

negatively charged muons from open heavy flavor at forward and backward rapidity in $d+\mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV.

The $d+\mathrm{Au}$ and $p+p$ data presented here were recorded with the PHENIX detector during the 2008 and 2009 RHIC running periods, respectively. Minimum-bias collisions are selected by using the beam-beam counter (BBC) [18], and this selection covers $88 \pm 4\%$ ($55 \pm 5\%$) of the total $d+\mathrm{Au}$ ($p+p$) inelastic cross section [19]. The integrated luminosity, sampled using single muon triggers [8] in coincidence with the minimum-bias trigger, used for this analysis of $d+\mathrm{Au}$ ($p+p$) collisions is 50 nb^{-1} (10 pb^{-1}). The $d+\mathrm{Au}$ collisions are categorized into four centrality classes: 0%–20%, 20%–40%, 40%–60%, and 60%–88%, where 0%–20% represents the 20% highest multiplicity events, as determined by the amount of total charge deposited in the BBC on the Au-going side. For each centrality class, the average number of binary nucleon-nucleon collisions $\langle N_{\mathrm{coll}} \rangle$ is calculated from the BBC charge in a Glauber model [20]. The values of $\langle N_{\mathrm{coll}} \rangle$ for the $d+\mathrm{Au}$ centrality classes specified above are 15.1 ± 1.0, 10.2 ± 0.7, 6.6 ± 0.4, and 3.2 ± 0.2, respectively. A correction for the underlying event correlation and the efficiency of the BBC trigger is applied, as in [21,22]. Unbiased collisions (0%–100%, $\langle N_{\mathrm{coll}} \rangle = 7.6 \pm 0.4$) are also analyzed.

Two muon spectrometers [23] provide full azimuthal coverage in the pseudorapidity range $-2.2 < \eta < -1.2$ (backward rapidity) and $1.2 < \eta < 2.4$ (forward rapidity). Each muon arm, located behind copper (19 cm) and iron (60 cm) absorbers, comprises a muon tracker (MuTr) followed by a muon identifier (MuID). The MuTr comprises three stations of cathode strip chambers surrounded by a radial magnetic field, and the MuID comprises five interleaved layers of steel absorber and Iarocci tube planes. The MuTr provides the momentum measurement for charged tracks in the magnetic field. The momentum information for each charged track is then combined with its penetration depth reported by the MuID to provide effective discrimination between muons and hadrons (pion rejection rate: $\sim 10^{-3}$) [24].

Despite the large hadron rejection power of the muon arms and strict selection criteria, most of the tracks reaching the last MuID layer are not heavy-flavor muons. Simulation studies show that the majority of these background tracks for $p_T < 3$ GeV/c originate from the decays of light-flavor mesons (mostly $\pi^{\pm}$ and $K^{\pm}$) into muons before reaching the absorber material. Another source of background, called "punch-through hadrons," are the hadrons produced at the collision vertex, which penetrate all MuID layers. Other, less significant sources of background include muons from hadrons that decay inside the MuTr which are misreconstructed with erroneously high p_T , muons from heavy-flavor resonances (J/ψ, ψ', and Υ), and muons from light vector mesons (ρ, ϕ, and ω). The J/ψ is the most significant of these lesser sources, contributing less than 5% at high p_T [8,25]. The backgrounds are subtracted as follows.

For each data set, we measure the double differential heavy-flavor muon invariant yield, defined as

$$\frac{d^2N^{\mu}}{2\pi p_T dp_T dy} = \frac{1}{2\pi p_T \Delta p_T \Delta y} \frac{N_I - N_C - N_F - N_{J/\psi}}{(N_{\mathrm{evt}}/\epsilon_{\mathrm{BBC}}) A\epsilon}, \quad (1)$$

where Δp_T and Δy are the bin widths in p_T and y, N_I is the number of inclusive muon candidates, N_C is the number of decay and punch-through hadron background tracks determined using a hadron cocktail method (described below), N_F is the estimated number of fake tracks that pass the selection criteria, $N_{J/\psi}$ is the number of muons from J/ψ decays, N_{evt} is the number of sampled events, $A\epsilon$ is the detector acceptance and efficiency correction, and ϵ_{BBC} is the BBC bias-correction factor for the trigger efficiency and centrality determination of events containing a heavy-flavor muon. Only negative muons are used because the signal-to-background ratio is better than for positive muons [8]. The typical signal-to-background ratio, $N^{\mu}/(N_C + N_F + N_{J/\psi})$, increases from 0.3 at $p_T = 1$ GeV/c to 0.6 at $p_T = 6$ GeV/c. The hadron-cocktail method estimates the overall background owing to light-hadron sources using a GEANT simulation based on measured p_T spectra. Details on the background-estimation procedure and associated systematic uncertainty are described in [3,8,25].

Figure 1 shows the invariant yield of heavy-flavor muons as a function of p_T in $d+\mathrm{Au}$ collisions at backward and forward rapidity along with the invariant yield in $p+p$ collisions. The vertical bars represent statistical uncertainties, while boxes are systematic uncertainties in the acceptance and efficiency correction, background estimate, and trigger bias correction for each centrality class. The main source of the systematic uncertainty is the background estimate including initial hadron production ($\sim$10%) and interactions of hadrons with the absorber material ($\sim$10%). All components of the systematic uncertainty are added in quadrature. Solid lines show a modified Kaplan function $A(1 + [p_T/8.3(\mathrm{GeV}/c)]^2)^{-3.9}$ [26], fit to the p_T spectrum in $p+p$ collisions, and then scaled by $\langle N_{\mathrm{coll}} \rangle$ for each $d+\mathrm{Au}$ centrality class. The $p+p$ results are consistent with previous PHENIX measurements [8].

To quantify nuclear effects in $d+\mathrm{Au}$ collisions, we calculate the ratio of heavy-flavor muon yields in $d+\mathrm{Au}$ to $p+p$ collisions scaled by the average number of binary collisions for a given centrality bin,

$$R_{dA} = \frac{dN^{\mu^-}_{dA}/dp_T}{\langle N_{\mathrm{coll}} \rangle dN^{\mu^-}_{pp}/dp_T}. \quad (2)$$

Figure 2 shows R_{dA} as a function of p_T for heavy-flavor muons in different $d+\mathrm{Au}$ centrality classes. Vertical bars

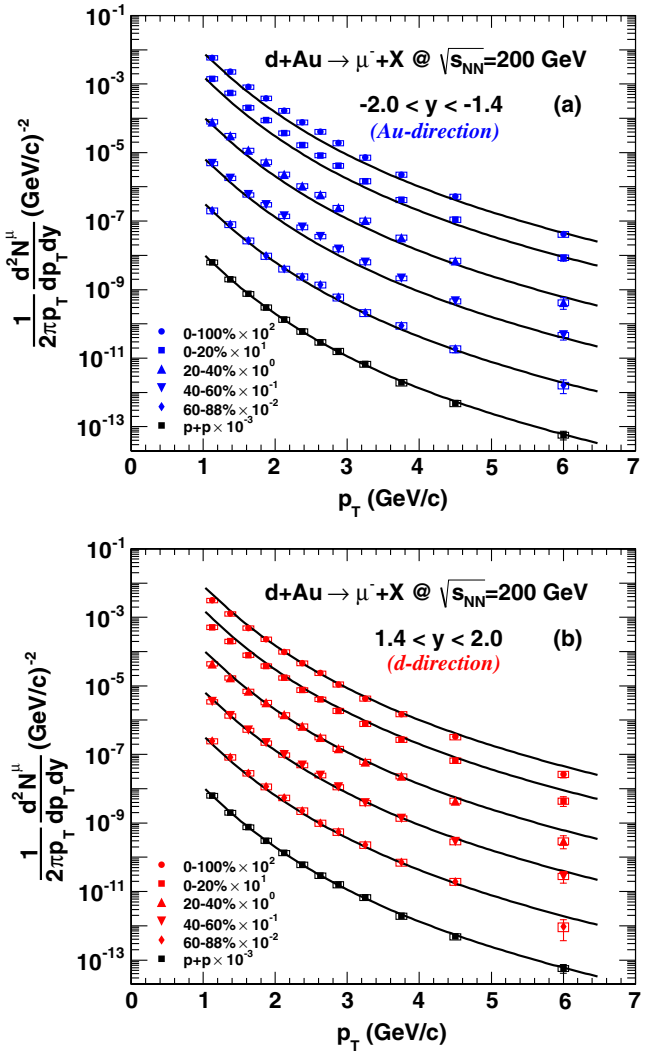

FIG. 1 (color online). Invariant yield of negatively charged heavy-flavor muons as a function of p_T in $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV (black squares) and in $d+\mathrm{Au}$ collisions for different centralities at (a) backward rapidity (Au-going) and (b) forward rapidity (d-going). The solid lines represent a fit to the $p+p$ invariant yield, scaled by the number of binary collisions $\langle N_{\mathrm{coll}} \rangle$ for each centrality class.

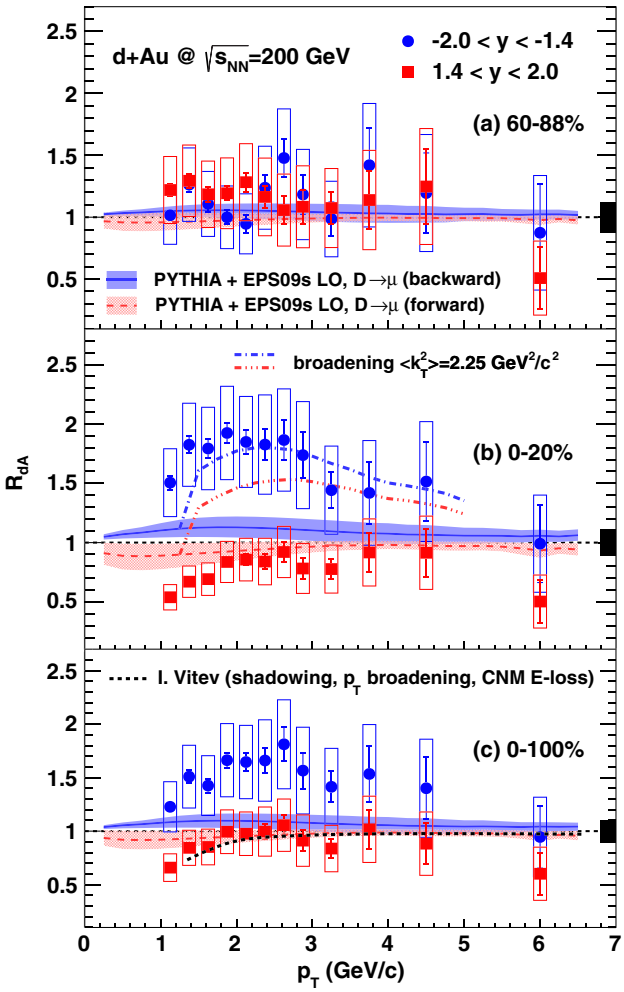

FIG. 2 (color online). The nuclear modification factor R_{dA} for negatively charged heavy-flavor muons in $d+\mathrm{Au}$ collisions for the (a) most peripheral (60%–88%) and (b) most central (0%–20%) centrality classes, and (c) unbiased (0%–100%) data. The black boxes on the right side indicate the global scaling uncertainty. The red dashed (blue solid) lines in each panel are calculations at forward (backward) rapidity based on the EPS09s nPDF set [14]. Dot-dashed curves in (b) are the same calculations plus an additional nuclear-p_T broadening. The theoretical calculation shown in (c) is for forward rapidity [16].

(boxes) represent the statistical (systematic) uncertainties for R_{dA} , which are the quadratic sum of the uncertainties for the invariant yields of $p+p$ and $d+\mathrm{Au}$ collisions. The systematic uncertainties related to detector performance do not cancel in R_{dA}, because the two data sets were taken under different running conditions. The global scaling uncertainty in $\langle N_{\mathrm{coll}} \rangle$ and the BBC efficiency is shown as a box centered around unity at the right edge of the plot.

For the most peripheral collisions in both rapidity ranges, R_{dA} shows no overall modification. For the most central collisions, a clear enhancement is observed at backward rapidity. This enhancement suggests nuclear-p_T broadening at moderate p_T , which is similar to that seen at midrapidity [17], and gluon antishadowing. In the 0%–20% of most central collisions, the forward rapidity R_{dA} shows a global suppression, presumably caused by gluon shadowing and/or partonic energy loss, which becomes stronger at low p_T and is probably a sign of nuclear-p_T broadening.

The dotted line in Fig. 2(c) is a prediction of R_{dA} for muons from D and B mesons at forward rapidity, $y = 1.7$ [16,27]. This prediction, including CNM effects such as shadowing, initial-state energy loss, and nuclear-p_T broadening, is consistent with the data at forward rapidity for the 0%–100% centrality class. The same model, with additional energy loss in deconfined hot nuclear matter, also describes the forward heavy-flavor muon results in central $\mathrm{Cu}+\mathrm{Cu}$ collisions within uncertainties [8]. This

agreement and the suppression at forward rapidity in central $d+\mathrm{Au}$ collisions suggest that CNM effects are important for the interpretation of the suppression of heavy-flavor muon production at forward rapidity at RHIC [8] and the Large Hadron Collider [28].

We use the EPS09s leading-order (LO) nuclear PDF (nPDF) set [14] to calculate R_{dA} for muons from D mesons at backward (solid lines) and forward (dashed lines) rapidity based solely on initial parton density modifications. As described in [29], the input parameters for the EPS09s calculation [14], which incorporates a spatial dependence within the nucleus based on the previous nPDF EPS09 model [13], are the parton momentum fraction x, momentum transfer (Q^2) of charm production generated by PYTHIA [15], and transverse radial positions of binary collisions in the nucleus for each centrality class. The uncertainty bands are calculated as described in [13].

In central collisions, shown in Fig. 2(b), the EPS09s-nPDF-based calculation does not reproduce the data at backward rapidity (Au-going direction), particularly in the moderate p_T region. At forward rapidity (d-going direction), R_{dA} calculated with the EPS09s nPDF is consistent with the data over the entire p_T range within the uncertainties of the data and calculation. The same EPS09s-nPDF-based calculations with a nuclear-multiple-scattering broadening $\langle k_T^2 \rangle = 2.25\ \mathrm{GeV}^2/c^2$ (dot-dashed lines), when selected to match the backward rapidity data, overshoot the data at forward rapidity. There is no consistent combination of nuclear-p_T broadening and modified nPDF that can describe the entire rapidity dependence of the data. A model incorporating scattering and recombination with soft and hard final-state gluons [30] explains the enhancement of hadrons at the higher-parton-density backward rapidity and no enhancement at the lower-parton-density forward rapidity [30], noting the larger particle production resulting from higher parton density [31,32]. It would be interesting to see if this model, once extended to charm hadrons, accommodates the entire rapidity of the data presented here.

Figure 3 shows the heavy-flavor muon and electron [17] R_{dA} as a function of $\langle N_{\mathrm{coll}} \rangle$ for (a) $1 < p_T < 3\ \mathrm{GeV}/c$ and (b) $3 < p_T < 5\ \mathrm{GeV}/c$. Bars (boxes) around the data points represent the statistical (total) uncertainties determined as the quadratic sum of statistical (total) uncertainties on R_{dA} for each centrality class. The global uncertainty reflects the BBC efficiency for $p+p$ collisions. For more central $d+\mathrm{Au}$ collisions, the R_{dA} at midrapidity and backward rapidity show a similar enhancement ($R_{dA} > 1$) in both p_T ranges. The low-and high-p_T bins show comparable suppression patterns as a function of centrality. The EPS09s-nPDF-based calculations are qualitatively consistent with the data.

Quarkonia and open heavy-flavor hadrons are sensitive to the same effects on heavy-quark production. However, quarkonium states are additionally influenced by breakup

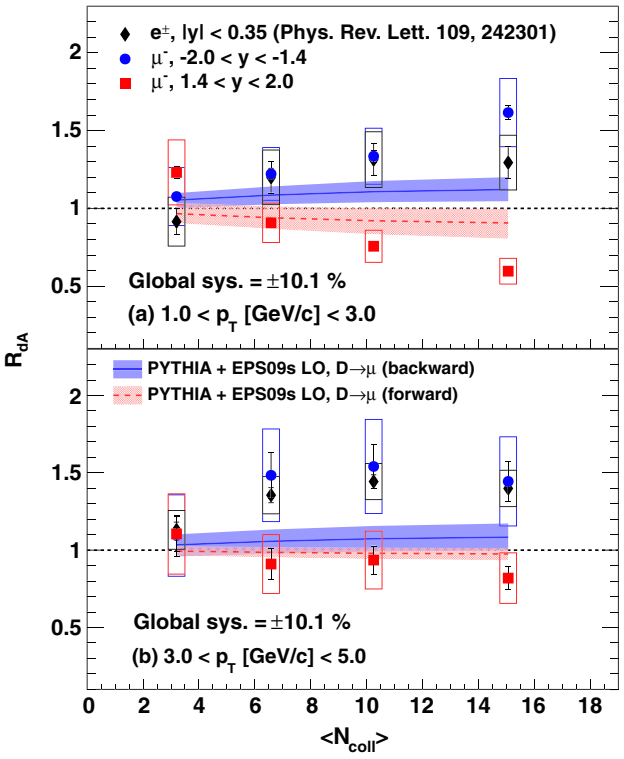

FIG. 3 (color online). Comparison of R_{dA} as a function of $\langle N_{\mathrm{coll}} \rangle$ for heavy-flavor leptons from different rapidity and p_T bins. Data in the top (bottom) panel are from low ($1 < p_T < 3\ \mathrm{GeV}/c$) and moderate ($3 < p_T < 5\ \mathrm{GeV}/c$) p_T ranges. Diamonds represent heavy-flavor electrons at midrapidity [17] and squares (circles) represent heavy-flavor muons at forward (backward) rapidity.

in nuclear matter. Therefore, open heavy-flavor production can provide a baseline for interpreting the nuclear breakup of quarkonia. Previous measurements suggest that nuclear breakup has a significant effect on quarkonium production in p-nucleus and nucleus-nucleus collisions [21,29,33–37].

Figure 4 shows a comparison of R_{dA} between heavy-flavor muons and J/ψ [21] for central collisions. A similar behavior across the entire p_T range is observed at forward rapidity, within the total uncertainties, whereas a distinct difference is seen at backward rapidity, particularly for $p_T < 2.5\ \mathrm{GeV}/c$, where charm contributions dominate over those from the bottom [38]. The larger difference of the R_{dA} between J/ψ and open charm at backward rapidity compared to forward rapidity could be related to the longer time this $c\bar{c}$ state requires to traverse the nuclear matter or the larger density of comoving particles after the initial collision at backward rapidity [39]. This comparison suggests that an additional CNM effect, nuclear breakup, significantly affects J/ψ production both at backward rapidity and, as seen earlier [17,21], at midrapidity. This measurement provides a key additional constraint on theoretical models attempting to describe quarkonia yields in nuclear collisions.

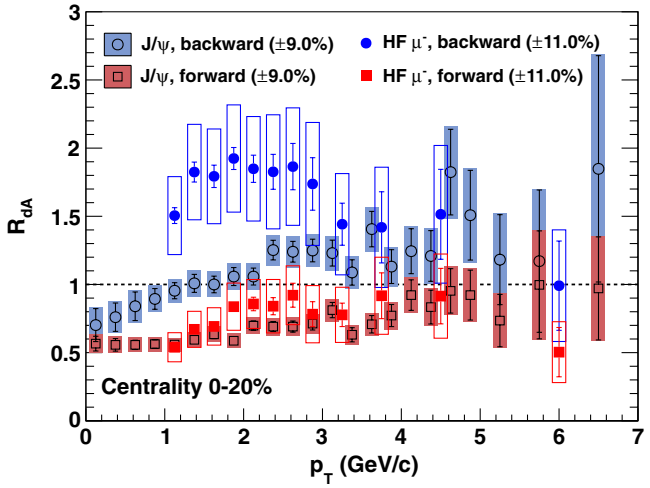

FIG. 4 (color online). The nuclear modification factor R_{dA} for J/ψ [21] and heavy-flavor muons for the 0%–20% centrality class. The global systematic uncertainty on each distribution is shown as a percentage in the legend.

We have presented a measurement of negatively charged heavy-flavor muons produced at forward and backward rapidity in $d+\mathrm{Au}$ collisions at $\sqrt{s_{NN}}=200$ GeV, for several centrality classes. We observe no significant modification in the most peripheral $d+\mathrm{Au}$ collisions. However, in central $d+\mathrm{Au}$ collisions, suppression (enhancement) of heavy-flavor muons is observed at forward (backward) rapidity. The large difference between forward and backward rapidity, which cannot be reproduced by PYTHIA calculations with the EPS09s nPDF sets nor with the combination of additional nuclear-p_T broadening, suggests the importance of CNM effects beyond nPDF modification, as well as the possibility of final-state interaction in $d+\mathrm{Au}$ collisions. A model including some of these effects successfully reproduces an enhanced hadron production in a higher-parton-density system. A comparison between the measured nuclear modification factors for J/ψ and open heavy-flavor production provides a strong indication that nuclear breakup significantly affects quarkonium production.

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