

Multiplicity dependent J/ψ and $\psi(2S)$ production at forward and backward rapidity in $p+p$ collisions at $\sqrt{s}=200$ GeV

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Recent measurements of J/ψ production as a function of event charged-particle multiplicity at the collision energies of both the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC) show enhanced J/ψ production yields with increasing multiplicity. One potential explanation for this type of dependence is multiparton interactions (MPI). We present the first study of potential autocorrelations at RHIC energies and forward and backward rapidity of self-normalized J/ψ yields and $\psi(2S)$ to J/ψ ratio, as a function of self-normalized multiplicity in $p + p$ collisions. In addition, detailed PYTHIA studies tuned to RHIC energies were performed to investigate the MPI impacts. We find that the PHENIX data at RHIC are consistent with recent LHC measurements and can only be described by PYTHIA calculations that include MPI effects. The forward and backward $\psi(2S)$ to J/ψ ratio is found to be less dependent on the charged-particle multiplicity.

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Charmonium, a bound $c\bar{c}$ state, has been studied extensively over the past several decades, but a clear understanding of its formation has not yet been reached. Several models are currently available to describe the evolution of a $c\bar{c}$ pair into the bound J/ψ or $\psi(2S)$ meson, such as the nonrelativistic-quantum-chromodynamics (NRQCD) [1], color-evaporation [2], color-singlet [3], and jet-fragmentation [4] models. The formation appears to involve both perturbative (above the Λ_{QCD} scale) and nonperturbative (below the Λ_{QCD} scale) aspects of QCD. The initial creation of $c\bar{c}$ pairs through hard scattering can be described as perturbative, and their evolution into a color-neutral state is likely nonperturbative.

In this Letter, we present PHENIX measurements at the Relativistic Heavy Ion Collider (RHIC) of the self-normalized J/ψ production versus self-normalized event

multiplicity to study the multiparton-interaction (MPI) effects at forward rapidity as well as the $\psi(2S)$ to J/ψ ratio, which is sensitive to final-state interactions in $p + p$ collisions at RHIC energies. We measure inclusive J/ψ and $\psi(2S)$ production without separating prompt from non-prompt charmonium because the nonprompt contributions are less than 3% of the total charmonium production.

The STAR experiment at RHIC has measured the self-normalized J/ψ yields as a function of self-normalized charged-particle multiplicity at midrapidity in $p + p$ collisions [5]. The results show an increase in the J/ψ yields with increasing multiplicity, a dependence suggesting MPI. Additionally, at Large-Hadron-Collider (LHC) energies, the ALICE experiment has reported similar results for the normalized J/ψ yields versus event multiplicity at both forward rapidity [6,7] and midrapidity [8]. In addition to potential MPI, the $\psi(2S)$ to J/ψ ratio could reveal final-state effects from either hot (formation of quark-gluon plasma [9–12]), or cold (comover-interaction model [13]) hadronic-matter effects. Recently, ALICE (both midrapidity and forward rapidity) [14] and LHCb (forward rapidity) [15] reported the ratio of the normalized $\psi(2S)$ to J/ψ ratio in $p + p$ collisions at $\sqrt{s} = 13$ TeV.

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The present analysis relies on the data from the PHENIX experiment [16] obtained using the muon-arms detector subsystem covering $1.2 < |\eta| < 2.4$, which includes the muon tracker (MuTr), the muon identifier (MuID), the hadron absorbers, the forward silicon vertex detectors (FVTX) [17–20] in the forward rapidity region and the central arm barrel silicon vertex tracker (VTX) [21] at $|\eta| < 1.0$. Two beam-beam counters (BBC), located at $z = \pm 144$ cm from the nominal interaction point and covering the full azimuth and $3.1 < |\eta| < 3.9$, measure the vertex position along the beamline. The BBCs also serve as the minimum-bias (MB) trigger and measure the beam luminosity.

The $p + p$ dataset used in this analysis was collected in 2015 and recorded at $\sqrt{s} = 200$ GeV center-of-mass energy. The analyzed events were selected by the MB trigger and the dimuon triggers, which required two or more muon tracks in the MuID. The collision vertex was constrained to be within ± 10 cm with respect to the center of the interaction region. The total sampled luminosity for the $p + p$ dataset is 47 pb^{-1} .

The observable used in this analysis has theoretical [22] and experimental [23] motivations. We first define the self-normalized event charged-particle multiplicity $N_{\text{ch}}/\langle N_{\text{ch}} \rangle$, where N_{ch} represents the number of reconstructed charged-particle tracks detected by the forward- or backward-rapidity FVTX with $1.2 < \eta < 2.4$ and $-2.4 < \eta < -1.2$, and $\langle N_{\text{ch}} \rangle$ represents the average N_{ch} for MB events. Then the relative yield of J/ψ , denoted as $N_{J/\psi}/\langle N_{J/\psi} \rangle$ in a given $N_{\text{ch}}/\langle N_{\text{ch}} \rangle$ range, is measured by the forward or backward muon arms covering $1.2 < y < 2.2$ and $-2.2 < y < -1.2$, respectively

$$N_{J/\psi}/\langle N_{J/\psi} \rangle = \frac{N_{J/\psi}^{\text{raw}}}{N_{\text{evt}}} \frac{N_{\text{evt}}^{\text{total}}}{N_{J/\psi}^{\text{raw, total}}} \frac{\epsilon_{\text{trig}}^{\text{MB}}}{\epsilon_{\text{trig}}^{J/\psi}} \frac{\langle \epsilon_{\text{trig}}^{J/\psi} \rangle}{\langle \epsilon_{\text{trig}}^{\text{MB}} \rangle} f_{\text{coll}}, \quad (1)$$

where $N_{J/\psi}^{\text{raw}}$ is the raw number of J/ψ signal yield extracted from the dimuon-invariant-mass fit, and N_{evt} is the number of recorded MB events for a certain N_{ch} bin. The average MB efficiency is $\langle \epsilon_{\text{trig}}^{\text{MB}} \rangle = 55 \pm 5\%$ and the J/ψ efficiency is $\langle \epsilon_{\text{trig}}^{J/\psi} \rangle = 79 \pm 2\%$. The superscript “total” stands for quantities integrated over all N_{ch} . The $\epsilon_{\text{trig}}^{\text{MB}}$ is the MB trigger efficiency, $\epsilon_{\text{trig}}^{J/\psi}$ is the dimuon trigger efficiency. The f_{coll} is a correction factor for multiple collisions. The same observable is then measured for $\psi(2S)$, and the ratio of relative yields is defined as $(N_{\psi(2S)}/N_{J/\psi})/\langle N_{\psi(2S)}/N_{J/\psi} \rangle$. We present the data in terms of the same arms defined as measuring N_{ch} and $N_{J/\psi}$ at the same rapidity range, and opposite arms defined as measuring N_{ch} and $N_{J/\psi}$ at the opposite rapidity range. When combining the data from two arms, we define $1.2 < |\eta| < 2.4$ for N_{ch} and $1.2 < |y| < 2.2$ for $N_{J/\psi}$.

The BBC MB trigger requires a coincidence between the forward and backward rapidity counters and a hit on both

sides. In PHENIX, the trigger efficiency has event-multiplicity dependence due to finite acceptance of the BBC. The MB trigger efficiency versus event multiplicity was evaluated with RHIC beam-crossing-clock triggered events [24,25] by checking whether the MB trigger is fired for events satisfying the MB trigger condition. These events are randomly selected for a certain beam crossing and provide unbiased samples compared to detector-level triggers.

To check the multiplicity dependence of the MB trigger for hard-scattering events, we require at least one electromagnetic-calorimeter cluster of $E > 2$ GeV on top of the RHIC beam-crossing-clock trigger. The MB trigger efficiency ranges from $\approx 47\%$ at $N_{\text{ch}} = 0$ to $\approx 90\%$ at $N_{\text{ch}} = 10$, while the J/ψ trigger efficiency approaches unity exponentially with increasing N_{ch} , ranging from $\approx 78\%$ ($\approx 98\%$) in the lowest (highest) multiplicity bin.

The possibility of multiple-collision events, defined as an event having $p + p$ collisions in addition to the one that produced the J/ψ or $\psi(2S)$, increases with increasing multiplicity. A data-driven method is utilized to estimate the fraction of multiple collision events, which assumes Poisson statistics and estimates the BBC (MB) trigger rate R_{BBC} using the following formula:

$$R_{\text{BBC}} = f_{\text{BC}}[1 - e^{-\mu\epsilon_F} - e^{-\mu\epsilon_B} + e^{-\mu(\epsilon_F + \epsilon_B + \epsilon_{\text{FB}})}], \quad (2)$$

where f_{BC} is the beam-crossing rate at RHIC, μ is the mean number of collisions, ϵ_F (ϵ_B) is the trigger efficiency ($\approx 75\%$) of each BBC at forward (backward) rapidity, and $\epsilon_{\text{FB}} = \langle \epsilon_{\text{trig}}^{\text{MB}} \rangle = 55\%$ when both BBCs are fired. The maximum R_{BBC} during the $p + p$ data run is 2.5 MHz, corresponding to an $\approx 10\%$ rate of double collision events. Due to the average R_{BBC} being ≈ 1 MHz and the low probability of having more than two collisions per beam crossing, only contributions from double collisions were considered. The ratio of double to single collisions, f_{coll} , is evaluated as a function of the measured-BBC-trigger rate R_{BBC} , and carries an average value of ≈ 1.06 .

A crystal-ball (CB) function [26] is used to model the J/ψ and $\psi(2S)$ signal shapes to extract the raw yields from the dimuon invariant-mass distribution. The tail parameters α and n of the CB function were fixed with values from integrated multiplicity data for J/ψ and simulation studies for $\psi(2S)$. The FVTX detector delivers the mass resolution needed for $\psi(2S)$ measurements [19] but reduces the acceptance due to a finite matching efficiency between the MuTr and FVTX detectors. For $N_{J/\psi}/\langle N_{J/\psi} \rangle$ as a function of $N_{\text{ch}}/\langle N_{\text{ch}} \rangle$ shown in Figs. 1 and 2, the FVTX detector is not used to maximize J/ψ signal statistics. For $\psi(2S)$ measurements with the FVTX detector, a Gaussian function is used alongside the CB function to account for the broadening of signal shape due to misassociation between the FVTX and MuTr detectors [27]. Additional parameters were fixed for the extraction of the $\psi(2S)$ yield, where the Gaussian mean is constrained by the ratio of

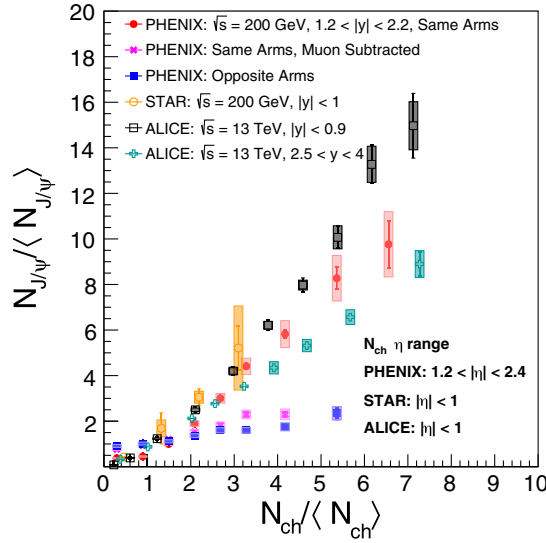


FIG. 1. The self-normalized J/ψ yield as a function of self-normalized charged-particle multiplicity in $p + p$ collisions at various energies. The PHENIX data combine forward and backward J/ψ with forward and backward FVTX, respectively. The contribution of J/ψ daughter-muon tracks included in the charged-particle multiplicity (solid circle) and the ones subtracting the J/ψ daughter-muon-tracks contribution (solid cross) in the same arms as well as the ones with opposite arm (solid square) are presented. The PHENIX measurements are compared with ALICE measurements at forward rapidity [7] and at midrapidity [8], and STAR [5] measurements at midrapidity. The error bars (boxes) denote the statistical (systematic) uncertainties.

PDG mass values for J/ψ and $\psi(2S)$, and the Gaussian width is constrained to 1.15 times the Gaussian width of the J/ψ signal shape [27,28]. The individual multiplicity bins are fitted by fixing the shape parameters α and n of the CB function to the integrated multiplicity(simulation) fit results to extract the J/ψ ($\psi(2S)$) signal yield.

For the J/ψ analysis without the FVTX detector, an exponential decay function is used to describe the background. For the $\psi(2S)$ to J/ψ ratio, a modified Hagedorn function is used to model the combinatorial and correlated-background contributions [27,30]. The shape of the combinatorial background is estimated with real data using the mixed-event method, where opposite sign single muons are selected from different events. The combinatorial background normalization is obtained from like-sign single muons selected from the same events. The correlated background shape is determined using detailed simulation studies [31] and is implemented in the total fit function by fixing three of the five parameters of the modified Hagedorn function to constrain the shape. Example invariant-mass distributions (with and without the FVTX requirement) and fit results can be found in Refs. [30,32].

The sources of systematic uncertainties for the J/ψ measurements include the following: the MB trigger efficiency, the J/ψ trigger efficiency, the J/ψ reconstruction efficiency, and the multiple-collision-correction factor f_{coll}

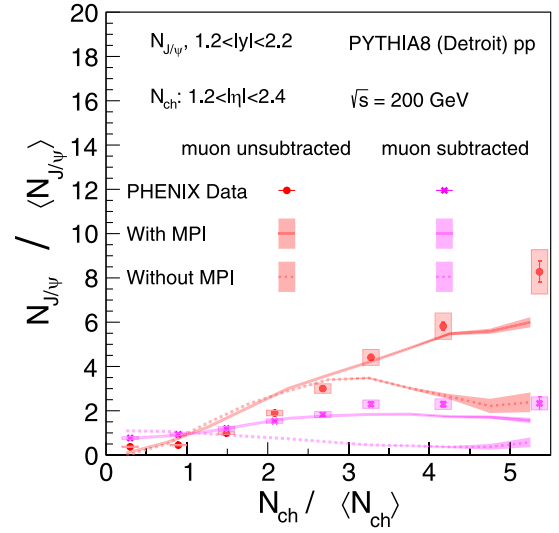


FIG. 2. The self-normalized J/ψ yields are shown as a function of self-normalized charged-particle multiplicity in $p + p$ collisions at $\sqrt{s} = 200$ GeV. The solid circle and solid cross data points, respectively, represent the measurements before and after the J/ψ muon tracks have been subtracted (see text for more details). The error bars (boxes) denote the statistical (systematic) uncertainties. Data are compared to PYTHIA8 Detroit tuned calculations in the pseudorapidity range of $1.2 < |\eta| < 2.4$ for charged particles with (solid lines) and without (dash lines) considering MPI effects [29].

per beam crossing. Further details on muon-arm efficiencies and systematic uncertainties are given elsewhere [33–36].

A flat systematic uncertainty is assigned for the J/ψ reconstruction efficiency based on the largest variation when three different z -vertex selections are applied (5.0%). The systematic uncertainty related to the J/ψ trigger efficiency decreases with increasing multiplicity. The efficiency as a function of N_{ch} is first fitted with the following function: $f(x) = p_0 + p_1 e^{-p_2 x}$. Then, the efficiency distribution is reevaluated by moving the parameter values by $\pm 1\sigma$ of the statistical uncertainty in the fit result. The largest difference with respect to the nominal value is assigned as the systematic uncertainty (1.5%–11.0%). The MB-trigger efficiency can be affected by multiple collisions. The systematic uncertainty related to the MB-trigger efficiency is determined by dividing the trigger efficiency into three different $p + p$ collision rates, determined by the MB trigger: 600–800, 1000–1500, and 2000–2500 kHz. The trigger efficiency for the high and low trigger rates are compared to the central rate, and the maximum deviation is scaled by $1/\sqrt{12}$ (the standard deviation of a uniform distribution), which is assigned as the systematic uncertainty (1.5%–1.7%). The systematic uncertainty related to the multiple-collision correction factor increases with increasing multiplicity and is evaluated by comparing factors using an alternate method, which is the ratio of probability distributions $P(N_{\text{ch}})$ between two different trigger rates, less than 500 and 1000–1500 kHz (0%–16%).

The sources of systematic uncertainty for the normalized $\psi(2S)$ to J/ψ ratio include the following: the mixed-event background normalization, the signal shapes (fixed CB tail parameters [19] and the second Gaussian width) [27,30], and the correlated background shape [34]. All other systematic uncertainties cancel for the double ratio, including uncertainties related to misassociated tracks between the FVTX and MuTr detectors and the multiple-collision correction factor.

The correlated background uncertainty was determined by allowing three of the five modified Hagedorn function parameters that determines its shape in the fit to vary and comparing the resulting signal yields from each fit (2%–5%). The determination of the uncertainty in the normalization of the mixed-event background ($\approx 1.9\%$) follows the methods described in Ref. [27].

The self-normalized J/ψ yields ($N_{J/\psi}/\langle N_{J/\psi} \rangle$) as a function of self-normalized charged-particle multiplicity ($N_{ch}/\langle N_{ch} \rangle$) are shown in Fig. 1 and compared to STAR [5] and ALICE [7,8] data. The J/ψ decay-daughter-muon contributions to the charged-particle multiplicity have been subtracted in the PHENIX results to remove the autocorrelation effect. Before subtracting the J/ψ daughter-muon contributions, the PHENIX results show a multiplicity dependence that is similar to the STAR results at midrapidity. For ALICE at 13 TeV, the results at forward rapidity are systematically lower than at midrapidity, but it is difficult to reach conclusions for PHENIX and STAR at 200 GeV due to the larger systematic uncertainties. After subtracting the J/ψ daughter-muon contributions, the J/ψ

yields shift to lower $N_{ch}/\langle N_{ch} \rangle$, leading to a significant drop of $N_{J/\psi}/\langle N_{J/\psi} \rangle$, which is consistent with the results of opposite arms, where N_{ch} is free from the J/ψ daughter-muon contributions. The PHENIX results with subtraction are significantly lower than the ALICE results at forward rapidity, but a comparable slope is seen in STAR and ALICE results at midrapidity. Note that the autocorrelation correction was not applied to the ALICE and STAR results. The impact on the slope is expected to be more significant for the STAR than the ALICE results due to the smaller multiplicity.

The self-normalized J/ψ yields are also compared with PYTHIA8 calculations. In Fig. 2 where the simulations are compared to J/ψ normalized yield in data, the PYTHIA8 Detroit tuned with MPI calculations [37] agree with the data within $\approx 1\sigma$ while failing to describe the data without MPI effects. Therefore, MPI effects need to be included to accurately model J/ψ production in $p + p$ collisions at RHIC. In addition, comparison between the PHENIX and ALICE results at forward rapidity indicates that the MPI effects on the multiplicity dependence would be even stronger at LHC energies.

The $(N_{\psi(2S)}/N_{J/\psi})/\langle N_{\psi(2S)}/N_{J/\psi} \rangle$ as a function of $N_{ch}/\langle N_{ch} \rangle$, shown in Fig. 3, was measured to investigate final-state interaction effects on charmonium production. The self-normalized yield ratios of $\psi(2S)$ to J/ψ at forward rapidity are shown as a function of normalized charged-particle multiplicity, where the charged-particle multiplicity has been measured using both the forward (same arms) and backward (opposite arms) FVTX

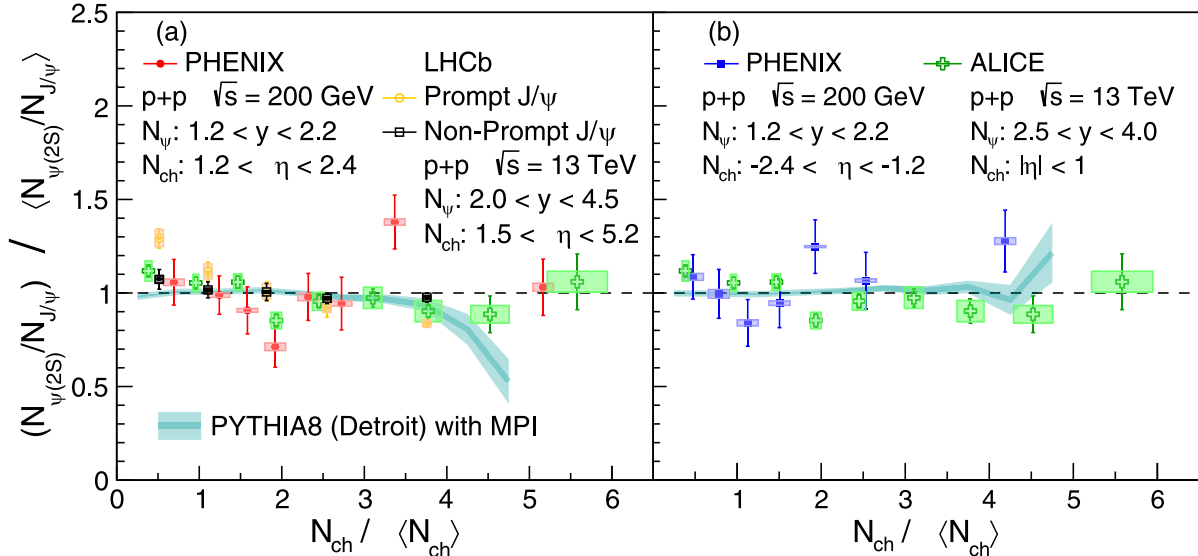


FIG. 3. The self-normalized $\psi(2S)$ to J/ψ ratio at forward rapidity as a function of self-normalized charged-particle multiplicity in $p + p$ collisions at $\sqrt{s} = 200$ GeV by PHENIX compared with the (a) LHCb [15] and (b) ALICE [14] results at $\sqrt{s} = 13$ TeV. The PHENIX data is compared when charged particles are measured at (a) forward rapidity and (b) backward rapidity. It should be noted that LHCb and ALICE measure charged particles at different pseudorapidity. In addition, the data are compared to PYTHIA8 Detroit tuned calculations [37] (cyan curve), including MPI effects. The error bars (boxes) denote the statistical (systematic) uncertainties.

detectors. The $(N_{\psi(2S)}/N_{J/\psi})/\langle N_{\psi(2S)}/N_{J/\psi} \rangle$ measurements are consistent with unity within $\approx 1\sigma$, and no significant rapidity dependence is observed as a function of normalized charged particle multiplicity, $N_{\text{ch}}/\langle N_{\text{ch}} \rangle$. Therefore, final-state interactions on charmonium production appear negligible at the measured multiplicity range and collision energy.

Furthermore, in Fig. 3, the ALICE forward rapidity prompt [14] and LHCb prompt and nonprompt [15] $\psi(2S)$ to J/ψ measurements are included for comparison. The ALICE results also demonstrate similar consistency near unity up to $N_{\text{ch}}/\langle N_{\text{ch}} \rangle \approx 6$. LHCb has reported suppression of $(N_{\psi(2S)}/N_{J/\psi})/\langle N_{\psi(2S)}/N_{J/\psi} \rangle$ in high multiplicity $p+p$ collisions. The final state comover effect [13] becomes more pronounced at high multiplicity, and may result in the increased breakup of $\psi(2S)$ compared to J/ψ due to its lower binding energy.

Finally, Fig. 3 also shows PYTHIA8 Detroit tuned with MPI effects for the $(N_{\psi(2S)}/N_{J/\psi})/\langle N_{\psi(2S)}/N_{J/\psi} \rangle$ as a function of $N_{\text{ch}}/\langle N_{\text{ch}} \rangle$ but without any final-state effects on quarkonia. The PYTHIA8 calculations yield similar results within uncertainties, and generally reproduce the data near unity. This indicates that the data favors no significant final-state interaction in $p+p$ collisions at $\sqrt{s} = 200$ GeV.

In summary, we have reported multiplicity-dependent studies of J/ψ and $\psi(2S)$ production at forward rapidity in $p+p$ collisions at $\sqrt{s} = 200$ GeV. The self-normalized J/ψ yields are measured up to ≈ 6 units of $N_{\text{ch}}/\langle N_{\text{ch}} \rangle$ and reasonable consistency with the STAR and ALICE data has been achieved when the J/ψ and charged particles are measured in the same pseudorapidity region. Results of self-normalized J/ψ yields before and after J/ψ decay-daughter-muon subtraction for N_{ch} counting can be well described by the PYTHIA8 Detroit tuned with MPI. Also, forward self-normalized $\psi(2S)$ to J/ψ yields as a function of forward and backward track multiplicity have been studied. Agreements with unity have been observed within uncertainties and the results are consistent at different rapidity gaps, suggesting no significant final-state interactions on charmonium production. The PYTHIA8 model without final-state interactions generally reproduces the self-normalized $\psi(2S)$ to J/ψ yields indicating that no such effect occurs in $p+p$ collisions at RHIC energies.

Consistency with unity is also reported by ALICE. However, LHCb observes a suppression of prompt $\psi(2S)$ production at high multiplicity, aligning with the prediction of final-state comover effects [38]. Note that LHCb and ALICE measure charged particles at different pseudorapidity. The LHCb results also demonstrate

consistency with the PHENIX data points within uncertainties. Investigations of PHENIX data for charmonium production in $p+Al$ and $p+Au$ collisions, particularly in the backward-rapidity region, would provide an excellent opportunity to further study final-state effects in small collision systems at RHIC energies.

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Data availability. The data that support the findings of this article are not publicly available. The values in the plots associated with this article are stored in HEPData [39].

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