Energy dependence of $J/\psi$ production in Au+Au collisions at $\sqrt{s_{NN}} = 39, 62.4$ and 200 GeV from the STAR experiment

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Abstract. In this article, we report on the measurements of $J/\psi$ invariant yields as a function of transverse momentum at midrapidity ($|y|<1.0$) in Au+Au collisions at $\sqrt{s_{NN}} = 39, 62.4$ and 200 GeV taken in 2010 by STAR with full Time-of-Flight detector and Barrel Electromagnetic Calorimeter detector in operation. Centrality dependence of $J/\psi$ production and nuclear modification factors are presented. Comparisons among different collision energies and model calculations are discussed.

1. Introduction
The Relativistic Heavy Ion Collider (RHIC) is built to search for the Quark-gluon Plasma (QGP) and to study its properties in laboratory through high energy heavy-ion collisions [1]. $J/\psi$ suppression in heavy-ion collisions, due to color screening of quark and anti-quark, has been proposed as a signature of QGP formation [2]. Various measurements of $J/\psi$ have been performed in different collision systems and at different energies, and indeed a suppression of $J/\psi$ production has been observed [3, 4, 5, 6]. A similar pattern of suppression was found at SPS and RHIC, even though the temperature and energy density reached in these collisions are significantly different. Furthermore, a stronger suppression at forward rapidity compared to midrapidity was observed at RHIC [7]. These observations indicate that effects other than color screening contribute to $J/\psi$ production. The regeneration of $J/\psi$ from the statistical coalescence of charm quarks was suggested to explain the similar suppressions at SPS and RHIC [8]. Despite the increase in collision energy, the increased regeneration contribution from the larger charm quark density could compensate for the additional suppression due to color-screening. This also explains a stronger suppression at forward rapidity at RHIC where the charm quark density is lower compared to midrapidity. In this paper, we further study the collision energy dependence of $J/\psi$ production under these two competing mechanisms.

We present the measurement of the $J/\psi$ production at midrapidity with the STAR experiment in Au+Au collisions at $\sqrt{s_{NN}} = 39, 62.4$ and 200 GeV using data collected during RHIC year 2010 run and study the nuclear modification factors at these energy points.

2. Experiment and Analysis
The STAR experiment is a large-acceptance multi-purpose detector which covers full azimuth and pseudorapidity of $|\eta|<1$ [9]. The Au+Au data were obtained using a minimum-bias trigger by selecting on coincidences in the Vertex Position Detector (VPD) and the Zero Degree Calorimeter (ZDC). The total number of minimum-bias events used in analysis is 182 million, 94 million, 304...
million for 39, 62.4 and 200 GeV, respectively. In this analysis, the $J/\psi$ is reconstructed through its decay into electron-positron pairs, $J/\psi \rightarrow e^+e^-$ (branching ratio $B_{e^+e^-} = 5.9\%$). The primary detectors used in this analysis are the Time Projection Chamber (TPC) [10], the Time-of-Flight (TOF) [11], and the Barrel Electromagnetic Calorimeter (BEMC) [12]. The TPC provides tracking and particle identification via the ionization energy loss ($dE/dx$) of charge particles. In year 2010, STAR has installed 100% of TOF trays (which measure the time of flight and velocity of particles) at midrapidity. This detector, combined with TPC, can clearly identify electrons by rejecting hadrons in the low and intermediate $p_T$ range. The BEMC is a lead-scintillator calorimeter and has been used to improve the electron identification at high $p_T$. We use two methods to estimate the combinatorial background in this analysis:

a. **Mixed-Event**: Events are categorized according to the $z$-position of event vertex and the centrality of event. Electrons from one event are paired with positrons from other random events from an event pool with similar global features.

b. **Like-Sign**: Electrons (or positrons) of the same charge sign are paired within same event.

Figure 1 shows the invariant mass distribution of $e^+e^-$ pairs in 0 - 60% central Au+Au collisions at 62.4 GeV. For the results reported in this paper, we use Mixed-Event method for the combinatorial background estimation and the Mixed-Event background is normalized to the Like-Sign in a mass range of 2.0 - 4.0 GeV/$c^2$. Good Signal-to-Background ratios (for 62.4 GeV, $S/B = 0.39$; for 39 GeV, $S/B = 0.62$) are observed.

3. Results

Figure 2 shows the $J/\psi$ invariant yield as a function of $p_T$ for 0 - 60% central Au+Au collisions at 39, 62.4 and 200 GeV. As expected, the $J/\psi$ invariant yields are larger in Au+Au collisions at larger center-of-mass energy.

There are several different ways to quantify the suppression of $J/\psi$ production. Since no $p+p$ reference baselines at $\sqrt{s_{NN}} = 39$ or 62.4 GeV were measured at RHIC, we first discuss the $J/\psi$ $R_{CP}$ which defined as follows:

$$R_{CP} = \frac{dN/dy}{<N_{coll}>} (central) \frac{dN/dy (peripheral)}{<N_{coll}>}$$

where $<N_{coll}>$ is the average number of nucleon-nucleon collisions in relative centrality bins. $R_{CP}$ is a ratio of $J/\psi$ production in central collisions (where QGP formation is expected) to peripheral collisions (which naively should be a superposition of $p+p$ interactions).
Figure 2. $J/\psi$ invariant yields for Au+Au collisions (centrality 0 - 60%) at 39, 62.4 and 200 GeV as a function of $p_T$. The error bars depict the statistical uncertainties. The boxes represent the systematic uncertainties.

Figure 3. $J/\psi$ $R_{CP}$ results with respect to 40 - 60% (peripheral) for Au+Au collisions at 39, 62.4 and 200 GeV as a function of the number of participating nucleons. The error bars represent the statistical uncertainties. The boxes represent the systematic uncertainties. The shaded bands around unity on the right-hand axis represent the normalization uncertainty from the average number of binary nucleon-nucleon collisions ($<N_{coll}>$) in different centrality bins.

The $R_{CP}$, as a function of the average number of participants ($<N_{part}>$) for Au+Au collisions at 39, 62.4 and 200 GeV, are shown in Fig. 3. Note that the peripheral bin selection for Au+Au collisions at these three energy points is 40 - 60% centrality. Significant suppression is observed in central Au+Au collisions at 62.4 GeV which is similar as at 200 GeV.

$R_{AA}$ is another way to quantify the suppression of $J/\psi$ production. It is defined as follows:

$$R_{AA} = \frac{1}{T_{AA}} \frac{d^2N_{AA}/dp_Tdy}{d^2\sigma_{pp}/dp_Tdy}$$

(2)

where $d^2N_{AA}/dp_Tdy$ is the invariant $J/\psi$ yield in A+A collisions and $d^2\sigma_{pp}/dp_Tdy$ is the $J/\psi$ cross section in p+p collisions. The nuclear overlap function is defined as $T_{AA} = <N_{coll}>/\sigma_{inel}$, and takes into account the inelastic cross section in p+p collisions ($\sigma_{pp}^{inel}$) and the number of nucleon-nucleon collisions in A+A collisions ($<N_{coll}>$). The STAR experiment has no $J/\psi$ cross section measurement for p+p collisions at 39 and 62.4 GeV. There are several p+p measurements from fixed target p+A experiment [13, 14, 15] and from Intersecting Storage Ring (ISR) collider experiments [16, 17] near these two energy points. However, the $p_T$ shapes from ref. [16] and ref. [17] at 63 GeV are inconsistent with each other and the cross section measurements at 39 GeV are comparable to (or even larger than) that at 63 GeV. Therefore, we use Color Evaporation Model (CEM) prediction as our p+p reference baselines for $\sqrt{s_{NN}} = 39$ and 62.4 GeV [18] because CEM calculation describes the $p_T$ and rapidity distribution in p+p 200 GeV collisions [18]. Figure 4 shows the $R_{AA}$ of $J/\psi$ as a function of $N_{part}$ for Au+Au collisions at 39, 62.4 and 200 GeV. The theoretical calculation curves, which contain two main components: initial suppression and regeneration, are from reference [7]. As the collision energy increases the QGP temperature increases, thus the $J/\psi$ color screening (initial suppression) becomes more significant. However, in this theoretical calculation, the regeneration contribution increases with collision energy due to the increase in the charm pairs production, and nearly compensates the additional suppression arising from higher temperature. Significant suppression of $J/\psi$ production is
observed in Au+Au collisions from 39 to 200 GeV with respect to N_{coll} scaled p+p yields. No significant energy dependence is observed for R_{AA} with uncertainties. Theoretical calculation describes the data within error bars.

**Figure 4.** J/ψ R_{AA} results as a function of N_{part} Au+Au collisions at 39, 62.4 and 200 GeV. The theoretical curves are from reference [7]. The error bars represent the statistical uncertainties. The boxes represent the systematic uncertainties. The shaded bands indicate the uncertainties from <N_{coll}>. The boxes on the vertical axis represent the uncertainties from CEM estimation for 39 and 62.4 GeV and the statistical uncertainty for 200 GeV p+p baseline.

**Figure 5.** J/ψ R_{AA} results for Au+Au collisions (centrality 0 - 60%) at 39, 62.4 and 200 GeV as a function of p_{T}. The error bars represent the statistical uncertainties. The boxes represent the systematic uncertainties. The boxes on the vertical axis represent the uncertainties from CEM estimation for 39 and 62.4 GeV and <N_{coll}> uncertainties.

Figure 5 shows the J/ψ R_{AA} as a function of p_{T} for Au+Au collisions at 39, 62.4 and 200 GeV. The CEM estimation is used as reference baseline for 39 and 62.4 GeV. Significant suppression is observed from 39 to 200 GeV. Similar suppression pattern within uncertainties is observed for these energies.

4. **summary**

In summary, we report on recent STAR measurements of J/ψ production in Au+Au collisions at 39, 62.4 and 200 GeV at midrapidity. Significant suppression of J/ψ production, with respect to number of binary collisions scaled p+p yields, is observed for these three energies. No significant energy dependence of nuclear modification factor (both for R_{AA} and R_{CP}) is found within uncertainties. Model calculations, which include direct suppression and regeneration, describe the centrality dependence of R_{AA} within uncertainties. Precise p+p reference measurements at 39 and 62.4 GeV are needed for further understanding of the J/ψ interactions with the nuclear matter at these energies.

**References**

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