Cold nuclear matter effects on $J/\psi$ production from PHENIX

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Abstract. It has become clear in recent studies of $d+Au$ collisions that quantifying the cold nuclear matter effects on $J/\psi$ production is critical to interpreting the results of $J/\psi$ production in heavy ion collisions at RHIC. Recent measurements of the rapidity and impact parameter dependence of $J/\psi$ production in $d+Au$ collisions at $\sqrt{s_{NN}}=200$ GeV by PHENIX show significant suppression at forward rapidity for collisions with small impact parameters, and require a modification which is stronger than linearly or exponentially dependent on the nuclear thickness to describe the forward rapidity data. New measurements of the transverse momentum dependence of the $J/\psi$ nuclear modification in $d+Au$ collisions show a cold nuclear matter effect which increases with increasing $p_T$ and suggests a cold nuclear matter contribution in heavy ion collisions which is large at high $p_T$.

1. Introduction
Measurements of quarkonia production in heavy ion (HI) collisions provide a unique probe of the screening length in the Quark Gluon Plasma (QGP) produced during HI collisions. The different binding energies, and therefore radii, of the various quarkonia states, coupled with precision measurements of their production in HI collisions should provide key insights into critical properties of the QGP.

A large suppression of $J/\psi$ production in Au+Au collisions relative to $p+p$ collisions has been measured by PHENIX at both mid and forward rapidities [1; 2]. However, interpreting these results in terms of suppression within a hot nuclear medium is impossible without a detailed understanding of the effects of producing a $J/\psi$ in a nuclear target, often termed Cold Nuclear Matter (CNM) effects. In order to provide the best chance at interpreting the heavy ion results, precision measurements of CNM effects at the same collision energy as the HI results are necessary.

A number of effects are predicted to modify $J/\psi$ production in a nuclear target, including nuclear breakup, nuclear shadowing, initial state energy loss, $p_T$-broadening, and gluon saturation (for a recent review, see [3]). Disentangling these effects is a daunting task but is facilitated by precision measurements over a broad range in collision centrality, rapidity ($y$) and transverse momentum ($p_T$).

Nuclear shadowing, the modification of parton distribution functions inside nuclei (nPDF’s), can be constrained by precision measurements of $J/\psi$ modification in $p+A$ collisions as a function of $y$ and $p_T$. Varying the measured rapidity and $p_T$ changes the sampled space in Feynman-$x$ and energy transfer ($Q^2$). $J/\psi$ production at RHIC energies can provide crucial constraints
on the gluon distributions which are only accessed indirectly by the deep inelastic scattering data which provides the bulk of the information used to derive the nPDF’s. Measurements as a function of collision centrality can also provide new and interesting insights into the geometric dependence of these nPDF distributions.

Measurements of the modification of $J/\psi$ production in nuclear targets as a function of $p_T$ provides constraints on $p_T$-broadening effects, which are not constrained by measurements of the rapidity or collision centrality alone.

Towards this end, PHENIX has made precision measurements of $J/\psi$ production in $d+Au$ collisions at $\sqrt{s_{NN}}=200$ GeV as a function of rapidity, $p_T$, and collision centrality using data taken in 2008 [4; 5]. These results show a number of interesting trends leading to new and exciting conclusions.

2. Rapidity dependence of the $J/\psi$ nuclear modification
The nuclear modification of $J/\psi$ production relative to $p+p$ collisions ($R_{dAu}$) is shown as a function of rapidity integrated over collision centrality and $p_T$ in Figure 1. The data show increasing suppression with increasing rapidity, with up to 40% suppression observed at forward rapidity (deuteron going direction) compared to 10% suppression observed at backward rapidity (Au going direction).

Also shown in Figure 1 are calculations of the nuclear modification from two models. The red curves are calculations which include nuclear shadowing, taken from the EPS09 nPDF set [6] combined with an example nuclear breakup cross section of $\sigma_{br} = 4$ mb which is constant across all rapidities. The EPS09 nPDF’s provide the nuclear modification of the free proton parton distribution functions as a function of $x$ and $Q^2$ for a given nucleus, $A$. Also included in EPS09 are 30 alternate sets which explore the plus and minus 1σ uncertainties in each of the parameters involved in their parameterization. The solid red curve in Figure 1 uses the central, or best fit, set from EPS09, while the two dashed red curves represent the sets which provide the maximum variation in the shape. In [4] the $\sigma_{br}$ value is chosen by eye to best match the backward rapidity $R_{dAu}$ when combined with the nuclear shadowing from the central EPS09 set, rather than fit to the data. This calculation shows good agreement with the measured $R_{dAu}$ across all rapidities.

The second calculation, shown by the green dashed line in Figure 1, incorporates gluon saturation at small-$x$ [7]. In this model, partons in the projectile nucleon’s can interact with multiple partons, possibly from different nucleons, in the target nucleus through coherent gluon scattering. The calculation is only valid in the small-$x$ region, and therefore is only valid at
Figure 2. The $J/\psi$ nuclear modification factors $R_{dAu}$ (0-20%) (a), $R_{dAu}$ (60-88%), and $R_{CP}$ as a function of rapidity [4]. The curves are calculations discussed in the text.

Figure 3. The $J/\psi$ $R_{CP}$ versus the collision centrality integrated $J/\psi$ $R_{dAu}$ [4]. The curves are discussed in the text.

forward rapidity at RHIC energies. The calculation shows good agreement with the forward rapidity data, however it deviates from the data at midrapidity, where the validity of the model is questionable.

The geometric dependence of the nuclear modification is probed by measuring the modification as a function of collision centrality. The $J/\psi$ $R_{dAu}$ for central (0-20%) and peripheral (60-88%) collisions is shown as a function of rapidity in Figure 2. Also shown in Figure 2 is the ratio of the modification in central events to that in peripheral events ($R_{CP}$). The advantage of the variable $R_{CP}$ is that many of the systematic uncertainties cancel, as the ratio is taken within the same data set. The data show constant suppression with rapidity in peripheral events, with an overall level of suppression consistent with unity within the systematic uncertainties. In contrast, a large suppression is observed at forward rapidity in central events, with a decrease in suppression with decreasing rapidity. This trend is also shown in the $J/\psi$ $R_{CP}$, which shows that the backward rapidity data is virtually unmodified between central and peripheral events, whereas the forward rapidity shows a large increase in suppression between central and peripheral events.

Calculations of the centrality dependence from the models presented in Figure 1 are also included in Figure 2. The gluon saturation shows good agreement with the data at forward rapidity, as in the centrality integrated case, but diverges from the data at midrapidity. EPS09 (and most other nPDF sets as well) calculate an average modification in the PDF’s across the nucleus. Therefore, when calculating the centrality dependence of the nuclear shadowing, some geometric dependence of the modification must be introduced. In [4], a linear dependence of the density weighted longitudinal thickness through the gold nucleus at the location of the struck nucleon, $r_T$,

$$\Lambda(r_T) = \frac{1}{\rho_0} \int dz \rho(r_T, z)$$  \hspace{1cm} (1)
is introduced, where \( \rho(r_T, z) \) is taken, on average, to follow a Woods-Saxon distribution. EPS09, with a linear dependence on \( \Lambda(r_T) \), combined with \( \sigma_{br} = 4 \text{ mb} \) agrees well with the \( R_{dAu} \) in central collisions across all rapidity. However, in peripheral collisions, it over predicts the suppression at forward rapidity. This is clearly shown in the difference between the calculation and the measured \( R_{CP} \) at forward rapidity.

To further investigate the geometric dependence of the \( d+Au \) data, three functional forms for the modification as a function of the longitudinal thickness, each with one free strength parameter \( a \) were tested,

\[
\text{Linear} : M(r_T) = 1 - a\Lambda(r_T) \\
\text{Quadratic} : M(r_T) = 1 - a\Lambda(r_T)^2 \\
\text{Exponential} : M(r_T) = e^{-a\Lambda(r_T)}.
\]

The nuclear modification factors can then be calculated for a given form of the modification, with a given value for the strength parameter \( a \), with \( r_T \) distributions of the PHENIX centrality bins obtained from a Glauber model of \( d+Au \) collisions. For a given form of the modification, a single value of \( a \) provides a unique relationship between \( R_{CP} \) and \( R_{dAu} \) (0-100%). Varying \( a \) for a given form of the modification creates a locus of points on the \( R_{CP} \) vs. \( R_{dAu} \) (0-100%) plane, on which any suppression with that geometric dependence must lie. The results for the three functional forms of the modification are shown in Figure 3, along with the data.

Figure 3 shows that at backward and midrapidity, the data is unable to distinguish between the three functional forms, as all three forms agree within uncertainties. At forward rapidity, however, there is no overlap between the data and the linear or exponential dependencies, and indeed, even the quadratic case is in poor agreement with the data. This shows that a longitudinal thickness dependence which is greater than exponential or linear is required by the forward rapidity data.

3. Transverse momentum dependence of the \( J/\psi \) nuclear modification

The \( J/\psi \) \( R_{dAu} \) as a function of \( p_T \) for centrality integrated \( d+Au \) collisions is shown in Figure 4 for three rapidity ranges, corresponding to the three PHENIX spectrometers [5]. When measuring the \( p_T \) dependence of \( J/\psi \) production the yield is integrated over the full rapidity of each spectrometer to maximize the \( p_T \) reach of the data, rather than using the same binning as shown, for example, in Figure 1. At mid and forward rapidities a suppression is observed at low-\( p_T \) which decreases with increasing \( p_T \), becoming consistent with an \( R_{dAu} \) of 1 at \( p_T \approx 3 - 4 \text{ GeV/c} \). A different behavior is observed at backward rapidity, where suppression is still observed at low-\( p_T \) but with a much more rapid decrease in suppression with increasing \( p_T \). The \( R_{dAu} \) at backward rapidity is consistent with, or greater than, 1 for \( p_T > 2 \text{ GeV/c} \).

Also shown in Figure 4 are two sets of calculations for the \( p_T \) dependence of \( R_{dAu} \). The pink dot-dashed curves are calculations by Kopeliovich et al. [8] which include nuclear shadowing (taken from the nDSg nPDF set), nuclear breakup, and the Cronin effect. The black dashed lines represent calculations by Ferreiro et al. [9] which include nuclear shadowing (also taken from the nDSg nPDF set) and nuclear breakup with \( \sigma_{abs} = 4.2 \text{ mb} \). In the calculation by Kopeliovich et al. a parameterization of the dipole cross section is used to calculate a nuclear breakup effect which is dependent on the \( J/\psi \) kinematics. At mid and forward rapidities, both sets of calculations agree reasonably well with the observed \( R_{dAu} \). At backward rapidity, neither calculation reproduces the rapid decrease in suppression seen at low-\( p_T \). This may indicate a different nPDF description is required at low-x, or an alternate physical effect which modifies the shape of the \( p_T \) distribution differently at backward rapidity than mid or forward rapidity.

The centrality dependence of the \( J/\psi R_{dAu} \) as a function of \( p_T \) is shown in Figures 5, 6, and 7 for backward, mid, and forward rapidity respectively. A strong centrality dependence is seen
in all three rapidity regions. In central events, suppression is seen at low-$p_T$ with a decrease in suppression with increasing $p_T$. Transitioning from central to peripheral events produces a flattening of the $p_T$ distribution, with the $R_{dAu}$ for peripheral events being relatively constant with $p_T$, with an $R_{dAu}$ consistent with 1 within the systematic uncertainties on the data at all three rapidities.

Two sets of calculations by Ferreiro et al. are also shown in Figures 5, 6, and 7, where the nuclear shadowing is assumed to be linearly dependent on the local density. The two sets of calculations only differ by the nPDF set used. The solid lines utilize the EKS98 nPDF set, which has a similar modification to EPS09, while the dashed curve utilizes the nDSg nPDF set. At mid and forward rapidities the difference manifests itself in an apparent overall scaling difference, with both sets of calculations agreeing well with the shape of the measured $R_{dAu}$. At backward rapidity, neither calculation is in agreement with the data. The EKS98 produces a $p_T$ dependence which has increasing suppression with increasing $p_T$, the opposite trend observed in the data. This difference between the EKS98 and nDSg calculations at backward rapidity is likely due to the difference in the modification in the EMC region of the shadowing curve.

At high-$x$, EKS98 predicts a transition from an enhancement in the gluon distribution to a suppression, whereas nDSg predicts little modification in either direction over the same region of $x$ and $Q^2$. This could be an indication that the backward rapidity data prefer no modification, or possibly a continued enhancement, of the gluon distribution at high-$x$ over the suppression included in EKS98.

A third set of calculations by Sharma and Vitev [10] is compared with the midrapidity centrality integrated $R_{dAu}$ in Figure 8. This model utilizes non relativistic quantum chromodynamics (NRQCD) to describe $J/\psi$ production. Nuclear shadowing is included through power suppressed coherent final-state scattering. Initial state energy loss and the Cronin effect...
Figure 5. The $J/\psi$ $R_{dAu}$ as a function of $p_T$ for 0-20% (a), 20-40% (b), 40-60% (c) and 60-88% $d+Au$ collisions at backward rapidity [5]. The curves are model calculations discussed in the text.

Figure 6. The $J/\psi$ $R_{dAu}$ as a function of $p_T$ for 0-20% (a), 20-40% (b), 40-60% (c) and 60-88% $d+Au$ collisions at mid rapidity [5]. The curves are model calculations discussed in the text.

Figure 7. The $J/\psi$ $R_{dAu}$ as a function of $p_T$ for 0-20% (a), 20-40% (b), 40-60% (c) and 60-88% $d+Au$ collisions at forward rapidity [5]. The curves are model calculations discussed in the text.

are also included. The solid red curve in Figure 8 shows the full calculation including the Cronin effect, while the dashed green line shows the calculation without the Cronin effect. The comparison of the two curves gives a direct indication of the strength of the Cronin effect, which is evidently over predicted compared to the data.

4. Implications on the measured suppression in heavy ion collisions

With precision measurements of the CNM effects on $J/\psi$ production in hand a detailed parameterization of the data, which describes well the measured rapidity, $p_T$ and centrality dependence, is required to make accurate qualitative predictions of the CNM effects in HI collisions. However, the data alone give a number of implications about the hot nuclear matter effects on $J/\psi$ production in HI collisions.

Measurements of the $J/\psi$ nuclear modification factor, $R_{AA}$, in Cu+Cu collisions by PHENIX [11] and STAR [12] as a function of $p_T$ is shown in Figure 9. Based on the high-$p_T$ behavior of $R_{dAu}$ an $R_{AA} \approx 1$ would be expected from CNM effects alone, possibly indicating that the observed $R_{AA}$ in Cu+Cu at high-$p_T$ could indicate a lack of suppression both from CNM and hot nuclear matter effects, rather than an enhancement in the $J/\psi$ production due to recombination effects. A detailed propagation of the CNM effects to HI collisions is required before making an stronger quantitative conclusions.

Similar arguments can give insight into the CNM baseline in Au+Au without a full propagation of the $d+Au$ results. The measured $p_T$ dependence of the $J/\psi$ $R_{AA}$ by PHENIX is shown in Figure 10. Strong suppression is seen for $p_T < 4$ GeV/c in central and mid-
Figure 8. The $J/\psi R_{dAu}$ as a function of $p_T$ for 0-100% $d$+Au collisions [5]. The curves are calculations from [10] described in the text.

Figure 9. The $J/\psi R_{AA}$ in Cu+Cu collisions as a function of $p_T$ at midrapidity [12].

Figure 10. The $J/\psi R_{AA}$ in Au+Au collisions as a function of $p_T$ at mid and forward rapidities [2].

central events, while the suppression pattern is unclear for peripheral events due to the large uncertainties on the data. At midrapidity the cold nuclear matter $R_{AA} (R_{AA}(CNM))$ can be approximated by $R_{dAu}^2$. It should be stressed that this is only an approximation, and no substitute to a detailed propagation of the $d$+Au results. At low-$p_T$ the $d$+Au data suggest an $R_{AA}(CNM) \approx 0.5$, while the observed $R_{AA} \approx 0.4$ in central events, indicating possible suppression beyond CNM effects from this crude approximation. At forward rapidity the $R_{AA}(CNM)$ can be approximated by folding the backward and forward $R_{dAu}$, giving $R_{AA}(CNM) \approx 0.5$ for low-$p_T$ at forward rapidity compared to the measured $R_{AA} \approx 0.2$ for central collisions. This shows possibly substantial suppression compared to CNM effects. While this is only an approximation, it does show that the CNM effects are likely large in HI collisions,
and cannot be neglected.

5. Summary
The PHENIX experiment has made precision measurements of the nuclear modification of $J/\psi$ production in $d+Au$ collisions as a function of rapidity, $p_T$, and collision centrality, paving the way for a detailed understanding of CNM effects on $J/\psi$ production at RHIC energies. These results include many interesting physical implications. The centrality dependence of the forward rapidity $R_{dAu}$ require a nuclear modification which is stronger than linearly or exponentially dependent on the longitudinal nuclear thickness. The $p_T$ dependence of $R_{dAu}$ show an $R_{dAu}$ which is consistent with 1.0 for $p_T > 4$ GeV/c at mid and forward rapidity, with an $R_{dAu} > 1$ for $p_T > 4$ GeV/c at backward rapidity. The backward rapidity $R_{dAu}$ also show a very different shape of the $p_T$ dependence when compared to mid and forward rapidity, a change which is unexplained by current theoretical models.

A parameterization able to describe the rapidity, $p_T$, and centrality dependence of the $J/\psi$ $R_{dAu}$ will allow the propagation of the CNM effects to HI collisions, allowing quantitative calculations of the hot nuclear matter effects at RHIC energies. This is the next step towards understanding quarkonia production in heavy ion collisions.

References
[1] Adare A et al. (PHENIX Collaboration) 2007 Phys.Rev.Lett. 98 232301
[2] Adare A et al. (PHENIX Collaboration) 2011 Phys.Rev. C 84 054912
[3] Brambilla N, Eidelman S, Heltsley B, Vogt R, Bodwin G et al. 2011 Eur. Phys. J. C 71 1534
[4] Adare A et al. (PHENIX Collaboration) 2011 Phys.Rev.Lett. 107 142301
[5] Adare A et al. (PHENIX Collaboration) 2012 (Preprint 1204.0777)
[6] Eskola K, Paukkunen H and Salgado C 2009 JHEP 0904 065
[7] Kharzeev D and Tuchin K 2006 Nucl.Phys. A770 40–56
[8] Kopeliovich B, Potashnikova I and Schmidt I 2011 Nucl. Phys. A 864 203–212
[9] Ferreiro E, Fleuret F, Lansberg J, Matagne N and Rakotozafindrabe A arXiv:1201.5574 (2012).
[10] Sharma R and Vitev I arXiv:1203.0329 (2012).
[11] Adare A et al. (PHENIX Collaboration) 2008 Phys. Rev. Lett. 101 122301
[12] Abelev B et al. (STAR Collaboration) 2009 Phys. Rev. c 80 041902