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J/Ψ Measurement in $p+p$, $d+Au$ and $Au+Au$ Collisions by the PHENIX Experiment at RHIC

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Abstract. J/ψ's are produced mostly via interactions involving gluons, and are a sensitive probe of the gluon structure function and its modification in nuclei. They are also considered as a leading signal for studying the creation of hot and dense matter in relativistic heavy ion collision. Measurement of J/ψ production in different colliding systems is important for understanding the nuclear modification factor, and setting a baseline for the study of J/ψ suppression in heavy ion collisions. In this talk we report the latest results on J/ψ measurements by the PHENIX experiment at RHIC in $p+p$, $d+Au$, and $Au+Au$ collisions at backward, forward, and mid-rapidity. Nuclear effects are studied as a function of transverse momentum, rapidity and centrality.

Keywords: J/ψ, relativistic heavy ion collisions
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1. Introduction

J/ψ's were long considered as a leading signal for studying the creation of hot and dense matter in relativistic heavy-ion collisions [1]. Also, since they are produced predominantly through diagrams involving gluons (e.g. gluon fusion) [2], J/ψ's are a sensitive probe of the gluon structure function and its modification in nuclei. In order to look for effects beyond what is expected from cold nuclear matter, such as the creation of Quark Gluon Plasma, "normal" nuclear effects must be understood first.

These normal nuclear effects include shadowing of partons (quarks or gluons) in nuclei, that is, a depletion of their population at small momentum fraction. Recent theoretical developments suggest that at very low momenta non-linear gluon saturation effects become important, and cause substantial modifications of the gluon densities, e.g. as in the Color Glass Condensate model [3].

Other nuclear effects on J/ψ production include the energy loss and multiple

scattering of the gluon in the initial state before production of the $c\bar{c}$, and absorption in the final state [4].

Theoretical analysis of these nuclear effects on J/ψ production is challenging, given the poorly known production mechanism, and the fact that approximately a third of the J/ψ 's are produced indirectly via decays from higher-mass resonances [5]. Thus, a detailed study involving different colliding systems with broad coverage in rapidity and transverse momentum is necessary.

Here we present measurements made by the PHENIX experiment at RHIC for the production of J/ψ 's in 200 GeV/nucleon proton-proton ($p+p$), deuterium-gold ($d+Au$) and gold-gold ($Au+Au$) collisions. These data provide the first nuclear dependence measurements at $\sqrt{s} = 200$ GeV, a much higher energy than previous measurements from fixed-target experiments near or below $\sqrt{s} = 40$ GeV [6–10].

2. Experimental Setup and Data Analysis

The measurements described here were made with two muon spectrometers at forward ($1.2 < \eta < 2.4$) and backward ($-1.2 < \eta < -2.2$) rapidities, along with two central arm spectrometers at mid-rapidity ($|\eta| \leq 0.35$). The two central arms each cover 90° of ϕ, while the muon arms have full ϕ coverage.

Electrons in the central arms are identified by matching charged particle tracks to clusters in an electromagnetic calorimeter (EMC), and to rings in a ring imaging Cerenkov (RICH) detector.

Muons are identified by their detection in identifier tubes after their penetration through 6.5 to 8.5 interaction lengths of copper and steel absorber.

More details can be found in [11] and [12].

For the di-muons the J/ψ yield is obtained after subtraction of the combinatoric background using like-sign muon pairs ($2\sqrt{N_{++} \cdot N_{--}}$) and by fitting the resulting mass peak with a Gaussian and an exponential to represent the small remaining continuum background underneath the peak. A variety of continuum shapes were checked for each fit, in order to establish the uncertainty due to the low-statistics background.

For the di-electrons the combinatoric background was subtracted using the sum of like-sign pairs and the J/ψ yield was taken as all remaining events in the mass range 2.6 to 3.6 GeV/c^2.

3. p+p results

In Fig. 1a, we show the measured $p+p$ differential cross section times branching ratio versus rapidity with a di-electron point at mid-rapidity and two di-muon points at large positive and negative rapidities. A fit to a shape generated with PYTHIA using the GRV98LO parton distributions is performed, and gives a total $p+p$ cross section, multiplied by the dilepton branching ratio of BR $\times\, \sigma_{pp}^{J/\psi} = 155$ nb $\pm$ 7.6%(fit)$\pm$10%(abs) where the first uncertainty comes from the fit and thus includes

both the statistical and point-to-point systematics and the second accounts for absolute normalization uncertainty. Variations in the parton distribution functions and models used to determine the shape were demonstrated to be less than 3% [11] and are neglected here.

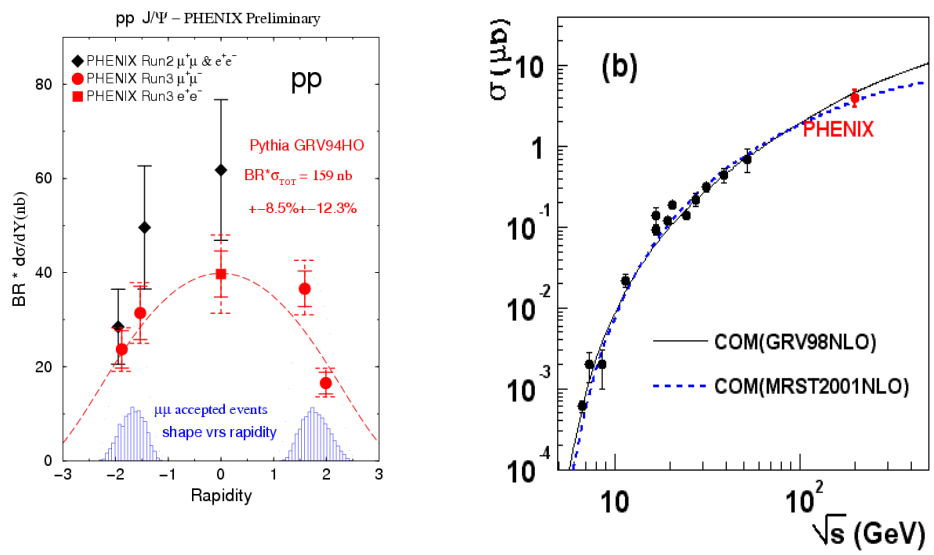

Fig. 1. (a) The 200 GeV J/ψ p+p differential cross section times dilepton branching ratio versus rapidity. (b) J/ψ total cross section as measured by the PHENIX experiment in p+p collisions compared with previous measurements at lower $\sqrt{s}$. The curves are discussed in the text.

The total J/ψ cross section determined in this analysis is shown in Fig. 1b, along with cross sections determined by lower energy experiments [13] and predictions from the COM [14] using two different PDFs. The $\sqrt{s}$ dependence of the cross section is sensitive to the factorization scale Q, since the shape of the PDFs depend on Q. The values of Q (3.1 GeV for GRV98NLO and 2.3 GeV for MRST2001NLO) were chosen to give good agreement with the data. The total cross section normalization was obtained using color octet matrix elements from [15], but has large theoretical uncertainties associated with the charm quark mass and the renormalization scale.

4. d+Au results

The ratio of the J/ψ differential cross section for $d+Au$ to that for $p+p$ scaled up by 2×197 (R_{dA}) is shown in Fig. 2a. The dashed error bars represent statistical and point-to-point systematic uncertainties relevant for comparing the two rapidity bins in each muon arm, while the solid error bars represent the overall uncertainties common to one spectrometer relevant for comparing points at negative, central or positive rapidity. A value of one for this ratio would correspond to binary scaling or no nuclear modification. While this ratio is close to unity at backward rapidity, it is significantly lower at forward rapidity, where the gluon parton distribution is expected to be shadowed in a heavy nucleus.

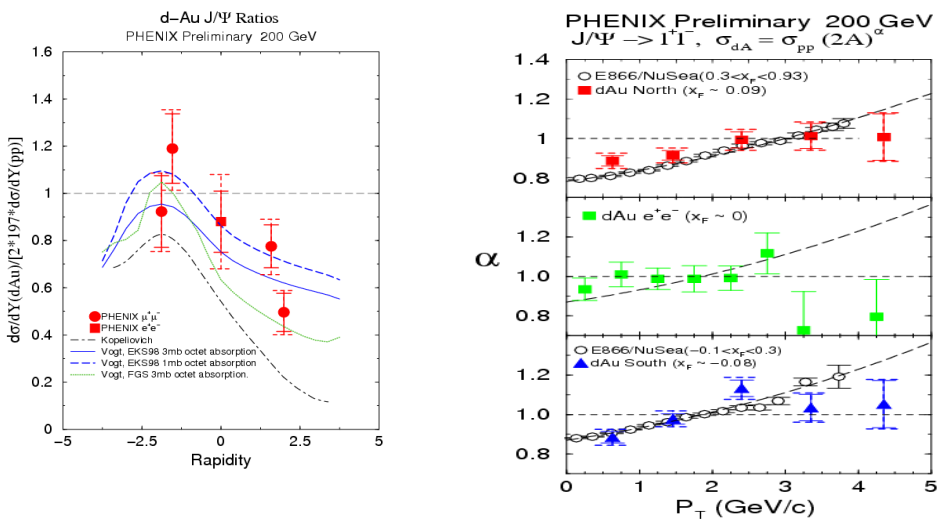

Fig. 2. (a) R_{dA} versus rapidity. Curves are theoretical predictions described in the text. (b) Nuclear modification factor α (defined in the text) versus p_T compared to lower energy measurements, shown for three different rapidity ranges. Solid error bars represent statistical and point-to-point systematic uncertainties. The dashed curves are empirical fits [7] to the lower energy results.

Theoretical predictions [16–18] that include the effects of absorption and shadowing are shown on the figure for comparison. The drop below one at large positive rapidity (small gluon momentum fraction in Au, $x_{Au} \sim 3 \times 10^{-3}$) is most consistent with the EKS shadowing. Sensitivity to the $c\bar{c}$ absorption cross section (3 or 1 mb), with present statistical errors, is marginal.

Our differential cross sections versus transverse momentum, $(d^2\sigma/dydp_T)/(2\pi p_T)$,

have been fitted to the form [19] $A \times (1 + (p_T/B)^2)^{-6}$. Average p_T^2 values resulting from these fits are 4.43 ± 0.21, 3.91 ± 0.28 and 3.64 ± 0.24 (GeV/c)^2 for $d + Au$ collisions at backward, central and forward rapidity, respectively; compared with 2.51 ± 0.21 and 4.19 ± 0.77 for forward/backward and central $p + p$ collisions, respectively. Our observed p_T broadening, as shown in Fig. 2b, is comparable to that of the lower energy ($\sqrt{s_{NN}} = 39$ GeV) measurements from E866/NuSea [7] which are also shown in the figure.

The suppression seen in Fig. 2a does not scale with x_{Au}, as would be expected if the suppression were dominated by shadowing at these energies. Instead, it appears to scale with $x_F = x_D - x_{Au}$ as shown in Fig. 3. Initial-state gluon energy loss might be expected to scale with x_F (since $x_F \approx x_D$) and could be important. However this scaling behavior remains a challenge to theoretical models.

It is also of interest that our nuclear dependence ratios are similar to those that were observed for inclusive charged hadrons [20] in $d + Au$ collisions, where a ratio near one was seen at negative and mid-rapidity, while a value of about 0.75 was seen at forward rapidity.

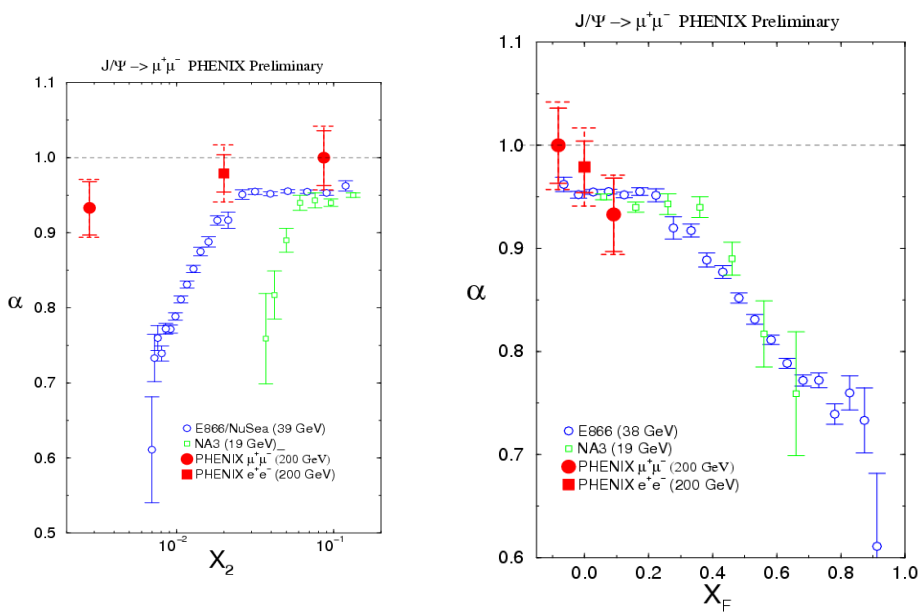

Fig. 3. α versus (a) x_F and (b) x_{Au} with present 200 GeV J/ψ results compared to lower energy results [7,10]. Here we use α, defined as $\sigma_{dA} = \sigma_{pp} \times (2 * A)^{\alpha}$, to allow comparison of measurements for different nuclei.

Another inportant tool for understanding the J/ψ production mechanizm is the study of J/ψ polarization. The polarization of J/ψ's produced in $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV is shown as a function of p_T in Fig. 4. Polarization parameter

λ was obtained from $1 + \lambda \cdot cos^2(\theta)$ fit to the data, where θ is the angle between lepton momentum in J/ψ rest frame and J/ψ momentum in lab frame. The result is consistent with no polarization. More data are necessary to draw any conclusions from this measurement.

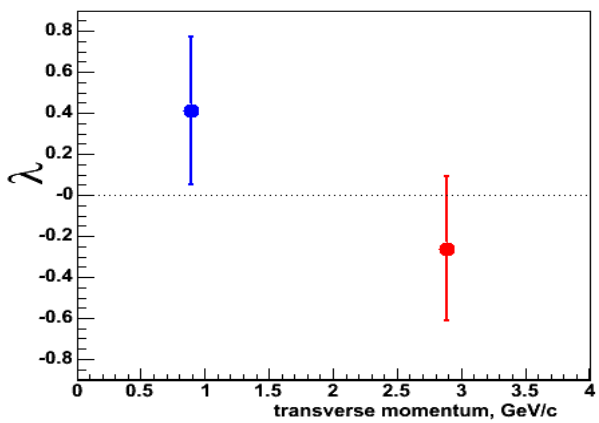

Fig. 4. J/ψ polarization vs p_T. Statistical errors only are shown. Systematic error is negligible compared to the statistical one.

5. Au+Au results

In Fig. 5, we show the J/ψ invariant yield per binary collision from $p+p$ reactions and three exclusive centrality ranges of $Au + Au$ reactions all at $\sqrt{s_{NN}} = 200$ GeV measured via electron-positron pairs. We find that models that predict J/ψ enhancement relative to binary collision scaling are disfavored, while we cannot discriminate between various scenarios leading to suppression relative to binary scaling due to low statistics of this measurement.

The lowest curve in Fig. 5 is a calculation including "normal" nuclear absorption in addition to substantial absorption in a high temperature quark-gluon plasma [22]. The curve above this is including recombinations of $c\bar{c}$ pairs that recreate J/ψs. The statistical model [23] result is shown as a dotted curve for mid-central to central collisions just above that. The four highest dashed curves are from the plasma coalescence model [21] for a temperature parameter of $T = 400$ MeV and charm rapidity widths of $\Delta y = 1.0$, 2.0, 3.0, 4.0, from the highest to the lowest curve respectively.

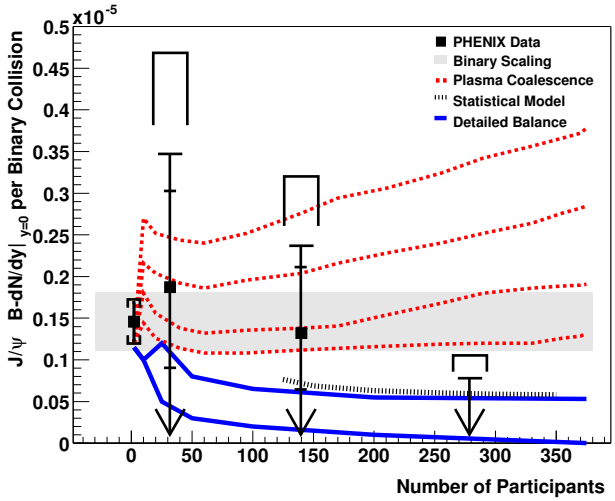

Fig. 5. The J/ψ invariant yield per binary collision is shown from proton-proton reactions and three exclusive centrality ranges of Au-Au reactions all at $\sqrt{s_{NN}}$ = 200 GeV. The curves are theoretical predictions desribed in the text.

6. Conclusions

In summary, the PHENIX experiment has measured J/ψ invariant yield in $p+p$, $d+Au$, and $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV as a function of rapidity and transverse momentum.

In $p+p$ collisions transverse momentum distributions above 2 GeV/c are reasonably well described by the COM. With the present statistical precision, our rapidity distribution shape is consistent with most of the available PDFs. COM calculations are able to reproduce the $\sqrt{s}$ dependence of the cross section using color octet matrix elements found in the literature, with a reasonable choice of QCD parameters.

In $d+Au$ collisions the rapidity dependence is consistent with weak shadowing of gluon distribution functions, and weak nuclear absorption. The usual p_T broadening in nuclear collisions is observed, similar to what was observed at lower $\sqrt{s}$. However, given the limited statistics, it is difficult to quantify the level of J/ψ absorption or to distinguish between various theoretical models of shadowing.

In $Au+Au$ collisions we find that models that predict J/ψ enhancement relative to binary collision scaling are disfavored, while we cannot discriminate between various scenarios leading to suppression relative to binary scaling.

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