# Beam energy and system size dependence of heavy flavor production at STAR

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**Abstract.** We report the measurements of quarkonia ($J/\psi$ and $\psi$(2S)) in heavy-ion collisions via the $e^+e^-$ decay channel at midrapidity ($|y| < 1$) by the STAR experiment. The centrality and transverse momentum dependence of the yield ratio of $\psi$(2S) to $J/\psi$ is measured for the first time in heavy-ion collisions at RHIC. These results, together with the new measurement of collision energy dependence of inclusive $J/\psi$ suppression in Au+Au collisions, allow for a comprehensive study of the quarkonium production in the medium. In addition, we present the first measurement of $J/\psi$ polarization in heavy-ion collisions at RHIC in both the Helicity and the Collins-Soper frames, which provides a new insight for studying the properties of the Quark-Gluon Plasma created in heavy-ion collisions.

## 1 Introduction

Heavy quarks (charm and beauty) emerge from initial hard partonic scatterings in heavy-ion collisions and undergo the entire evolution of the Quark-Gluon Plasma (QGP), offering an ideal probe to investigate the QGP properties. Quarkonia are bound states of heavy quarks and their anti-quarks, for example, the $J/\psi$ meson ($c\bar{c}$). The anticipated dissociation of $J/\psi$ production[1], owing to the presence of the hot medium, stands as a signature of the QGP formation.

Alongside the dissociation in the medium, the effects like regeneration, cold nuclear matter, and feed-down also contribute to the measured yields. Hence, a systematic analysis involving different quarkonium states, differential measurements against transverse momentum ($p_{\rm T}$), collision centrality, collision energy and colliding system, and exploration of polarization become imperative. This comprehensive approach aims to distinguish various effects, facilitating a deeper understanding of QGP properties from quarkonium measurements.

## 2 Analysis and Results

### 2.1 $J/\psi$ production in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 14.6, 19.6, and 27 GeV

The datasets utilized for this measurement are obtained from Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 14.6, 19.6, and 27 GeV by the STAR experiment. The $J/\psi$ candidates are reconstructed

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via the dielectron decay channel. After applying good event and track selection criteria, the electron candidates are identified using the Time Projection Chamber (TPC) and the Time of Flight (TOF) detector.

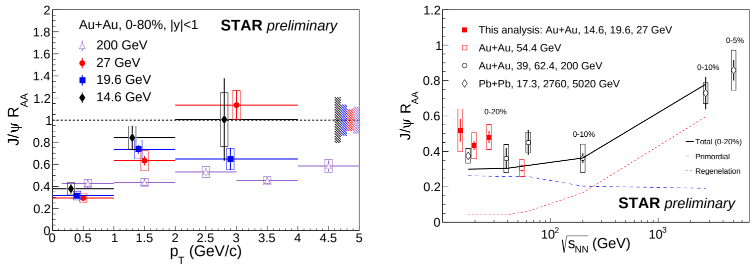


Figure 1: *Left panel*: Inclusive $J/\psi$ $R_{\mathrm{AA}}$ as a function of $p_{\mathrm{T}}$. Error bars represent the statistical uncertainties, while the boxes represent the systematic uncertainties. The bands around unity indicate the uncertainties from the nuclear overlap function $\langle T_{\mathrm{AA}}\rangle$ and the $p$+$p$ baselines. *Right panel*: $J/\psi$ $R_{\mathrm{AA}}$ as a function of collision energy for central collisions [2–7], compared with model calculations [8]. Error bars denote statistical uncertainties, while the boxes encompass systematic uncertainties, including those originating from $p$+$p$ baselines and $\langle T_{\mathrm{AA}}\rangle$.

The inclusive $J/\psi$ $R_{\mathrm{AA}}$ as a function of $p_{\mathrm{T}}$ in Au+Au collisions at different collision energies at midrapidity ($|y| < 1$) is presented in the left panel of Fig. 1. Due to unavailability of inclusive $J/\psi$ cross-section measurements in $p$+$p$ collisions at $\sqrt{s_{\mathrm{NN}}}$ = 14.6, 19.6, and 27 GeV, the $p$+$p$ baselines are derived through interpolations from world-wide datasets [9]. A larger suppression is observed at lower $p_{\mathrm{T}}$, and $R_{\mathrm{AA}}$ demonstrates an increasing trend with $p_{\mathrm{T}}$ at $\sqrt{s_{\mathrm{NN}}}$ = 14.6, 19.6, and 27 GeV. However, at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV, no significant $p_{\mathrm{T}}$ dependence is observed [5]. The different behavior might stem from a confluence of stronger regeneration effects at lower $p_{\mathrm{T}}$ and amplified dissociation effects at higher $p_{\mathrm{T}}$. Furthermore, the right panel of Fig. 1 illustrates the $R_{\mathrm{AA}}$ as a function of collision energy in central collisions. No significant energy dependence is observed for $\sqrt{s_{\mathrm{NN}}}$ below 200 GeV. This could be due to a combination of dissociation, regeneration, and cold nuclear matter effects. Moreover, the model calculation, incorporating these effects, can qualitatively describe the data but quantitatively underestimates them below $\sqrt{s_{\mathrm{NN}}}$ = 27 GeV.

### 2.2 $\psi(2S)$ production in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV

The dataset used in this analysis consist of 4 billion events from isobaric (Ru+Ru and Zr+Zr) collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV, collected in 2018 by the STAR experiment.

The inclusive $\psi(2S)$ to $J/\psi$ double ratio (with respect to $p$+$p$ results) as a function of $\langle N_{\mathrm{part}}\rangle$ in isobar collisions at midrapidity is presented in the left panel of Fig. 2. The red points show the new measurement, marking the first observation of charmonium sequential suppression in heavy-ion collisions at RHIC. The double ratio decreases from peripheral to central collisions. Additionally there is a hint that the trend of the double ratio seems more akin to SPS measurements (Pb+Pb, $0 < y < 1$, 17.3 GeV) than that at the LHC (Pb+Pb, $2.5 < y < 4$, 5.02 TeV). Moreover, the double ratio in isobar collisions is significantly lower than that in $p$+A collisions.

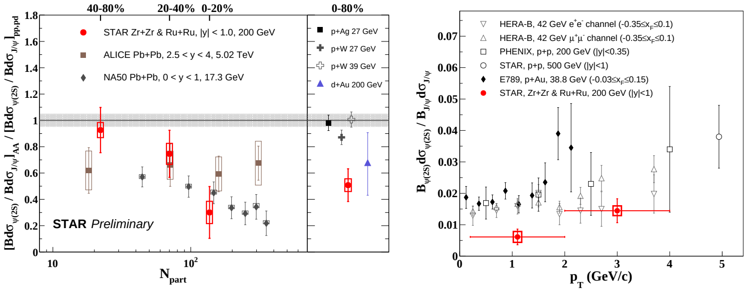


Figure 2: *Left panel*: Inclusive $\psi(2S)$ to $J/\psi$ double ratio as a function of $\langle N_{\text{part}} \rangle$. For measurements from heavy-ion collisions [10, 11], the error bars indicate statistical uncertainties, while the boxes denote systematic uncertainties. Other results only display total errors [12–14]. The $p$+$p$ baseline is a combined result from [15–17]. *Right panel*: $p_{\text{T}}$ dependence of the $\psi(2S)$ to $J/\psi$ yield ratio in $p$+$p$ [15, 18], $p$+A [19, 20], and A+A (this result) collisions.

The right panel of Fig. 2 illustrates the $\psi(2S)$ to $J/\psi$ yield ratio as a function of $p_{\text{T}}$. All results demonstrate an increasing trend with $p_{\text{T}}$. The ratio in isobar collisions is significantly lower than that in $p$+$p$ and $p$+A collisions at $p_{\text{T}}$ less than 2 GeV/c.

### 2.3 $J/\psi$ polarization in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{\text{NN}}}$ = 200 GeV

The polarization parameters for inclusive $J/\psi$ production, reconstructed via the dielectron decay channel, in isobar collisions at $\sqrt{s_{\text{NN}}}$ = 200 GeV in the Helicity and Collins-Soper reference frames [21] are shown in Fig. 3. The consistency of $\lambda_{\text{inv}}$ (frame-invariant polarization parameters) between two frames confirms the validity of the results. A hint of non-trivial $p_{\text{T}}$ dependence is observed in the HX frame, but overall no significant dependency on $p_{\text{T}}$ or centrality is observed in both reference frames. The results are consistent with those measured in $p$+$p$ collisions [22] and also consistent with zero within uncertainties. So, no significant impact from QGP on the polarization of $J/\psi$ is observed within uncertainties.

## 3 Conclusion

In this contribution, we report the $J/\psi$ $R_{\text{AA}}$ in Au+Au collisions at $\sqrt{s_{\text{NN}}}$ = 14.6, 19.6, and 27 GeV. No significant energy dependence of $R_{\text{AA}}$ is observed for $\sqrt{s_{\text{NN}}}$ less than 200 GeV. We also present the first measurements of $J/\psi$ polarization and charmonium sequential suppression in heavy-ion collisions at RHIC. The $\psi(2S)$ to $J/\psi$ ratio is significantly lower than those in $p$+$p$ and $p$+A collisions, while the $J/\psi$ polarization parameters are consistent with zero at the current precision.

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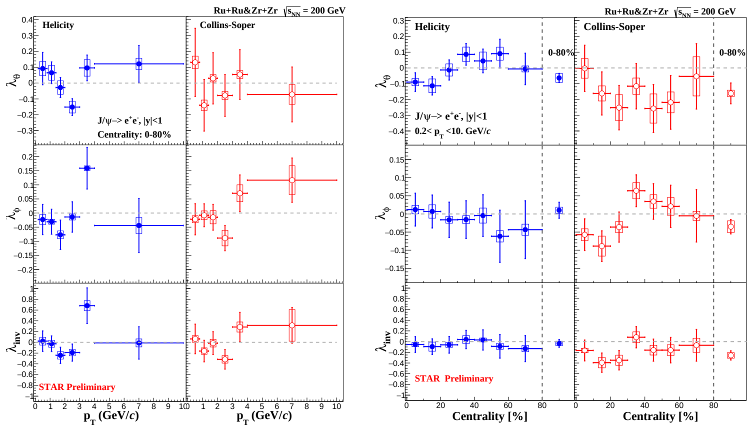


Figure 3: Inclusive $J/\psi$ polarization parameters as a function of $p_T$ (left) and centrality (right) in isobar collisions at 200 GeV. Error bars indicate statistical uncertainties, while the boxes denote systematic uncertainties.

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