陕西師範大學
SHAANXI NORMAL UNIVERSITY

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Recent results on the charmonium and X(6900) productions in pp collisions at the LHC energies from the PACIAE model

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Outline

1. Background and motivations
2. The PACIAE and DCPC models
3. Results and discussions
4. Summary

Background and Motivation

- J/ψ is the lightest vector charmonium meson.
- The suppression of J/ψ production was proposed as a signal of QGP formation in HI collisions.
- The J/ψ production could also be suppressed due to the CNM effects, such as modifications of nuclear PDFs.
- In order to disentangle the hot and cold medium effects, it is necessary to understand the J/ψ production in pp collisions where the initial state effects are absent.

Background and Motivation

- The J/ψ production was extensively investigated at colliders such as the Tevatron, RHIC and LHC.
- The ALICE collaboration had published the inclusive J/ψ production in the fwd- and mid-rapidity regions in pp collisions at $\sqrt{s}$ =2.76, 5.02, 7, 8 and 13 TeV.

Inclusive J/ψ:
- direct J/ψ
- feed-down from heavier charmonium decay
- beauty hadrons weak decay

Phys. Lett. B 718, 295 (2012),
JHEP 10, 084 (2019),
Phys. Lett. B 704, 442 (2011),
Eur. Phys. J. C 74, 2974 (2014),
Eur. Phys. J. C 76, 184 (2016),
Eur. Phys. J. C 81, 1121 (2021),
Eur. Phys. J. C 77, 392 (2017).

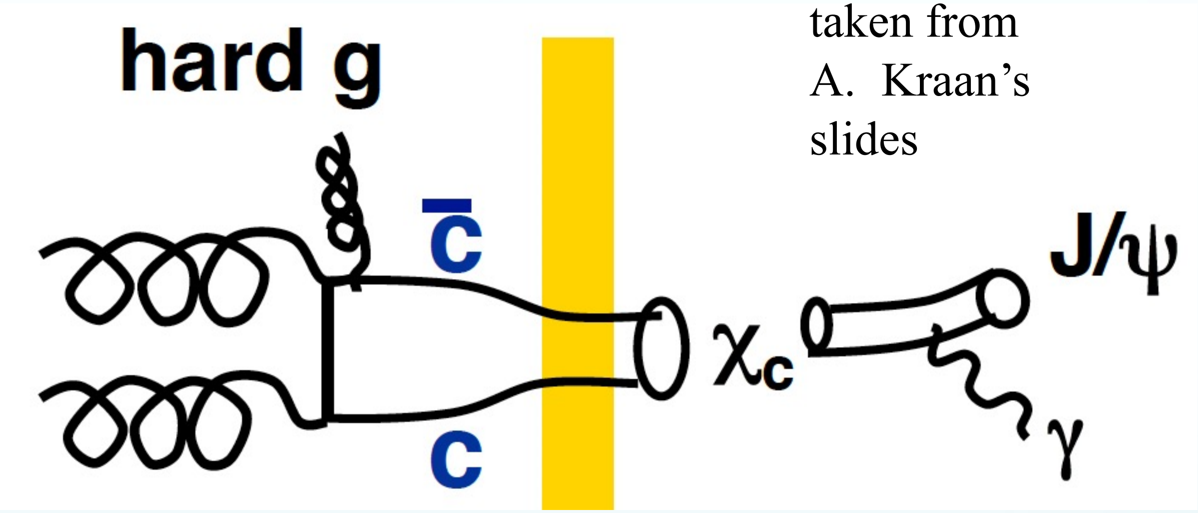
Background and Motivation

- The ALICE collaboration had also published multiplicity dependence of J/ψ production in pp collisions at $\sqrt{s} = 5.02$, 7 and 13 TeV. Phys. Lett. B 712, 165–175 (2012), Phys. Lett. B 810, 135758 (2020), JHEP 06, 015 (2022)
- Several theoretical approaches, such as CSM, COM and CEM have been utilized to describe the experimental data.
- They differ mostly in the treatment of non-perturbative evolution of the $c\bar{c}$ pair into the bound state J/ψ.

Background and Motivation

- Color Singlet Model   Phys. Lett. B 102, 364 (1981).

Color Singlet



perturbative   non-perturbative

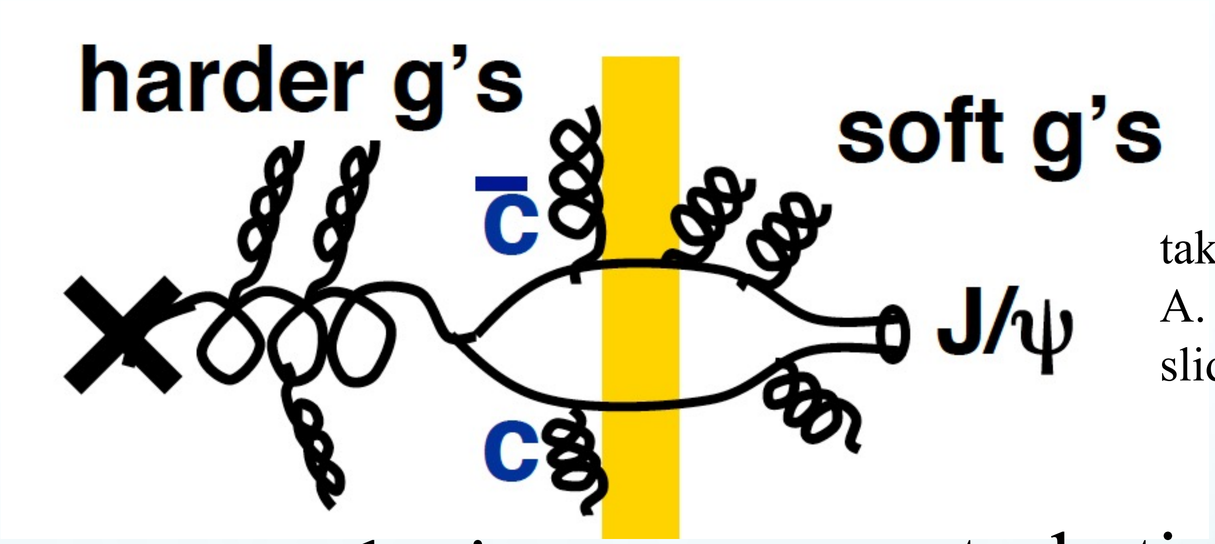
Color singlet→No gluon radiation J/ψ produced in isolation

Background and Motivation

- Color Octet Model Phys. Rev. D 51, 1125 (1995)

Color Octet

$g \rightarrow c\bar{c}^{(8)}$



taken from A. Kraan's slides

perturbative non-perturbative

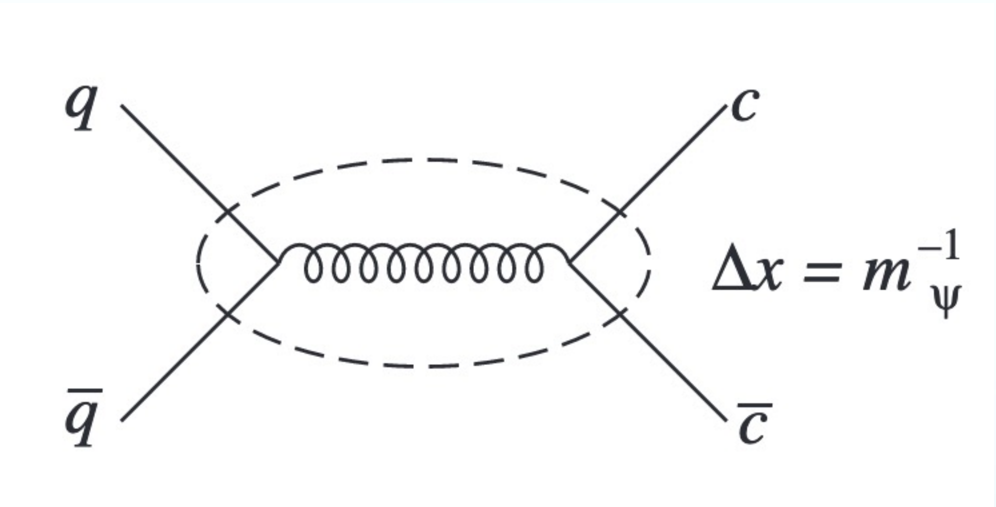
Color Octet→shower expected

J/ψ produced in shower

Background and Motivation

- Color Evaporation Model   Phys. Lett. B 390, 323-328 (1997)

Color Evaporation

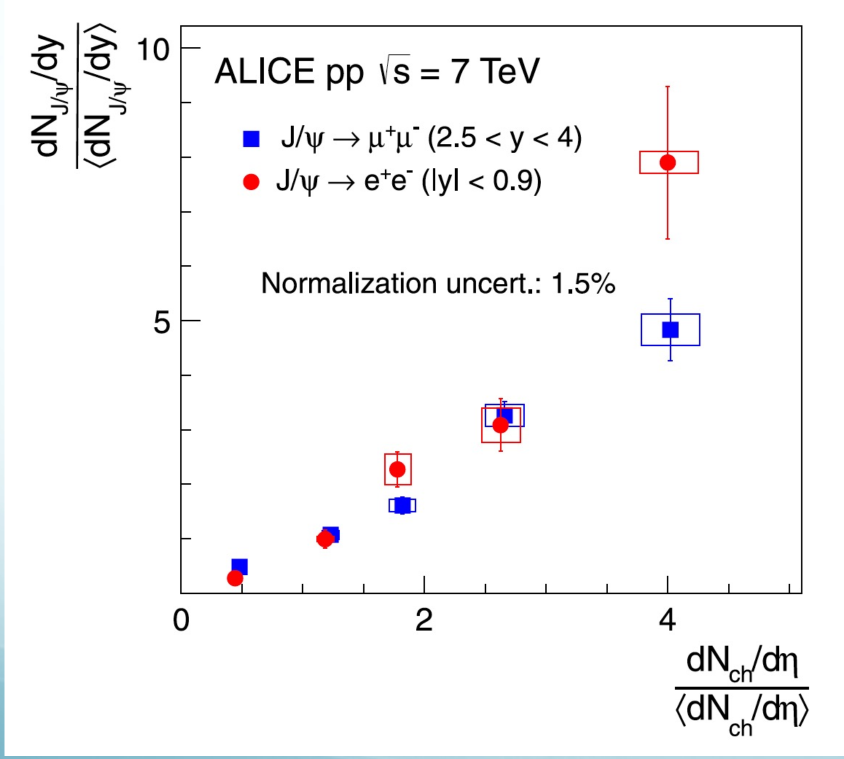


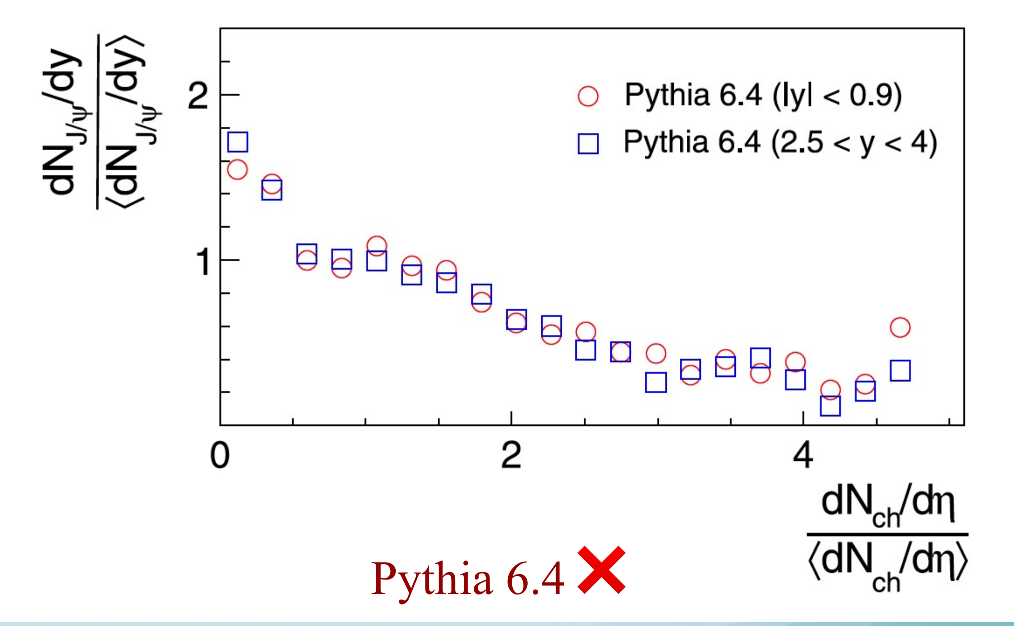
$q\bar{q}$ annihilation into $c\bar{c}$, similar to the Drelll-Yan process

There is an infinite time for soft gluons to readjust the color of the $c\bar{c}$ pair before it appears as an asymptotic J/ψ.

Background and Motivation

- The J/ψ production was also investigated by Monte Carlo simulations Phys. Lett. B 712 (2012) 165–175



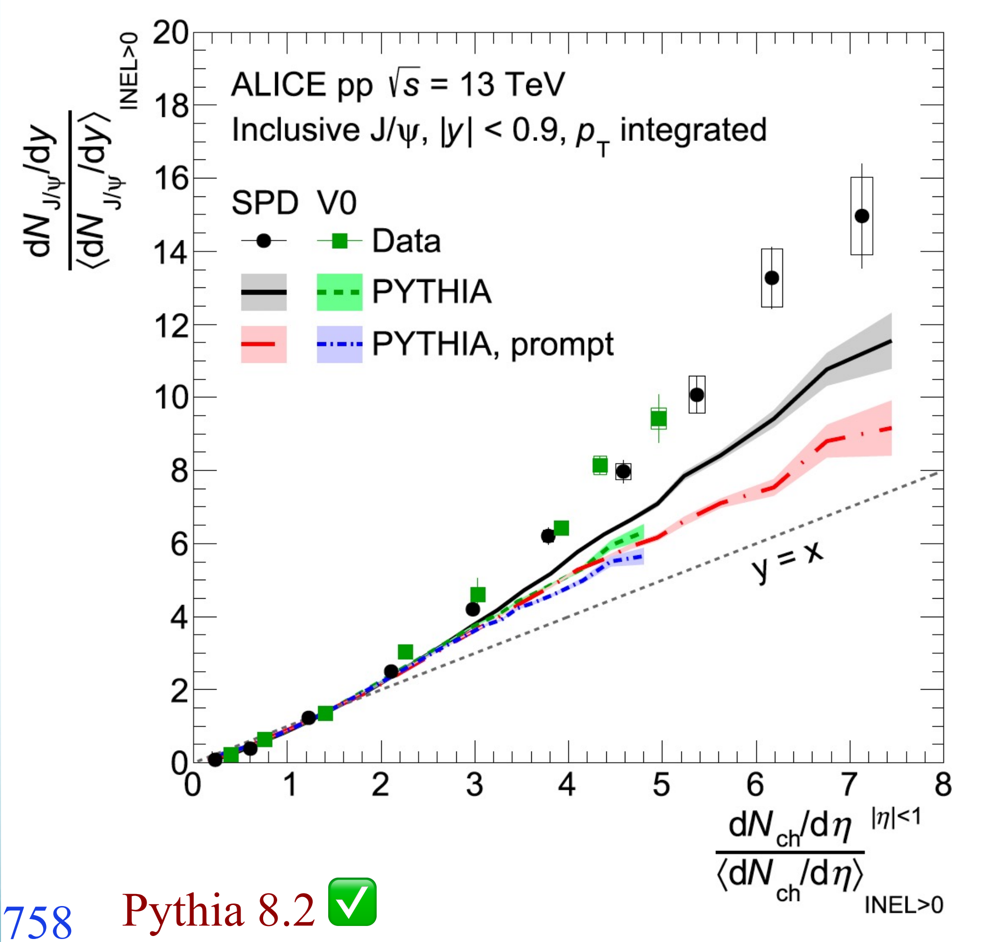


Pythia 6.4 ✗

Background and Motivation

- The J/ψ production was also investigated by Monte Carlo simulations

Different treatment of MPI in PYTHIA 6 and PYTHIA 8



Phys. Lett. B 810 (2020) 135758

Pythia 8.2 ✅

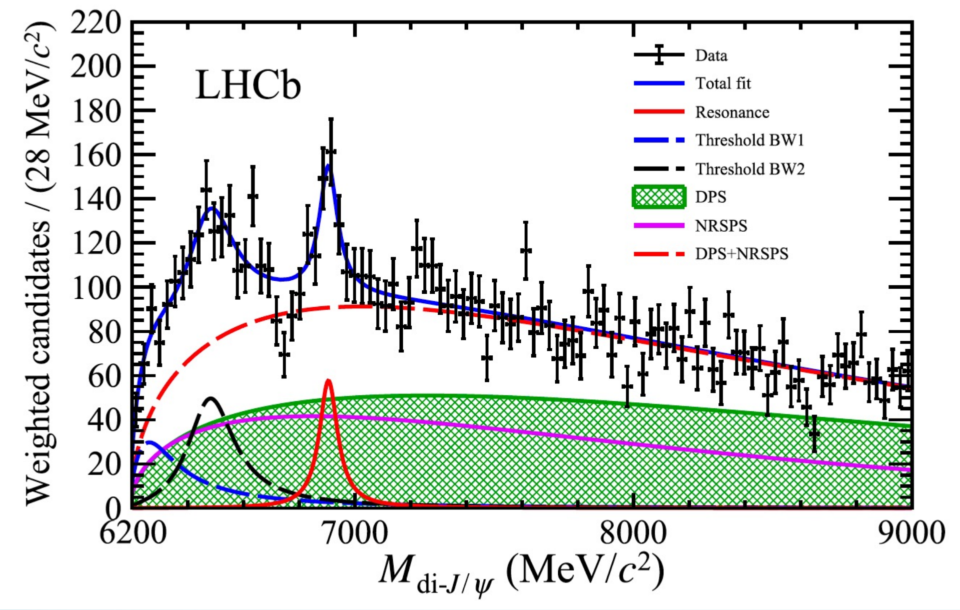
Background and Motivation

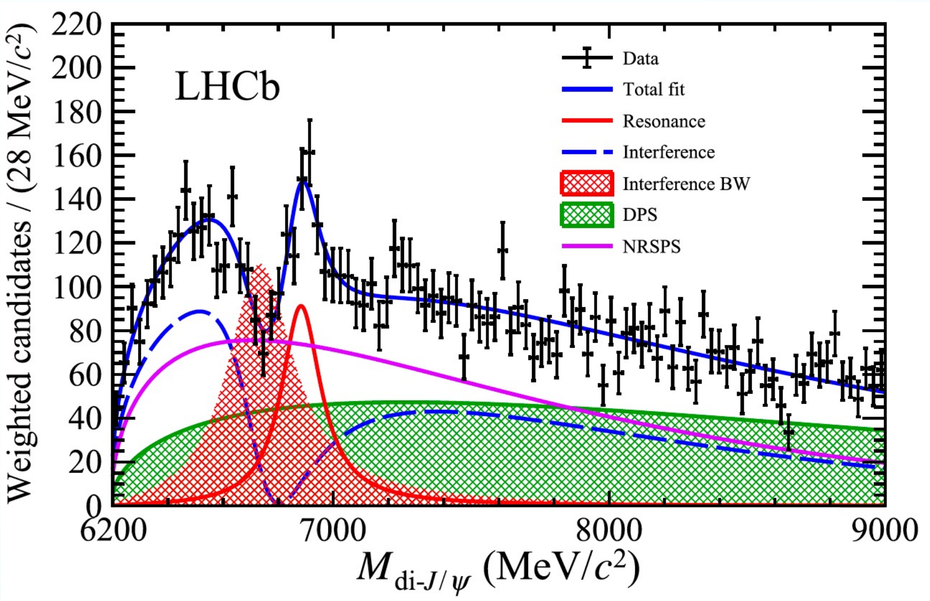
- In pp collisions, a pair of J/ψ mesons can be produced in two separate interactions of gluons or quarks, named double-parton scattering (DPS) or in a single-parton scattering (SPS).
- The SPS process includes both resonant production via intermediate states, which could be tetraquarks, and non-resonant production(NRSPS).
- Within the DPS process, the two J/ψ mesons are usually assumed to be produced independently.
- The fully tetraquark states are searched for by the LHCb collaboration in the di- J/ψ invariant mass spectra in pp collisions at $\sqrt{s} = 7$, 8 and 13 TeV.

Background and Motivation

- Experimental results of X(6900)

Science Bulletin 65, 1983 (2020)





$$m[X(6900)] = 6905 \pm 11 \pm 7\ \text{MeV}/c^2$$

$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\ \text{MeV}$$

w/o considering interference

$$m[X(6900)] = 6886 \pm 11 \pm 11\ \text{MeV}/c^2$$

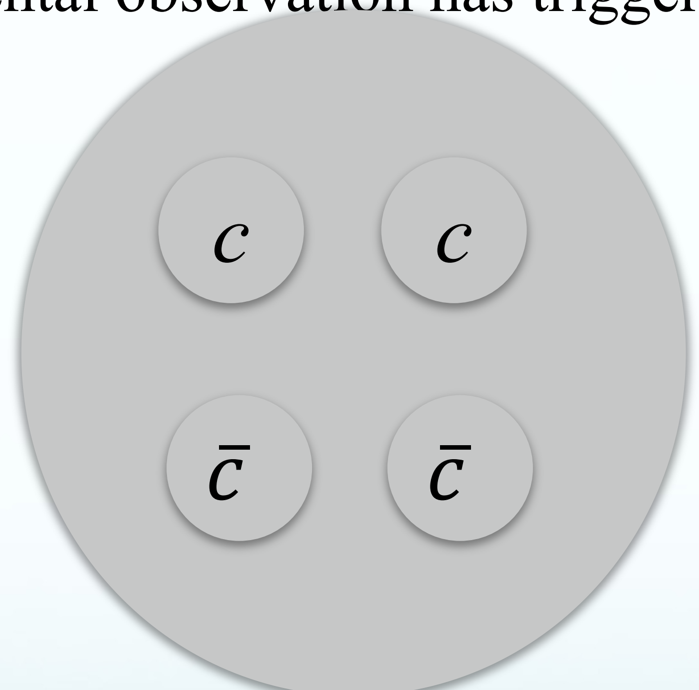
$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\ \text{MeV}$$

w/ considering interference

Background and Motivation

- The experimental observation has triggered tremendous studies.

Tetraquark
$c\bar{c}c\bar{c}$



X.-Z. Weng, X.-L. Chen, W.-Z. Deng, and S.-L. Zhu, Phys. Rev. D 103, 034001 (2021).
J.-Z. Wang, D.-Y. Chen, X. Liu, and T. Matsuki, Phys. Rev. D 103, L071503 (2021).
R.-H. Wu, Y.-S. Zuo, C.-Y. Wang, C. Meng, Y.-Q. Ma, and K.-T. Chao, JHEP 11, 023 (2022).
M.-S. Liu, F.-X. Liu, X.-H. Zhong, and Q. Zhao, Phys. Rev. D 109, 076017 (2024).
Z.-G. Wang, Nucl. Phys. B 985, 115983 (2022).
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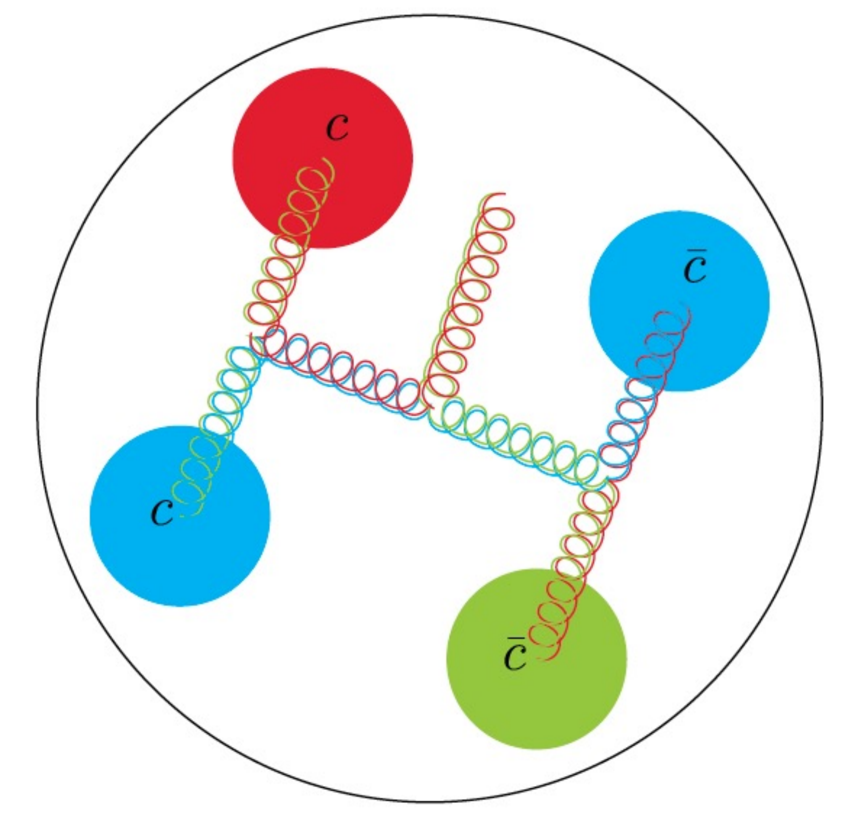
Background and Motivation

- The experimental observation has triggered tremendous studies.

Tetracharm hybrid



B.-D. Wan, C.-F. Qiao, Phys. Lett. B 817, 136339 (2021).

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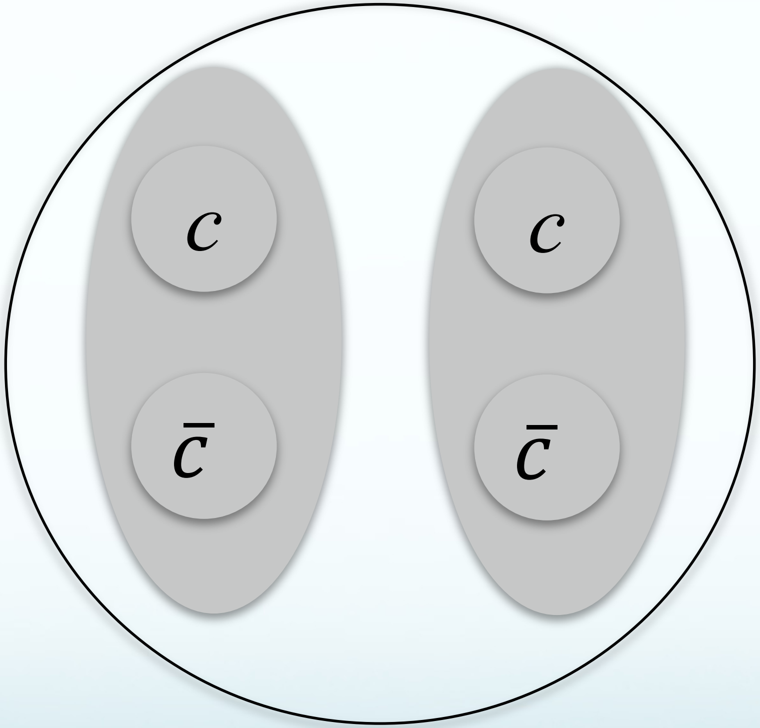
Background and Motivation

- The experimental observation has triggered tremendous studies.

Molecular state
$J/\psi J/\psi$



X.-K. Dong, V. Baru, F.-K. Guo, C. Hanhart, and A. Nefediev, Phys. Rev. Lett. 126, 132001 (2021)
Y. Lu, C. Chen, K.-G. Kang, G.-Y. Qin, and H.-Q. Zheng, Phys. Rev. D 107, 094006 (2023).
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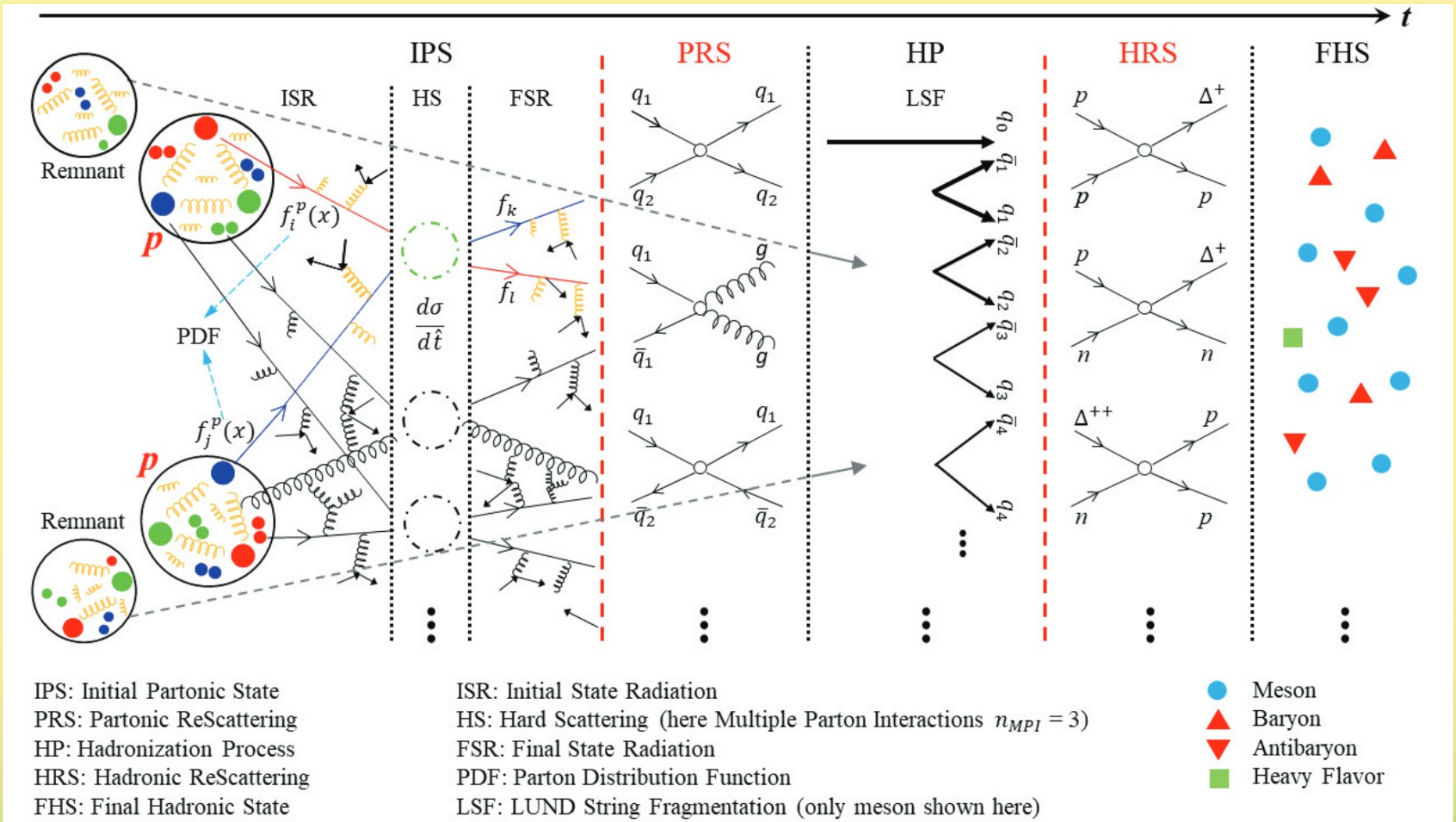
Background and Motivation

- In this work, we use a parton and hadron cascade model PACIAE 4.0 to investigate the J/ψ production in pp collisions at $\sqrt{s}$ =5.02, 7, and 13 TeV.
- We have also investigated the multiplicity dependence of J/ψ production in pp collisions at $\sqrt{s}$ = 5.02, 7 and 13 TeV.
- Finally, we have investigated the productions of X(6900) in the configuration of the tetraquark state and the double J/ψ molecular state.

The PACIAE Model



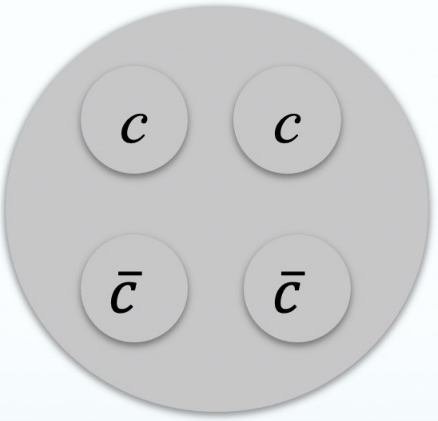
PACIAE4.0 is based on PYTHIA 8.3 but further considers the partonic rescattering before hadronization and the hadronic rescattering after hadronization.

A.-K. Lei et al., Computer Physics Communications 310, 109520 (2025).

The DCPC Model

- In the quantum statistical mechanics inspired dynamically constrained phase-space coalescence (DCPC) model, the yield of *N*-particle cluster in six-dimensional phase space can be estimated by Phys. Rev. C 85, 024907 (2012).

$$Y_{cluster} = \int \cdots \int \frac{d\vec{q}_1 d\vec{p}_1 \cdots d\vec{q}_N d\vec{p}_N}{h^{3N}}$$



- For the X(6900) tetraquark state, its yield reads

$$Y_{tetraquark} = \int \cdots \int \delta_{1234} \frac{d\vec{q}_1 d\vec{p}_1 d\vec{q}_2 d\vec{p}_2 d\vec{q}_3 d\vec{p}_3 d\vec{q}_4 d}{h^{12}}$$

$$\delta_{1234} = \begin{cases} 1. & if\ 1 = c, 2 = \bar{c}, 3 = c', 4 = \bar{c}' \\ & m_{X(6900)} - \Delta m < m_{inv} < m_{X(6900)} - \Delta m,\ \ R \leq 1fm \\ 0. & otherwise \end{cases}$$

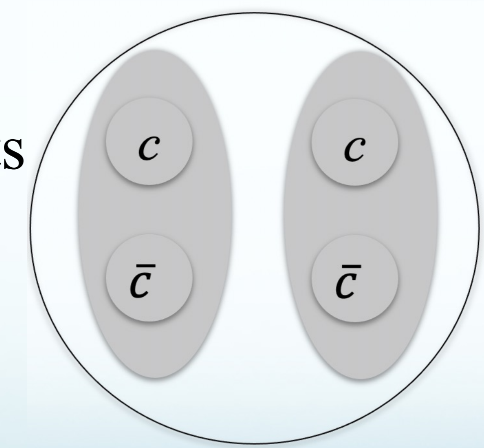
$\Delta m = m_{X(6900)}/10$, (6.2< m_{inv} <7.4 GeV/c^2), *R* is the radius of the cluster.

The DCPC Model

- In the quantum statistical mechanics inspired dynamically constrained phase-space coalescence (DCPC) model, the yield of *N*-particle cluster in six-dimensional phase space can be estimated by

$$Y_{cluster} = \int \cdots \int \frac{d\vec{q}_1 d\vec{p}_1 \cdots d\vec{q}_N d\vec{p}_N}{h^{3N}}$$

- For the X(6900) double J/ψ molecular state, its



yield reads as

$$Y_{glueball} = \frac{1}{2!} \int \int \delta_{12} \frac{d\vec{q}_1 d\vec{p}_1 d\vec{q}_2 d\vec{p}_2}{h^6}$$

$$\delta_{12} = \begin{cases} 1. & if\ 1 = J/\psi, 2 = J/\psi' \\ & m_{X(6900)} - \Delta m < m_{inv} < m_{X(6900)} - \Delta m, R > 1fm \\ 0. & otherwise \end{cases}$$

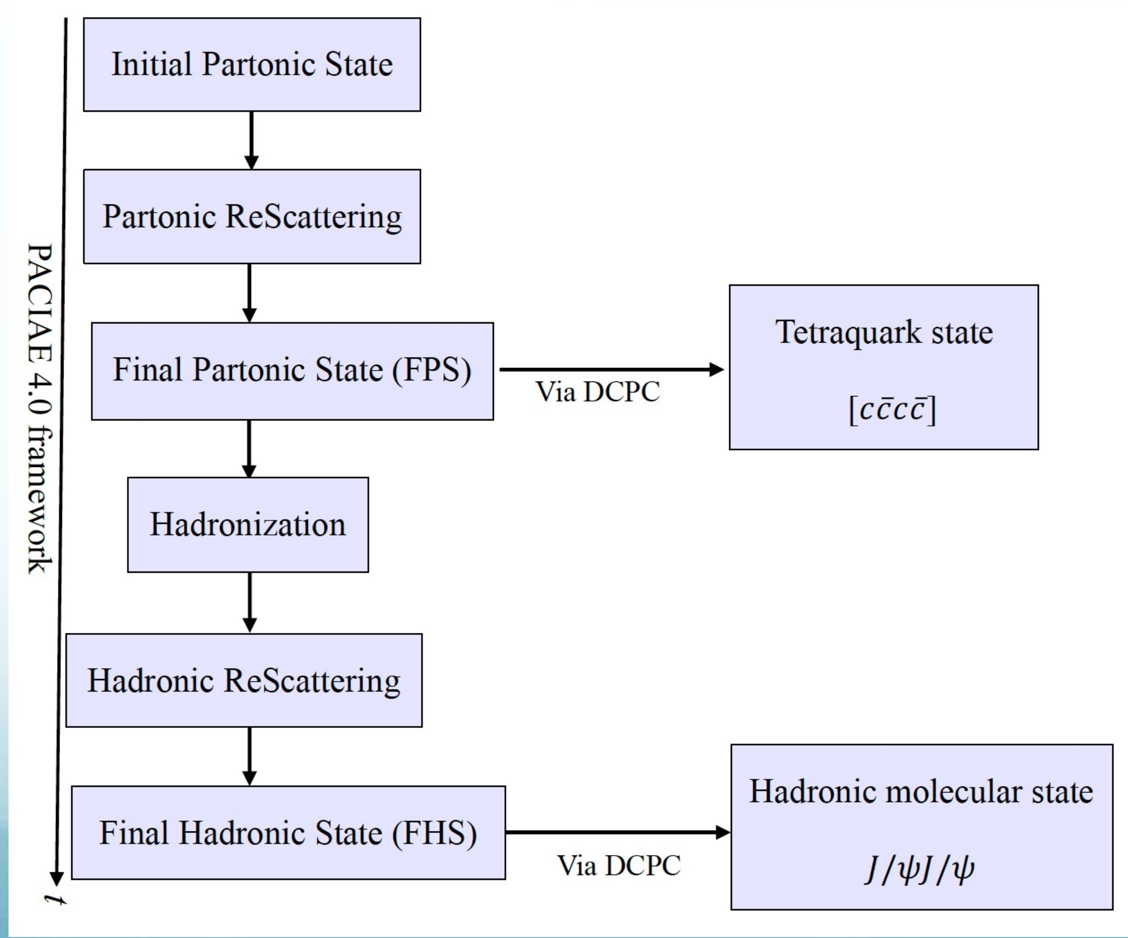
$\Delta m = m_{X(6900)}/10$, (6.2< m_{inv} <7.4 GeV/c^2), *R* is the radius of the cluster.

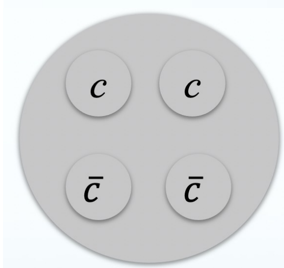
The DCPC Model

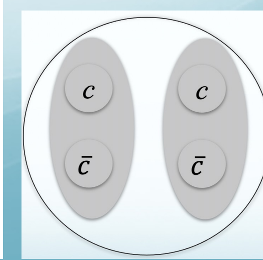
- Using the DCPC model, we have investigated the production of the glueball-like particle $X(2370)$, the exotic states $X(3872)$ and $G(3900)$ in e^+e^- and pp collisions. See the followings for details.
- $X(2370)$, Phys. Rev. D 110, 054046 (2024)
- $X(3872)$, Phys. Rev. C 110, 014910 (2024)
- $G(3900)$, arXiv: 2502.16822

The DCPC Model

- The tetraquark state and double J/ψ hadronic molecular state of $X(6900)$ are assumed to be coalesced via DCPC in PFS and HFS, respectively.







Results and Discussions

- In PACIAE 4.0, different charmonium production mechanisms are implemented.
- 1. In the perturbative scattering processes, leading order NRQCD channels via color-singlet and color–octet pre-resonant states are included.
- For color-octet state, one additional gluon is emitted in the transition to the physical color-singlet state.

Results and Discussions

- In PACIAE 4.0, different production mechanisms for the charmonium productions are implemented.
- 2. Charmonium can be produced from the cluster collapse mechanism.
- If c and $\bar{c}$ are close in phase space the potential energy in the string is sufficient to create a light quark-antiquark pair, and instead the two heavy quarks bin into a charmonium bound state.
- 3. In the so-called non-prompt charmonium production, charmonia can be produced from the weak decay of a hadron containing a beauty quark.

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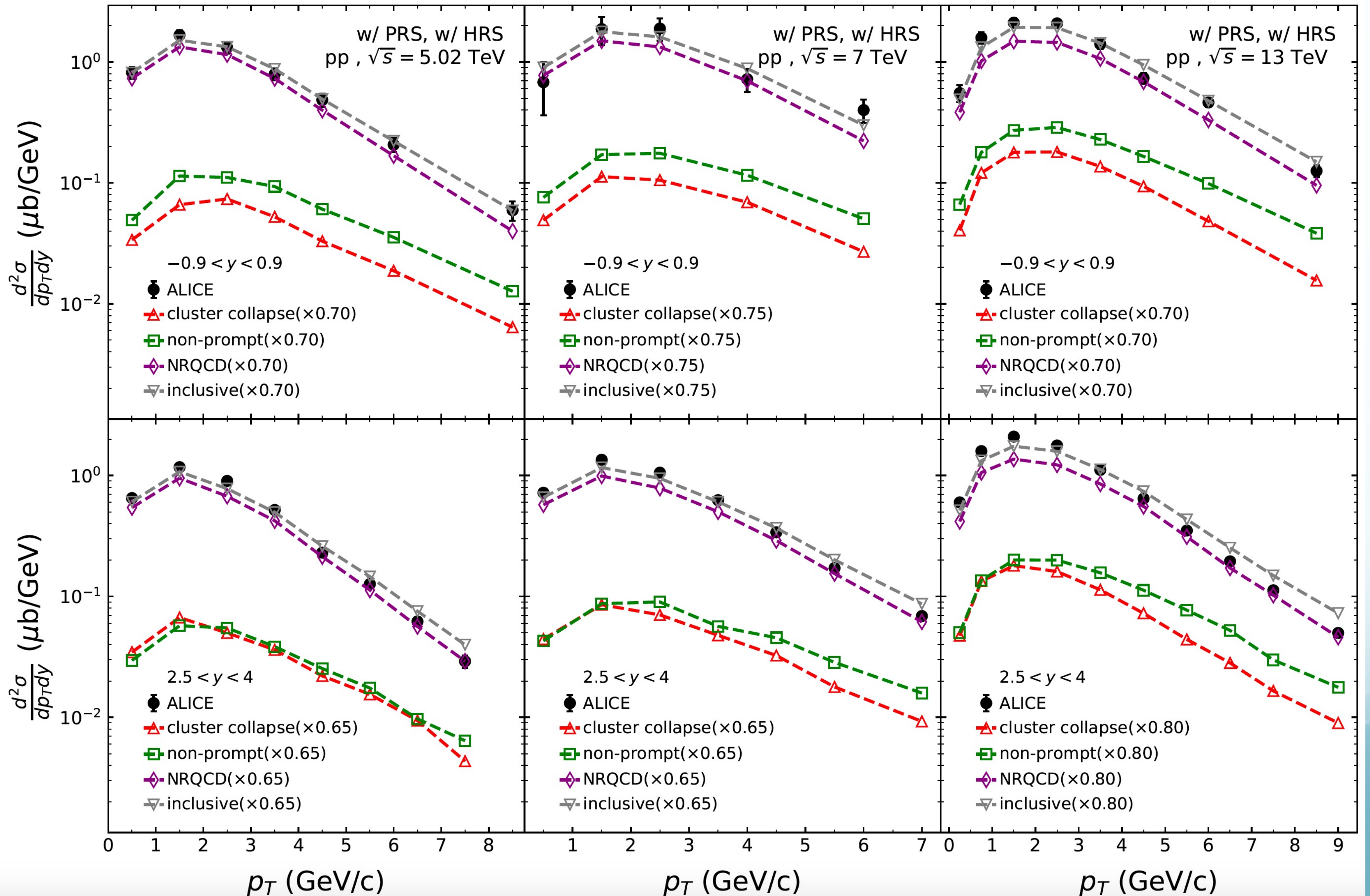
Results and Discussions

- For the J/ψ hadronic rescattering, besides the elastic scattering, so far the following inelastic processes are considered.
- So far, the scattering of J/ψ with partons is not considered in PACIAE4.0 .

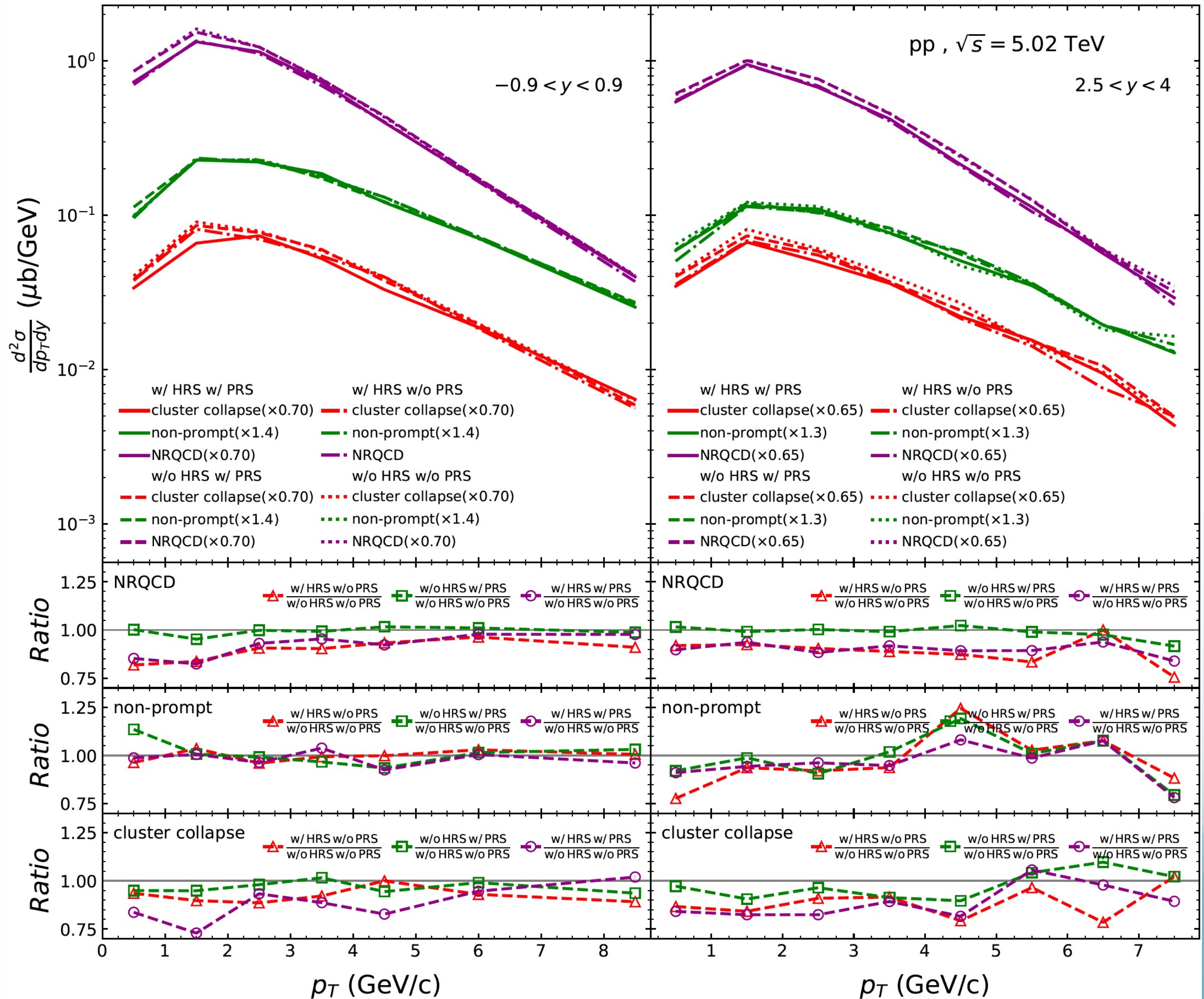
$$
\begin{aligned}
&J/\psi + n \to \Lambda_c^+ + D^-, \quad J/\psi + n \to \Sigma_c^+ + D^-,\\
&J/\psi + n \to \Sigma_c^0 + \bar{D}^0, \quad J/\psi + p \to \Lambda_c^+ + \bar{D}^0,\\
&J/\psi + p \to \Sigma_c^+ + \bar{D}^0, \quad J/\psi + p \to \Sigma_c^{++} + D^-,\\
&J/\psi + \pi^+ \to D^+ + \bar{D}^{*0},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

Phys. Rev. C 58, 2994 (1998).

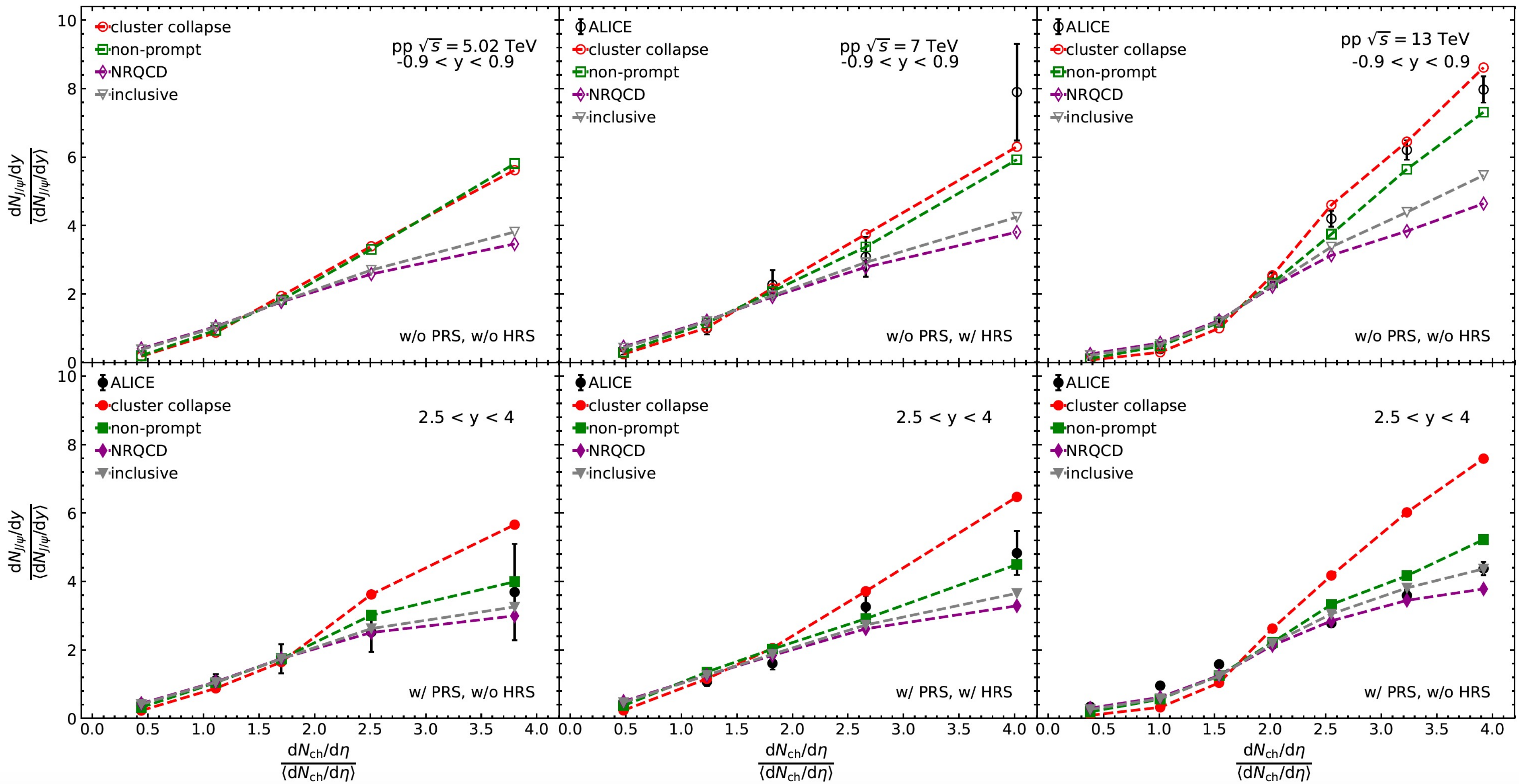
Results and Discussions



Results and Discussions

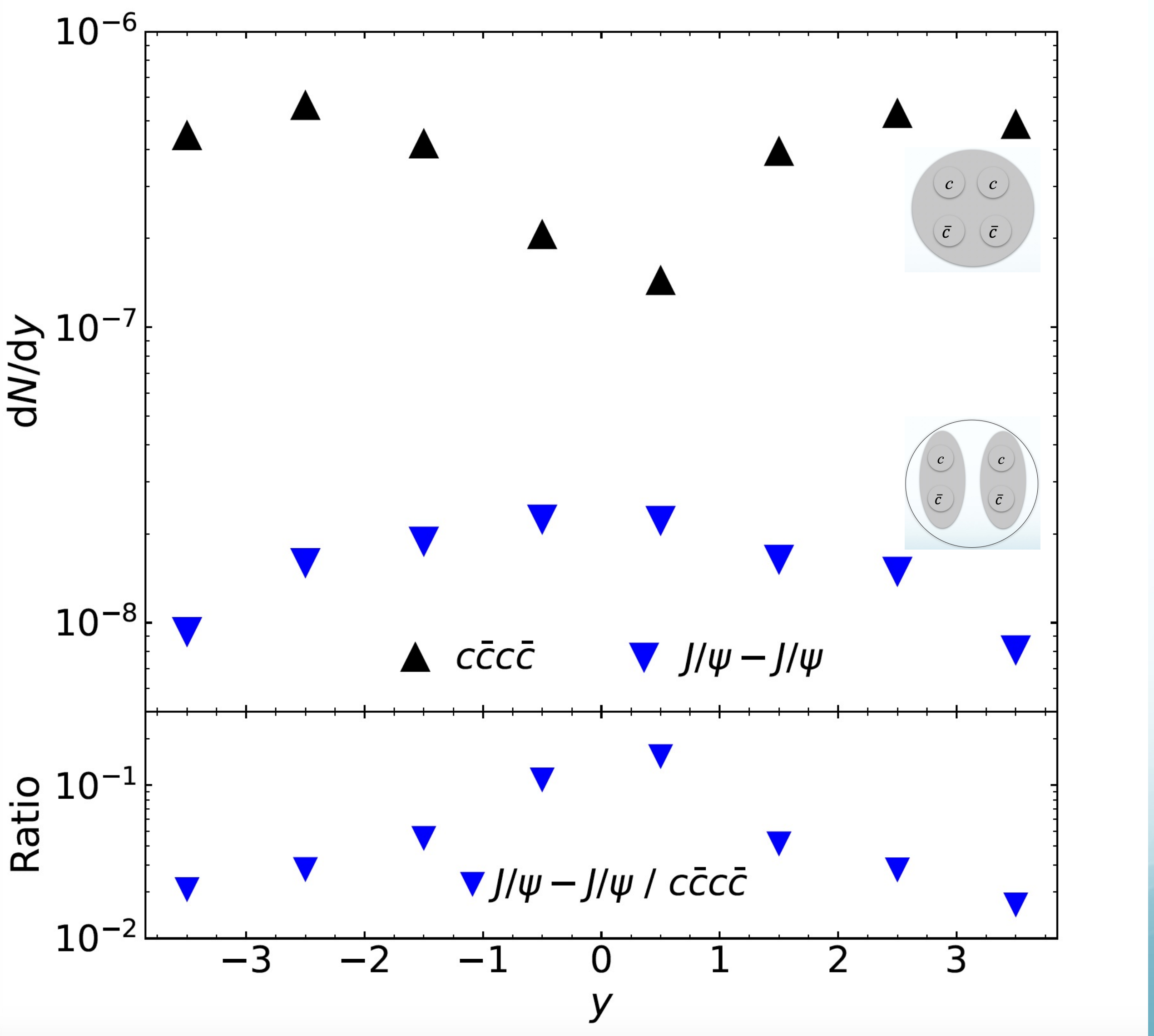


Results and Discussions

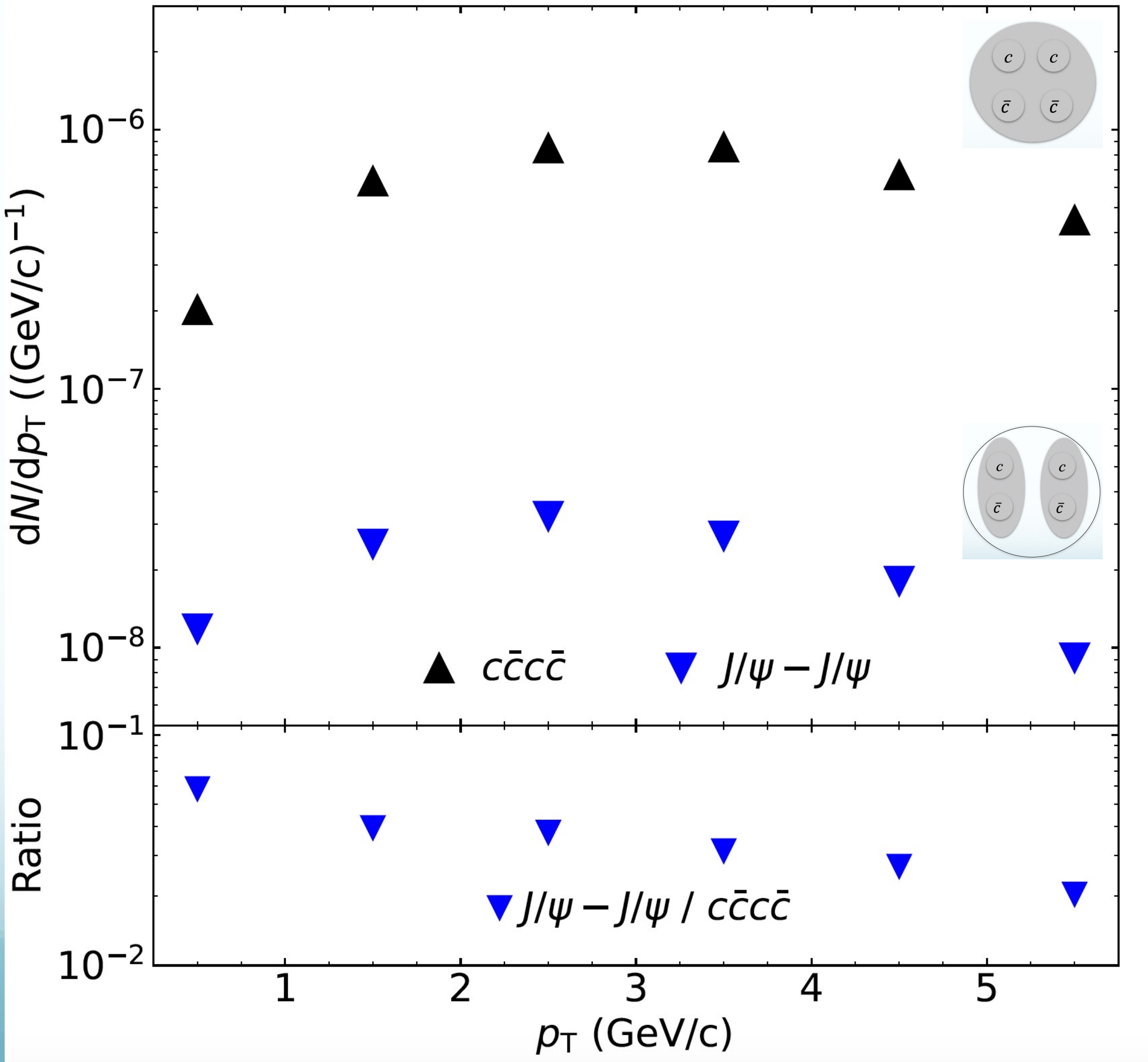


$< dN_{J/\psi} >$ and $< dN_{J/\psi} >$ are the average J/ψ yield and the charged particle multiplicity in minimum bias events.

Results and Discussions



Results and Discussions



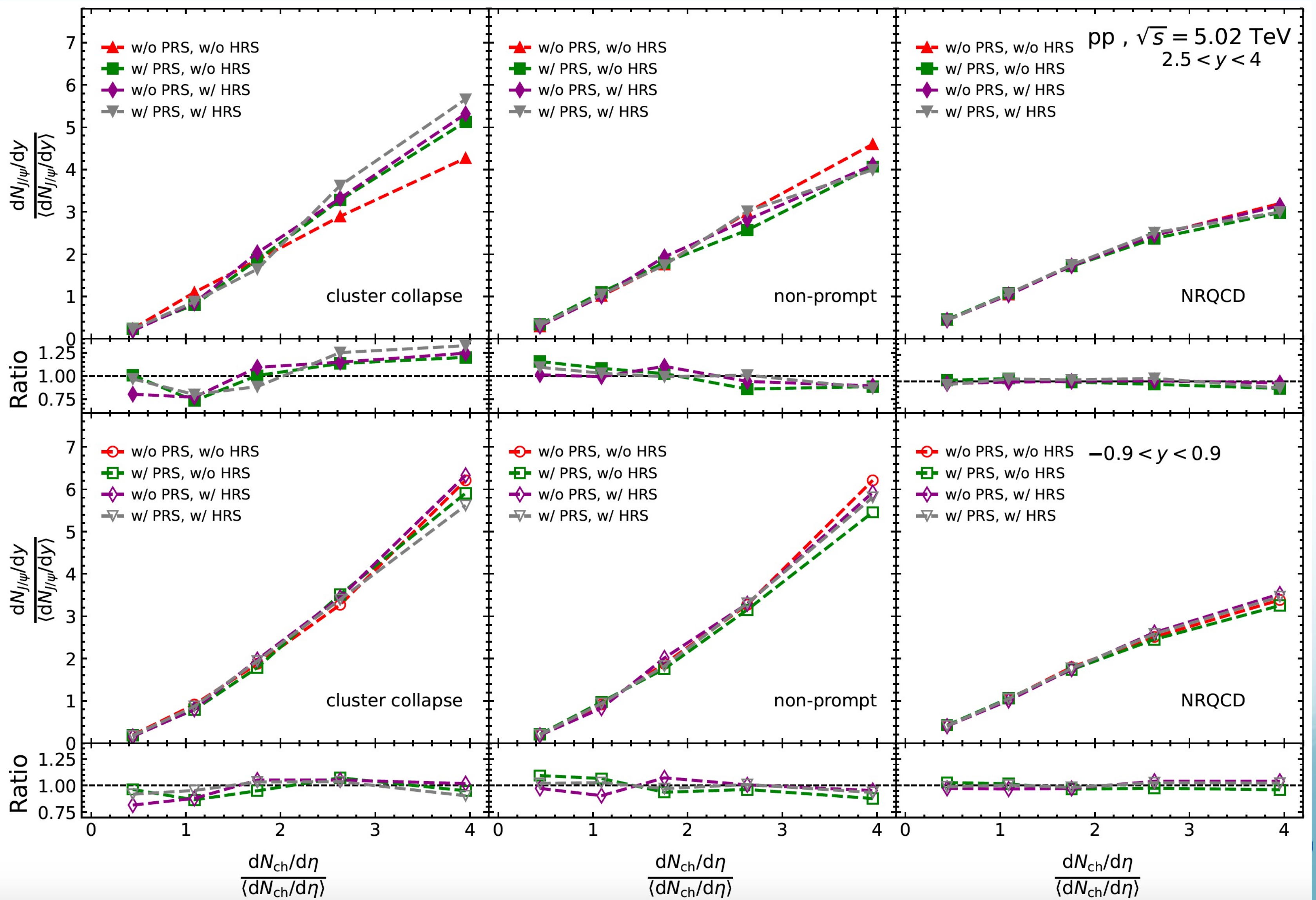
Conclusions

- We have investigated the J/ψ productions in pp collisions at $\sqrt{s}$ = 5.02, 7 and 13 TeV with PACIAE 4.0.
- We have also investigated the multiplicity dependence of J/ψ production in pp collisions at $\sqrt{s}$ = 5.02, 7 and 13 TeV.
- The contributions of the J/ψ productions from the NRQCD, cluster collapse and the weak decay from the B hadrons are analyzed in detail.
- The effect of the partonic and hadronic rescattering effects on the J/ψ production has been presented.
- Discrepancy between tetraquark- and molecule-state in the rapidity and p_T distributions can be served as a criterion for identifying the configuration of X(6900).

Back up

- If MPI were mainly affecting processes involving only light quarks and gluons, as implemented e.g. in PYTHIA 6.4, processes like J/ψ and open heavy flavor production should not be influenced and their rates are expected to be independent of the overall event multiplicity.
- However, at the high center-of-mass energies reached at the LHC, there might be a substantial contribution of MPI on a harder scale which can also induce a correlation between the yield of quarkonia and the total charged particle multiplicity.

Back up


pp , $\sqrt{s}$ = 5.02 TeV
2.5 < y < 4
−0.9 < y < 0.9
w/o PRS, w/o HRS
w/ PRS, w/o HRS
w/o PRS, w/ HRS
w/ PRS, w/ HRS
cluster collapse
non-prompt
NRQCD
$\frac{dN_{J/\psi}/dy}{\langle dN_{J/\psi}/dy \rangle}$
Ratio
$\frac{dN_{ch}/d\eta}{\langle dN_{ch}/d\eta \rangle}$

Back up

$$\frac{dN_{J/\psi}}{< dN_{J/\psi} >} = \frac{N_{J/\psi}^{i}}{N_{J/\psi}^{tot}} \cdot \frac{N_{evt}^{tot}}{N_{evt}^{i}}$$

$N_{J/\psi}^{i}$ and N_{evt}^{i} are the number of J/ψ and number of events in ith multiplicity bin, respectively. $N_{J/\psi}^{tot}$ and N_{evt}^{tot} are the total number of J/ψ produced and total number of minimum bias events, respectively.