Article

Review on recent results of J/ψ production at STAR

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Abstract: The production of J/ψ (bound state of charm and anti-charm quark) in proton-proton collisions gives an opportunity to test quantum chromodynamics (QCD) calculations, as the production of J/ψ involves both perturbative and non-perturbative processes. However, theoretical calculations are still unable to fully explain experimental results, such as polarization and p_{T} spectra. More studies are needed to investigate J/ψ production mechanism. In heavy-ion collisions, charmonia can be used to study the properties of the medium as they are expected to dissociate in the medium when the Debye radius, inversely proportional to the medium temperature, becomes smaller than their size. Other competing effects, such as recombination, have also been found to modify the observed J/ψ yield in heavy-ion collisions. We review recent measurements of J/ψ production in proton-proton and heavy-ion collisions at various collision energies measured with the STAR experiment at RHIC. The data are compared with recent model calculations on charmonia production.

Keywords: J/ψ production; charmonia suppression; heavy-ion collisions; proton+proton collisions; STAR experiment

1. Introduction

Understanding the production mechanisms of J/ψ mesons is crucial for testing QCD calculations in proton-proton ($p+p$) collisions and probing the properties of the strongly interacting medium created in heavy-ion collisions. J/ψ suppression provides evidence of QGP formation, where color screening prevents the binding of charm quarks, depending on the energy density and temperature of the medium [1]. Describing charmonium production in a medium is challenging due to the competing effects of recombination and dissociation processes. Systematic studies of various collision systems and energies may help to disentangle the charmonium production mechanism. Accordingly, the following text provides an overview of recent results on J/ψ production from the STAR experiment.

2. Experimental setup

All of the analyses presented here were obtained from data collected using the STAR (Solenoidal Tracking at RHIC) detector [2]. Some of the key detectors utilized in J/ψ-related analyses at mid-rapidity include the Time Projection Chamber (TPC) [3], which provides charged particle tracking, momentum determination, and energy loss measurements for particle identification. The Time-of-Flight (TOF) detector [4] is used for complementary particle identification. The Barrel Electromagnetic Calorimeter (BEMC) [5] operates as for particle detection based on deposited energy, provides high-p_{T} triggering, and features fine granularity in $(\eta, \varphi) = (0.05, 0.05)$ with full azimuthal coverage: $0 \leq \varphi < 2\pi$.

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3. Results

Firstly, the results focused on suppression of J/ψ production in heavy-ion collisions across various collision systems and energies will be presented. This will be followed by a discussion of the analyses related to J/ψ production in proton-proton collisions, including studies of multiplicity dependence and J/ψ production within jets.

3.1. Inclusive J/ψ R_{AA}

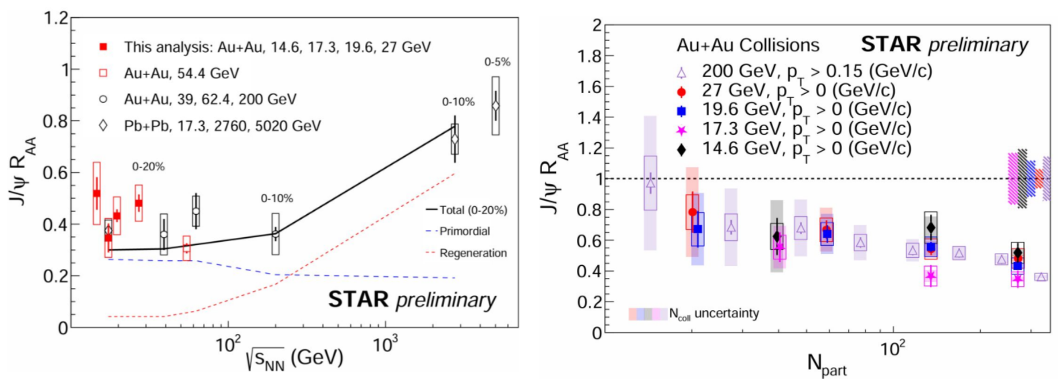
To study the influence of the medium on J/ψ production, one can use the nuclear modification factor R_{AA} defined as:

$$R_{AA} = \frac{\sigma_{\text{inel}}}{\langle N_{\text{coll}} \rangle} \frac{\mathrm{d}^2 N_{\text{AA}}/\mathrm{d}y\mathrm{d}p_{\text{T}}}{\mathrm{d}^2\sigma_{pp}/\mathrm{d}y\mathrm{d}p_{\text{T}}}, \tag{1}$$

where $\langle N_{coll} \rangle$ corresponds to a scaling factor representing an average number of binary nucleon-nucleon collisions based on the Glauber model predictions [6]. N_{AA} and N_{pp} are the numbers of particles produced in A+A and $p+p$ collisions, respectively with transverse momentum p_{T} and rapidity y.

Figure 1(**a**) shows the dependence of the J/ψ R_{AA} on collision energy in the range of $\sqrt{s_{\text{NN}}} = 14.6 - 200$ GeV [7,8], and includes a comparison with SPS [9], ALICE data [10,11] and model predictions [12,13]. Energy dependence can be qualitatively described by the transport model [5,6], with primordial production being dominant at RHIC energies and regeneration at the LHC [7,8], as illustrated by the model curves in the figure. No significant energy dependence of J/ψ R_{AA} is observed in central collisions within uncertainties of up to 200 GeV.

Another measurement, the measurement of J/ψ R_{AA} as a function of centrality in Au+Au collisions at different collision energies, is presented in Figure 1(**b**), where the J/ψ R_{AA} indicates a slightly decreasing trend, hence suggesting a stronger suppression in central collisions compared to the peripheral collisions. No significant energy dependence is observed in a given $\langle N_{\text{part}} \rangle$.



(**a**) (**b**)

Figure 1. (**a**) J/ψ R_{AA} as a function of collision energy with data from the STAR experiment $\sqrt{s_{\text{NN}}} = 14.6 - 200$ GeV [7,8], compared with SPS and ALICE measurements [9–11] and model predictions [12,13]. (**b**) Measurement of the J/ψ R_{AA} as a function of centrality in Au+Au collisions for various collision energies at the STAR experiment.

3.2. *ψ(2S) over J/ψ Double Ratio*

The first observation of sequential charmonium suppression in heavy-ion collisions at STAR is shown in the Figure 2 and quantified by the $\psi(2\mathrm{S})$ over J/ψ double ratio:

$$\frac{\left[\left(\mathrm{B d}\sigma_{\psi(2\mathrm{S})}\right)/\left(\mathrm{B d}\sigma_{\mathrm{J}/\psi}\right)\right]_{\mathrm{AA}}}{\left[\left(\mathrm{B d}\sigma_{\psi(2\mathrm{S})}\right)/\left(\mathrm{B d}\sigma_{\mathrm{J}/\psi}\right)\right]_{pp,pd}}, \tag{2}$$

which is described by the production cross sections of the excited charmonium state $\psi(2\mathrm{S})$ and of the ground state J/ψ (i.e. $\sigma_{\psi(2\mathrm{S})}$ and $\sigma_{\mathrm{J}/\psi}$, respectively) and their branching ratios B, comparing heavy-ion (AA) collisions to proton-proton (pp) or proton-deuteron (pd) collisions.

It is observed that $\psi(2\mathrm{S})$ is overall more suppressed than J/ψ, reflecting its weaker binding energy and greater sensitivity to QGP. Suppression grows with centrality, driven by higher energy density and QGP lifetime in central collisions. Other measurement for different collision systems and energies are shown for comparison. The data are further compared with an average $p+p$ reference from NA51, ISR and PHENIX [14–16]. The double ratio appears to be smaller in the isobar system than in the $p+$ A system (see right panel of the Figure 2).

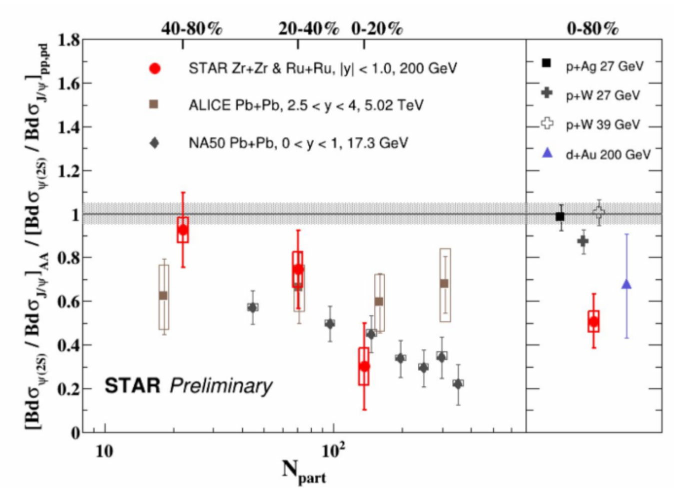


Figure 2. $\psi(2\mathrm{S})$ over J/ψ double ratio as a function of N_{part} for various A+A collision systems (left), and the results for $p+$ A systems (right panel). The data are compared with an average $p+p$ reference from NA51, ISR and PHENIX [14–16].

3.3. *J/ψ Production vs Multiplicity in $p+p$*

In high multiplicity $p+p$ collisions, multiple parton interactions (MPI) and string percolation effects are expected to play a significant role in modifying J/ψ production. These mechanisms can enhance the initial parton density and increase the probability of interactions, potentially affecting the yield of the produced J/ψ mesons.

The measured data are compared to previous results at $\sqrt{s} = 200$ GeV [17] in Figure 3. Normalized yields at $\sqrt{s}$= 510 GeV are consistent with those at $\sqrt{s}$= 200 GeV, with a wider multiplicity range achieved at $\sqrt{s}$= 510 GeV. There is an indication of a splitting between the results obtained at RHIC and LHC energies [18,19].

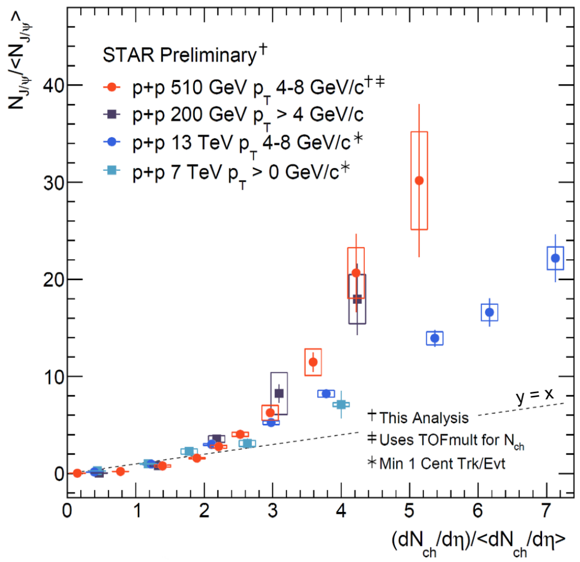


Figure 3. The measurement of the J/ψ production vs multiplicity in $p+p$ collisions for different collision energies.

3.4. J/ψ Production in Jets in $p+p$ collisions

Study of J/ψ production in jets provides additional discriminative power for production mechanisms. The fraction z of charged-particle jet transverse momentum carried by J/ψ is defined as the ratio of the J/ψ transverse momentum to the transverse momentum of the jet:

$$z(\mathrm{J}/\psi) = \frac{p_{\mathrm{T}}^{\mathrm{J}/\psi}}{p_{\mathrm{T}}^{jet}}. \tag{3}$$

The measured z distribution for inclusive J/ψ in jets in $p+p$ collisions at $\sqrt{s}$= 500 GeV normalized by the J/ψ cross-section [20], is compared to model prediction (PYTHIA 8) and shown in Figure 4. The results show discrepancy with the model predictions. The z distribution remains relatively flat, while PYTHIA predicts a steep rise toward $z = 1$, where most the jet momentum is carried by the J/ψ.

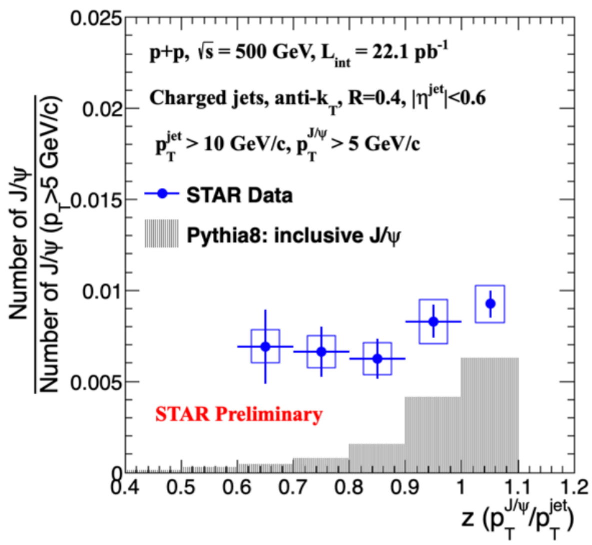


Figure 4. The normalized z distributions for inclusive J/ψ mesons produced within a jet compared to prediction from PYTHIA 8. The data are normalized by the J/ψ cross-section at the same collision energy [20].

4. Summary and Outlook

Recent measurements of charmonium production have been shown in A + A collisions, including the study of J/ψ R_{AA} and the charmonium suppression using the ψ(2S) over J/ψ double ratio. The J/ψ production dependence on charged-particle multiplicity at $\sqrt{s} = 510$ GeV and its production in jets in $p + p$ collisions at $\sqrt{s} = 500$ GeV was presented.

Further charmonia measurements have not been covered in this paper, such as the study of azimuthal anisotropy and polarization. Studies of J/ψ polarization in jets in $p + p$ collisions are ongoing to provide deeper insights into the J/ψ production mechanism The high luminosity $p + p$ and Au+Au data at 200 GeV from 2023-2025 will enable more precise measurements of J/ψ elliptic anisotropy and ψ(2S) production [21].

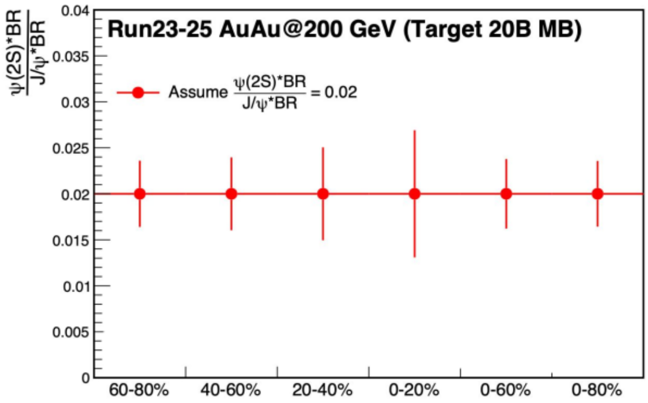


Figure 5. Projection of ψ(2S) to J/ψ ratios vs centrality for the planned 2023–2025 data-taking period at the STAR experiment [21].

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