

Inclusive J/ψ productions in pp collisions at $\sqrt{s} = 5.02, 7$, and 13 TeV with the parton and hadron cascade model PACIAE

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We investigate the inclusive J/ψ production in proton-proton (pp) collisions at center-of-mass energies $\sqrt{s} = 5.02, 7$, and 13 TeV using the parton and hadron cascade model PACIAE 4.0. This model extends PYTHIA 8.3 by incorporating partonic and hadronic rescatterings before and after hadronization, respectively. Compared to our earlier study [K.-F. Ye *et al.*, *Phys. Rev. C* **109**, 035201 (2024)], which considered only the color-singlet processes, the present work includes both the color-singlet and color-octet contributions within the nonrelativistic QCD (NRQCD) framework. In addition to the NRQCD, we also consider the contributions from the cluster collapse and weak decays of b hadrons. We find that the simulated inclusive J/ψ transverse momentum differential cross sections agree well with the experimental data at both the middle and forward rapidities. We provide a quantitative analysis of the relative contributions for different production mechanisms and their energy and rapidity dependence in the inclusive J/ψ production. Furthermore, we offer a quantification of the relative contributions of the various components and their energy and rapidity dependence in the NRQCD channels, including the direct production via the hard scattering and the feed-down from the decays of heavier charmonium states such as $\psi(2S)$, χ_{c0} , χ_{c1} , and χ_{c2} . Finally, we examine the effects of partonic and hadronic rescatterings and offer the quantitative estimate of their impact on the J/ψ production. These results are entirely new and represent a significant step forward in understanding the mechanisms of the inclusive J/ψ production in high-energy pp collisions.

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I. INTRODUCTION

J/ψ , the lightest vector charmonium state composed of a charm and anticharm quark pair, serves as a critical probe in heavy-ion physics. Its suppression in nucleus-nucleus collisions was originally proposed as a signature of the quark-gluon plasma [1]. However, this suppression can also be attributed to cold nuclear matter effects, such as the modification of nuclear parton distribution functions (PDFs) [2,3]. In order to disentangle these hot and cold nuclear matter effects, a precise knowledge of the J/ψ production in the

absence of a nucleus in the initial state is indispensable. The J/ψ yields in proton-proton (pp) collisions provide an essential reference for quantifying nuclear modifications in both proton-nucleus and nucleus-nucleus collisions.

In pp collisions at the Large Hadron Collider (LHC), the J/ψ production predominantly originates from the hard scattering of two gluons, which generates a charm-anticharm ($c\bar{c}$) pair. A color-singlet $c\bar{c}$ pair may hadronize directly into a J/ψ , whereas a color-octet pair must first emit soft gluons to transition to the physical color-singlet state. While the initial gluon fusion process is calculable within perturbative QCD (pQCD), the subsequent hadronization remains a nonperturbative phenomenon that cannot be derived directly from pQCD. Several theoretical approaches, such as the color-singlet model [4], the nonrelativistic QCD (NRQCD) [5,6], and the color evaporation model [7,8], have been proposed to describe the J/ψ production. A key distinction among these models lies on their description of the nonperturbative evolution of the initial $c\bar{c}$ pair into the observed J/ψ bound state. The production of J/ψ mesons has also been studied using Monte Carlo simulations [9–15]. According to Refs. [9–12], PYTHIA 8.2 [16] successfully reproduces the positive correlation between the

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J/ψ yield and the charged particle multiplicity ($dN_{\text{ch}}/d\eta$) observed in pp collisions, whereas PYTHIA 6.4 [17] predicts a negative correlation. This discrepancy may be attributed to differences in the treatment of multiparton interactions across the two PYTHIA versions. In Ref. [10], the EPOS3 event generator [18,19] was also employed to investigate the correlation between J/ψ production and $dN_{\text{ch}}/d\eta$. Meanwhile, Ref. [13] applied a modified ultrarelativistic quantum molecular dynamics (UrQMD) transport model [20,21] to examine J/ψ suppression in high-multiplicity pp collisions at $\sqrt{s} = 7$ TeV. In Refs. [14,15], the JPACIAE model was used to simulate the J/ψ production in ultrarelativistic nucleus-nucleus collisions.

In our previous study [22], we used the parton and hadron cascade model PACIAE 2.2a [23], based on PYTHIA 6.4 [17], to investigate direct J/ψ production in pp collisions at the LHC energies. In that work, only color-singlet processes such as $gg \rightarrow J/\psi g$, $gg \rightarrow \chi_{c0}g$, $gg \rightarrow \chi_{c1}g$, $gg \rightarrow \chi_{c2}g$, $gg \rightarrow \chi_{c1}$, $gg \rightarrow \chi_{c2}$, and $gg \rightarrow J/\psi \gamma$ were taken into account, while color-octet mechanisms were excluded. The higher-mass excited states χ_{c0} , χ_{c1} , and χ_{c2} were included via their subsequent decays into J/ψ . However, the feed-down from other excited states, such as $\psi(2S)$ and $\psi(3770)$, was not considered.

As a complementary study to our previous work in Ref. [22], we investigate the inclusive J/ψ production at both middle and forward rapidities in pp collisions at $\sqrt{s} = 5.02, 7$, and 13 TeV using the parton and hadron cascade model PACIAE 4.0 [24]. Based on PYTHIA 8.3 [25], this model incorporates the partonic rescattering (PRS) before hadronization and the hadronic rescattering (HRS) afterward. The inclusive J/ψ yield comprises both prompt and nonprompt contributions. The prompt component includes directly produced J/ψ as well as feed-down from decays of heavier charmonium states such as $\psi(2S)$ and χ_c , while the nonprompt component stems from the weak decay of b hadrons [26]. In the model, the prompt J/ψ production proceeds via the leading-order NRQCD channels, including both the color-singlet and color-octet contributions. The prompt J/ψ can also be generated through the cluster-collapse mechanism [27] during hadronization. This occurs when a charm quark and its antiquark, being sufficiently close in phase space, form a quarkonium bound state directly, as the string potential energy is insufficient to produce a light quark-antiquark pair. The simulated transverse momentum (p_T) spectra of the inclusive J/ψ are compared with experimental data [26,28–31]. We also present the relative contributions of the NRQCD, the cluster-collapse, and the nonprompt processes as well as their energy and rapidity dependence in the inclusive J/ψ productions. Furthermore, in the NRQCD process, the fractions of the direct production from the parton hard scattering as well as the production from the decays of $\psi(2S)$, χ_{c0} , χ_{c1} , and χ_{c2} are quantified and their energy and rapidity dependence is provided. Finally, the effects of partonic and hadronic rescatterings on the J/ψ production are systematically examined and quantitatively estimated.

The organization of this paper is as follows. Section II commences with a description of the PACIAE 4.0 model. This is followed by a presentation of the results and a comprehensive

discussion in Sec. III. The paper concludes with a summary in Sec. IV.

II. THE PACIAE MODEL

The PACIAE 4.0 model [24] extends PYTHIA 8.3 [25] by incorporating partonic rescattering before hadronization and hadronic rescattering afterward. It describes ultrarelativistic pp collisions through four sequential stages: parton initialization, partonic rescattering, hadronization, and hadronic rescattering.

In the initial stage, the partonic state is generated by first disabling string fragmentation and then breaking diquarks and antidiquarks into constituent partons. Along with initial- and final-state radiation, the system undergoes $2 \rightarrow 2$ hard rescatterings, modeled using leading-order pQCD parton-parton cross sections [32,33]. A K factor is empirically applied as a multiplicative correction to the hard-scattering cross sections [34]. Following the partonic rescattering, the hadronization proceeds via either Lund string fragmentation [17] or coalescence [34]. In this work, the Lund string fragmentation scheme is employed. The subsequent hadronic rescattering stage is implemented via a double loop over all hadron pairs i and j . The minimum approach distance D between their straight-line trajectories is computed, and a collision is considered possible if $D \leq \sqrt{\sigma_{ij}^{\text{tot}}/\pi}$, where σ_{ij}^{tot} denotes the total cross section for the pair. The corresponding collision time t_{ij} is then evaluated [35]. An initial hadron-hadron collision time list is constructed for all possible pairs. The collision with the shortest time is selected and executed probabilistically, after which both the hadron list and collision time list are updated [34]. This procedure repeats until the collision time list is empty, marking the onset of the kinetic freeze-out.

For J/ψ hadronic rescattering, in addition to the elastic processes, the following inelastic channels are incorporated [34,36]:

$$\begin{aligned} J/\psi + n &\rightarrow \Lambda_c^+ + D^-, & J/\psi + n &\rightarrow \Sigma_c^+ + D^-, \\ J/\psi + n &\rightarrow \Sigma_c^0 + \bar{D}^0, & J/\psi + p &\rightarrow \Lambda_c^+ + \bar{D}^0, \\ J/\psi + p &\rightarrow \Sigma_c^+ + \bar{D}^0, & J/\psi + p &\rightarrow \Sigma_c^{++} + D^-, \\ J/\psi + \pi^+ &\rightarrow D^+ + \bar{D}^{*0}, & J/\psi + \pi^- &\rightarrow D^0 + D^{*-}, \\ J/\psi + \pi^0 &\rightarrow D^0 + \bar{D}^{*0}, & J/\psi + \pi^0 &\rightarrow D^+ + D^{*-}, \\ J/\psi + \rho^+ &\rightarrow D^+ + \bar{D}^0, & J/\psi + \rho^- &\rightarrow D^0 + D^-, \\ J/\psi + \rho^0 &\rightarrow D^0 + \bar{D}^0, & J/\psi + \rho^0 &\rightarrow D^+ + D^-. \end{aligned}$$

Other approaches, such as the comover interaction model, also incorporate the hadronic rescattering effects [37–44].

III. RESULTS AND DISCUSSIONS

We generated 400 million inelastic nondiffractive events in pp collisions at $\sqrt{s} = 5.02, 7$, and 13 TeV with the PACIAE 4.0 model. The model employed the default parameter set from the PYTHIA 8.3 Monash tune [45], with the exception of the K factor. To align the simulation results with experimental data, the K factors were adjusted

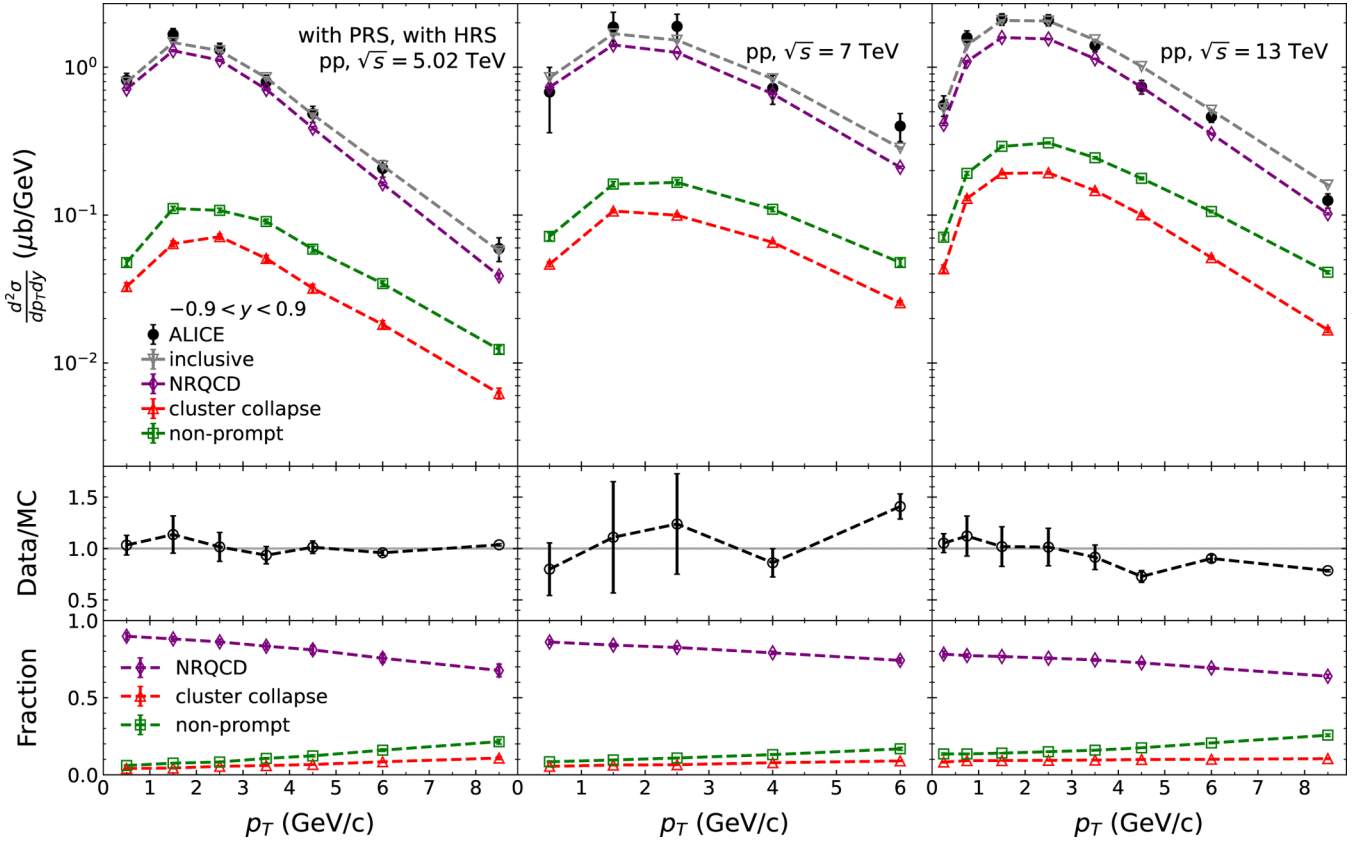


FIG. 1. Top row: The p_T -differential cross sections of J/ψ from the inclusive process (inverted triangles), the NRQCD (diamonds), the cluster collapse (triangles), and the nonprompt process (squares) at midrapidity in pp collisions at $\sqrt{s} = 5.02, 7$, and 13 TeV in the PACIAE model. The solid circles are experimental data taken from Refs. [26,29,31]. Middle row: The ratio between the experimental data and the inclusive J/ψ results from the PACIAE model. Bottom row: The fractions for the NRQCD, cluster-collapse, and nonprompt components in the inclusive J/ψ productions.

to 0.68, 0.71, and 0.75 for $\sqrt{s} = 5.02, 7$, and 13 TeV, respectively. The simulation includes critical mechanisms such as multiple-parton interactions (MPIs) [46] and color reconnections (CRs) [47]. MPIs comprise multiple independent $2 \rightarrow 2$ partonic scatterings that primarily contribute to the underlying event. In high-energy pp collisions, however, a substantial fraction of MPIs can be sufficiently hard to produce a J/ψ , thereby increasing the total J/ψ yield in events with high charged-particle multiplicity. These MPIs lead to the formation of overlapping color strings. The CR mechanism reduces the overall string length, effectively leading to a reduction of the total multiplicity. It is found that the MPI with the CR well reproduces the dependence of the mean transverse momentum on the charged particle multiplicity in pp collisions observed by the ALICE Collaboration at the LHC [48].

The top row of Fig. 1 presents the p_T -differential inclusive J/ψ cross sections at midrapidity in pp collisions at $\sqrt{s} = 5.02, 7$, and 13 TeV. Solid circles denote the experimental data, while open inverted triangles represent the inclusive J/ψ results from the PACIAE model, which incorporates PRS and HRS effects. In the PACIAE model, the J/ψ cross section is obtained by normalizing the per-event differential J/ψ yield to the nucleon-nucleon inelastic nondiffractive cross

section ($\sigma_{\text{ND}}^{\text{NN}}$) [29], as given by

$$\frac{d^2\sigma_{J/\psi}}{dp_T dy} = \frac{\sigma_{\text{ND}}^{\text{NN}}}{N_{\text{ND}}^{\text{NN}}} \frac{d^2N_{J/\psi}}{dp_T dy}, \quad (1)$$

where $N_{\text{ND}}^{\text{NN}}$ is the total number of inelastic nondiffractive events. The values of $\sigma_{\text{ND}}^{\text{NN}}$ for pp collisions at $\sqrt{s} = 5.02, 7$, and 13 TeV are 47.72, 50.76, and 56.42 mb, respectively, as calculated by PACIAE 4.0. These values are consistent with the estimations from the experimental measurements [49]. The middle row displays the ratios between the data and the inclusive results from the model, showing that the PACIAE model describes the data reasonably well. Except for the last data point at $\sqrt{s} = 7$ TeV, the discrepancy between data and model is within 30%. The top row also shows the p_T -differential cross sections for the J/ψ mesons from the NRQCD channels (open diamonds), the cluster collapse (open triangles), and the nonprompt process (open squares). The bottom row presents their corresponding fractions in the inclusive J/ψ production. The results indicate that the dominant contribution comes from the NRQCD production, while the fractions of J/ψ from the cluster collapse and the nonprompt process are relatively small. The p_T average fractions of prompt and nonprompt components in inclusive J/ψ

TABLE I. The p_T average fractions for the NRQCD, cluster-collapse, and nonprompt components in the inclusive J/ψ production at both the middle (mid) and forward (fwd) rapidities in pp collisions at $\sqrt{s} = 5.02, 7$, and 13 TeV. The uncertainties quoted are statistical errors.

$\sqrt{s}$ (TeV)	y	NRQCD	Cluster collapse	Nonprompt
5.02	mid	$(84.92 \pm 0.87)\%$	$(5.58 \pm 0.12)\%$	$(9.50 \pm 0.17)\%$
	fwd	$(86.27 \pm 1.19)\%$	$(6.86 \pm 0.18)\%$	$(6.87 \pm 0.18)\%$
7	mid	$(81.75 \pm 0.58)\%$	$(6.90 \pm 0.09)\%$	$(11.34 \pm 0.23)\%$
	fwd	$(83.03 \pm 0.75)\%$	$(7.69 \pm 0.13)\%$	$(9.29 \pm 0.27)\%$
13	mid	$(74.22 \pm 0.33)\%$	$(9.53 \pm 0.09)\%$	$(16.26 \pm 0.13)\%$
	fwd	$(76.31 \pm 0.44)\%$	$10.20 \pm 0.13)\%$	$(13.49 \pm 0.15)\%$

production at midrapidity in pp collisions at $\sqrt{s} = 5.02, 7$, and 13 TeV are summarized in Table I. With increasing collision energy, the relative contributions of the cluster-collapse and nonprompt processes to the inclusive J/ψ production exhibit a growing trend, while the fraction originating from the NRQCD channel decreases. This behavior stems from the distinct energy dependence of the production cross sections in each channel. At LHC energies, the J/ψ cross section from the NRQCD process grows relatively slowly, scaling roughly as $\sigma \propto s^{-\alpha}$ with $\alpha > 0$ [5]. In contrast, the cross section for $b\bar{b}$ production rises more rapidly with energy than that for

$c\bar{c}$ [50]. Consequently, although the absolute yield from NRQCD still increases, its relative contribution is gradually diluted by the faster-growing cluster-collapse and nonprompt channels.

The top row of panels in Fig. 2 present the p_T -differential inclusive J/ψ cross sections at forward rapidity in pp collisions at $\sqrt{s} = 5.02, 7$, and 13 TeV. The markers are the same as those at midrapidity in Fig. 1. The middle row shows the ratio between the experimental data and the inclusive J/ψ results from the PACIAE model. These ratios indicate that the model agrees with the data within 30%. We emphasize that the J/ψ productions at middle and forward rapidities are studied simultaneously. In the high- p_T region, the model overestimates the data for all the three energies. The bottom row of panels shows the production fractions of the NRQCD, the cluster-collapse, and the nonprompt components in the inclusive J/ψ yield, with their p_T average values at forward rapidity summarized in Table I. At forward rapidity, the energy dependence of these fractions is consistent with that observed at midrapidity. However, their absolute values differ significantly: the contributions from both the NRQCD and cluster-collapse processes are enhanced, while the nonprompt component is suppressed. This could be understood as follows. The forward-rapidity region amplifies an asymmetric collision environment where the extremely high density of small- x partons significantly enhances the J/ψ production from the NRQCD and the cluster-collapse processes, while

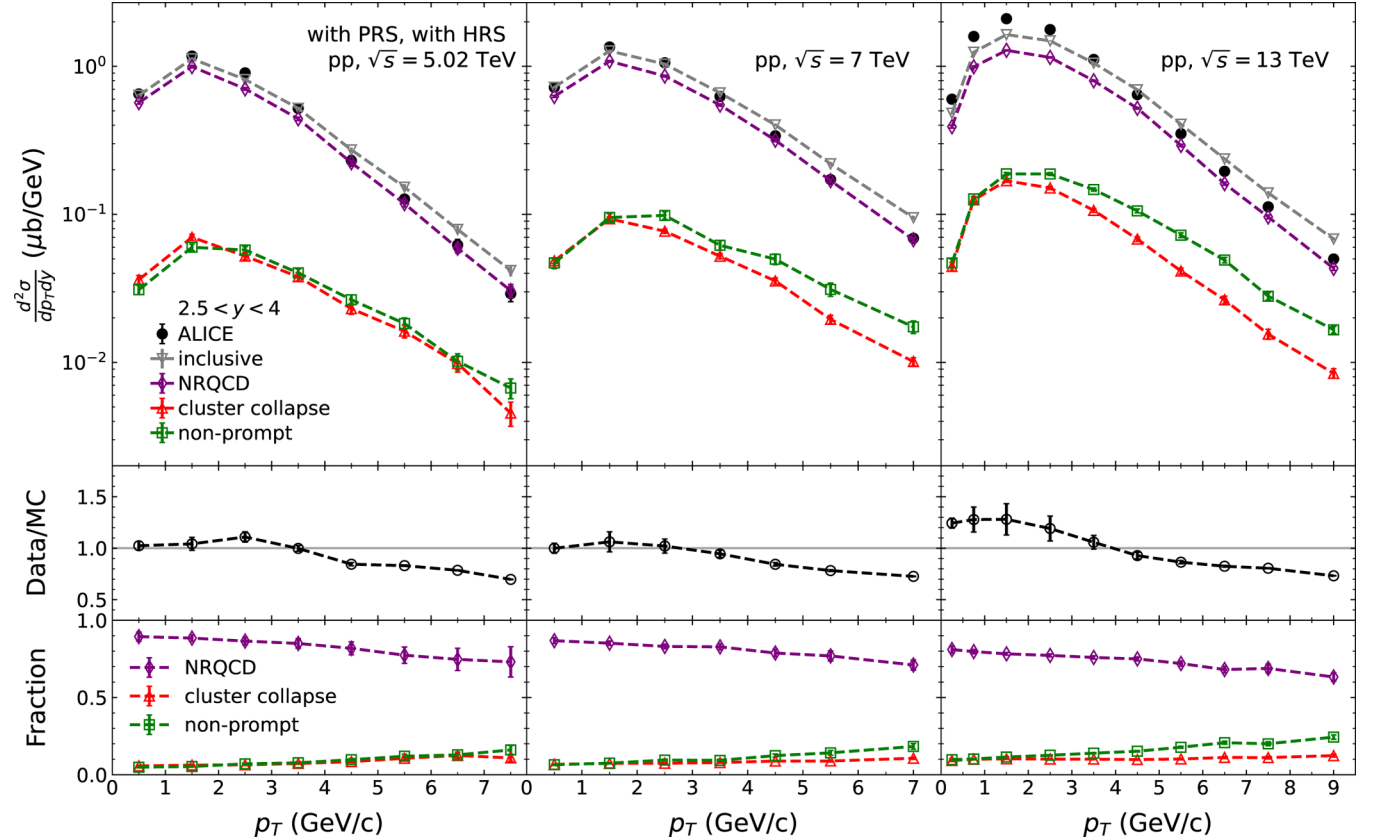


FIG. 2. Similar to that in Fig. 1, but for the p_T -differential inclusive J/ψ cross sections at forward rapidity in pp collisions at $\sqrt{s} = 5.02, 7$, and 13 TeV. The experimental data are taken from Refs. [28,30].

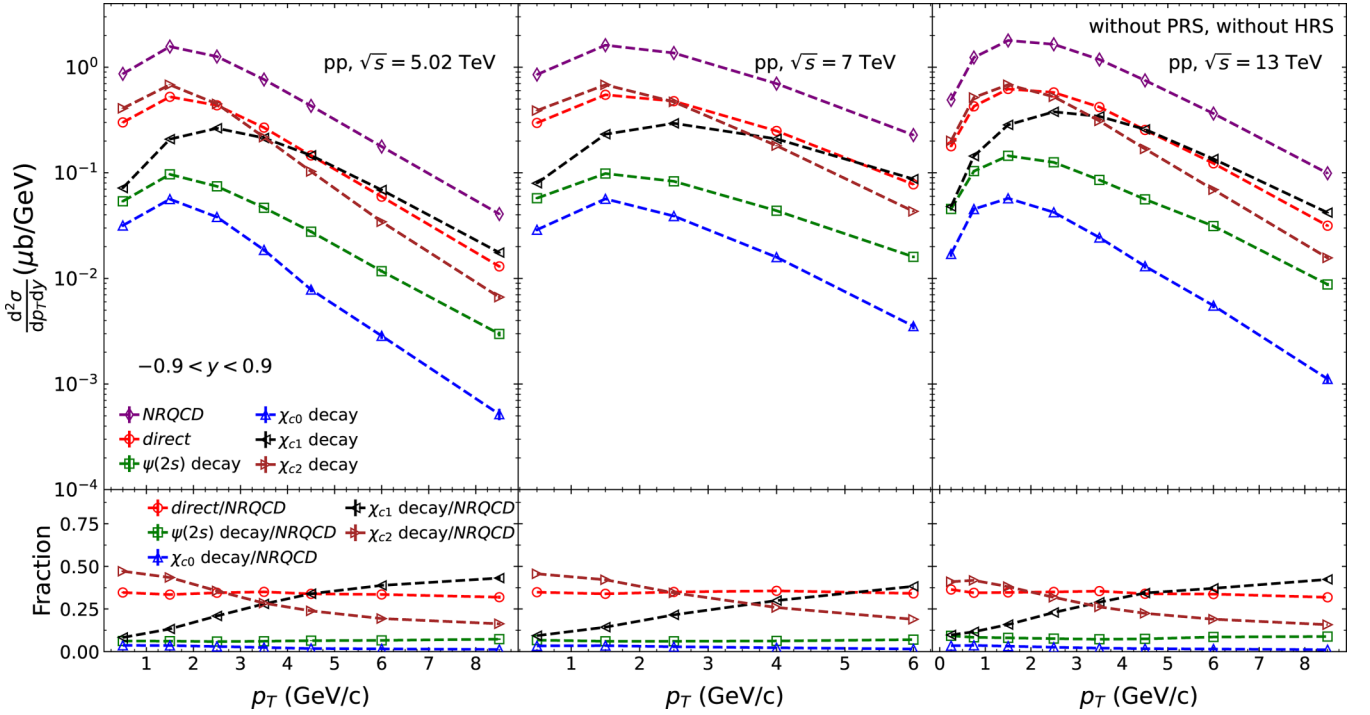


FIG. 3. Top: The p_T -differential cross sections for J/ψ from the direct production (circles) as well as the feed-down contributions from the decays of $\psi(2S)$ (squares), χ_{c0} (triangles), χ_{c1} (left-pointing triangles), and χ_{c2} (right-pointing triangles) at midrapidity in pp collisions at $\sqrt{s} = 5.02, 7$, and 13 TeV. The p_T -differential cross sections for J/ψ from the total NRQCD processes are represented by the open diamonds. Bottom: The fractions of different components in the NRQCD processes.

the scarcity of large- x partons suppresses the bottom-quark production, which requires a higher energy threshold. This in turn reduces the nonprompt J/ψ yield from the b hadron weak decays.

As the yield of J/ψ from NRQCD includes the direct production from the parton hard scattering as well as the feed-down from decays of heavier charmonium states such as $\psi(2S)$, χ_{c0} , χ_{c1} , and χ_{c2} , we investigate the relative contribution of each production mechanism. In the upper panels of Figs. 3 and 4, we present the p_T -differential inclusive J/ψ cross sections from different NRQCD production mechanisms at both the middle and forward rapidities in pp collisions at $\sqrt{s} = 5.02, 7$, and 13 TeV from the PACIAE model. In this model, the PRS and HRS are deactivated because, when enabled, they technically prevent the tracing of the J/ψ 's mother particle. The open circles, squares, triangles, left-pointing triangles, and right-pointing triangles represent the p_T spectra of the J/ψ mesons from the direct production, as well as the decays of $\psi(2S)$, χ_{c0} , χ_{c1} , and χ_{c2} , respectively. The feed-down contributions from the decay of h_c and $\psi(3770)$ are negligible; thus, they are not presented in the figure. The total NRQCD yield, being the sum of all these components, is represented by open diamonds. The corresponding production fractions are detailed in the lower panels. It is observed that at low (high) p_T the dominant contributions come from the direct production and the χ_{c2} (χ_{c1}) decay. The feed-down fractions from $\psi(2S)$ and χ_{c0} are relatively small. The differing contributions of various charmonium states to the inclusive J/ψ yield stem primarily from the interplay between their distinct long-distance matrix

elements (LDMEs) and the short-distance production mechanisms (color singlet vs color octet). For the directly produced J/ψ , at low p_T the color-singlet process, such as $gg \rightarrow J/\psi g$, is the largest contributor, while at high p_T the color-octet process becomes significant [51]. For the χ_{cJ} ($J = 0, 1, 2$) states, the key to their relative sizes lies in the values of their color-octet LDMEs. The hierarchy of the LDMEs is $\chi_{c1} > \chi_{c2} > \chi_{c0}$ [52]. At low p_T , the χ_{cJ} production is dominated by the gluon-gluon fusion, $gg \rightarrow \chi_{cJ}$. The spin structure of χ_{c2} matches the total angular momentum of two gluons more favorably. This results in larger short-distance coefficients for the χ_{c2} production compared to χ_{c1} . Even though χ_{c1} 's LDME is intrinsically larger, the advantage of larger short-distance coefficients causes the absolute production cross section of χ_{c2} to surpass that of χ_{c1} . At high p_T , the production of χ_{cJ} via high-energy gluon fragmentation channel becomes important. It is easier for a high-energy gluon (spin-1) to transfer and reconfigure its angular momentum into χ_{c1} (spin-1) than into χ_{c2} (spin-2) during the fragmentation process. Thus, χ_{c1} , with its larger color-octet long-distance matrix element and more favorable fragmentation function, surpasses χ_{c2} at high p_T . For $\psi(2S)$, as a radial excitation, its wave function has a node at the origin, resulting in a much smaller cross section compared to the ground-state J/ψ [53]. For χ_{c0} , the extremely small LDME strongly suppresses its color-octet production. Moreover, in the color-singlet channel, the leading-order process $gg \rightarrow \chi_{c0}$ is forbidden at tree level due to the angular momentum conservation. The p_T average fractions for all components in the NRQCD process at different energies are summarized in Table II. It is observed that the fraction of

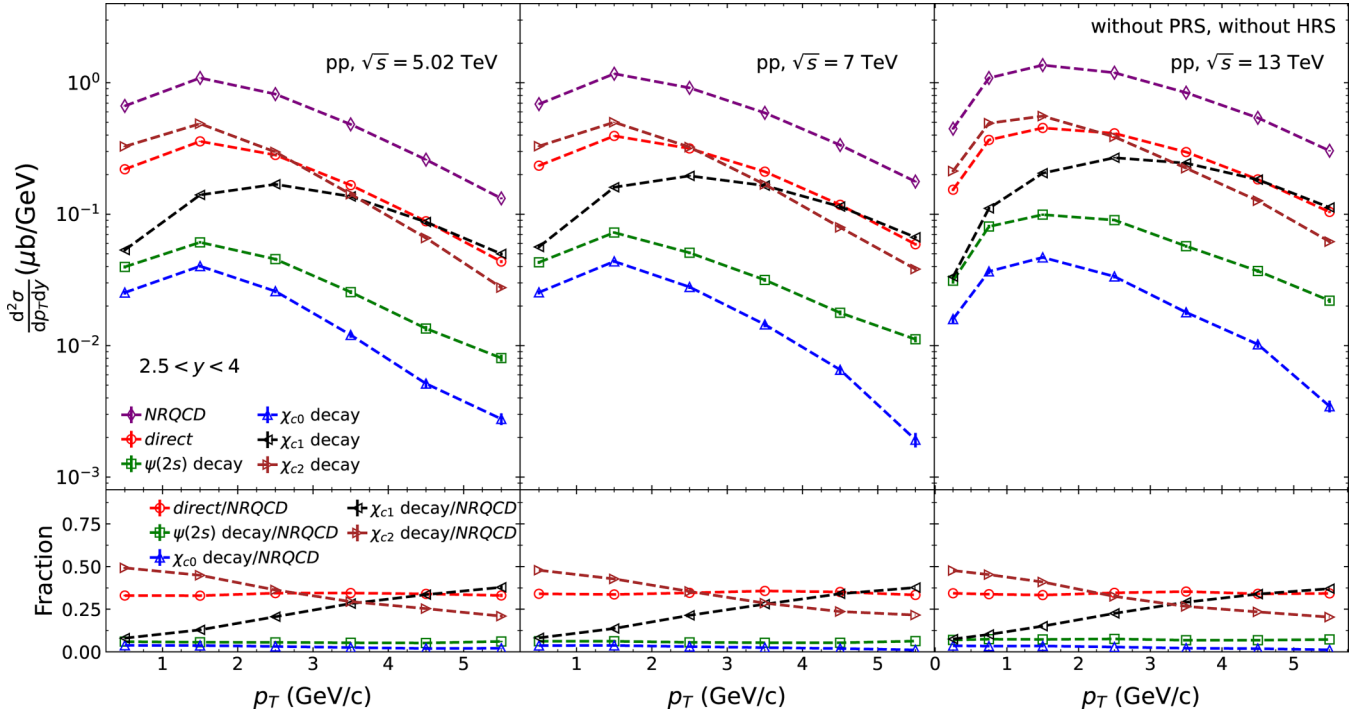


FIG. 4. Similar to that in Fig. 3, but for the p_T -differential cross sections for J/ψ from different NRQCD processes at forward rapidity in pp collisions at $\sqrt{s} = 5.02, 7$, and 13 TeV.

directly produced J/ψ increases modestly with collision energy and appears to saturate at $\sqrt{s} = 13$ TeV. Furthermore, the feed-down contributions from the $\psi(2S)$ and χ_{c1} decays grow with energy, whereas those from χ_{c0} and χ_{c2} exhibit a declining trend. The observed energy dependence could be understood as follows. With increasing collision energy, the dominant production mechanism evolves from the color-singlet hard scattering toward the color-octet fragmentation. The vector nature and large associated LDME of χ_{c1} make it a primary beneficiary. Similarly, the favorable spin alignment of $\psi(2S)$ also allows it to gain from this evolution. In contrast, for χ_{c2} , its spin-2 structure places it at an angular momentum disadvantage in fragmentation compared to χ_{c1} . For χ_{c0} , as its color-octet LDME is extremely small, its production relies mainly on the color-singlet mechanism, causing its relative share to decline. These results provide strong observational grounds for using energy scans to separate and constrain the various LDMEs in NRQCD, particularly for distinguishing

among the matrix elements for different χ_{cJ} states. A clear rapidity dependence is also observed: at forward rapidity, the fractions originating from direct production as well as from $\psi(2S)$ and χ_{c1} decays are slightly suppressed relative to their values at midrapidity, while the contributions from χ_{c0} and χ_{c2} decays are moderately enhanced. This pattern is a direct consequence of the differing sensitivities of various production mechanisms to the parton momentum fraction x . The forward-rapidity region suppresses the color-octet fragmentation that requires efficient production of a parent parton from the large- x region, while it enhances the color-singlet hard scattering that can effectively utilize the extremely high small- x gluon density. Finally, we investigate the effects of PRS and HRS on the J/ψ production. As an example, in Figs. 5(a) and 5(b), we present the p_T -differential J/ψ cross sections at middle and forward rapidities in pp collisions at $\sqrt{s} = 13$ TeV in the PACIAE model under different rescattering scenarios. The gray, red, green, and purple curves represent

TABLE II. The p_T average fractions of J/ψ from the direct production, and from the decays of $\psi(2S)$, χ_{c0} , χ_{c1} , and χ_{c2} in the NRQCD component at both the middle and forward rapidities in pp collisions at $\sqrt{s} = 5.02, 7$, and 13 TeV. The uncertainties quoted are statistical errors.

$\sqrt{s}$ (TeV)	y	Direct	$\psi(2S)$	χ_{c0}	χ_{c1}	χ_{c2}
5.02	mid	$(34.13 \pm 0.14)\%$	$(6.18 \pm 0.05)\%$	$(2.98 \pm 0.04)\%$	$(20.40 \pm 0.10)\%$	$(36.30 \pm 0.15)\%$
	fwd	$(33.60 \pm 0.19)\%$	$(5.61 \pm 0.07)\%$	$(3.23 \pm 0.05)\%$	$(18.44 \pm 0.13)\%$	$(39.12 \pm 0.21)\%$
7	mid	$(34.76 \pm 0.14)\%$	$(6.31 \pm 0.05)\%$	$(2.87 \pm 0.04)\%$	$(21.09 \pm 0.11)\%$	$(34.97 \pm 0.14)\%$
	fwd	$(34.35 \pm 0.19)\%$	$(5.85 \pm 0.07)\%$	$(3.10 \pm 0.05)\%$	$(19.56 \pm 0.14)\%$	$(37.14 \pm 0.20)\%$
13	mid	$(34.60 \pm 0.14)\%$	$(8.01 \pm 0.06)\%$	$(2.50 \pm 0.03)\%$	$(24.39 \pm 0.11)\%$	$(30.51 \pm 0.13)\%$
	fwd	$(34.10 \pm 0.17)\%$	$(7.24 \pm 0.07)\%$	$(2.70 \pm 0.04)\%$	$(22.61 \pm 0.13)\%$	$(33.35 \pm 0.17)\%$

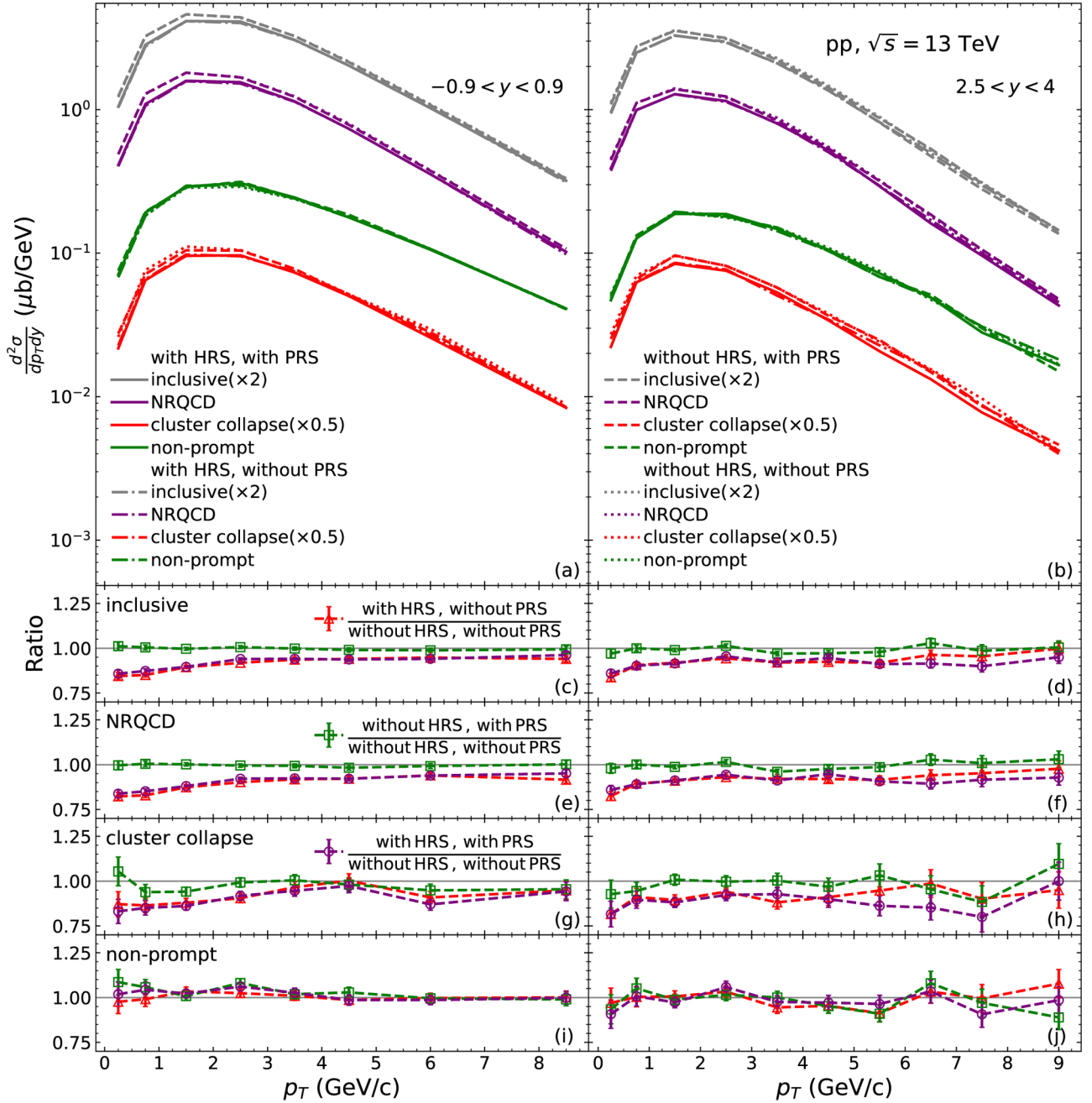


FIG. 5. Panels (a) and (b): The p_T -differential cross sections of J/ψ from the inclusive process (gray curves) as well as the NRQCD (red curves), cluster-collapse (green curves), and nonprompt (purple curves) processes at middle and forward rapidities in pp collisions at $\sqrt{s} = 13$ TeV in the PACIAE model under different rescattering scenarios: both PRS and HRS included (solid curves), HRS only (dash-dotted curves), PRS only (dashed curves), and neither PRS nor HRS, the baseline (dotted curves). Panels (c) and (d) [(e) and (f), (g) and (h), (i) and (j)]: The ratios of the spectra from the inclusive, NRQCD, cluster-collapse, and nonprompt processes with HRS only (triangles), PRS only (squares), and both PRS and HRS (circles) to this baseline.

the p_T spectra of J/ψ from the inclusive process as well as the NRQCD, cluster-collapse, and nonprompt processes, respectively. The line styles denote the following rescattering configurations: solid curves (both PRS and HRS included), dash-dotted curves (HRS only), dashed curves (PRS only), and dotted curves (neither PRS nor HRS, the baseline). Figures 5(c) and 5(d) [5(e) and 5(f), 5(g) and 5(h), 5(i) and 5(j)] present the ratios of the spectra from the inclusive (NRQCD,

cluster collapse, nonprompt) with HRS only (open triangles), PRS only (open squares), and both PRS and HRS (open circles) to this baseline. The p_T average ratios are presented in Table III. It is observed that the PRS exhibits negligible impact on the J/ψ yield across all production sources. In contrast, the HRS suppresses J/ψ production from both the NRQCD and cluster-collapse mechanisms, while leaving nonprompt J/ψ yield largely unaffected. The total suppression effect of the

TABLE III. The p_T average ratios of the J/ψ cross section from the inclusive, NRQCD, cluster-collapse, and nonprompt processes with HRS only, PRS only, and both PRS and HRS to that with neither PRS nor HRS at both the middle and forward rapidities in pp collisions at $\sqrt{s} = 13$ TeV. The uncertainties quoted are statistical errors.

	y	Inclusive	NRQCD	Cluster collapse	Nonprompt
With PRS, without HRS	mid	$(99.84 \pm 0.40)\%$	$(99.61 \pm 0.46)\%$	$(97.12 \pm 1.25)\%$	$(102.86 \pm 1.06)\%$
	fwd	$(99.11 \pm 0.51)\%$	$(99.17 \pm 0.58)\%$	$(99.02 \pm 1.56)\%$	$(98.80 \pm 1.43)\%$
With HRS, without PRS	mid	$(91.46 \pm 0.37)\%$	$(89.57 \pm 0.42)\%$	$(91.79 \pm 1.20)\%$	$(101.01 \pm 1.05)\%$
	fwd	$(92.43 \pm 0.48)\%$	$(91.54 \pm 0.55)\%$	$(91.14 \pm 1.47)\%$	$(98.96 \pm 1.43)\%$
With PRS, with HRS	mid	$(92.27 \pm 0.37)\%$	$(90.63 \pm 0.43)\%$	$(90.31 \pm 1.18)\%$	$(102.02 \pm 1.05)\%$
	fwd	$(92.46 \pm 0.48)\%$	$(91.77 \pm 0.55)\%$	$(89.61 \pm 1.45)\%$	$(99.11 \pm 1.43)\%$

HRS on the inclusive J/ψ cross section is around 8%. It is understandable for the following reasons. As shown in Sec. II, in the HRS J/ψ scatters with p , n , $\pi^\pm$, π^0 , $\rho^\pm$, and ρ^0 inelastically, which will reduce the J/ψ yields from the NRQCD and the cluster collapse. As the nonprompt J/ψ is produced from the b hadron decay, and we do not consider the b hadron rescattering, the effect of HRS on the nonprompt J/ψ yield is negligible. Moreover, in the PRS we do not include the scattering of J/ψ with partons, such as $J/\psi + g \rightarrow c + \bar{c}$ and $J/\psi + \text{parton} \rightarrow c + \bar{c} + \text{parton}$ (parton = $g, q, \bar{q}$) [54]. Thus, the PRS has little effect on the J/ψ production.

IV. CONCLUSIONS

We have investigated the inclusive J/ψ production in pp collisions at $\sqrt{s} = 5.02, 7$, and 13 TeV using the PACIAE 4.0 model. This model, which extends PYTHIA 8.3 with partonic and hadronic rescatterings, incorporates the NRQCD, cluster-collapse, and nonprompt production mechanisms. Our simulations reproduce the measured p_T -differential cross sections at middle and forward rapidities. We find that the NRQCD channel provides the dominant contribution to the total yield, with subleading shares from the cluster-collapse and nonprompt productions. As the collision energy rises, the relative contributions from the cluster-collapse and nonprompt processes increase, while the fraction from the NRQCD channel decreases. Furthermore, at forward rapidity the contributions from both the NRQCD and cluster-collapse processes are enhanced relative to midrapidity, whereas the nonprompt component is suppressed. A decomposition of the NRQCD component reveals that the direct production together with the χ_{c2} feed-down dominates the yield at low p_T , while at high p_T the dominant contribution comes from the direct production combined with the χ_{c1} feed-down. The feed-down from $\psi(2S)$ and χ_{c0} accounts for about 5–8% and 2–3% of the NRQCD yield, respectively. We also observe clear energy and rapidity dependence in the fractional contributions of the different NRQCD subchannels. Furthermore, we find that the partonic rescattering has a negligible effect, while the hadronic rescattering selectively suppresses the J/ψ yields from the NRQCD and cluster-collapse processes.

As with any Monte Carlo approach, such as EPOS3 and UrQMD [18–21], our model relies on a number of parameters to simulate complex processes for the J/ψ production, which inevitably introduces phenomenological uncertainties. Nevertheless, we emphasize that the primary goal of this study is not to derive first-principles theoretical insights, but rather to establish a comprehensive phenomenological benchmark for the inclusive J/ψ production across multiple LHC energies using an up-to-date event generator. By systematically comparing the contributions from different production mechanisms and investigating the effect of final-state rescatterings, this work provides valuable insights into the relative importance of these components, which may serve as a useful reference for both experimentalists and theorists. Detailed phenomenological studies of this kind are essential for bridging the gap between fundamental theory and experimental data, and they contribute to a deeper understanding of the quarkonium production in hadronic collisions.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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