Role of multiparton interactions on J/ψ production in $p+p$ collisions at LHC energies

Dhananjaya Thakur, Sudipan De, and Raghunath Sahoo*

Discipline of Physics, School of Basic Sciences, Indian Institute of Technology Indore, Simrol, Indore 453552, India

Soumya Dansana

Department of Physical Sciences, Indian Institute of Science Education and Research, Kolkata-741246, India

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The production mechanism of quarkonia states in hadronic collisions is still to be understood by the scientific community. In high-multiplicity $p+p$ collisions, underlying event observables are of major interest. The multiparton interactions (MPIs) are underlying event observables, in which several interactions occur at the partonic level in a single $p+p$ event. This leads to dependence of particle production on event multiplicity. If the MPI occurs in a harder scale, there will be a correlation between the yield of quarkonia and total charged-particle multiplicity. The ALICE experiment at the LHC in $p+p$ collisions at $\sqrt{s}=7$ and 13 TeV has observed an approximate linear increase of relative J/ψ yield, $(\frac{dN_{J/\psi}/dy}{\langle dN_{J/\psi}/dy\rangle})$, with relative charged-particle multiplicity density, $(\frac{dN_{\mathrm{ch}}/dy}{\langle dN_{\mathrm{ch}}/dy\rangle})$. In our present work, we have performed a comprehensive study of the production of charmonia as a function of charged-particle multiplicity in $p+p$ collisions at LHC energies using the perturbative QCD–inspired multiparton interaction model, PYTHIA8 tune 4C, with and without the color reconnection scheme. A detailed multiplicity and energy-dependent study is performed to understand the effects of MPI on J/ψ production. The ratio of $\psi(2S)$ to J/ψ is also studied as a function of charged-particle multiplicity at LHC energies.

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I. INTRODUCTION

Understanding the production mechanisms of quarkonia states in proton-proton collisions is a great challenge for existing theoretical models. Various theoretical models such as the color-singlet, nonrelativistic QCD approach and the color evaporation model try to explain the heavy resonance states produced in hard processes [1,2]. The recent theoretical works [3–5] are dedicated to understanding the production cross section and polarization of J/ψ by taking the inputs from recent LHC measurements [6–9]. In high-energy $p+p$ collisions, the total event multiplicity can have a substantial contribution from multiparton interactions (MPIs) [10,11], which are underlying event observables (UE). The sum of all the processes that build up the final hadronic state in a collision is referred as the underlying event . The UE includes fragmentation of beam remnant, multipartonic interactions and initial and final state radiation (ISR and FSR, respectively) associated with each interaction. In MPIs, several interactions at the partonic level occur in a single $p+p$ collision. This leads to a strong dependence of particle production on total event multiplicity. MPIs are commonly used to describe the soft underlying events such as the production of light quark and gluons. But it is observed that they can also contribute on the hard and semihard scales such as the production of particles containing heavy quarks like J/ψ, open heavy flavor, etc. This contribution becomes more and more prominent with increasing energy [12]. An early study of the NA27 experiment reported that the charged-particle multiplicity distributions are affected by the UEs with open charm production [13]. This indicates a correlation between the yield of quarkonia and the total charged-particle multiplicity. According to Ref. [14], the probability of MPIs increases toward smaller impact parameters. So, the multiplicity dependence study in $p+p$ collisions is very interesting to understand the MPI effects on quarkonia production.

Recently, the ALICE experiment has observed an approximately linear increase of relative J/ψ yields

*Raghunath.Sahoo@cern.ch

$\frac{dN_{J/\psi}/dy}{\langle N_{J/\psi}/dy\rangle}$ as a function of relative charged-particle multiplicity density $\frac{dN_{\mathrm{ch}}/dy}{\langle dN_{\mathrm{ch}}/dy\rangle}$ [15]. The QCD-inspired model PYTHIA6 could not describe the results and shows the exactly opposite behavior. An updated version of PYTHIA has been proposed, in which MPI plays an important role in the production of heavy quarks like charm and beauty quarks. PYTHIA8 describes the increasing trend of open charm and nonprompt J/ψ production as a function of charged-particle multiplicity measured by the ALICE experiment at $\sqrt{s} = 7$ and 13 TeV [16,17]. The color reconnection (CR) is an important mechanism to describe the interactions that can occur between colored fields during the hadronization process. CR is expected to occur at a significant rate at LHC energies because of the high number of colored partons from both MPI and parton showers. CR is the most important ingredient in the UE contributions and hence plays an important role in the interplay between soft and hard processes. As there is no first-principle calculation, the only way is to study its effect via realistic models. It is found that PYTHIA8 describes the $\langle p_T\rangle$ as a function of charged-particle multiplicity by including the MPI with CR [18] as well as explains the flowlike pattern in pp collisions [19]. In this work, we have studied the effect of MPI with and without a CR scheme on J/ψ production as a function of charged-particle multiplicity using a 4C-tuned [20] PYTHIA8 event generator at different LHC energies. In the present work, for the first time, we have studied the energy dependence of the event activity of J/ψ, which can provide more insight into the processes in an event in hadronic collisions.

The paper is organized as follows. Event generation and analysis methodology are described in Sec. II. The results are discussed in Sec. III. Section III is divided into three subsections. The multiplicity dependence of J/ψ production is discussed in Sec. III A. In Sec. III B, we show the energy dependence behavior, and in Sec. III C, we study the ratio between the higher resonance state of J/ψ [$\psi(2S)$] and J/ψ as a function of charged-particle multiplicity. Finally, in Sec. IV, we summarize our work.

II. EVENT GENERATION AND ANALYSIS METHODOLOGY

PYTHIA8 is the advanced version of PYTHIA6 coded in C++. One of the major improvements in PYTHIA8 with respect to PYTHIA6 is the implementation of the MPI scenario, in which c and b quarks can be produced via $2 \to 2$ hard subprocesses. The heavy-flavor production in PYTHIA8 includes the following main processes:

(i) Initial c or b quarks originate via the first hardest $2\to 2$ partonic interactions (e.g., $q\bar{q}\to\bar{c}c$, $g\bar{g}\to\bar{c}c$) and also have the finite production probability from the subsequent hard processes in MPI via the same mechanism.

(ii) Heavy quark production from the gluon splitting hard processes (e.g., $g \to c\bar{c}$).

(iii) These gluons may originate from ISR and FSR.

Detailed explanation on PYTHIA8.2 physics processes can be found in Ref. [21]. At the LHC energies, it is possible to have multiple parton-parton interaction in $p + p$ collisions. Many of the models have included it in different ways to explain the LHC $p + p$ data [22–24]. In our present study, we have used the 4C-tuned PYTHIA8.2. We have included the varying impact parameter (MultipartonInteractions: bProfile = 3) to allow all incoming partons to undergo hard and semihard interactions as well. We have used the MPI-based scheme of color reconnection [ColourReconnection: mode(0)] of PYTHIA8.2. In this scheme, the produced partons are classified by the MPI system that undergoes a reconnection in which partons from lower-p_T MPI systems are added to the dipoles defined by the higher p_T MPI system in such a way that minimizes total string length. This model of CR describes the UE observables very well compared to the other models, as is reported by the ATLAS Collaboration in Ref. [25]. More details on various models of CR included in PYTHIA8.2 and their performance with respect to experimental data can be found in Refs. [26,27]. After color reconnection, all the produced partons, connected with strings, fragment into hadrons via the Lund string model [28,29].

In this study, we have simulated the inelastic, non-diffractive component of the total cross section for all hard QCD processes (HardQCD: all = on), which includes the production of heavy quarks. A p_T cut of 0.5 GeV/c (using PhaseSpace:pTHatMinDiverge) is used to avoid the divergences of QCD processes in the limit $p_T \to 0$. J/ψ production is measured in the dimuon channel. We have specifically decayed J/ψ to the dimuon channel and measured the yield of the reconstructed particles by defining an external decay mode.

We have generated 100 million events for $p + p$ collisions at $\sqrt{s} = 0.9$, 2.76, 5.02, 7, and 13 TeV using the option with and without the CR scheme available in PYTHIA8.2. J/ψ are reconstructed via dimuon channel ($J/\psi \to \mu^+ + \mu^-$). The relative charged-particle multiplicity yield, which is defined as $N_{\mathrm{ch}}/\langle N_{\mathrm{ch}}\rangle$, is measured at midrapidity ($|y| < 1.0$), where N_{ch} is the mean of the charged-particle multiplicity in a particular bin and $\langle N_{\mathrm{ch}}\rangle$ is the mean of the charged-particle multiplicity in minimum-bias events. The relative J/ψ yield is measured in forward rapidity ($2.5 < y < 4.0$) using the relation

$$\frac{Y_{J/\psi}}{\langle Y_{J/\psi}\rangle} = \frac{N^i_{J/\psi}}{N^{\mathrm{total}}_{J/\psi}}\frac{N_{\mathrm{evt}}}{N^i_{\mathrm{evt}}}, \tag{1}$$

where $N^i_{J/\psi}$ and N^i_{evt} are the number of J/ψ and number of events in ith multiplicity bin, respectively. $N^{\mathrm{total}}_{J/\psi}$ and N_{evt} are the total number of J/ψ produced and total number of minimum-bias events, respectively. As the frequency of lower-multiplicity events is higher, the bin width is taken smaller at lower multiplicity and then subsequently higher to maximize the statistics at high-multiplicity bins. To have a direct comparison of the obtained results with experimental data, charged-particle multiplicity bins are chosen according to the available experimental measurements [15].

The statistical uncertainties are calculated in each multiplicity bin for both relative charged-particle multiplicity ($N_{\mathrm{ch}}/\langle N_{\mathrm{ch}}\rangle$) and relative J/ψ yield ($N_{J/\psi}/\langle N_{J/\psi}\rangle$). Uncertainty in the N_{ch} measurement is given by the ratio of the rms value of the charged-particle multiplicity and square root of the number of charged particles in that bin ($N_{\mathrm{RMS}}/\sqrt{N_{\mathrm{bin}}}$). The ratio between the rms value of the minimum-bias (MB) charged-particle multiplicity and square root of the number of minimum-bias charged particles ($N^{\mathrm{MB}}_{\mathrm{RMS}}/\sqrt{N_{\mathrm{MB}}}$) gives the uncertainty in $\langle N_{\mathrm{ch}}\rangle$. The uncertainty to measure the number of J/ψ particles is simply $\sqrt{N_{J/\psi}}$. These uncertainties are propagated using the standard error propagation formula to estimate the uncertainties in relative charged-particle multiplicity as well as in the relative J/ψ yield.

III. RESULTS AND DISCUSSION

To check the compatibility of PYTHIA8 with the experimental data, we have compared J/ψ production between data and PYTHIA8 in same kinematic range. Figures 1 and 2 show the comparison of the J/ψ production cross section as a function of p_T and rapidity (y), respectively, between data and PYTHIA for minimum-bias events. The open symbols represent the data obtained from ALICE, and the solid circles and stars show the results from the PYTHIA8 model at $\sqrt{s} = 5.02$ TeV [30]. The lower panels of the figures show the ratio between data and model for both the CR and no-CR cases. It is observed that PYTHIA8 explains the data very well. A similar study has been performed in other available LHC energies. We found a maximum of 60% deviation of Monte Carlo (MC) p_T spectra from data for 13 TeV in certain p_T bins except for two low-p_T bins ($p_T \sim 1$ GeV/c), where deviation is larger. For the rapidity spectra, the deviation of MC from experimental data is less than 1%. Similarly, for 7, 5.02, and 2.76 TeV, the maximum deviation of (p_T, y) spectra are (50%, 1%), (1%, 6%), and (50%, 1%), respectively, for a few p_T and rapidity bins. In most of the p_T bins, the deviation is around 10%–20%, whereas rapidity spectra are very well reproduced by MC. These measurements provide us the confidence to study the quarkonia production using PYTHIA8 in $p + p$ collisions at LHC energies.

Figure 3 shows the relative J/ψ yield as a function of charged-particle multiplicity for $\sqrt{s} = 7$ TeV. The open circles show the results from the ALICE experiment [15]. The star markers and solid circles represent our measurement with PYTHIA8. It is observed that the 4C-tuned PYTHIA8 with CR and without CR qualitatively reproduce the ALICE results. In the experimental data, there were statistical and systematic uncertainties. We have added both the errors in quadrature and put a single error bar in each data point. The PYTHIA8 data points have statistical uncertainties that are obtained using the method described in the Sec. II. Direct comparison of data to PYTHIA is not possible

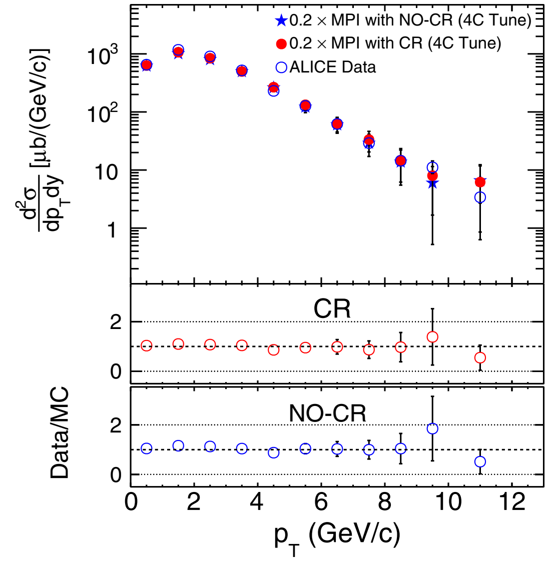

FIG. 1. The upper panel shows the comparison of ALICE data [30] and PYTHIA8 of the J/ψ production cross section at $\sqrt{s} = 5.02$ TeV. The open circles are ALICE data, and solid circles and stars represent PYTHIA8 results with CR and without CR, respectively. The lower panels show the ratio between data and PYTHIA8 for both the CR and no-CR cases.

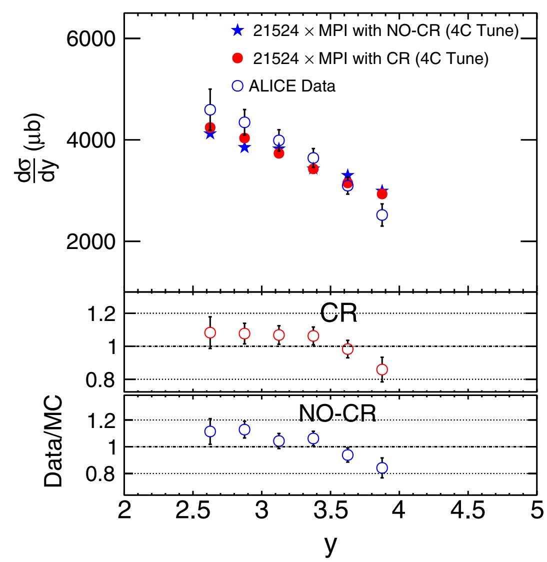

FIG. 2. The upper panel shows the comparison of ALICE data [30] and PYTHIA8 for $d\sigma/dy$ of J/ψ at $\sqrt{s} = 5.02$ TeV. The open circles are ALICE data, and solid circles and stars represent the PYTHIA8 results with CR and without CR, respectively. The lower panels show the ratio between data and PYTHIA8 for both the CR and no-CR cases.

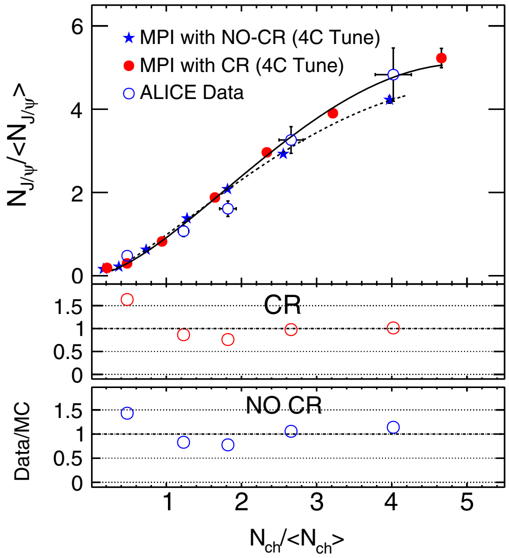

FIG. 3. The upper panel shows the comparison of ALICE data [15] and PYTHIA8 of the relative J/ψ yield ($N_{J/\psi}/\langle N_{J/\psi}\rangle$) as a function of the relative charged-particle multiplicity ($N_{\rm ch}/\langle N_{\rm ch}\rangle$) for $\sqrt{s} = 7$ TeV at forward rapidities. The open circles are ALICE data, and solid circles and stars represent the PYTHIA8 results with CR and without CR, respectively. The lines are the fitted curves using the function as described in Eq. (2). The lower panels show the ratio between the data and PYTHIA for both the CR and no-CR cases.

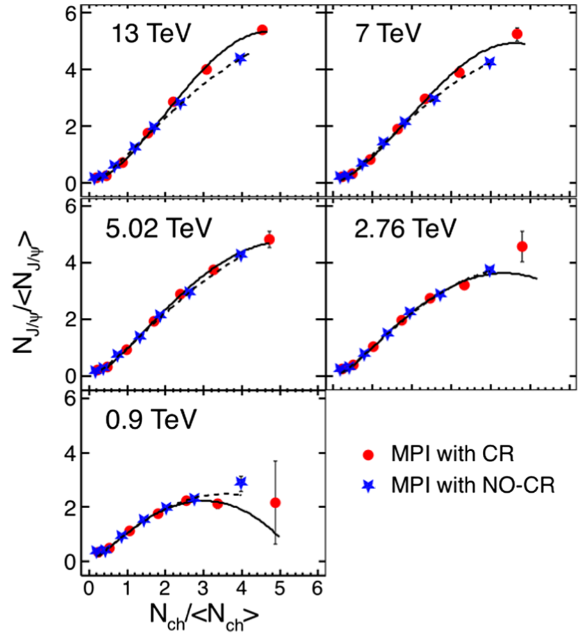

FIG. 4. Relative J/ψ yield as a function of relative charged-particle multiplicity at forward rapidities at $\sqrt{s} = 0.9$, 2.76, 5.02, 7, and 13 TeV using PYTHIA8. The circles and stars show the results with CR and without CR, respectively. The dotted line is fitted to MPI with no-CR using Eq. (2), whereas the solid line represents the fitting to MPI with CR using Eq. (2).

as the $N_{\rm ch}/\langle N_{\rm ch}\rangle$ values are different for different cases. So, we have fitted the results obtained from the PYTHIA8 model using a percolation-inspired function [31] as described in the Sec. III A and interpolated the relative J/ψ yield at the experimental $N_{\rm ch}/\langle N_{\rm ch}\rangle$ values to make the ratio between the data and PYTHIA. From the ratio, it is clear that PYTHIA8 explains the data well for both the CR and no-CR cases.

The color reconnection is a final state effect, which takes place in $p+p$ collisions as implemented in PYTHIA8 [21]. In our current studies, we use the MPI-based color reconnection, and it is observed that the difference in the number of J/ψ in CR and no-CR is less than one per event. However, in the highest two multiplicity bins, it exceeds one. A quantitative study is performed in the next section. Therefore, one can conclude that the final-state effect (CR) has little contribution to J/ψ production. Although both CR and no-CR describe experimental data well within the uncertainties, it is found that toward the higher-multiplicity bins MPI with CR seems to reproduce the data better than that of MPI with the no-CR case.

To explore the effect of MPI on quarkonia production with collision energies, we extend the analysis using PYTHIA8 to other available energies at the LHC.

A. Multiplicity dependence of J/ψ production

Figure 4 shows the relative J/ψ yield as a function of relative charged-particle multiplicity at forward rapidity ($2.5 < y < 4.0$) for 4C tuned with and without CR at $\sqrt{s} = 0.9$, 2.76, 5.02, 7, and 13 TeV using PYTHIA8 simulated data. The J/ψ are reconstructed via a dimuon channel. However, the ALICE results [15,17] reveal that the relative J/ψ yield as a function of charged-particle multiplicity at $\sqrt{s} = 7$ TeV gives very similar results for both dimuon and dielectron channels except the highest-multiplicity bin.

The circles show the results with the CR scheme, and the stars show the results without CR. It is observed that the relative J/ψ yield is linearly increasing with charged-particle multiplicity for all the center-of-mass energies for both cases with and without CR. We have fitted the results with a percolation-inspired function [31]. It is found that the function itself cannot describe the results well unless we add an extra term x^n in the function,

$$\frac{Y_{J/\psi}}{\langle Y_{J/\psi}\rangle} = A[Bx + Cx^2 + Dx^n], \qquad (2)$$

where A, B, C, D, and n are the parameters and $x = N_{\rm ch}/\langle N_{\rm ch}\rangle$. The solid lines show the fittings with CR, and the dashed lines show the fittings without CR. The difference between the solid line and dashed line increases with higher-multiplicity bins as well as with higher center-of-mass energies, in particular, at $\sqrt{s} = 7$ and 13 TeV. This indicates that the CR effects on J/ψ

production are more prominent at the high-multiplicity region of higher center-of-mass energies.

Until now, the percolation theory has been successful in describing the relative J/ψ yield as a function of relative charged-particle multiplicity [31]. To see if a string percolation scenario of particle production in $p+p$ collisions is valid at the highest available energy, i.e., at $\sqrt{s} = 13$ TeV, we take PYTHIA8 simulated data in our current study. We compare string percolation model expectations using the function ($f(x) = Ax + Bx^2$) and find a deviation at large-multiplicity bins, where a kind of saturation behavior is seen in PYTHIA8. An additional term in the above equation, x^n, seems to describe the behavior. This is shown in Fig. 5. This study shows that the increase of the J/ψ yield as a function of charged-particle multiplicity from PYTHIA simulated data does not seem to follow exactly like a percolation type of behavior but rather has a tendency to saturate at the high-multiplicity domain. The $p+p$ experimental data at other LHC energies would be very useful in understanding the particle production at higher multiplicities, helping to validate the percolation theory and/or tuning the PYTHIA8 event generator with new physics inputs.

To understand the CR effects on J/ψ production quantitatively, we have subtracted the yield of relative J/ψ production with no-CR from the yield with CR and plotted it as a function of charged-particle multiplicity for different center-of-mass energies, which is shown in Fig. 6. It is found that the difference of the relative J/ψ yield between with CR and without CR increases as a function of charged-particle multiplicity as well as with increase of the center-of-mass energy. The excess values of relative J/ψ are shown in the Table I, for different multiplicity bins at all the discussed energies. We could not perform our studies at lower center-of-mass energies for higher-multiplicity bins

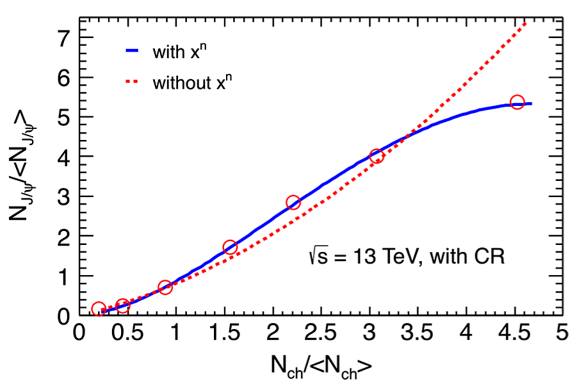

FIG. 5. Relative J/ψ yield as a function of the relative charged-particle multiplicity for $p+p$ collisions at $\sqrt{s} = 13$ TeV using PYTHIA8 with CR. The phenomenological function given by Eq. (2) without the term x^n is fitted to understand the validity of string percolation. This is shown by the dotted line. The solid line shows the fitting using Eq. (2), which has an additional term, x^n, over the string percolation function. This explains a possible saturation effect toward higher multiplicities.

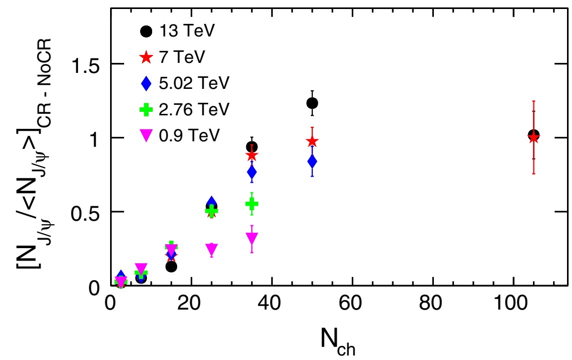

FIG. 6. Difference of relative J/ψ yield from MPI with CR to MPI without CR as a function of the charged-particle multiplicity at $\sqrt{s} = 0.9$, 2.76, 5.02, 7, and 13 TeV using PYTHIA8.

due to higher statistical fluctuations. Although the numbers are very small, they are very significant as the J/ψ yield is measured on an event-by-event basis and normalized with total MB events using Eq. (1). It should be noted that the relative J/ψ yield is the excess of J/ψ production per event in a given multiplicity bin with respect to J/ψ per event in MB.

It is expected that CR occurs in a significant rate at the LHC energies due to the higher number of colored partons from MPI. In our current study, we have used the default MPI-based CR. Here, partons from lower-p_T MPI are merged with the ones at higher-p_T MPI [32]. At LHC energies due to the high density of colored partons, there is a substantial degree of overlap of many colored strings in the position and momentum phase space. Therefore, there is a higher probability of color reconnection. The partons from two different MPIs can reconnect via color strings with the minimization of the string length. This study reveals that with the increase of MPIs the probability of color reconnection increases and hence the probability to combine charm and anticharm quark becomes higher, thereby producing a higher number of J/ψ particles.

B. Energy dependence of J/ψ production

As experimental data at different energies are not yet available, it is worth studying the effect of MPI and CR on charmonia production at various collision energies using PYTHIA8. Figure 7 shows the relative J/ψ yield as a function of the center-of-mass energy for different charged-particle multiplicity bins using PYTHIA8 with CR. It is observed that for higher-multiplicity bins the relative J/ψ production increases with energy and the trend changes as we go to lower-multiplicity bins. To get a quantitative idea, we have fitted the results with a phenomenological function, $y = Ax^n$, where A and n are the parameters. The parameter, n, indicates the rate of increase of relative J/ψ as a function of center-of-mass energy for a particular multiplicity bin. Figure 8 shows n as a function of different multiplicity bins. It is found that n increases with

TABLE I. The difference values of relative J/ψ with CR and without CR, $(N_{J/\psi}/\langle N_{J/\psi}\rangle)_{\mathrm{CR-No\,CR}}$, for $\sqrt{s} = 0.9$, 2.76, 5.02, 7, and 13 TeV.

N_{ch} bin	$\sqrt{s} = 0.9$ TeV	$\sqrt{s} = 2.76$ TeV	$\sqrt{s} = 5.02$ TeV	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 13$ TeV
0–5	0.019 ± 0.026	0.024 ± 0.016	0.059 ± 0.013	0.025 ± 0.013	0.020 ± 0.011
5–10	0.108 ± 0.018	0.088 ± 0.012	0.063 ± 0.011	0.077 ± 0.010	0.052 ± 0.009
10–20	0.236 ± 0.025	0.260 ± 0.020	0.217 ± 0.019	0.197 ± 0.018	0.129 ± 0.017
20–30	0.239 ± 0.046	0.505 ± 0.042	0.558 ± 0.041	0.500 ± 0.041	0.535 ± 0.038
30–50	0.314 ± 0.091	0.553 ± 0.075	0.768 ± 0.070	0.881 ± 0.070	0.938 ± 0.066
50–100	⋯	⋯	0.840 ± 0.101	0.975 ± 0.095	1.233 ± 0.083
100–150	⋯	⋯	⋯	1.001 ± 0.246	1.017 ± 0.161

the increase in charged-particle multiplicity (N_{ch}). The values of n are negative up to 10–20 multiplicity bins and become positive toward higher-multiplicity bins. This indicates that MPI effects dominate for J/ψ production for $N_{\mathrm{ch}} > 20$. This brings a threshold number for charged-particle multiplicity in the final state for $p + p$ collisions in order to observe substantial MPI effects on charmonia production.

C. Ratio of $\psi(2S)$ and J/ψ

As $\psi(2S)$ is the first excited state of J/ψ, we have made an attempt to study the ratio of both as a function of

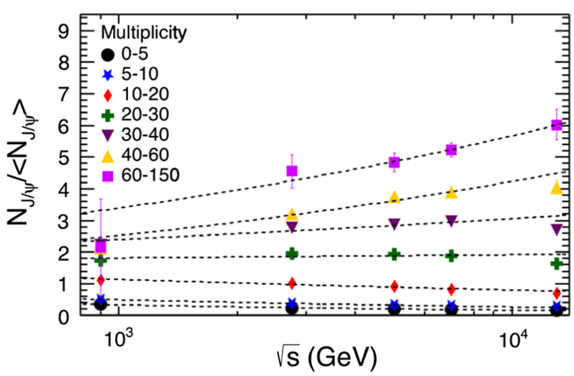

FIG. 7. Relative J/ψ yield as a function of center-of-mass energy ($\sqrt{s}$), using PYTHIA8 with CR. Different symbols are for different charged-particle multiplicity bins. The dashed lines are the phenomenological fitting using the function, $y = Ax^n$.

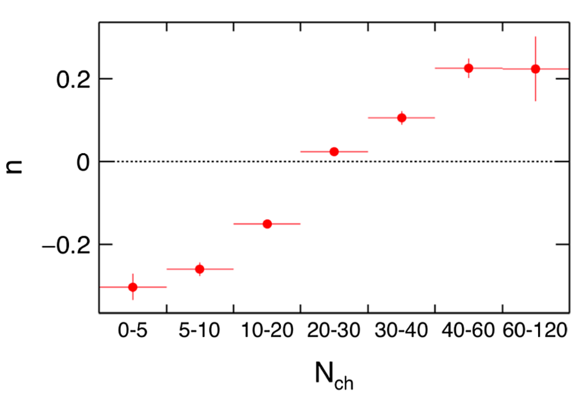

FIG. 8. The fitting parameter, n, for different multiplicity bins.

charged-particle multiplicity for different collision energies. The same procedure for the reconstruction of $\psi(2S)$ is followed as is done for J/ψ, which is discussed in the previous sections. Figure 9 shows the multiplicity dependence of the ratio of the relative yield of $\psi(2S)$ to J/ψ using PYTHIA8 MPI with CR. It is interesting to see that the ratio is independent of collision energy as well as multiplicity within statistical uncertainties. The energy-independent behavior of the ratio of relative yields of $\psi(2S)$ to J/ψ is also supported by color evaporation models [33]. At LHC energies, there are sufficient energies to produce $c\bar{c}$, and as the mass difference between the two charmonia states is smaller compared to the collision energy, the production probability would be similar for both the cases in each multiplicity bin. This could be the reason for energy- and multiplicity-independent behavior of the ratio of relative yields of $\psi(2S)$ to J/ψ. The CMS experiment preliminary results also show a similar trend at $\sqrt{s} = 7$ TeV [34]. From Eq. (1), we can write the relative ratio of $\psi(2S)$ to J/ψ as

$$\frac{Y_{\psi(2S)}/\langle Y_{\psi(2S)}\rangle}{Y_{J/\psi}/\langle Y_{J/\psi}\rangle} = \frac{N_{\psi}^{\mathrm{total}}}{N_{J/\psi}^{\mathrm{total}}} \frac{N_{J/\psi}^{i}}{N_{\psi}^{i}}. \quad (3)$$

Here, the ratio $N_{\psi}^{\mathrm{total}}/N_{J/\psi}^{\mathrm{total}}$ is fixed for a particular collision energy. This implies that the $\psi(2S)$ and J/ψ in each multiplicity bin are almost produced in the same proportion within statistical uncertainties. This requires

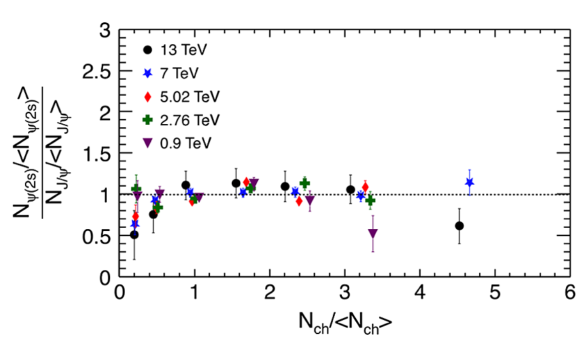

FIG. 9. Ratio of the relative yields of $\psi(2S)$ and J/ψ as a function of relative multiplicity for different center-of-mass energies ($\sqrt{s}$), using PYTHIA8 MPI with CR.

further investigation for a clear understanding of the underlying physics mechanism(s). The availability of experimental data in the near future will make the scenario more clear.

IV. SUMMARY

In summary, energy-dependent study of J/ψ production as a function of charged-particle multiplicity has been performed using a 4C-tuned PYTHIA8 MC event generator. The relative J/ψ are measured as a function of charged-particle multiplicity in $p+p$ collisions at $\sqrt{s} = 0.9$, 2.76, 5.02, 7, and 13 TeV. The J/ψ are reconstructed via the dimuon channel at forward rapidity ($2.5 < y < 4.0$), whereas the charged particles are measured at the mid-rapidity region ($|y| < 1$). PYTHIA8 simulated data are generated with CR and without CR. It is found that both explain the ALICE data qualitatively for $p+p$ collisions at $\sqrt{s} = 7$ TeV. A detailed quantitative study is performed to understand the CR effects on MPI for J/ψ production. We observe that the difference between CR and no-CR increases with charged-particle multiplicity as well as with the center-of-mass energy. The CR effects mostly dominate at high-multiplicity bins for $\sqrt{s} = 7$ and 13 TeV. The relative J/ψ yield as a function of $\sqrt{s}$ shows a monotonic increase for higher-multiplicity bins, whereas for bins with $N_{\rm ch} \leq 20$, it shows the opposite behavior. This brings a threshold number for charged-particle multiplicity in the final state for $p+p$ collisions in order to observe substantial MPI effects on charmonia production. This is a very important observation in view of the interesting properties shown by high-multiplicity events in $p+p$ collisions at the LHC energies. The ratio of relative yield between $\psi(2S)$ and J/ψ, measured at all center-of-mass energies, is presented as a function of relative charged particle multiplicity. The $\psi(2S)$ to J/ψ ratio shows both energy- and multiplicity-independent behavior. It will be very interesting to get the experimental measurements, which can help one to understand the production mechanism of charmonia states in $p+p$ collisions.

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