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Impact parameter dependence of the nuclear modification of J/ψ production in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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The centrality dependence of $\sqrt{s_{NN}} = 200$ GeV d+Au J/ψ data, measured in 12 rapidity bins that span $-2.4 < y < 2.4$, has been fitted using a model containing an effective breakup cross section combined with EPS09 shadowing. The centrality dependence of the shadowing contribution was allowed to vary nonlinearly, employing a variety of assumptions, in an effort to explore the limits of what can be determined from the data. It is found that the onset of shadowing is a highly nonlinear function of impact parameter. The impact parameter dependencies of the effective breakup cross section and the shadowing parameterization are sufficiently distinct to be determined separately.

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The modification of the gluon distributions in nuclear targets in high energy collisions, referred to here as gluon shadowing, is inherently interesting because of what it can teach us about the behavior of gluons at low Bjorken momentum fraction, x, where the gluon densities are high and saturation effects are expected to become important [1]. In addition, the modification of parton distributions in nuclei determines the initial conditions in a high energy nuclear collision. The initial conditions must be sufficently well understood before final-state hot matter effects can be isolated.

Parameterizations of the dependence of nuclear modified parton distribution functions (nPDFs) on x and squared momentum transfer, Q^2, have been extracted by several groups from data that include deep inelastic electron-nucleus scattering (DIS) and Drell-Yan (DY) dilepton production in $p + A$ collisions. The DIS and DY data together provide strong constraints on valence and sea quark modifications [2–5]. Including neutrino-induced DIS data from heavy targets can discriminate between quarks and antiquarks [3, 4]. Inclusive pion production data from RHIC have also been incorporated to better constrain the gluon modifications [4, 5].

The measurements used to extract the nPDFs cited above [2–5] were all averaged over impact parameter. Therefore these nPDFs represent the parton modification averaged over the entire nucleus. If the modification of these nPDFs is desired as a function of the impact parameter, a specific dependence has been assumed [6]. A different approach, employing Gribov theory and incorporating diffractive data, allows the spatial information to be retained [7].

Recently, the impact parameter dependence of the EPS09 [5] and EKS98 [8] nPDF's has been parameterized [9] using the target mass dependence of the EPS09 and EKS98 parameter sets themselves. Terms up to fourth order in the nuclear thickness were necessary to produce A-independent coefficients.

In this paper, we address the impact parameter dependence of gluon shadowing in a different way, using the collision centrality and rapidity dependence of the J/ψ yields measured in $\sqrt{s_{NN}} = 200$ GeV d+Au collisions at RHIC [10]. We were motivated by the observation [10, 11] that the onset of J/ψ suppression at forward rapidity suggests a quadratic or higher dependence on the nuclear thickness function at impact parameter r_T, $T_A(r_T)$.

Gluon-gluon interactions dominate J/ψ production in high-energy hadronic collisions. Therefore, J/ψ production in p(d)+A collisions must reflect the gluon modification in the nuclear target. However, the measured modifications of J/ψ yields in p(d)+A collisions relative to $p + p$ collisions are also sensitive to the breakup of bound $c\bar{c}$ pairs by collisions with nucleons as the pairs pass through the medium. This effect, as well as effects due to any processes aside from shadowing, are usually parameterized by an effective absorption cross section, $\sigma_{\rm abs}$, fitted to the measured data (see *e.g.* Ref. [12]). The main goal of this work was to determine whether the effects of shadowing could be separated from those embodied in $\sigma_{\rm abs}$. Because the magnitude of the effect due to $\sigma_{\rm abs}$ depends exponentially on nuclear thickness for a constant $\sigma_{\rm abs}$, such separation may be possible if shadowing has a stronger thickness dependence.

We assumed that the shadowing modification, integrated over all r_T, could be described by the EPS09 gluon modification [5] and fitted the r_T dependence of shadowing and the magnitude of $\sigma_{\rm abs}$ to the data. A Glauber Monte Carlo calculation [13] allows the modification, calculated for individual nucleon-nucleus collisions, to be correctly averaged and integrated over centrality, rapidity and p_T. It also accounts for the effects of trigger efficiency in peripheral events. The Glauber parameters used here are identical to those used by PHENIX when calculating the experimental centrality distributions [10]. The Woods-Saxon nuclear density distribution has a radius of 6.34 fm and a diffuseness of 0.54 fm. No nuclear modification is assumed for the deuteron. The baseline J/ψ p_T and rapidity distributions used in the calculation were the $p+p$ distributions measured by PHENIX [14].

The values of the target momentum fraction, x_2, and squared momentum transfer, Q^2, were assumed to obey approximate $2 \to 1$ kinematics as a functions of J/ψ rapidity and transverse momentum:

$$x_2 = \frac{\sqrt{M^2 + p_T^2}}{\sqrt{s_{NN}}} e^{-y} , \quad (1)$$

$$Q^2 = M^2 + p_T^2 , \quad (2)$$

where M is the J/ψ mass. The $2 \to 1$ kinematics are not strictly correct since a high p_T J/ψ requires production of an associated hard parton. However, Eqs. (1) and (2) differ from exact $2 \to 1$ kinematics since the p_T of the J/ψ is finite. This approximation is close to the inclusive J/ψ kinematics in the CEM calculation described in Ref. [15], NLO in the total cross section. Thus modifications of the gluon distribution in the nucleus are similar in the CEM calculation and the Glauber Monte Carlo using Eqs. (1) and (2). The results also agree with those found using PYTHIA [11].

We tested several assumptions of the r_T dependence of shadowing. Each of the postulated behaviors had one or two parameters that were adjusted to the data, along with the magnitude of $\sigma_{\rm abs}$. The Glauber Monte Carlo was employed to compare the modification of the J/ψ yields to the PHENIX d+Au data, averaged over four centrality bins and twelve rapidity bins, then integrated over all p_T. We fitted $\sigma_{\rm abs}$ and the shadowing parameters to the PHENIX data using a modified $\bar{\chi}^2$ function that properly accounts for all of the experimental uncertainties. Systematic uncertainties are included by moving the data points through $\pm 3\sigma$ in each systematic uncertainty while taking an appropriate $\bar{\chi}^2$ penalty [16].

We first assume that the shadowing strength is proportional to $T_A^n(r_T)$. The power n was allowed to be unphysically large, $n \leq 50$. By allowing such arbitrarily large values of n, we test the sensitivity of the data to the centrality dependence of the shadowing. The values of $\sigma_{\rm abs}$ and n were determined individually at each rapidity, giving an overall $\bar{\chi}^2$/dof of 1.0.

The $\bar{\chi}^2$ contours in $\sigma_{\rm abs}$ and n corresponding to $\Delta\bar{\chi}^2 = 1.0$ and 2.3 are shown in Fig. 1 for the most backward rapidity, midrapidity, and the most forward rapidity. At midrapidity, the fits are insensitive to n because the shadowing effects are weak. At forward and backward rapidity, the optimum n is large, $n \geq 10$, indicating that the data require a strongly nonlinear onset of shadowing or antishadowing as a function of impact parameter. Additionally, there is relatively little correlation, and thus little ambiguity, between n and $\sigma_{\rm abs}$ for n greater than a few.

The uncertainties in the fitted parameters at each rapidity were taken from the maximum extent of the $\Delta\bar{\chi}^2 = 1$ contour. The optimum value of $\sigma_{\rm abs}$ and the corresponding uncertainty at each rapidity is shown by the red squares in Fig. 2. The $\sigma_{\rm abs}$ values are reasonably well defined, with a minimum near midrapidity. Because

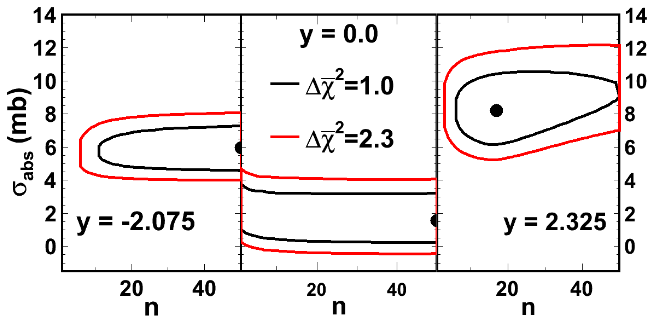

FIG. 1: The $\bar{\chi}^2$ distributions for the most backward, mid and most forward rapidities when $\sigma_{\rm abs}$ and n are optimized separately at each rapidity.

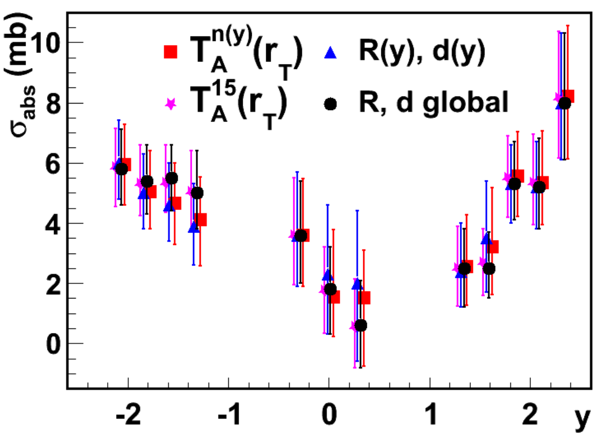

FIG. 2: The optimum values and uncertainties on $\sigma_{\rm abs}$ as a function of rapidity obtained from the four fits described in the text. For clarity, the rapidities for each fit are slightly offset.

the data at all rapidities are consistent with $n \geq 5$, we repeated the fit assuming a rapidity-independent value of n. The optimum value $n = 15$ gave a good description of the data, with $\bar{\chi}^2$/dof $= 0.84$ overall. The best fit values of $\sigma_{\rm abs}$ with $n = 15$ are given by stars in Fig. 2.

The fits favor (or at midrapidity are consistent with) a highly nonlinear dependence of shadowing on $T_A(r_T)$. The resulting modification is negligible at large r_T, but drops sharply as r_T decreases below $\sim 2-3$ fm. This behavior suggested that a step function onset of shadowing, including a radius, R, and a diffuseness, d, parameter,

$$M_{\rm shad} = 1 - \left(\frac{1 - R_g(x, Q^2)}{a(R, d)}\right)/(1 + e^{(r_T - R)/d}) , \quad (3)$$

would be more appropriate. Here $R_g(x, Q^2)$ is the EPS09 gluon modification and the normalization factor, $a(R, d)$, is adjusted so that the integral over all impact parameters returns the average EPS09 modification.

We first fitted the parameters R and d, along with $\sigma_{\rm abs}$, at each rapidity, finding $\bar{\chi}^2/{\rm dof} = 1.8$. The optimum $\sigma_{\rm abs}$ values, triangles in Fig. 2, are very similar to those obtained from the earlier fits employing $T_A^n(r_T)$. The fits favor R values of about half the Au radius, $R \leq 3.5$ fm, and a small diffuseness parameter although they are relatively insensitive to the value of d.

Finally, we fitted $\sigma_{\rm abs}$ to the data at each rapidity while fitting global values of R and d. We find $\bar{\chi}^2/{\rm dof} = 0.84$ over all values of y. The best fit $\sigma_{\rm abs}$ values at each rapidity are shown by circles in Fig. 2. The fit results and $R_{\rm dAu}$ are compared as a function of r_T in Fig. 3. The dashed curves indicate the uncertainty in $R_{\rm dAu}$ due to the uncertainty in $\sigma_{\rm abs}$. Because $\bar{\chi}^2$ includes the global uncertainties on the data, the best fit values may have a slight vertical offset from the data to achieve the best overall $\bar{\chi}^2$. The $\bar{\chi}^2$ contours in R and d are shown in Fig. 4. The optimum global parameter values are $R = 2.2^{+0.69}_{-0.56}$ fm and $a = 0.22^{+0.38}_{-0.20}$ fm, where the uncertainties are obtained from the maximum extent of the $\Delta\bar{\chi}^2 = 1.0$ contour.

The $\sigma_{\rm abs}$ values obtained from our various assumptions of the centrality dependence of shadowing are all compared in Fig. 2. The fitted values of $\sigma_{\rm abs}$ are well defined and show little dependence on the shadowing prescription, suggesting that the effects of shadowing can be separated from the effective breakup of the $c\bar{c}$ pair due to collisions with nucleons. Evidently, the strongly nonlinear onset of shadowing with decreasing r_T exhibits a distinctly different centrality dependence than the exponential dependence of $\sigma_{\rm abs}$ on $T_A(r_T)$.

The gluon modification obtained from the EPS09 parameterization using Eq. (3), with global fit values of R and d, is shown by the solid red line in Fig. 5. The effect of the combined uncertainty in R and d can be visualized by plotting the modifications for all combinations of R and d that produce a $\bar{\chi}^2$ value inside the $\Delta\bar{\chi}^2 = 2.3$ contour [17] (see Fig. 4). These are represented by the thin blue lines in Fig. 5. In all cases, the calculated modification is significant only for $r_T \lesssim 3$ fm. Therefore, we conclude that the data place strong constraints on the nuclear modification so that it becomes significant only at small r_T. The modification obtained with the best fit global power, $T_A^n(r_T)$, $n = 15$, is shown as the solid orange line in Fig. 5. Although there is some difference in the details at small r_T, albeit within the uncertainties, the two prescriptions give essentially the same value of $\bar{\chi}^2/{\rm dof}$. Thus the data appear to be insensitive to the detailed shape of the modification at low r_T, because the d+Au centrality bins are wide with significant overlap.

We compare our results obtained from the fits to the J/ψ data with those given by the newly-available impact parameter dependent EPS09 sets (EPS09s) [9], shown by the dotted magenta line in Fig. 5. The EPS09s result has a much weaker dependence on r_T than obtained in our fits.

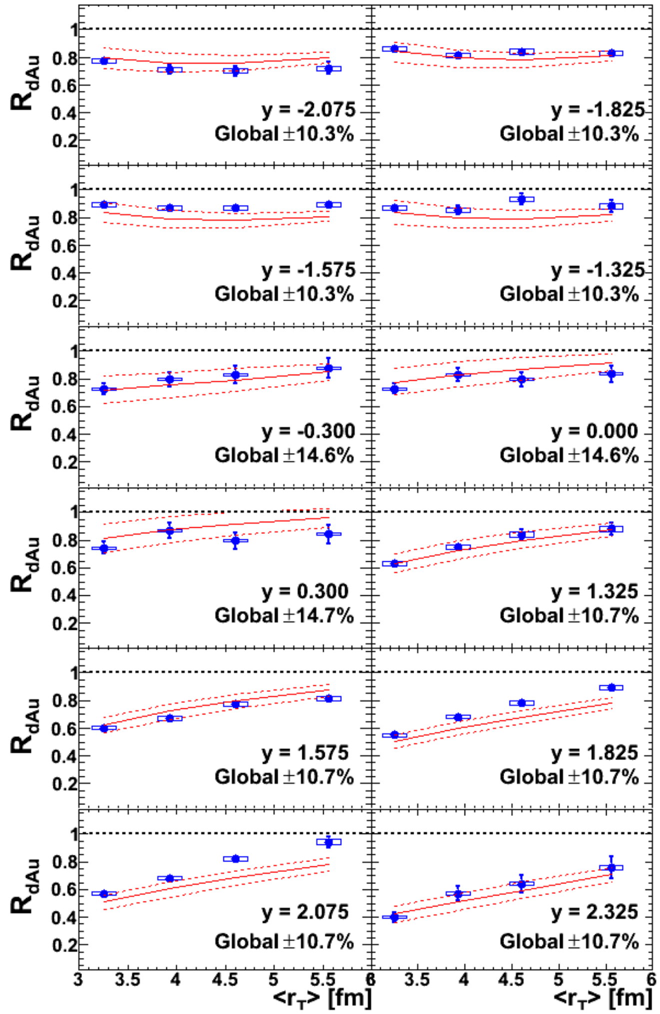

FIG. 3: Comparison to the data of the best fits with global R and d values.

In summary, we have fitted the centrality and rapidity dependent PHENIX $\sqrt{s_{NN}} = 200$ GeV d+Au J/ψ data with Glauber calculations employing an effective breakup cross section, $\sigma_{\rm abs}$, with several prescriptions for the impact parameter dependence of the central EPS09 gluon shadowing parameterization. The fits properly account for all of the experimental systematic uncertainties. We find little ambiguity between $\sigma_{\rm abs}$ and the functional form of the centrality dependence of shadowing. The values of $\sigma_{\rm abs}$ exhibit a characteristic rapidity dependence, with a minimum at midrapidity. The centrality dependence of shadowing suggested by the data turns on sharply for $r_T \leq 3$ fm, in significant disagreement with the weaker r_T dependence of EPS09s. Indeed, the EPS09s dependence is somewhat weaker than the linear dependence on the thickness function assumed in Ref. [6]. While we have

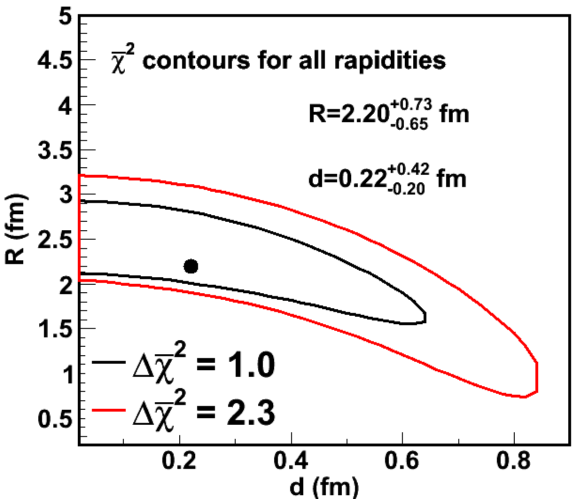

FIG. 4: The $\bar{\chi}^2$ contours obtained from the fits with global values of R and d, Eq. (3), with $\sigma_{\rm abs}$ fixed at the optimum value at each rapidity. The uncertainties in R and d are taken from the maximum extent of the $\Delta\bar{\chi}^2 = 1$ contour.

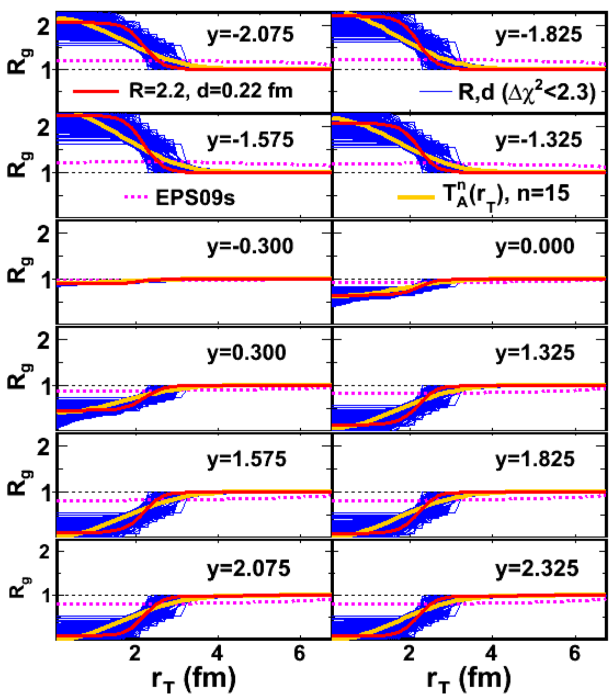

FIG. 5: The gluon modification from the best fit global R and d parameters (solid red line), along with the modifications from all combinations of R and d that fall within the $\Delta\bar{\chi}^2 = 2.3$ contour in Fig. 4 (thin blue lines). The modification from the best fit global analysis of $T_A^n(r_T)$ ($n = 15$) is shown by the solid orange line. The dashed magenta line is the recently released EPS09s impact parameter dependence [9].

employed only the central EPS09 set in our calculations, using all 31 EPS09 sets would not affect our overall conclusions regarding the sharp turn on of shadowing with r_T, only increase the uncertainty in the value of $\sigma_{\rm abs}$ as a function of rapidity. Rather, the strong impact parameter dependence suggested here is in better accord with the 'hot spots' conjectured in a saturated medium of high gluon density. Such behavior at backward rapidity, in the antishadowing region, is, however, at odds with the saturation picture and may more simply suggest that shadowing effects are concentrated in the core of the nucleus instead of throughout the nuclear volume.

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