\( J/\psi \) production at high transverse momenta in \( p+p \) and \( Au+Au \) collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \)

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Abstract

We report $J/\psi$ spectra for transverse momenta $p_T > 5$ GeV/c at mid-rapidity in $p+p$ and $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The inclusive $J/\psi$ spectrum and the extracted $B$-hadron feed-down are compared to models incorporating different production mechanisms. We observe significant suppression of the $J/\psi$ yields for $p_T > 5$ GeV/c in 0-30% central $Au+Au$ collisions relative to the $p+p$ yield scaled by the number of binary nucleon-nucleon collisions in $Au+Au$ collisions. In 30-60% mid-central collisions, no such suppression is observed. The level of suppression is consistently less than that of high-$p_T \pi^\pm$ and low-$p_T J/\psi$ at RHIC and high-$p_T J/\psi$ at the LHC.

Keywords: $J/\psi$ suppression, color-screening, quarkonium, heavy-ion collisions, STAR

1. Introduction

Ultrarelativistic heavy-ion collisions provide a unique environment to study strongly interacting matter at high temperature and energy density where a transition from the hadronic phase of matter to a new partonic phase, the Quark-Gluon Plasma (QGP), takes place. Measurements of the in-medium dissociation probability of the different quarkonium states are expected to provide an estimate of the initial temperature of the system \cite{1,2,3}. The $J/\psi$ is the lightest and most abundantly produced quarkonium state accessible in experiment. However, significant decay contributions ($\approx 40\%$ \cite{2}) from excited $c\bar{c}$ states, such as the $\chi_c$ and $\psi(2S)$, and from $B$ mesons could complicate the suppression picture suggested by dissociation models \cite{4}. In addition, other contributions absent in $p+p$ collisions are likely to have a significant impact on the observed $J/\psi$ yields in relativistic heavy-ion collisions.
at CERN-SPS [3], BNL-RHIC [6] and CERN-LHC [7, 8, 9]. These contributions include cold nuclear matter (CNM) effects such as initial state parton scattering, nuclear shadowing and nuclear absorption, the combined contribution of finite $J/\psi$ formation time and the finite space-time extent of the hot and dense volume where the dissociation can occur, and recombination of unassociated $c$ and $\bar{c}$ in the medium [10]. Some of these processes are expected to decrease with increasing $J/\psi$ $p_T$ [11, 12]. It is therefore anticipated that $J/\psi$ measurements at high-$p_T$ provide an important tool to decouple some of the mechanisms mentioned above and provide a cleaner way to extract the contribution from color-screening effects [11, 12, 13, 14]. Our previous $J/\psi$ measurements are consistent with no suppression for $p_T > 5$ GeV/c in Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV, to within the limited precision of the data [15]. The small system size created in Cu+Cu collisions may result in high- $p_T$ $J/\psi$ formation outside the medium. Precise measurements in Au+Au collisions are thus crucial for a systematic study of $J/\psi$ production in the hot and dense medium.

The interpretation of medium-induced $J/\psi$ modification requires a good understanding of its production mechanisms in $p+p$ collisions, which include direct production via gluon fusion, parton fragmentation, and feed-down from higher charmonium states and $B$-hadron decays [4]. The initial hard interactions required to create the charm quark pairs can be well calculated in perturbative QCD (pQCD). However, the subsequent soft processes required to form the $J/\psi$ hadron and the $J/\psi$ formation time are theoretically not well understood [4]. No model at present fully explains the $J/\psi$ observations in elementary collisions [4]. The $J/\psi$ spectrum in the intermediate and high-$p_T$ range, together with the angular correlations of a high-$p_T$ $J/\psi$ and associated charged hadrons, may provide additional insights in the underlying production mechanisms.

In this letter, we report a measurement of $J/\psi$ production for $2 < p_T < 14$ GeV/c in $p+p$ and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV with the STAR detector [16]. The $J/\psi$ $p_T$ spectra at mid-rapidity ($|y| < 1$) in $p+p$ and Au+Au collisions are presented. The nuclear modification factor, $R_{AA}$ - the ratio of the yield in Au+Au to that in $p+p$ collisions scaled by the number of underlying binary nucleon-nucleon collisions ($N_{bin}$ - is calculated and compared to theoretical calculations.
2. Data analysis

The Au+Au data used for this analysis were recorded in 2010, and the \( p+p \) data in 2009. The minimum bias (MB) trigger was defined to be a coincidence of the two Vertex Position Detectors [17]. Online trigger conditions that utilized a MB trigger condition and two thresholds for the energy deposited in any single Barrel Electromagnetic Calorimeter (BEMC) [18] tower, with a size of \( \Delta \eta \times \Delta \phi = 0.05 \times 0.05 \), were used to maximize the sampled luminosity. To increase the trigger efficiency, the \( p+p \) data with high BEMC threshold were recorded without a MB requirement. The \( p+p \) data with low BEMC threshold were pre-scaled to keep the data rate manageable. The integrated luminosities of the data samples used for this analysis are 23.1 pb\(^{-1}\) and 1.8 pb\(^{-1}\) with a transverse energy threshold of \( E_T > 6.0 \) and 2.6 GeV, respectively, in \( p+p \) collisions and 1.4 nb\(^{-1}\) with \( E_T > 4.3 \) GeV in Au+Au collisions. In the Au+Au data, the collision centrality is determined by the distribution of charged-particle multiplicity within the pseudorapidity range \( |\eta| < 0.5 \) [19].

In this analysis, \( J/\psi \rightarrow e^+e^- \) decays were reconstructed using the STAR Time Projection Chamber (TPC) [21] and the BEMC [18] with full azimuthal coverage over the pseudorapidity range \( |\eta| < 1 \) [15, 22]. Electron identification (eID) for the BEMC triggered tracks was achieved by measuring the ionization energy loss (dE/dx) and track momentum from the TPC, as well as the energy deposition in the BEMC. In addition, the shower profile in the barrel shower maximum detector [18] was used in Au+Au collisions to further suppress hadron contamination. At moderate \( p_T \) (1 \( \lesssim p_T \lesssim 3 \) GeV/c), TPC dE/dx provides eID with reasonable efficiency and purity. At low \( p_T \) (0.2 \( < p_T \lesssim 3 \) GeV/c), the eID significantly benefits from a recently installed large area time-of-flight (TOF) detector covering \( |\eta| < 0.9 \) [23, 24]. The complete TOF detector was available for the 2010 Au+Au run, whereas 72% was available for the \( p+p \) data collected in 2009.

The \( J/\psi \) signal was extracted by subtracting from the unlike-sign ee invariant mass spectrum the random combinatorial background that was reproduced by the like-sign spectrum in \( p+p \) collisions and unlike-sign spectrum from mixed-events in Au+Au collisions [25]. Figure 1 shows the invariant mass distribution before and after the combinatorial background subtraction in \( p+p \) and Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV. The \( J/\psi \) raw yields were obtained from a mass window of \( 2.7 < M_{ee}^{inv} < 3.3 - 3.4 \) GeV/c\(^2\) in \( p+p \) collisions depending on the \( J/\psi \) \( p_T \), and \( 2.9 < M_{inv}^{ee} < 3.2 \) GeV/c\(^2\) in Au+Au collisions.
Figure 1: (Color online.) (a) The unlike-sign $e^+e^-$ invariant mass distribution from same-event pairs (filled circles) and mixed-event pairs (solid curve) in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. (b) The background subtracted $e^+e^-$ invariant mass distribution in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. (c, d) The unlike-sign (filled circles) and like-sign (solid curve) $ee$ invariant mass distribution from same-event pairs in $p+p$ collisions at $\sqrt{s} = 200$ GeV. For both systems the data are shown for two intervals in $J/\psi$ $p_T$. 
Figure 2: (Color online.) The invariant $J/\psi$ cross section versus $p_T$ in $p+p$ collisions at $\sqrt{s} = 200$ GeV. The vertical bars and boxes depict the statistical and systematic uncertainties, respectively. Also shown are results published by STAR [15] and PHENIX [20]. The curves show theoretical calculations described in the text.
Figure 3: (Color online.) The fraction of $B \to J/\psi$ over the inclusive $J/\psi$ yield in $p+p$ collisions. The FONLL+CEM model calculation is also shown.
Table 1: Summary of assigned systematic uncertainties of $J/\psi$ spectra in $p+p$ and Au+Au collisions, and $J/\psi R_{AA}$ in Au+Au collisions.

| Description            | $p+p$   | Au+Au | $R_{AA}$ |
|------------------------|---------|-------|----------|
| Kinematic and eID cuts | 1-16%   | 3-28% | 3-28%    |
| Efficiency             | 7.5%    | 7.5%  | -        |
| Yield extraction       | 8-26%   | 2%    | 4%       |
| Normalization          | 8.1%    | -     | 8.6-23.4%|

Collisions. The yields were corrected for $\approx 10\%$ radiation losses that cause some of the decay daughters to be reconstructed with $M_{ee}^{inv}$ outside the above mass ranges. The total $J/\psi$ yield was $\approx 1100$ ($p_T > 2$ GeV/c) in $p+p$ collisions. It was $\approx 1000$, 600 and 300 ($p_T > 3$ GeV/c) in 0-20%, 20-40% and 40-60% Au+Au collisions, respectively. The signal to background ratio (S/B) was $\approx 4$ in $p+p$ collisions and $\approx 1/7 (1/2)$ in 0-20% (40-60%) Au+Au collisions. In the $J/\psi$-hadron correlation analysis, different invariant mass and particle identification cuts were selected to provide a better S/B ratio. About 400 $J/\psi$ with $p_T > 4$ GeV/c and $3.0 < M_{ee}^{inv} < 3.2$ GeV/c$^2$ were observed with a S/B ratio of 22/1 in $p+p$ collisions.

Acceptance and efficiency corrections were studied using Monte Carlo (MC) GEANT simulations [19]. The systematic uncertainty on this procedure is estimated by varying kinematic and eID cuts in both data analysis and MC simulations. It is uncorrelated with $p_T$ and collisions systems. An additional systematic uncertainty of 7.5%, obtained from two complementary simulation methods, was assigned for the $p_T$ spectra in $p+p$ and Au+Au collisions. This contribution cancels in the uncertainty on $R_{AA}$. We have also varied the invariant mass window for signal counting to evaluate the systematic uncertainty on the yield extraction procedure, including the contributions from radiation losses and correlated background. This contribution is larger in $p+p$ than in Au+Au collisions due to the wider mass window used in $p+p$ collisions. Since it is correlated in $p+p$ and Au+Au collisions, this systematic uncertainty on $R_{AA}$ is estimated by varying the mass window in the same way in $p+p$ and Au+Au collisions. The normalization uncertainty for the cross section in $p+p$ collisions is 8.1% [26]. The normalization uncertainty for $R_{AA}$ has also a contribution from the uncertainty on the calculation of $N_{bin}$. The combined uncertainty varies from 8.6% in 0-10% central Au+Au collisions to 23.4% in 40-60% central Au+Au collisions. The systematic uncertainties are summarized in Tab. 1.
Figure 4: (Color online) $J/\psi p_T$ distributions in Au+Au collisions with different centralities at $\sqrt{s_{NN}} = 200$ GeV. For clarity, the data and curves have been scaled as indicated in the legends. The PHENIX results are reported in [6]. The curves are model fits described in the text.
3. Results and discussion

Figure 2 shows the $J/\psi$ invariant cross-section times the branching ratio $(B_{ll})$ at mid-rapidity ($|y| < 1$) as a function of $p_T$ for $p+p$ collisions at $\sqrt{s} = 200$ GeV. The new results are consistent with those previously published by STAR [15] and PHENIX [20]. The dashed curves depict the uncertainty band of next-to-leading order (NLO) theoretical Non-Relativistic QCD (NRQCD) calculations from color-octet (CO) and color-singlet (CS) transitions [28] for prompt $J/\psi$ production in $p+p$ collisions. The CS+CO calculations match the $p_T$ spectra for $p_T > 4$ GeV/c to within the uncertainties. The solid curve shows the calculation from the color evaporation model (CEM) for prompt $J/\psi$ [29]. It describes the $p_T$ spectra reasonably well at low and high $p_T$, but overpredicts the data by a factor of 2 at $p_T$ around 3 GeV/c. The bottom panel shows the ratios of the data and NRQCD calculations to the CEM calculation. Not shown in this figure is the model based on NNLO CS [30], which predicts a too steep $p_T$ dependence, as discussed in [15].

The relative contribution of $B$-hadron feed-down to the inclusive $J/\psi$ yield was obtained by fitting the azimuthal angular correlation between high-$p_T$ $J/\psi$ and charged hadrons with simulated correlation functions for prompt $J/\psi$ and $J/\psi$ from $B$-hadron feed-down from PYTHIA [31, 32]. Details of this procedure are described in [15, 22]. The separation of the correlation functions for the two above contribution sources increases as a function of $p_T$. We note that this method is data-driven, although it relies also on the validity of PYTHIA’s modeling of the near-side associated hadron distributions. The $B$-hadron feed-down contribution is found to be within 10-25% in the range $4 < p_T < 12$ GeV/c as shown in Fig. 3. Within errors our data are consistent with the Fixed Order plus Next-to-Leading Logarithms (FONLL) plus CEM prediction [33, 34], indicated by the curve and uncertainty band. More precise measurements using displaced vertex techniques similar to those employed by CDF in $p+\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV and by ATLAS and CMS in $p+p$ collisions at $\sqrt{s} = 7$ TeV [36, 37, 38] are needed to quantify the anticipated energy dependence [33, 34].

The measured $J/\psi$ $p_T$ spectra in Au+Au collisions for different centralities are shown in Fig. 4. The shape of the $J/\psi$ $p_T$-distribution depends not only on the production mechanism but in heavy ion collisions also on the level of charm quark thermalization. $J/\psi$ produced from direct pQCD processes have no initial collective motion and may acquire radial flow through interaction with the hot and dense medium. $J/\psi$ produced from charm
Figure 5: (Color online.) $J/\psi$ $R_{AA}$ versus $p_T$ for several centrality bins for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The statistical (systematic) uncertainties are shown with vertical bars (open boxes). The filled boxes about unity on the right show the size of the normalization uncertainty. PHENIX low-$p_T$ $J/\psi$ results [6] and STAR high-$p_T$ results in Cu+Cu collisions [12] are shown for comparison. The curves are from the predictions by Model I (Liu et al.) [11] and Model II (Zhao et al.) [12].
quark recombination should inherit the flow of charm quarks and exhibit an enhancement of yield at low $p_T$. Thus the study of $J/\psi$ $p_T$ spectra with a thermal model may provide insight in its production mechanism and thermalization. The solid curves depict fits based on the Tsallis statistics Blast-wave (TBW) model to the combined STAR and PHENIX data with the radial flow velocity $\beta$ fixed to zero [39]. The fits reproduce the data reasonably well. Under the assumption that the $J/\psi$ flows like light hadrons [39, 40], the TBW calculations shown as dashed curves underpredict the yields at low $p_T$. This could be due to a small (or zero) radial flow or a significant contribution from charm quark recombination that would enhance the yield at low $p_T$, or both.

Figure 5 shows the $J/\psi$ $R_{AA}$ versus $p_T$ for different centrality bins. The STAR Cu+Cu $J/\psi$ results [15] are also shown. For $p_T > 5$ GeV/c, $J/\psi$ $R_{AA}$ in the 40-60% centrality bin is consistent with unity and with our previous measurement in Cu+Cu collisions with a similar average number of participants ($N_{part}$). The curves show two theoretical calculations [11, 12] describing the
data reasonably well. These calculations include contributions from prompt production and statistical charm quark regeneration. The suppression of the prompt $J/\psi$ component in the model calculations is mainly due to the color-screening effect. The model from Zhao et al. (Model II) \cite{12} also includes the $J/\psi$ formation-time effect and the $B$-hadron feed-down contribution.

For $p_T > 5$ GeV/c, $J/\psi$ production follows the scaling of the cross section at mid-rapidity, \( \frac{d^2\sigma}{2\pi p_T dp_T dy} = g(x_T)/((\sqrt{s})^n) \), where \( x_T = 2p_T/\sqrt{s} \). For $p_T > 5$ GeV/c, \( J/\psi \) suppression in this $p_T$ region should provide a cleaner probe of the hot medium suppression effects. Furthermore, a color-screening model based on AdS/CFT predicts that the dissociation temperature of direct $J/\psi$ in QGP decreases to $1.5T_c$, which is believed to be reached in RHIC collisions, at $p_T > 5$ GeV/c \cite{13}.

We present high-$p_T$ ($p_T > 5$ GeV/c) $R_{AA}$ as a function of $N_{part}$ in Fig. 6. No significant suppression of high-$p_T$ $J/\psi$ production is observed in mid-central to peripheral collisions (30-60%, $N_{part} \lesssim 140$). However, in central collisions (0-30%, $N_{part} \gtrsim 140$), high-$p_T$ $J/\psi$ are significantly suppressed. The $R_{AA}$ of low-$p_T$ ($0 < p_T < 5$ GeV/c) $J/\psi$ measured by PHENIX \cite{6} and high-$p_T$ ($p_T > 5$ GeV/c) charged pions measured by STAR \cite{41, 42} are shown in Fig. 6(a) for comparison. The high-$p_T$ $J/\psi R_{AA}$ is systematically higher. Note, that the $B$-hadron feed-down contribution is not subtracted and that part of the suppression could for instance reflect $b$-quark energy loss. Based on our measurement, $R_{AA}$ for prompt $J/\psi$ with $p_T > 5$ GeV/c in the most central collisions will be $0.80 \pm 0.17$ if $B$-hadron $R_{AA}=0$ and $0.55 \pm 0.17$ if $B$-hadron $R_{AA}=1$. The predictions of high-$p_T$ $J/\psi R_{AA}$ from Model I (Liu et al.) \cite{17} and Model II (Zhao et al.) \cite{12} are shown as solid and dashed curves, respectively. Model I describes our data reasonably well. Model II underpredicts $J/\psi R_{AA}$ ($p$-value=0.0018 with all of the uncertainties taken into account). Fig. 6(b) shows the comparison of high-$p_T$ $J/\psi R_{AA}$ versus
$N_{\text{part}}$ from STAR at RHIC and CMS at the LHC [8]. The STAR results are higher for all centralities.

The high-$p_T$ $J/\psi R_{AA}$ versus centrality is different from that of high-$p_T$ pions. This is expected from differences in their production. Dissociation is considered to be the dominant mechanism that determines the $R_{AA}$ in the case of $J/\psi$ production, and induced gluon radiation in the case of pion production. For $p_T > 5$ GeV/$c$, the recombination and initial parton scattering effects are expected to be negligible [11, 12]. The observed $J/\psi R_{AA}$ dependence on system size in this $p_T$ range might be due to the interplay of formation time, color screening and parton distribution functions in heavy nuclei [10]. The model calculations of [12] include formation time effects and CNM effects, and predict that $J/\psi R_{AA}$ is close to unity for $p_T > 5$ GeV/$c$. Therefore significant suppression observed in central 0-30% Au+Au collisions points to the color screening features. Empirically, the $J/\psi$ is the only measured hadron that exhibits significant suppression in $R_{AA}$ and has neither observable elliptic flow [48] nor model-extracted radial flow [39] at RHIC. The strong suppression of $J/\psi$ at high $p_T$ and the sequential $\Upsilon$ suppression observed at LHC by the CMS Collaboration [8, 49, 50] are consistent with this interpretation. Comparison of low-$p_T$ $J/\psi$ yields at RHIC and LHC [51] and study of the $J/\psi$ azimuthal anisotropy [48, 52] could quantitatively further constrain the model interpretation.

4. Summary

This letter reports measurements of $J/\psi$ production in $\sqrt{s_{NN}} = 200$ GeV $p+p$ and Au+Au collisions for $p_T > 2 - 3$ GeV/$c$ at RHIC. The $p_T$ spectrum in $p+p$ collisions is compared to various theoretical calculations. Currently, only the CEM model and NLO CS+CO calculation describe our data. Based on the measurement of azimuthal correlations between high-$p_T$ $J/\psi$ and charged hadrons we estimate the fraction of $J/\psi$ from $B$-hadron decay to be 10-25% in the $p_T$ range of 4-12 GeV/$c$ in $p+p$ collisions. We report the first measurement of high-$p_T$ $J/\psi$ suppression in Au+Au collisions at RHIC. The nuclear modification factor $R_{AA}$ in Au+Au increases from low to high $p_T$. For $p_T > 5$ GeV/$c$, $J/\psi R_{AA}$ is consistent with no suppression from mid-central to peripheral collisions (30-60% centrality), and significantly smaller than unity in the most central Au+Au collisions. The results on $R_{AA}$ versus $p_T$ and $N_{\text{part}}$ provide new insight in the study of color screening features for charmonium.
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