# $J/\psi$ Production and Nuclear Effects for $d + Au$ and $p + p$ Collisions at $\sqrt{s_{NN}} = 200$ GeV

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$J/\psi$ production in $d + Au$ and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV has been measured by the PHENIX experiment at rapidities $-2.2 < y < +2.4$. The cross sections and nuclear dependence of $J/\psi$ production versus rapidity, transverse momentum, and centrality are obtained and compared to lower energy $p + A$ results and to theoretical models. The observed nuclear dependence in $d + Au$ collisions is found to be modest, suggesting that the absorption in the final state is weak and the shadowing of the gluon distributions is small and consistent with DGLAP-based parameterizations that fit deep-inelastic scattering and Drell-Yan data at lower energies.

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$J/\psi$ production in hadron collisions, since it proceeds predominantly through diagrams involving gluons (e.g.

gluon fusion) [1], is a sensitive probe of the gluon structure function in the nucleon and its modification in nuclei. It is also a leading signal for the creation of hot-dense matter in heavy-ion collisions [2]. Shadowing of partons (quarks or gluons) in nuclei is a depletion of their population at small momentum fraction of the nucleon, $x$, compared to that in a free nucleon, with a corresponding enhancement at moderate $x$ (anti-shadowing). In $\sqrt{s_{NN}} = 200$ GeV deuteron-gold ($d + Au$) collisions at the Relativistic Heavy Ion Collider (RHIC), for forward (deuteron direction) rapidities, gluons are probed that lie well into the shadowing region with momentum fractions in $Au$, $x_2 \sim 3 \times 10^{-3}$. Models of gluon shadowing predict suppressions of $J/\psi$ production in nuclei that differ by as much as a factor of three [3–5]. Recent theoretical developments, e.g. the Color Glass Condensate model [6], suggest that at very low $x$ non-linear gluon saturation effects become important and cause substantial modifications of the gluon densities.

The connection of the observed $J/\psi$ suppression to the modified gluon distribution in nuclei can be clouded by the absorption of the final-state $c\bar{c}$ [7] which depends on the poorly known production mechanism [1] and by the energy loss of the intial-state gluon - although the latter is thought to be small at RHIC energies [5]. This connection is also distorted by the fact that approximately a third of the $J/\psi$ 's come from decays of higher-mass resonances [8].

Here we present measurements made by the PHENIX experiment at RHIC for the production of $J/\psi$ 's in $\sqrt{s_{NN}} = 200$ GeV $d + Au$ and proton-proton ($p + p$) collisions. These data provide the first measurement of the nuclear dependence of $J/\psi$ production at this energy, a much higher energy than previous $p + A$ measurements from fixed-target experiments at $\sqrt{s_{NN}} \lesssim 40$ GeV [9–13]. Although our measurements are for $d + A$, the nuclear effects on the $J/\psi$ in deuterium were found to be small at lower energies [14]. Besides the shadowing region at small $x$, these data also probe larger gluon momentum fractions (at negative rapidity) nearer the rest frame of the residual nucleus. Finally, these measurements also serve as a baseline for the upcoming results from the high-luminosity $Au + Au$ and $Cu + Cu$ runs and must be understood in order to look for effects beyond what is expected from cold nuclear matter.

The measurements described here are similar to earlier ones with PHENIX [15] for $p + p$ [16] and $Au + Au$ [17] collisions, but with a second muon spectrometer added and higher luminosity. The two muon spectrometers are especially valuable for asymmetric collisions such as $d + Au$ where simultaneous measurements at forward ($1.2 < y < 2.4$) and backward ($-2.2 < y < -1.2$) rapidities, along with central ($|y| \leq 0.35$) rapidity from $e^+e^-$, are then available. 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 Čerenkov (RICH) detector. Muons are identified by their detection in Iarocci tubes after their penetration through 8 to 11 interaction lengths of copper and steel absorber.

The data used in this analysis were recorded in 2003 using a trigger that required hits in each of the two beam-beam counters located at negative and positive rapidity ($3 < |\eta| < 3.9$). In addition, for the di-muons at least two tracks in the muon identifier of appropriate absorber depth were required, while for the di-electrons a one-track trigger with a signal above threshold in the EMC with a matching hit in the RICH was required. After quality and vertex cuts, the samples for the three arms correspond to integrated luminosities from 180 to 250 nb$^{-1}$ ($p + p$) and 1.4 to 1.7 nb$^{-1}$ ($d + Au$).

For the di-muons the $J/\psi$ yield is obtained after subtraction of the combinatoric background using like-sign muon pairs ($2\sqrt{N_{++}N_{--}}$) and by fitting the resulting mass peak with a Gaussian plus 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 $J/\psi$ yield was taken as all remaining events in the mass range 2.6 to 3.6 GeV/$c^2$. A total ($p+p$ plus $d+Au$) of about 2100 and 500 $J/\psi$'s were obtained in the $\mu\mu$ and $ee$ channels, respectively.

The differential cross sections are calculated as,

$$B_{ll}\frac{d\sigma_{J/\psi}}{dy} = \frac{N_{J/\psi}}{A\,\epsilon_{rec}\,\epsilon_{trig}\,\epsilon^{BBC}_{J/\psi}\,(N_{evt}/(\sigma^{tot}_{MB}\cdot\epsilon^{BBC}_{MB}))}\frac{1}{\Delta y} \tag{1}$$

and the nuclear modification factor, $R_{dA}$, is

$$R_{dA} = \frac{d\sigma^{dAu}_{J/\psi}/dy}{(2\times 197)\times d\sigma^{pp}_{J/\psi}/dy} \tag{2}$$

In the above expressions $B_{ll}$ is the $J/\psi$ branching ratio to di-leptons, $N_{J/\psi}$ is the measured $J/\psi$ yield, $A$ is the geometrical acceptance, $\epsilon_{rec}$ is the di-lepton reconstruction efficiency, $\epsilon_{trig}$ is the trigger efficiency, $N_{evt}$ the number of min-bias triggers sampled, $\sigma^{tot}_{MB}$ the total minimum-bias (MB) cross section, $\Delta y$ is the rapidity bin width, and $\epsilon^{BBC}_{MB}$ and $\epsilon^{BBC}_{J/\psi}$ are the beam-beam trigger efficiencies for min-bias and $J/\psi$ events respectively. The factor of $2 \times 197$ causes $R_{dA}$ to be one if the $d + A$ cross section is just additive from $p + p$, i.e. if there are no nuclear modifications.

For $p + p$ we use the cross section for our beam-beam trigger, $\sigma^{tot}_{MB}(pp)\cdot\epsilon^{BBC}_{MB}(pp) = 23.0\pm2.2$ mb; and the efficiency for events with a $J/\psi$, $\epsilon^{BBC}_{J/\psi}(pp) = 0.79\pm0.02$. For $d+Au$ collisions we use a beam-beam trigger cross section of $\sigma^{tot}_{MB}(dAu)\cdot\epsilon^{BBC}_{MB}(dAu) = 1.99 \pm 0.10\ b$ from our measurement [18] using photo-dissociation of the deuteron as a reference [19], which is consistent with our calculated Glauber result of $1.92 \pm 0.18\ b$. For the $J/\psi$ we use $\epsilon^{BBC}_{J/\psi}(dAu) = 0.94 \pm 0.02$ [20].

For $d+Au$ collisions, the centrality of the collision can be characterized by measuring the charge deposited in the beam-beam counter in the $Au$ beam direction [20]. An approximate number of nucleon+nucleon collisions $\langle N_{coll}\rangle$ can be obtained through a Glauber calculation that relates this $\langle N_{coll}\rangle$ to the observed charge. In this case $R_{dA}(N_{coll})$ is calculated as,

$$R_{dA}(\langle N_{coll}\rangle) = \frac{N^{dAu}_{inv}(\langle N_{coll}\rangle)}{\langle N_{coll}\rangle \times N^{pp}_{inv}} \tag{3}$$

where the invariant yield $N_{inv}$ is,

$$N_{inv}(\langle N_{coll}\rangle) = \frac{N_{J/\psi} \cdot C_{bias}(\langle N_{coll}\rangle)}{A\,\epsilon_{rec}\,\epsilon_{trig}[N_{evt} \cdot (\Delta w/w)]} \tag{4}$$

with $\langle N_{coll}\rangle$ being the average number of binary collisions for a particular $d+Au$ centrality bin and $N_{evt} \cdot (\Delta w/w)$ the number of $d+Au$ min-bias triggers sampled that lie in this fraction, $\Delta w$, of the total minimum-bias centrality range, $w$. This prescription is equivalent to that of Eq. 1,2 for minimum bias. For $p+p$ collisions $\Delta w/w$ is one. $C_{bias} = \epsilon^{BBC}_{MB}/\epsilon^{BBC}_{J/\psi}$ is a correction for the smaller trigger efficiency in minimum-bias events compared to those with a $J/\psi$. For $d+Au$, $C_{bias}$ depends on $\langle N_{coll}\rangle$ and takes into account the effect of the underlying event multiplicity on both the trigger efficiency and the centrality measurement [20]. Its variation with centrality is up to 7% from unity.

For the electron analysis, $A\,\epsilon_{rec}$ and $\epsilon_{trig}$ were determined using a Geant [21] simulation of the central arms and a trigger response software emulation [16]. $\epsilon_{rec}$ was confirmed by studying pairs identified as photon conversions in the data. The systematic uncertainty of 10.4% is dominated by run-to-run efficiencies (5%), yield extraction (5%), and the occupancy dependence of the efficiency (4.4%).

For the muon arms, $A\,\epsilon_{rec}\,\epsilon_{trig}$ was determined within each rapidity and $p_T$ bin, using a Geant simulation with $J/\psi$ events generated by Pythia [22]. The dominant systematic uncertainties in our result are $+6/-9\%$ from the muon identifier efficiency and up to 10% (for the most central negative rapidity $d+Au$ data) from the combinatoric background.

Figure 1a shows 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 negative and positive rapidities. A fit to a shape generated with Pythia is performed and, using a di-lepton branching ratio of 5.9% [23], gives a total cross section $\sigma^{J/\psi}_{pp} = 2.61 \pm 0.20(\text{fit}) \pm 0.26(\text{abs})\ \mu\text{b}$. Variations in the parton distribution functions and models used to determine the shape are negligible compared to the fit errors.

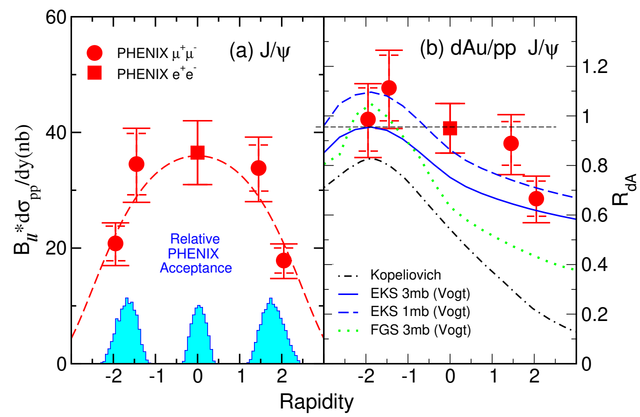


FIG. 1: (color online) (a) The 200 GeV $J/\psi$ $p+p$ differential cross section times di-lepton branching ratio versus rapidity (10% overall normalization uncertainty is not included). (b) The minimum bias $R_{dA}$ versus rapidity (12% overall normalization uncertainty not included). For both panels the dashed error bars represent systematic uncertainties relevant for comparing the two rapidity bins in each muon arm, while the solid error bars represent the overall uncertainties relevant for comparing points at negative, central, or positive rapidity. The curve in (a) represents a fit as described in the text while the curves in (b) are theoretical calculations [5, 24, 25] as described in the text.

This result is smaller by about two sigma than our previous lower statistics result [16].

Figure 1b shows the nuclear modification factor $R_{dA}$ (Eq. 2) versus rapidity, where a value of one would correspond to no nuclear modification. While this ratio is consistent with unity at backward rapidity, it is significantly lower at the most forward rapidity where gluons are expected to be shadowed in a heavy nucleus. Theoretical predictions [5, 24, 25] that include the effects of absorption and shadowing are shown for comparison in Fig. 1b. The data favor a relatively modest shadowing in agreement with the parametrization of EKS98 based on a leading-twist DGLAP-evolved parametrization of nuclear deep inelastic scattering and Drell-Yan data at lower energies [3], rather than the stronger gluon shadowing of Kopeliovich [5] or FGS [4] based on models involving coherence for a $q\bar{q}$ dipole in the nucleus. The $c\bar{c}$ absorption cross section is not well determined by our data but is probably nearer to 1 mb and is certainly smaller than the $4.1 \pm 0.4$ mb found at lower energy [26].

Lower energy $p+A$ measurements showed that $J/\psi$ suppression did not follow a universal behavior vs $x_2$ [27], the momentum fraction in the heavy nucleus, as would be expected if the suppression was dominated by shadowing [10]. As shown in Fig. 2a, our data confirm this $x_2$ scaling violation with the addition of a smaller $x_2$ point; but with our small range in $x_F$ have little to add

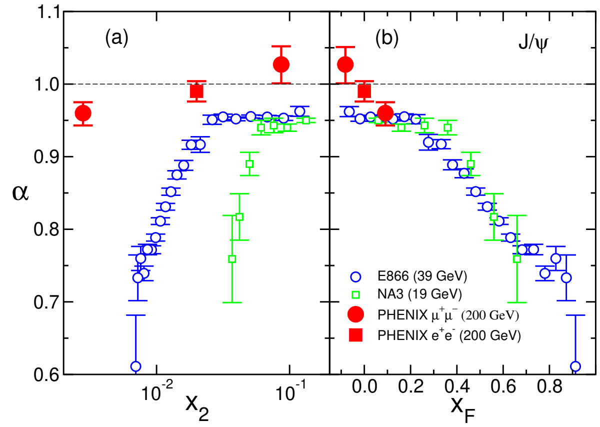


FIG. 2: (color online) $\alpha$ versus (a) $x_2$ and (b) $x_F$ with present 200 GeV $J/\psi$ results compared to lower energy results [10, 13]. An additional overall uncertainty of 0.02 in our $\alpha$ values is not shown.

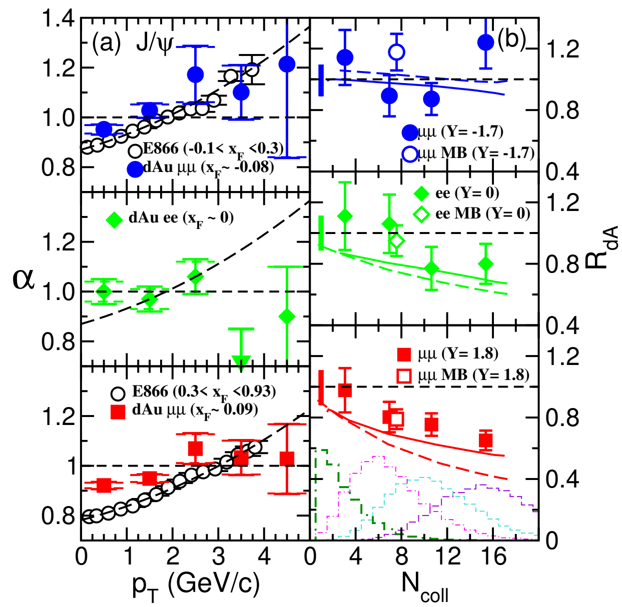


FIG. 3: (color online) (a) $\alpha$ versus $p_T$ compared to lower energy measurements, shown for three different rapidity ranges. The error bars have the same meaning as in Fig. 1. An additional 0.02 overall uncertainty is not shown. The dashed curves are simple fits [10] to the lower energy results. (b) Nuclear modification factor versus centrality as given by the number of nucleon+nucleon collisions shown for three different rapidity ranges, compared to theoretical calculations[24, 25] including final-state absorption and EKS (solid) or FGS (dashed) shadowing. The bars at the low end of each plot represent the systematic errors between different rapidity ranges. An additional 12% global error bar is not shown. The histograms at the bottom of the lower panel indicate the distribution of the number of collisions for each of the four centrality bins.

to the approximate $x_F$ scaling observed in these lower energy measurements (Fig. 2b). Here $\alpha$ is defined by $\sigma_{dA} = \sigma_{pp} \times (2A)^\alpha$ and $x_F = x_1 - x_2$, where $x_1$ is the momentum fraction of the gluon in the deuteron. This $x_F$ scaling may be caused by energy loss of the gluon in the intial state [7], or by an energy conservation effect ("Sudakov suppression") [28] which causes a universal suppression that increases with $x_F$ for production of $J/\psi$'s and other hadrons. It is also similar to that observed for more forward rapidity hadron production in the $d + Au$ "limiting fragmentation" region [29].

Invariant cross sections versus transverse momentum, $(d^2\sigma/dydp_T)/(2\pi p_T)$, have been fit to the form $A \times (1 + (p_T/B)^2)^{-6}$ [30]. Average $p_T^2$ values resulting from these fits are $4.28 \pm 0.31$, $3.03 \pm 0.40$ and $3.63 \pm 0.25$ GeV/$c^2$ for $d + Au$ collisions at backward, mid, and forward rapidity, respectively; compared with $2.51 \pm 0.21$ and $4.31 \pm 0.85$ GeV/$c^2$ for forward/backward and mid rapidity $p + p$ collisions, respectively. The observed $p_T$ broadening is shown in Fig. 3a. For negative $x_F$ it is consistent with that of the lower energy ($\sqrt{s_{NN}} = 39$ GeV) measurements from E866/NuSea [10], but may be flatter at positive rapidity. At central rapidity no $p_T$ broadening is seen within errors.

$R_{dA}$ (Eq. 3) is shown in Fig. 3b for four centrality classes and for minimum bias collisions. This classification into centrality bins for these results can only be approximate, as indicated by the overlapping histograms of $N_{coll}$. At forward rapidity (small $x_2$, or the shadowing region), a weak drop for more central collisions is observed, while no significant centrality dependence is seen for backward rapidity or for central rapidity. The theoretical curves on Fig. 3b correspond to different amounts of density dependent shadowing and anti-shadowing [24, 25] and also include absorption. They are consistent with our data except at positive rapidity where the EKS shadowing curve is closest to our results, although slightly lower perhaps due to the amount of absorption that is included.

In summary, during the RHIC 2003 run, the PHENIX experiment measured nuclear effects on $J/\psi$ production for $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Increasing suppression for larger rapidity (smaller $x_2$) and for more central collisions (higher nuclear densities sampled) both are consistent with models containing a small amount of impact-parameter dependent shadowing and with weak absorption. Theoretical calculations which include EKS shadowing seem most consistent with the data. However comparisons with other measurements at lower energies show that shadowing cannot be the dominant effect, at least not for the lower energy measurements. We also see some transverse momentum broadening which is consistent with that seen at lower energy. Higher luminosity $d + Au$ running in the future yielding higher numbers of

$J/\psi$ 's will be necessary to quantify these nuclear effects and to more clearly distinguish between various theoretical models of shadowing, absorption and other cold nuclear matter effects.

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