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Simulation study of multiplicity-dependent charmonia production with PYTHIA

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Abstract
Production of charmonia has been studied in various collision systems, from proton–proton (*pp*) to nucleus–nucleus (*AA*) collisions, to understand their production mechanism and behavior inside nuclear matters. Depending on the collision system and event multiplicity, several physics effects contribute to the charmoina production. In *pp* collisions, the J/ψ yield increases with the event multiplicity at RHIC and the LHC, indicating that the multi-parton interaction contributes to the charmonia production. In proton-nucleus (*pA*) collisions, the relative production of $\psi(2S)$ to J/ψ is smaller than that in *pp* collisions. Final-state effects, such as interaction with a hot nuclear medium or co-moving particles, are necessary to describe the experimental results. To fully understand the contribution of various physics effects, it is essential to have a model with selected physics effects to compare with experimental results. We perform a detailed study on the multiplicity-dependent charmonia production in *pp* collisions with the PYTHIA Monte Carlo event generator. Various options are explored, such as different tunes for underlying events and the hadronic rescattering effect for final-state interactions.

Keywords Charmonia · Multi-parton interaction · Rescattering · PYTHIA

1 Introduction

Charmonia, a bound state of a charm and anti-charm quark, production in high-energy collision experiments have been extensively studied to understand mechanisms involved in their production and modification. The production of heavy quarks can be calculated by perturbative Quantum Chromodynamics (pQCD), but the later process to bind them into a colorless charmonia state is a non-perturbative process. The non-relativistic QCD (NRQCD) effective theory [1] can describe experimental measurements in proton–proton collisions [2]. Several partonic interactions exist in a single collision in high-energy proton–proton (*pp*) collisions at RHIC and the LHC. These multi-parton interactions (MPI) affect the number of produced particles in the collision. Several experimental measurements show the yield of J/ψ is strongly correlated with the event multiplicity, indicating that the MPI contributes to the production of charmonia [3–5]. One interesting observation is that the multiplicity dependence is similar between RHIC and the LHC results. Such measurements in various collision energies will provide new insights into the relationship between hard and soft processes for charmonia production.

In proton–nucleus (*pA*) and nucleus–nucleus (*AA*) collisions, charmoina produced at initial hard scatterings can be modified due to interactions inside the partonic and hadronic medium [6, 7]. The final-state effects can be studied by measuring charmonia states with different binding energies, such as J/ψ and $\psi(2S)$, because initial-state effects are expected to be similar. Therefore, a detailed study of the multiplicity-dependent production of J/ψ and $\psi(2S)$ will be beneficial in fully understanding their production and modification mechanisms. In experimental results, the modification of the excited state $\psi(2S)$ is stronger than the ground state J/ψ in proton-nucleus collisions, but the multiplicity dependence is weak within uncertainties [8–11]. The yield ratio between J/ψ and $\psi(2S)$ as a function of multiplicity in *pp* collisions at $\sqrt{s} = 13$ TeV also shows a quite flat trend.

Several initial and final-state effects could be convoluted differently in experimental results with various conditions, such as kinematic regions of charmonia and multiplicity, and

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collision energies. To help interpret experimental results, we have performed a detailed simulation study with PYTHIA Monte Carlo event generator [12]. The event generator incorporating MPI shows a reasonable description of multiplicity-dependent J/ψ yield, and the yield ratio between $\psi(2S)$ and J/ψ in *pp* collisions at $\sqrt{s}$ = 13 TeV [3, 4, 11]. No specific comparison has been made yet in the case of RHIC energy [5, 13], and we perform a simulation with a recent PYTHIA tune for RHIC energies called Detroit tune [14]. The PYTHIA simulation generally does not include final-state interaction, but several options for partonic and hadronic interactions have been recently introduced [15, 16]. We also explore a recent implementation of hadronic rescatterings in PYTHIA to check how it affects the multiplicity-dependent J/ψ yield and yield ratio between J/ψ and $\psi(2S)$.

2 Model study

For this study, we use the PYTHIA Monte-Carlo (MC) event generator [12] and produce non-diffractive *pp* events at $\sqrt{s}$ = 13 TeV and 200 GeV which are close to event samples collected with a Minimum Bias (MB) trigger in experiments. We force J/ψ and $\psi(2S)$ to decay into dielectrons or dimuons, usually used to measure charmonia in experiments. The decay product of J/ψ and $\psi(2S)$ is tagged to calculate the charged particle multiplicity with and without its contribution.

We use Monash tune [17] and Detroit tune [14] for this study. The Monash tune, the default tune from PYTHIA v8.2, is based on early results from LHC experiments such as charged particle multiplicity, pseudorapidity density ($dN_{ch}/d\eta$), transverse momentum (p_T) spectra, and $\langle p_T \rangle$. This tune includes a set of parameters for initial and final-state radiations, string fragmentation, and MPI. The Detroit tune is a set of adjusted parameters for MPI based on the Monash tune to describe underlying event measurements at RHIC energies. The Monash tune is used for the simulation at both energies, and the Detroit tune is also used for the simulation at $\sqrt{s}$ = 200 GeV.

Two sets of events are generated with and without an option for hadronic rescattering effect [16] to quantify the effect on charmonia yields as a function of particle multiplicity. The hadronic rescattering effect is a newly implemented feature from PYTHIA v8.3 to describe elastic and inelastic scattering among hadrons on the way out, and this framework is similar to UrQMD [18] and SMASH [19]. Previous studies in *pp*, *pA*, and *AA* collisions show that the hadronic rescattering effect modifies the p_T spectra of hadrons and generates a long-range correlation [16, 20]. We use the framework to check how the charmonia yield is affected by this type of final-state interaction.

Figure 1 shows the $dN_{ch}/d\eta$ distributions for MB events and events with inclusive J/ψ from PYTHIA simulation using the Monash tune at $\sqrt{s}$ = 13 TeV. The rapidity range of J/ψ is selected for the ALICE experiment. Note that the decay product of J/ψ is excluded in the multiplicity calculation. Compared to MB events, about 50% more charged particles are produced in events with J/ψ, and the distribution is very similar when J/ψ is observed at mid-rapidity and forward rapidity. Figure 2 shows the $dN_{ch}/d\eta$ distributions for MB events and events with inclusive J/ψ from PYTHIA simulation using the Monash (left) and Detroit (right) tunes at $\sqrt{s}$ = 200 GeV. The rapidity range of J/ψ is selected for the PHENIX experiment in this collision energy. The charged particle multiplicity is about 30% larger in events with J/ψ than in MB events, and a tiny difference is seen in the $dN_{ch}/d\eta$ shape for two different rapidity regions of J/ψ.

3 Results

3.1 *pp* collisions at $\sqrt{s}$ = 13 TeV

Figure 3 shows the scaled inclusive J/ψ yields $((dN_{J/\psi}/dy)/\langle dN_{J/\psi}/dy\rangle)$ as a function of scaled multiplicity ($N_{ch}/\langle N_{ch}^{MB}\rangle$). The left (right) panel represents events with J/ψ at mid-rapidity (forward rapidity), and the charged particle multiplicity is calculated at mid-rapidity. In each panel, results with and without hadronic rescattering are compared. In the default case, the J/ψ yield increases as the multiplicity become larger. The increasing trend in PYTHIA is consistent with the experimental data [3, 4], but the data shows a stronger multiplicity dependence. This indicates that MPI processes contribute to the J/ψ production. When using the hadronic rescattering option, the scaled J/ψ yield

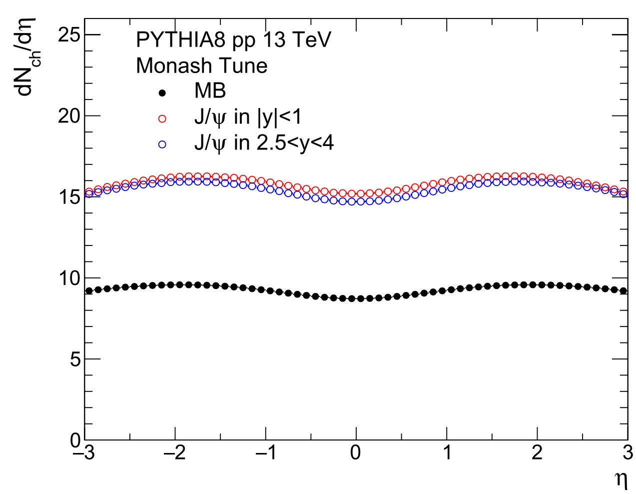

Fig. 1 Charged particle pseudorapidity density in MB events and events with inclusive J/ψ from 13 TeV PYTHIA *pp* events

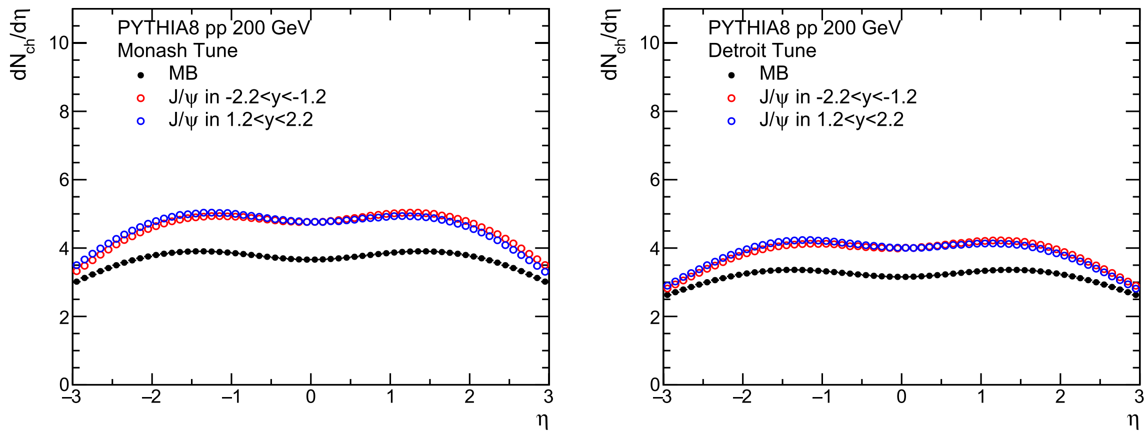

Fig. 2 Charged particle pseudorapidity density in MB events and events with inclusive J/ψ from 200 GeV PYTHIA *pp* events

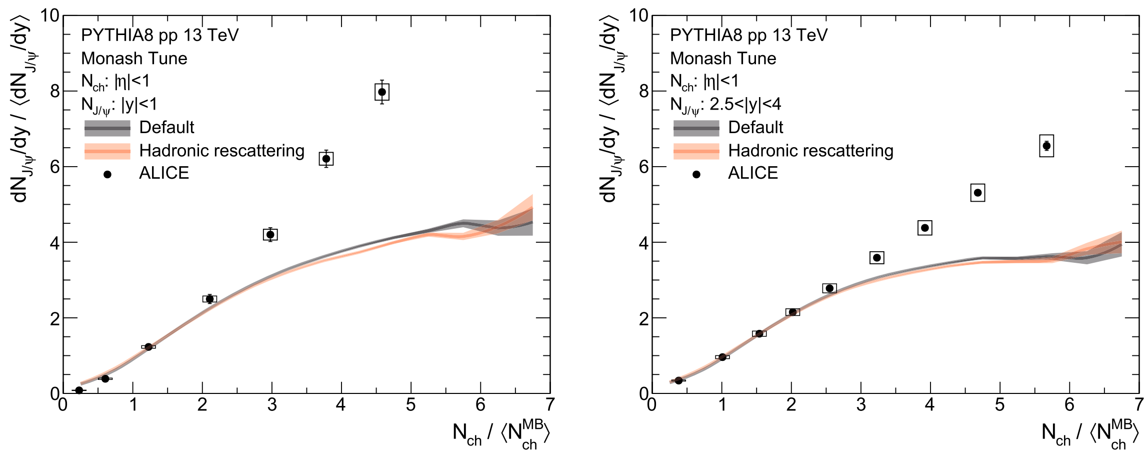

Fig. 3 Scaled inclusive J/ψ yield at mid-rapidity (left) and forward rapidity (right) as a function of scaled charged particle multiplicity in 13 TeV *pp* events from PYTHIA with and without hadronic rescattering. The charged particle multiplicity is calculated in $|\eta| < 1$

is slightly lower than that from the default case in high multiplicity events ($N_{ch}/\langle N_{ch}^{MB}\rangle > 4$). The yield modification could result from the hadronic rescattering effect between J/ψ and co-moving particles. Note that the decay product of J/ψ is not included in the charged particle multiplicity calculation. This is different from the analysis procedure of experimental results [3]. Still, the effect is expected to be small because the number of charged particles is large enough compared to the number of particles from J/ψ decays.

To further test the hadronic scattering effect with different charmonia states, we compare the scaled ratio of J/ψ and $\psi(2S)$ ($(N_{\psi(2S)}/N_{J/\psi})/\langle N_{\psi(2S)}/N_{J/\psi}\rangle$) as a function of the scaled charged particle multiplicity, as shown in Fig. 4. The scaled ratio with and without hadronic rescattering is consistent at both rapidity regions. This result indicates that the hadronic rescattering effect reduces the J/ψ and $\psi(2S)$ yields similarly in high multiplicity. Interestingly, the scaled ratio at mid-rapidity increases with the multiplicity, whereas the scaled ratio at forward rapidity is almost independent. The experimental data at forward rapidity is consistent with the trend in PYTHIA. The different multiplicity dependence is likely due to a multiplicity correlation between MPI processes and the hard scattering process. More discussion is in the following section.

3.2 *pp* collisions at $\sqrt{s} = 200$ GeV

Figure 5 shows the scaled inclusive J/ψ yields as a function of scaled multiplicity. The left (right) panel represents events with the Monash (Detroit) tune, and the hadronic rescattering effect is not used in this set of simulations. The rapidity range of J/ψ is $1.2 < y < 2.2$, and the charged particle multiplicity is calculated at various η ranges corresponding to the acceptance of silicon trackers in PHENIX. When the multiplicity is calculated at the

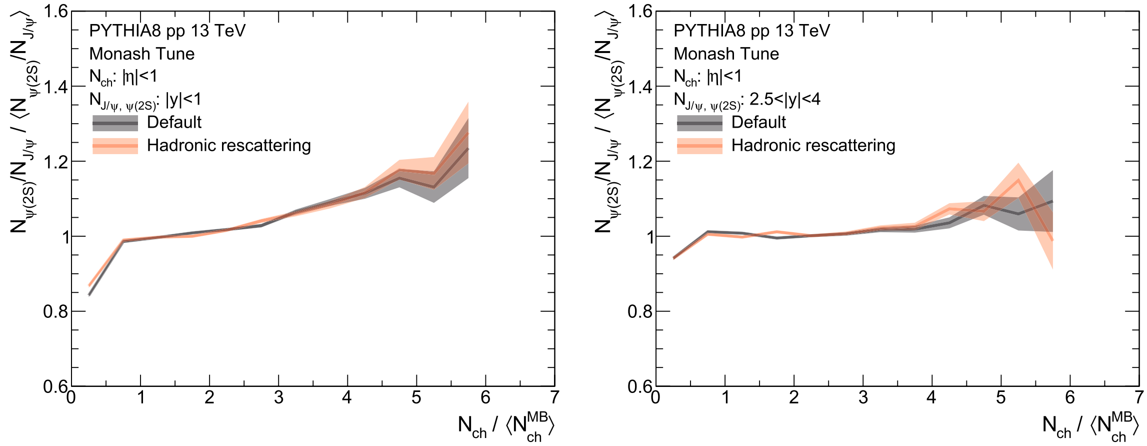

Fig. 4 Scaled yield ratio between inclusive $\psi(2S)$ and J/ψ at mid-rapidity (left) and forward rapidity (right) as a function of scaled charged particle multiplicity in 13 TeV *pp* events from PYTHIA with and without hadronic rescattering. The charged particle multiplicity is calculated in $|\eta| < 1$

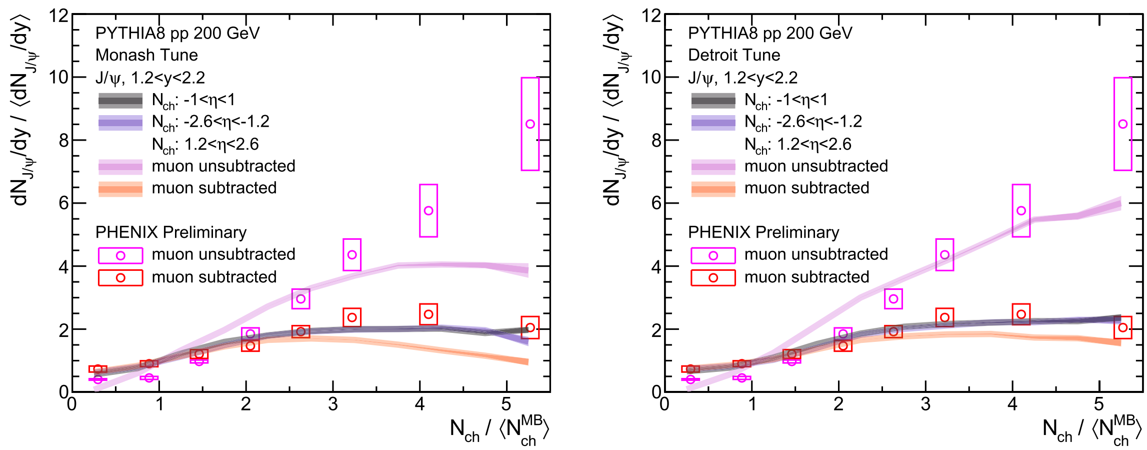

Fig. 5 Scaled inclusive J/ψ yield at forward rapidity as a function of scaled charged particle multiplicity in 200 GeV *pp* events from PYTHIA with Monash (left) and Detroit (right) tunes. The charged particle multiplicity is calculated in various pseudorapidity ranges. The PYTHIA results are compared with the PHENIX preliminary results

same acceptance of J/ψ, the multiplicity dependence is significantly affected by the decay product of J/ψ. The large influence is because the overall multiplicity is small in *pp* collisions at $\sqrt{s} = 200$ GeV as shown in Fig. 2. In case the multiplicity is calculated at different acceptances, $|\eta| < 1$ and $-2.6 < \eta < -1.2$, the scaled yield shows a consistent multiplicity dependence. Compared with the results at $\sqrt{s} = 13$ TeV, the only case including the decay product of J/ψ in the multiplicity shows a similar trend, which is consistent with the experimental data [5]. The multiplicity dependence of J/ψ yield in *pp* collisions is weaker at $\sqrt{s} = 200$ GeV, which indicates that the contribution from MPI processes depends on the collision energy. Regarding the comparison between the two PYTHIA tunes, it only shows a slight difference when measuring the multiplicity and J/ψ at the same acceptance. The results with the Detroit tune show a better agreement with the PHENIX preliminary results [13]. When the final results are released, a more detailed discussion on the MPI contribution can be done.

To further investigate how MPI is essential to describe the multiplicity-dependent J/ψ production, we run another set of simulations without the MPI process (`PartonLevel:MPI=off`), and Fig. 6 shows results from events without MPI. The results with different PYTHIA tunes are consistent, meaning that the Detroit tune only affects underlying events. Interestingly, the only case including the decay product of J/ψ to the multiplicity calculation shows an increasing trend at $N_{ch}/\langle N_{ch}^{MB}\rangle < 3$, and other results show a consistent trend. It indicates that the MPI is still

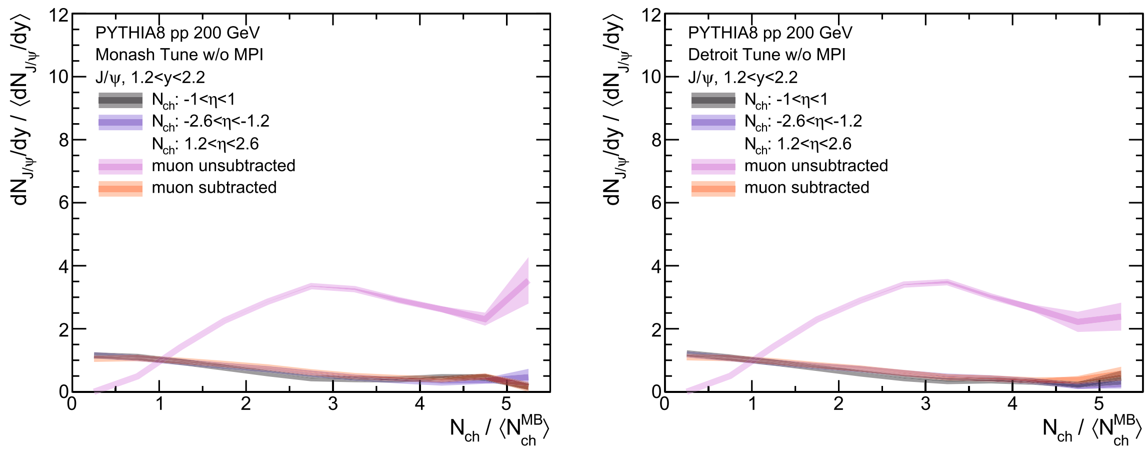

Fig. 6 Scaled inclusive J/ψ yield at forward rapidity as a function of scaled charged particle multiplicity in 200 GeV *pp* events from PYTHIA with Monash (left) and Detroit (right) tunes. The option for MPI is set to off. The charged particle multiplicity is calculated in various pseudorapidity ranges

important to describe the multiplicity-dependent J/ψ production at the RHIC energy.

We study the hadronic rescattering effect on the J/ψ production at 200 GeV by comparing the results of multiplicity-dependent scaled yield with and without hadronic rescattering as shown in Fig. 7. In this result, the decay product of J/ψ is not included in the charged particle multiplicity at the same acceptance of J/ψ. For both cases of the η range for the multiplicity, there is no visible difference with and without the hadronic rescattering option. The trend is different from the results at the LHC energy shown in Fig. 3, where the $dN_{\mathrm{ch}}/d\eta$ in MB events is a factor of three larger.

Lastly, we check the multiplicity-dependent yield ratio between J/ψ and $\psi(2S)$. In terms of the hadronic rescattering effect, we can expect a minimal impact on the yield ratio because the hadronic rescattering effect does not modify the J/ψ yield at $\sqrt{s} = 200$ GeV. However, it is still interesting to compare the multiplicity dependence of the yield ratio between different PYTHIA tunes because the maximum momentum scale to be allowed for MPI is related to the scale of the hard process. The scale of the hard process is slightly different because of the mass difference between J/ψ (3.096 GeV$/c^2$) and $\psi(2S)$ (3.686 GeV$/c^2$). The small difference may be impactful, because the multiplicity at 200 GeV is small. Therefore, the multiplicity dependence of the yield ratio would be related to the description of underlying events.

Figure 8 shows the charged particle multiplicity distributions for *pp* events, including inclusive J/ψ or $\psi(2S)$ at forward rapidity, and results with the Monash (left) and

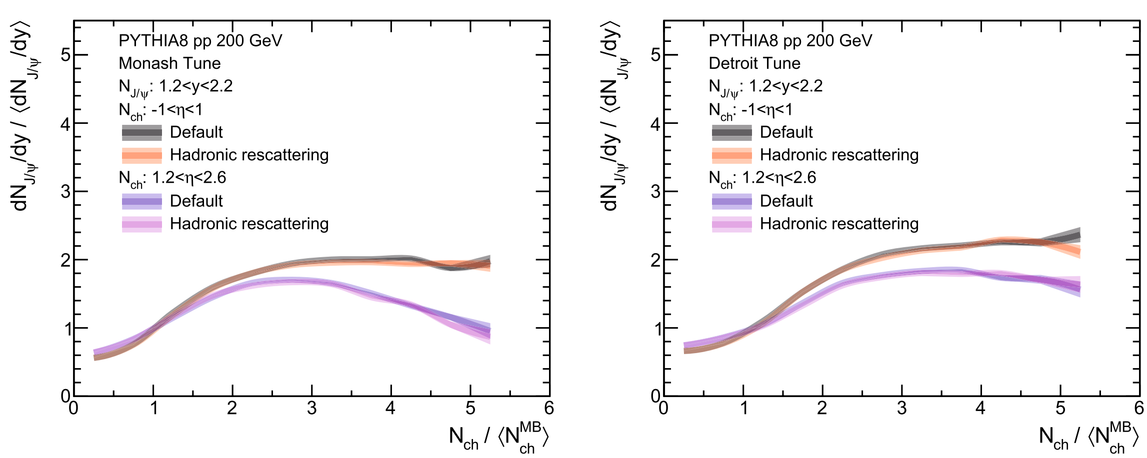

Fig. 7 Scaled inclusive J/ψ yield at forward rapidity as a function of scaled charged particle multiplicity in 200 GeV *pp* events from PYTHIA with Monash (left) and Detroit (right) tunes. Results from two simulation sets with and without the hadronic rescattering effect are presented. The charged particle multiplicity is calculated in various pseudorapidity ranges

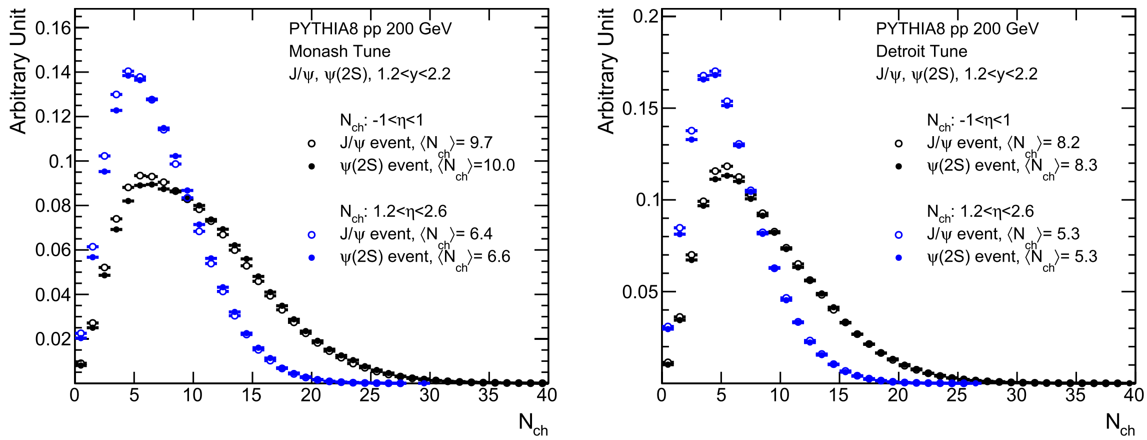

Fig. 8 Charged particle multiplicity distributions for J/ψ and $\psi(2S)$ events from PYTHIA with the Monash (left) and Detroit (right) tunes

Detroit (right) tunes are presented. Note that each distribution is scaled to unity to compare the shape of distributions. In each panel, the $N_{\rm ch}$ distributions in two different η ranges are shown for J/ψ (open circles) and $\psi(2S)$ (closed circles) events, and the mean $N_{\rm ch}$ value for each distribution is also indicated in the legend. The shape of distributions is quite similar for J/ψ and $\psi(2S)$ events regardless of η ranges and PYTHIA tunes. In the results of the Monash tune, the mean $N_{\rm ch}$ value of $\psi(2S)$ events is larger by 0.2-–0.3 than that of J/ψ events, so the overall distribution of $\psi(2S)$ events is slightly shifted to the right compared to the distribution of J/ψ events. On the other hand, distributions from J/ψ and $\psi(2S)$ events are more similar in the case of the Detroit tune.

Figure 9 shows the scaled yield ratio inclusive $\psi(2S)$ and J/ψ at forward rapidity as a function of scaled charged particle multiplicity in pp events at $\sqrt{s}$ = 200 GeV from PYTHIA. The results with the Monash (Detroit) tunes are presented in the left (right) panel. As discussed with Fig. 7, the hadronic rescattering effect does not change the relative yield at the entire multiplicity range. The results of the Monash tune show an increasing trend as the multiplicity becomes larger for both η ranges, and this results from the small shift of the distribution of $\psi(2S)$ events. In the case of the Detroit tune, the scaled yield ratio at forward rapidity is almost independent of the multiplicity at mid-rapidity, whereas a decreasing trend is seen when measuring charmonia and multiplicity at the same acceptance. This could be related to the correlation of energy scale and particle production between hard and soft scatterings. It will be very helpful to have experimental measurements of the multiplicity-dependent yield ratio between J/ψ and $\psi(2S)$ for further constraining underlying events at the RHIC energy. In addition, precise measurements of the two-dimensional correlation in pseudorapidity and

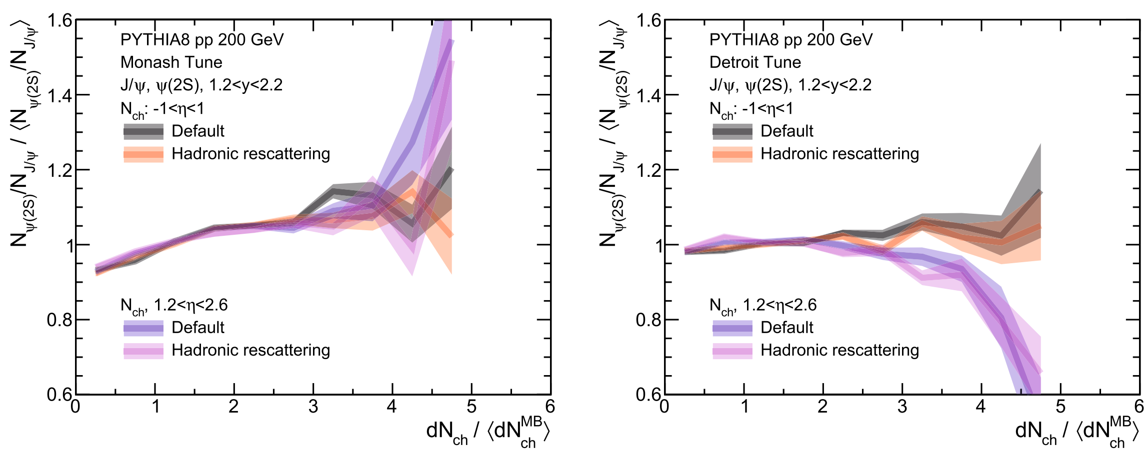

Fig. 9 Scaled yield ratio between inclusive $\psi(2S)$ and J/ψ at forward rapidity as a function of scaled charged particle multiplicity in 200 GeV pp events from PYTHIA with Monash (left) and Detroit (right) tunes. The charged particle multiplicity is calculated in various pseudorapidity ranges

azimuthal angle between charmonia and charged particles will also provide crucial information.

4 Summary

In summary, we have performed a detailed study of the multiplicity-dependent charmonia production at $\sqrt{s} = 200$ GeV and 13 TeV with the PYTHIA Monte Carlo event generator. In comparing simulation results with and without MPI, its contribution is important for the increasing trend of J/ψ yield as a function of multiplicity. We found that it is crucial to consider the decay product of charmonia in the multiplicity calculation, particularly at RHIC energy, where the event multiplicity is small. Simulation with the newly released Detroit tune for RHIC energies shows a better description of J/ψ yield as a function of multiplicity at $\sqrt{s} = 200$ GeV than the Monash tune. Two PYTHIA tunes show a different trend in the yield ratio of J/ψ and $\psi(2S)$ as a function of multiplicity. Further discrimination can be done with experimental results in the future. Lastly, we explored the hadronic rescattering effect in PYTHIA on charmonia production. The J/ψ yield is slightly reduced in high multiplicity *pp* events only at 13 TeV, where the event multiplicity in MB events is four times larger than that at 200 GeV, and the effect is similar between J/ψ and $\psi(2S)$ in *pp* events.

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