



粲偶素和奇特强子的蒙特卡洛模拟探究

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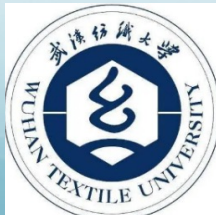
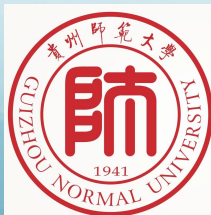
in collaboration with

Qian Yang, An-Ke Lei, Zhi-Lei She, Hua Zheng, Dai-Mei Zhou, Yu-Liang Yan, Ben-Hao Sa

Phys. Rev. C 109, 035201 (2024), Phys. Rev. C 110, 014910 (2024)

Phys. Rev. D 110, 054046 (2024), Phys. Rev. D 112, 014033 (2025)

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中国原子能科学研究院
CHINA INSTITUTE OF ATOMIC ENERGY



Outline

1. J/ψ production
2. Exotic hadrons
3. Summary



J/ψ production

- 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.



J/ψ production

- 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).



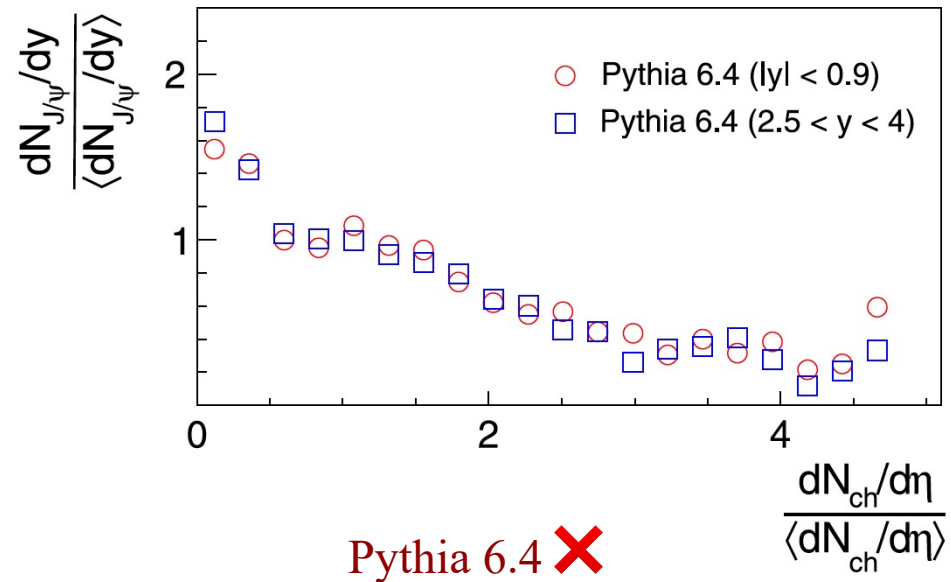
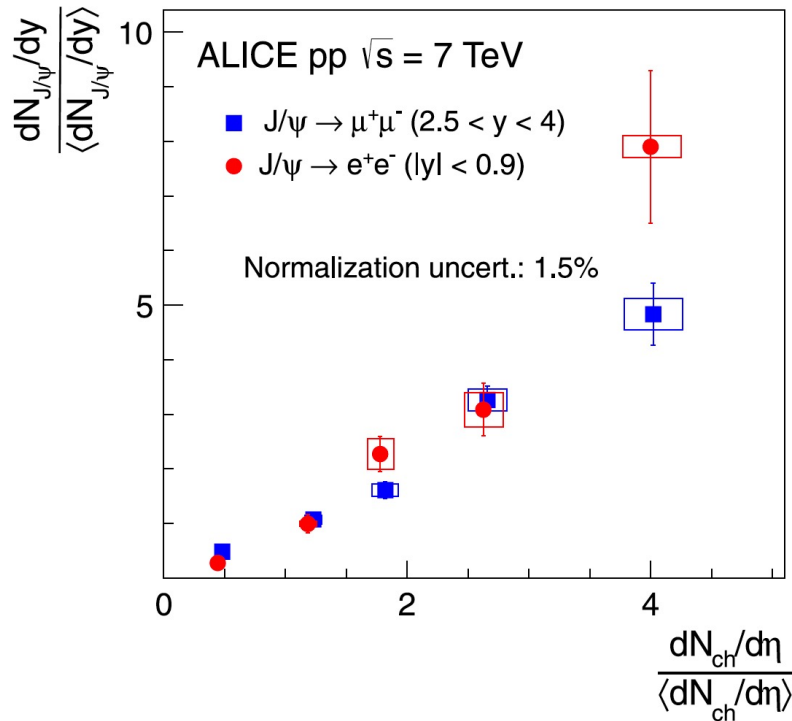
J/ψ production

- In order to investigate the **interplay** between the **hard** and **soft** mechanisms in particle productions, 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 .

J/ψ production

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

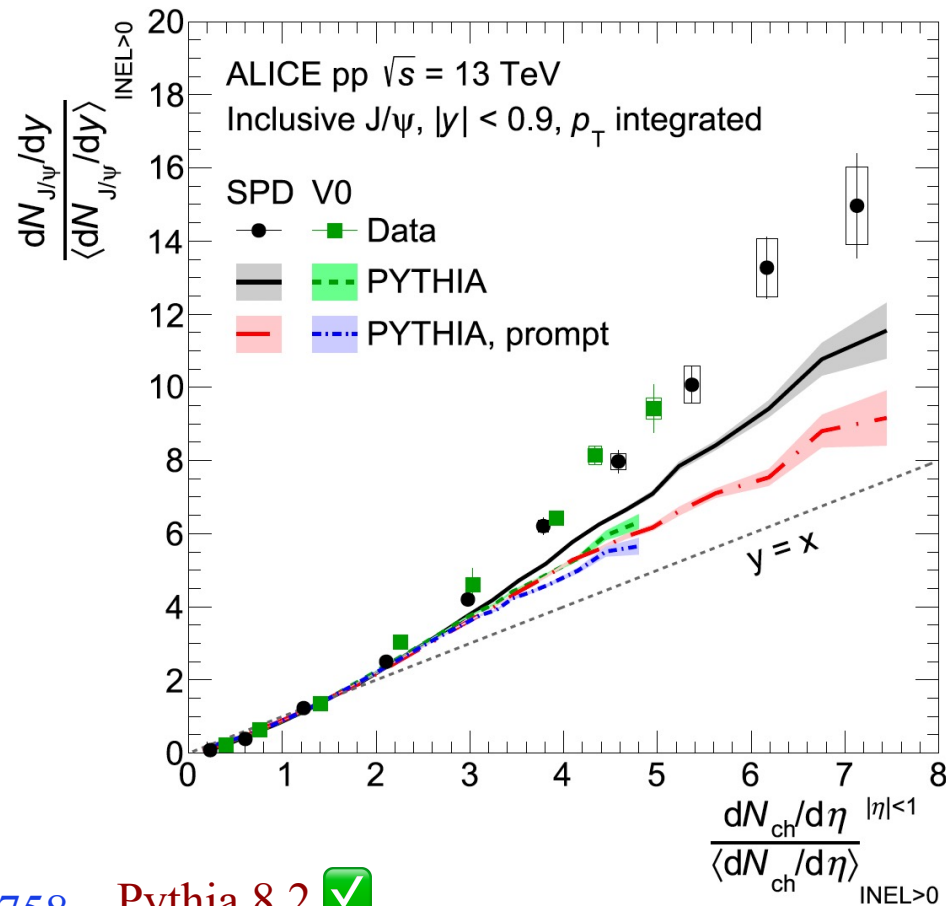
simulations [Phys. Lett. B 712 \(2012\) 165–175](#)



J/ψ production

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

Different treatment of MPI in PYTHIA 6 and PYTHIA 8

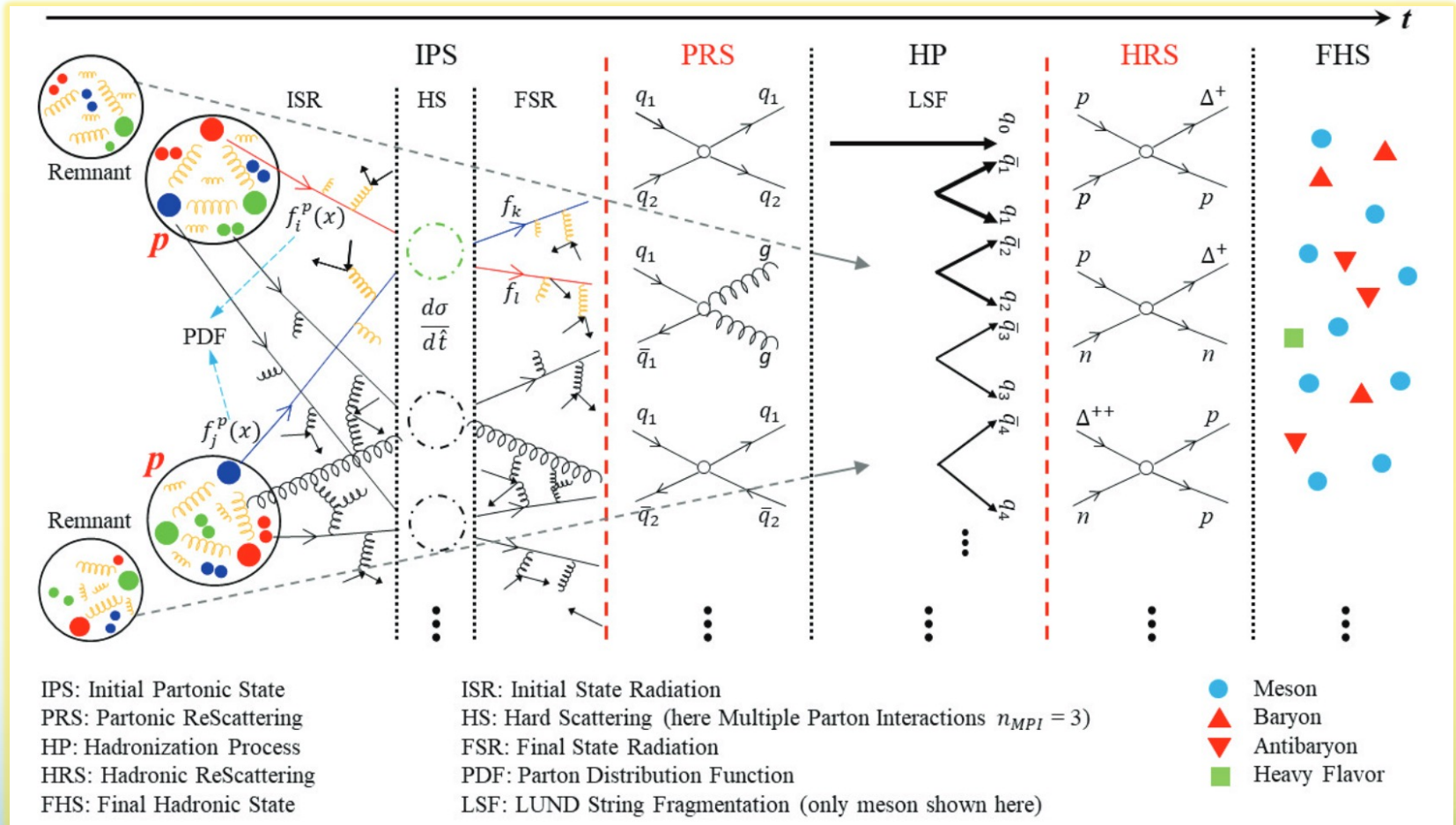




J/ψ production

- In our first 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.

The PACIAE Model



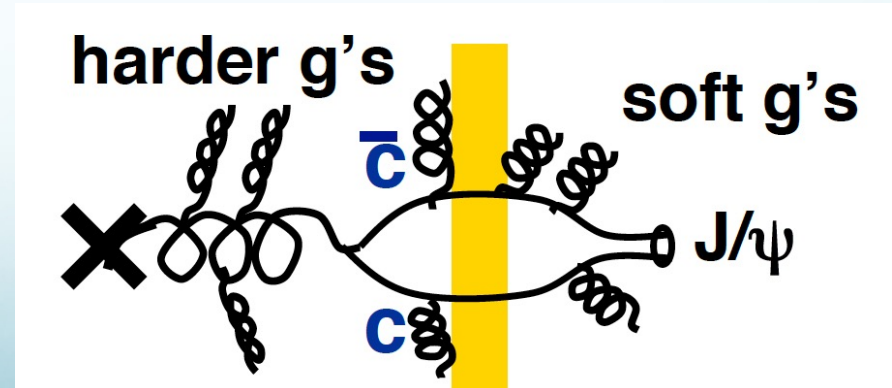
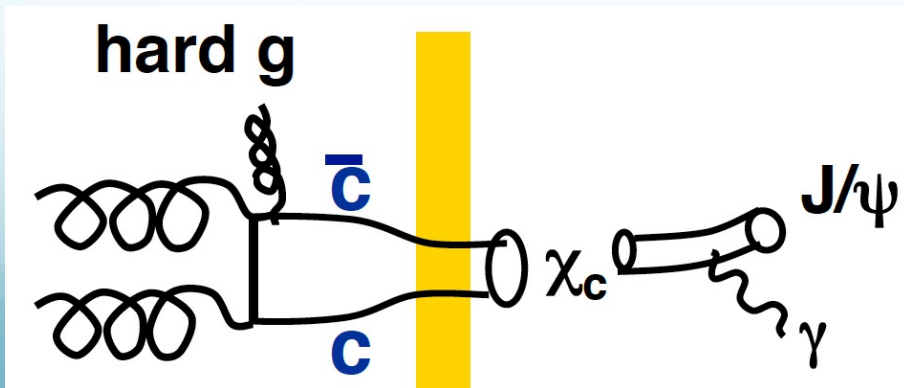
PACIAE4.0 is based on PYTHIA 8.3 but further considers the partonic rescattering before hadronization and the hadronic rescattering after hadronization.

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



J/ψ production

- 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.





J/ψ production

- 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 bind 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.

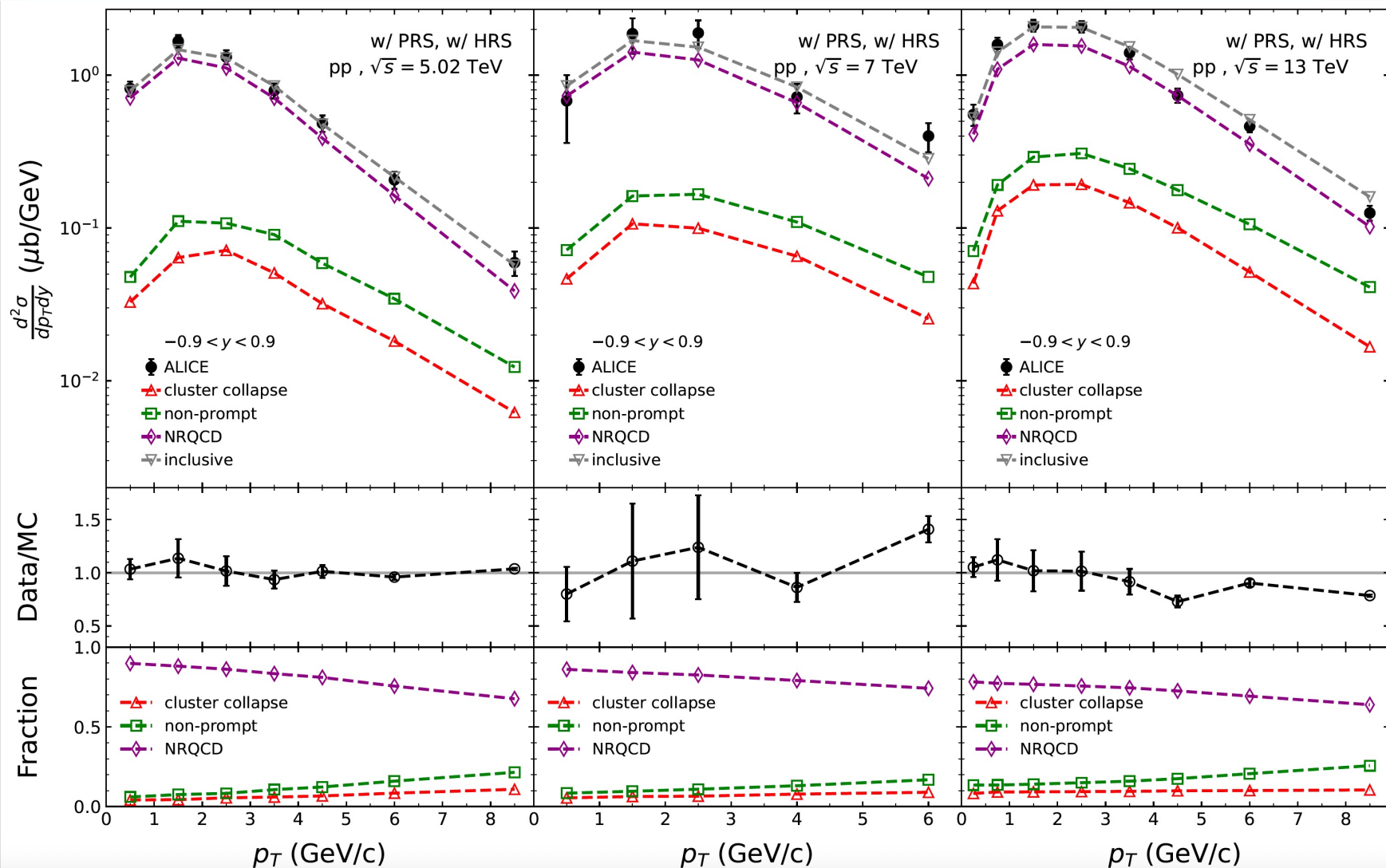


J/ψ production

- 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 .

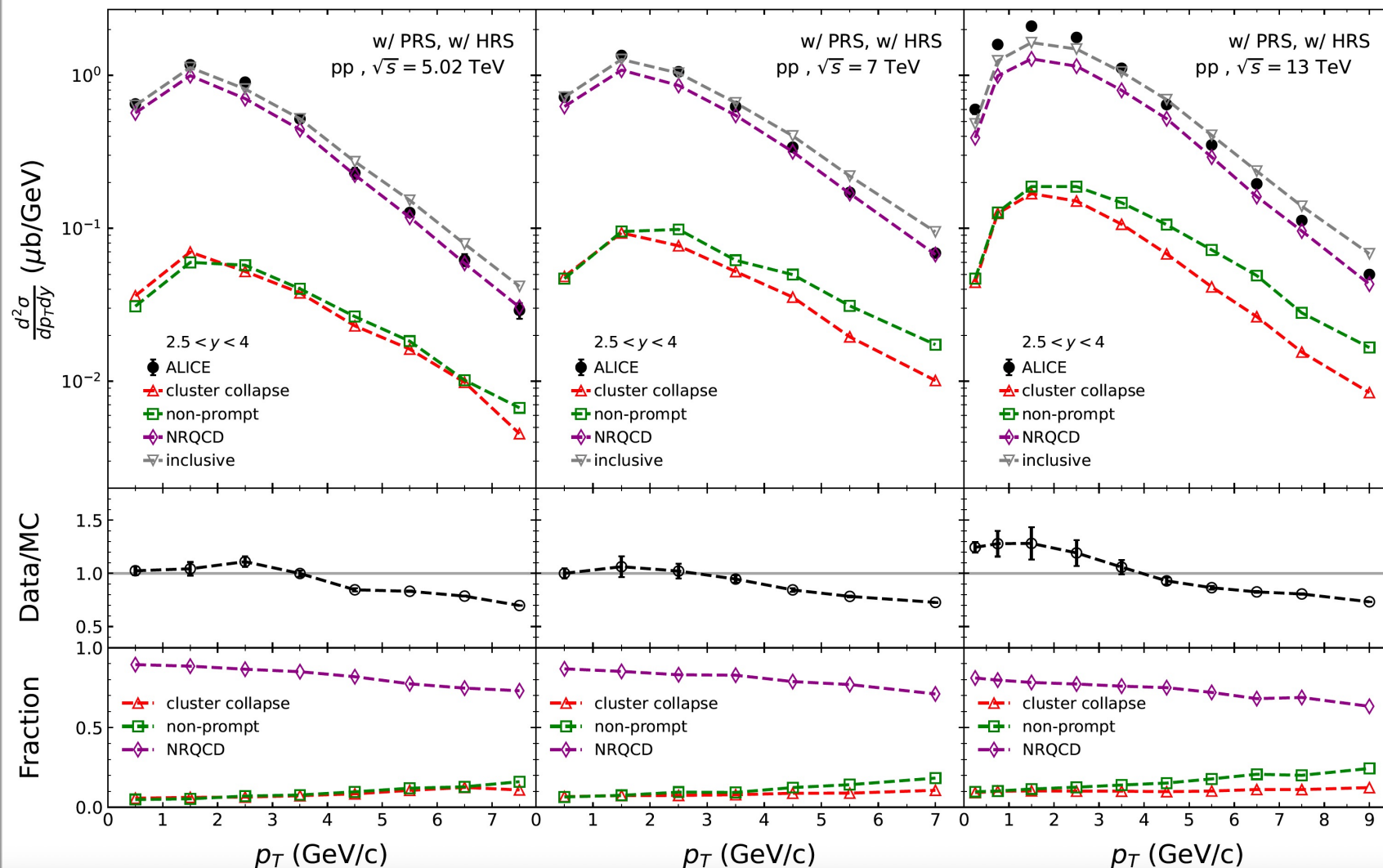
$$\begin{aligned} J/\psi + n &\rightarrow \Lambda_c^+ + D^-, & J/\psi + n &\rightarrow \Sigma_c^+ + D^-, \\ J/\psi + n &\rightarrow \Sigma_c^0 + \bar{D}^0, & J/\psi + p &\rightarrow \Lambda_c^+ + \bar{D}^0, \\ J/\psi + p &\rightarrow \Sigma_c^+ + \bar{D}^0, & J/\psi + p &\rightarrow \Sigma_c^{++} + D^-,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

J/ψ production

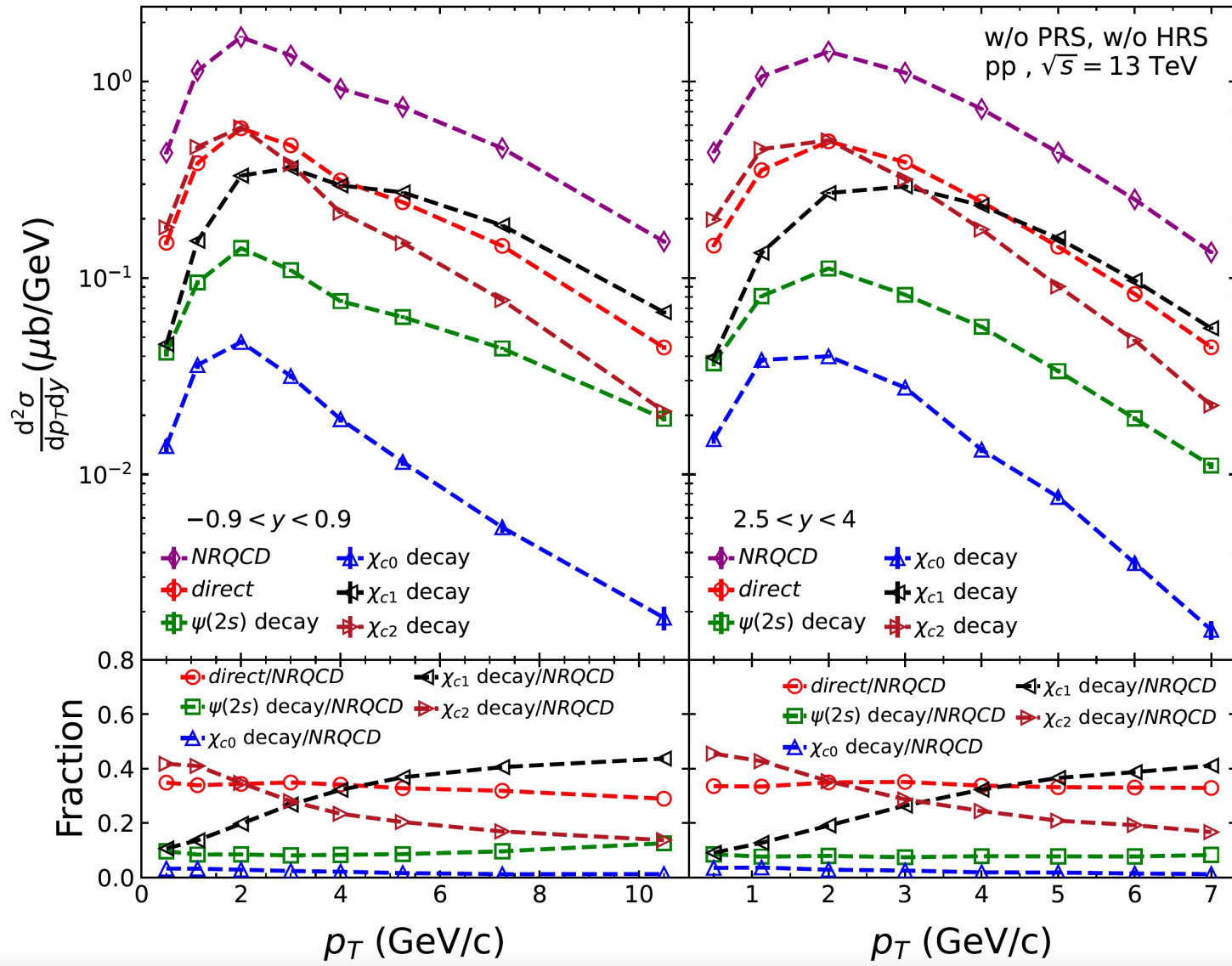




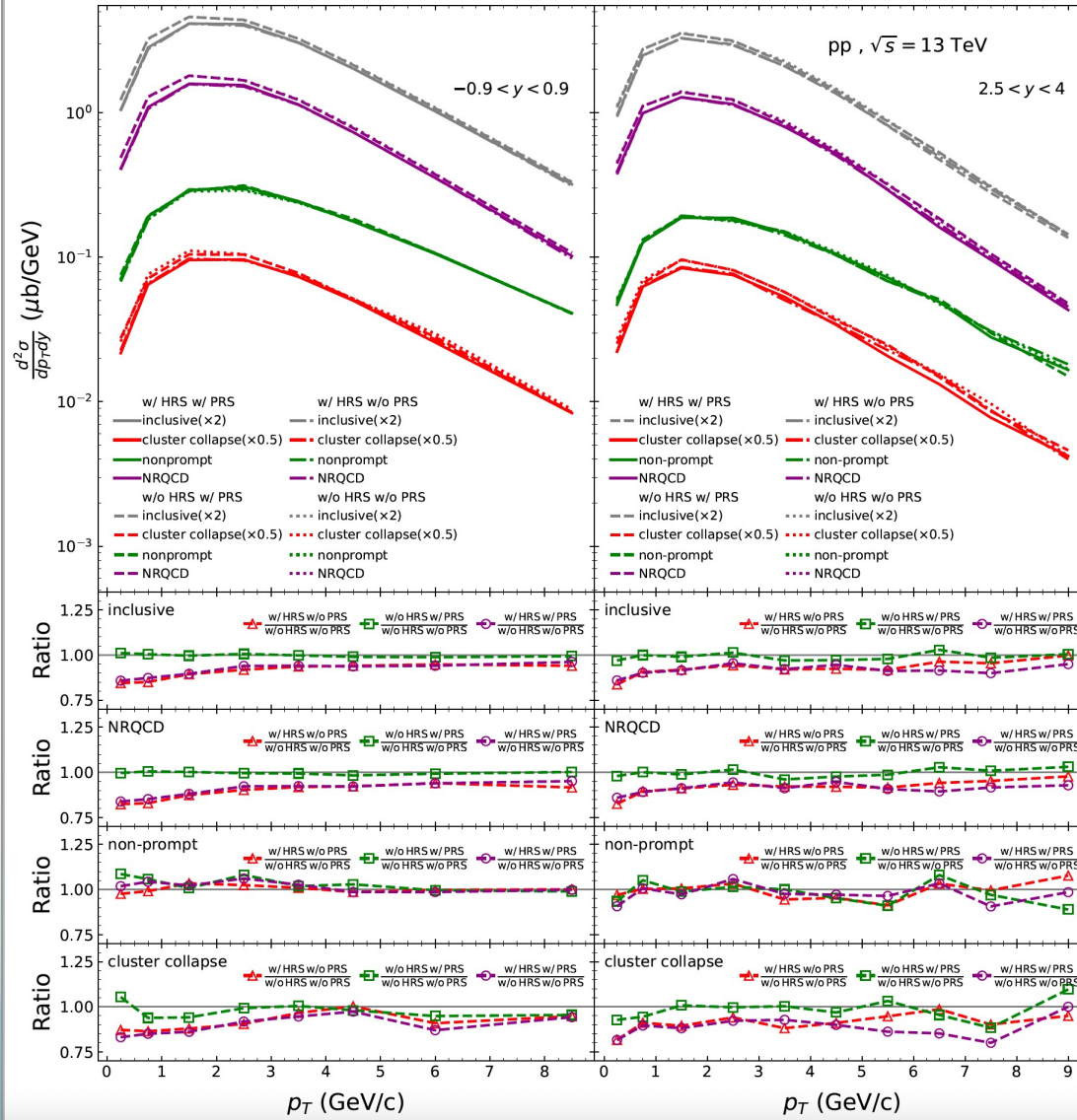
J/ψ production



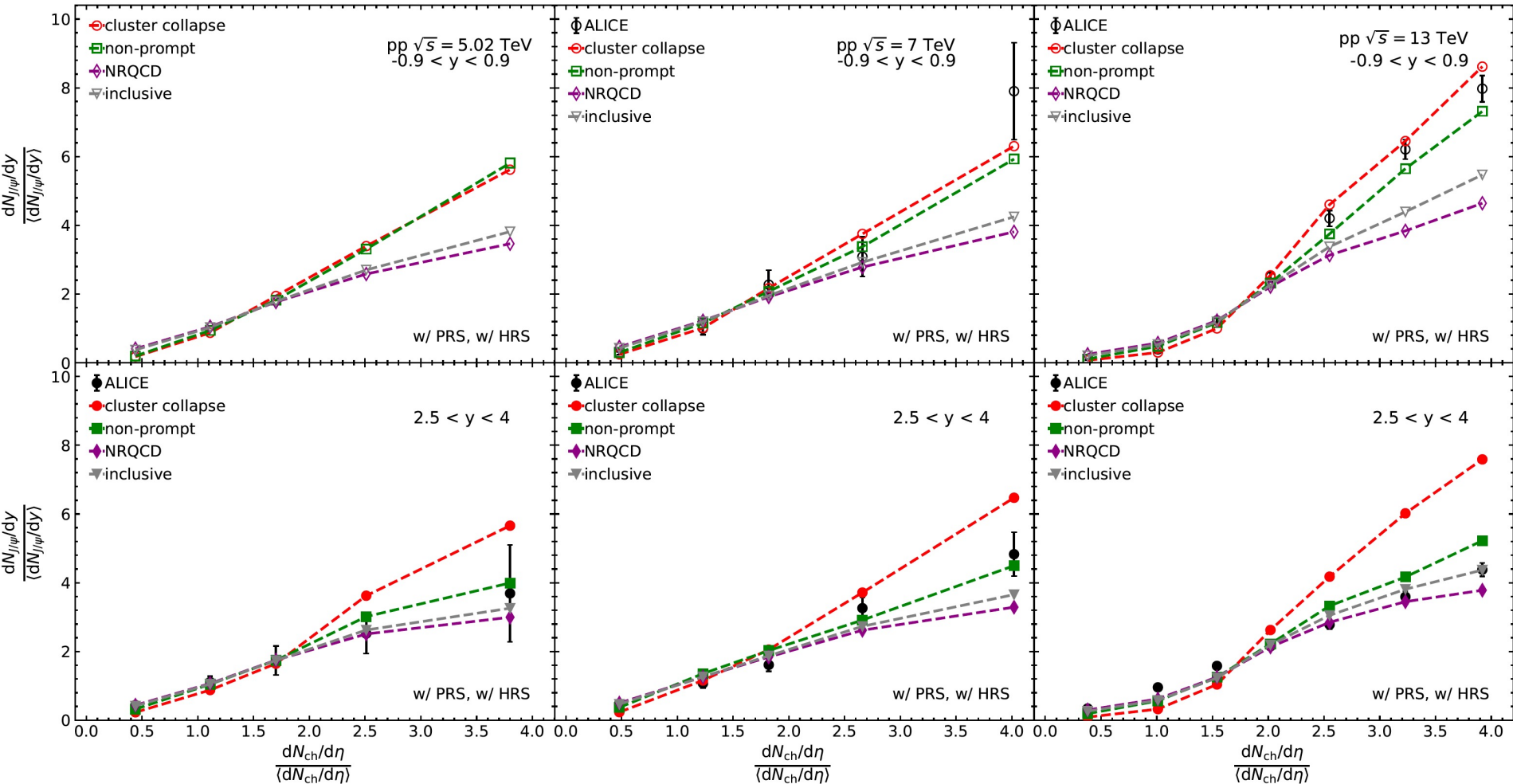
J/ψ production



J/ψ production



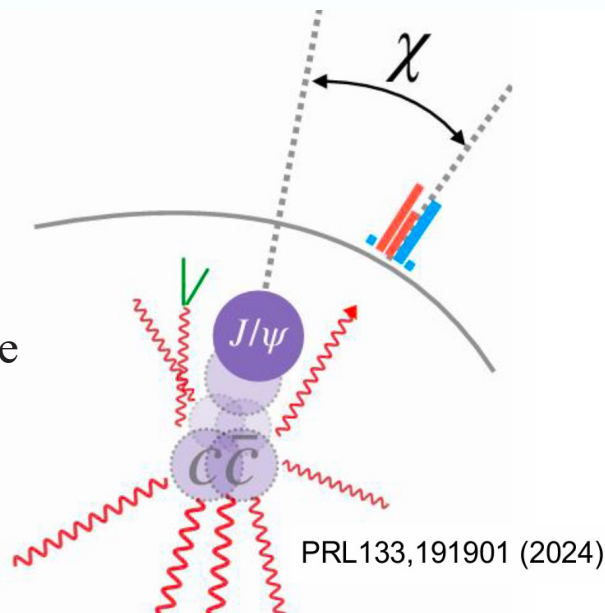
J/ψ production



$\langle dN_{J/\psi} \rangle$ and $\langle dN_{ch}/d\eta \rangle$ are the average J/ψ yield and the charged particle multiplicity in minimum bias events.

J/ψ energy correlator

helicity frame



the total energy carried by particles propagating at the angle χ with respect to J/ψ

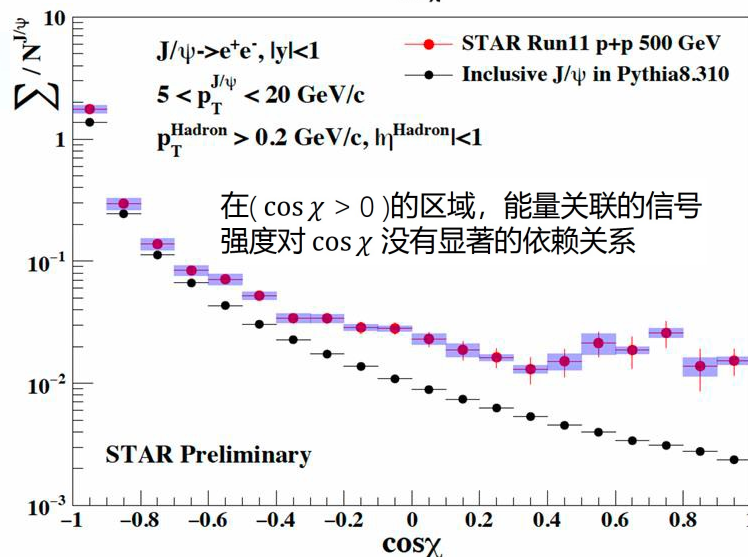
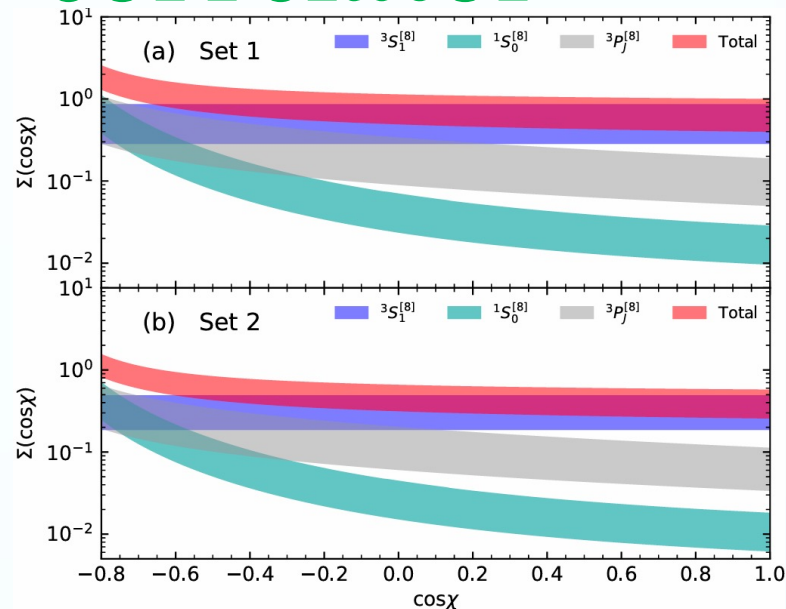
$$\Sigma(\cos \chi) = \int d\sigma \sum_i \frac{E_i}{M} \delta(\cos \chi - \cos \theta_i)$$

is the differential cross section responsible for generating the J/ψ

the J/ψ mass

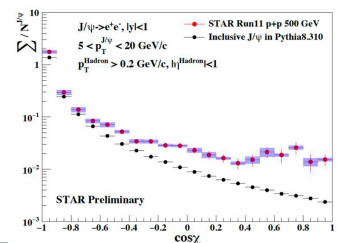
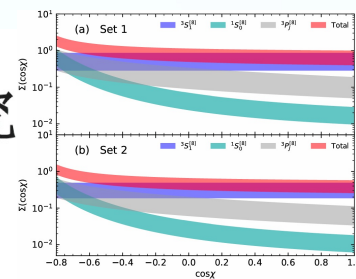
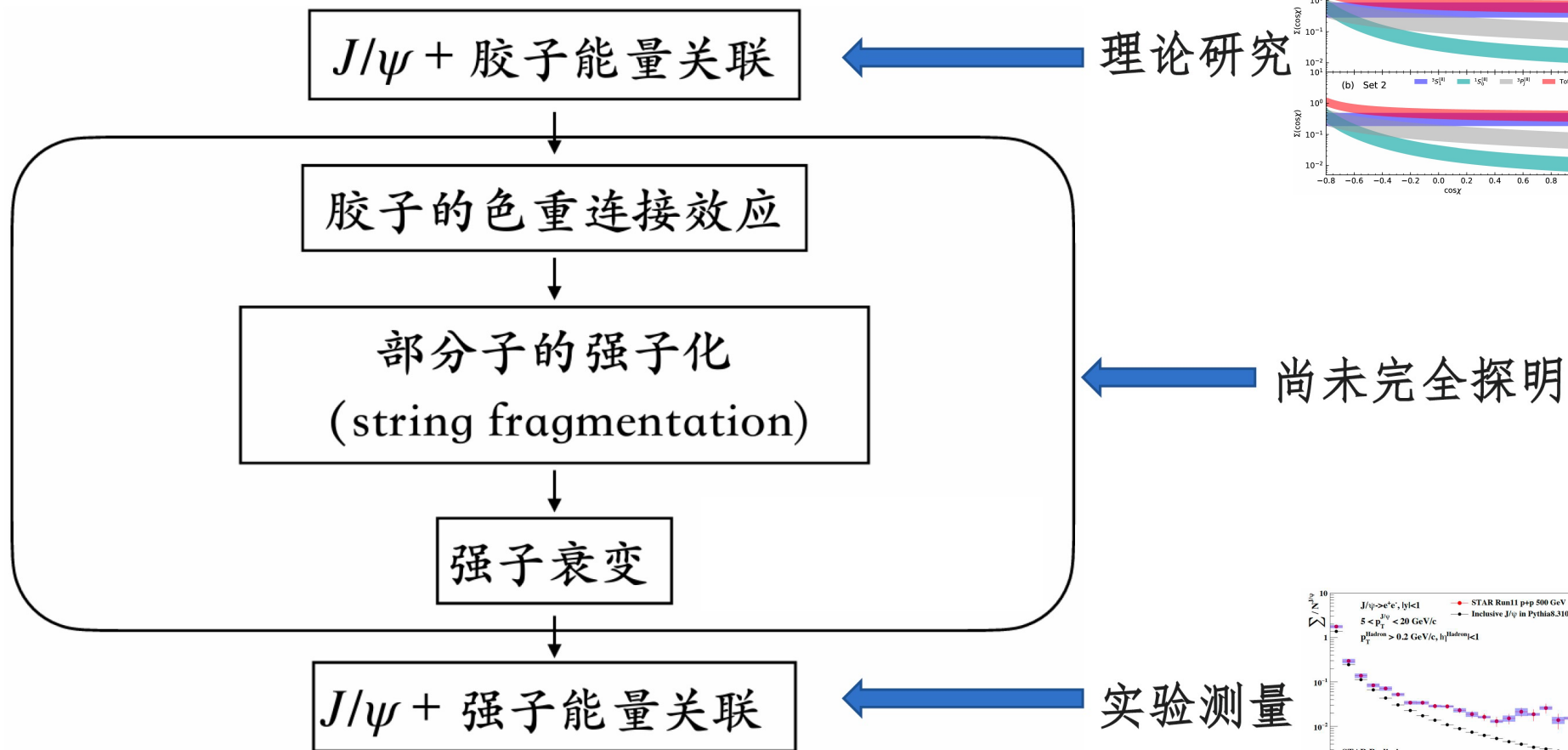
$\cos \chi < 0$ hard radiation P.T process

$\cos \chi > 0$ soft radiation N.P.T process

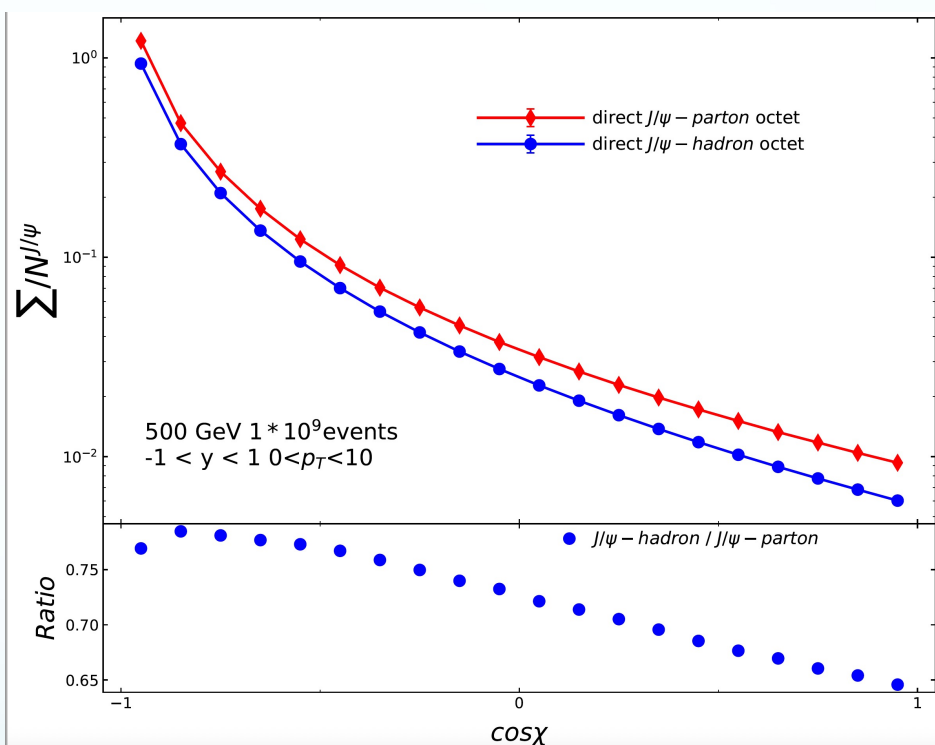
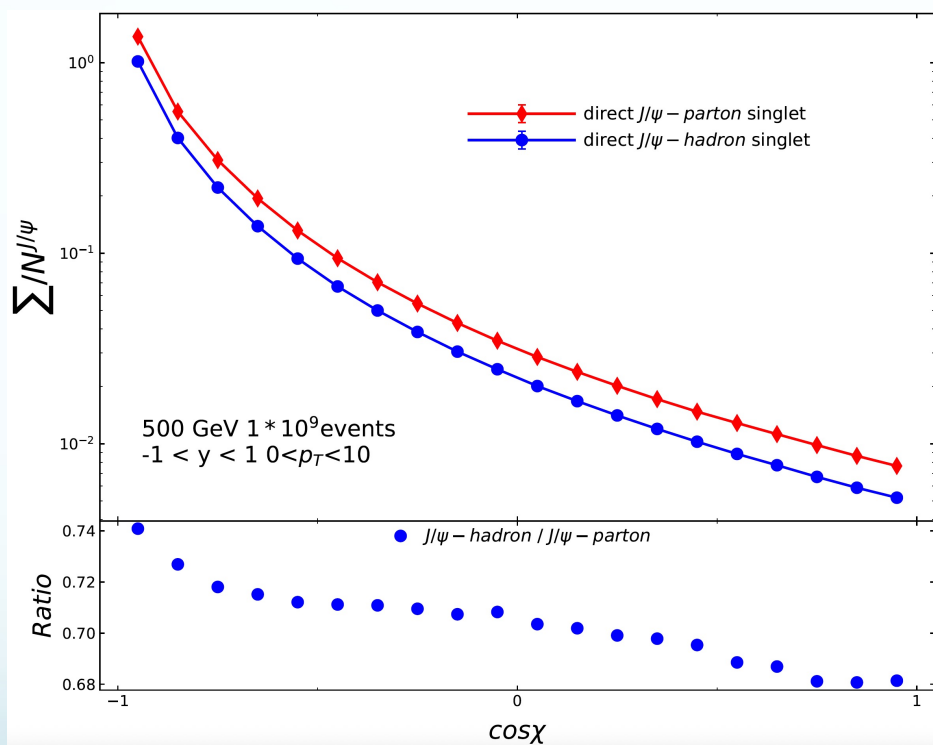




J/ψ energy correlator

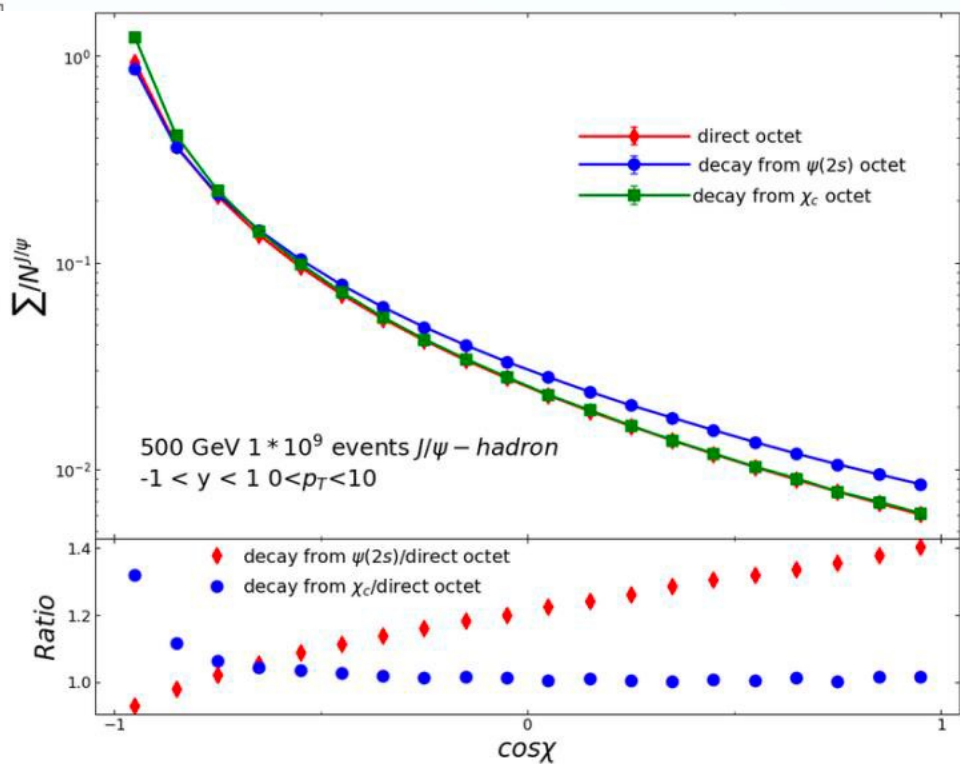
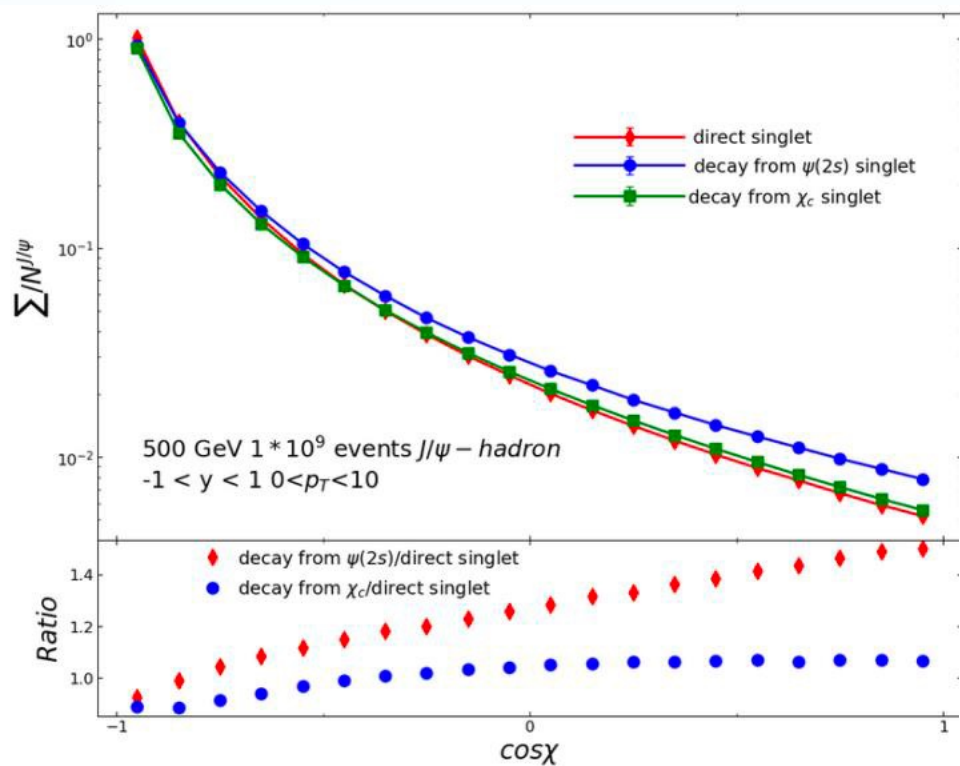


J/ψ energy correlator

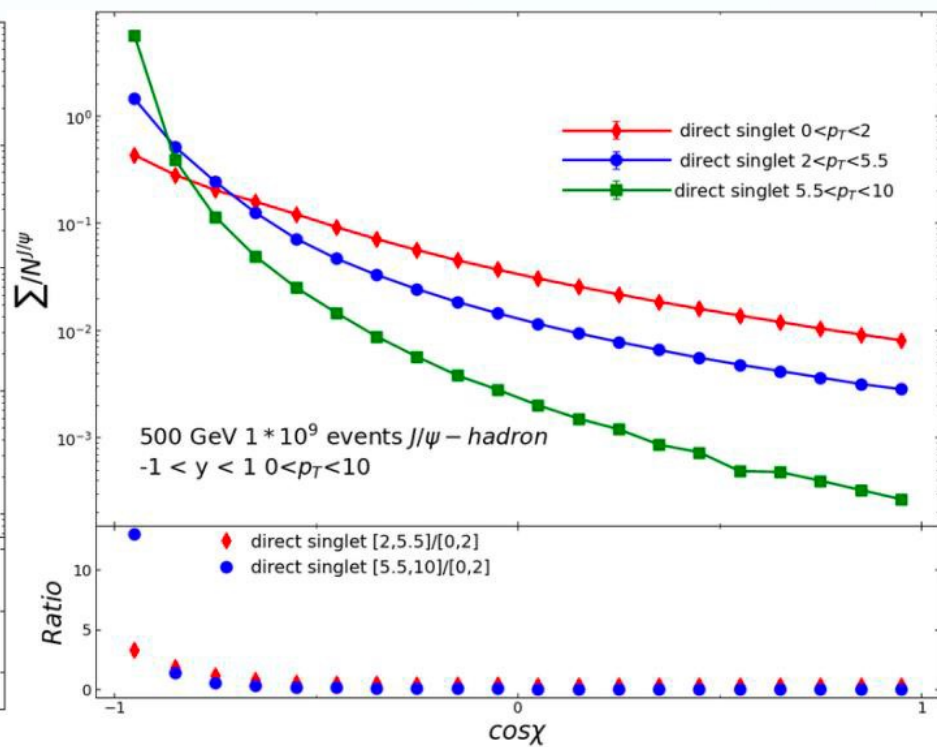
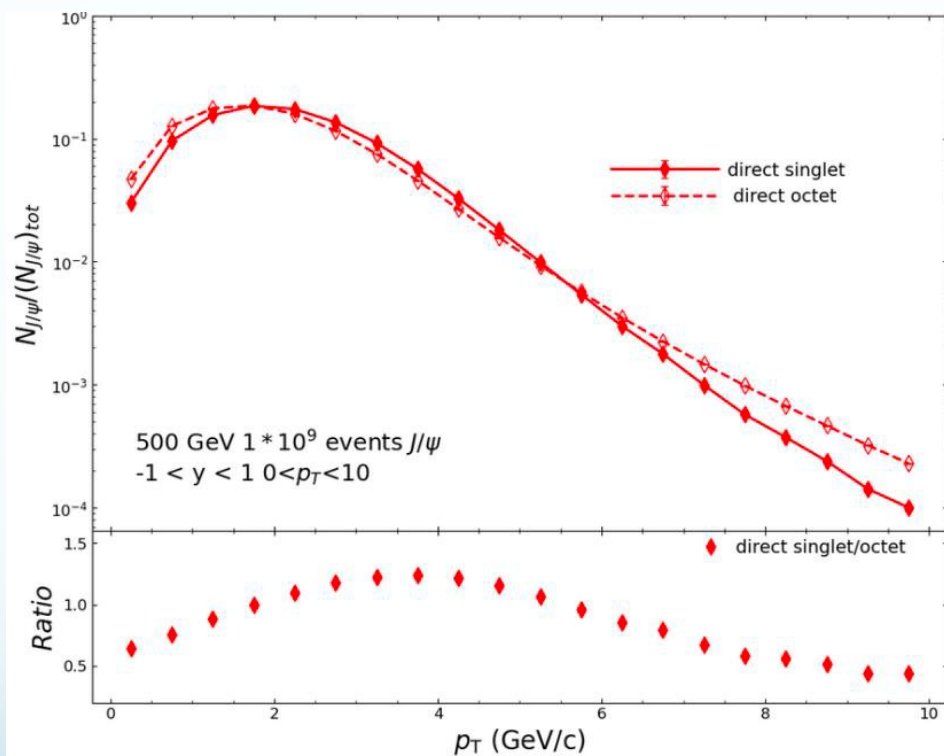


部分子强子化会弱化初始能量关联性

J/ψ energy correlator



J/ψ energy correlator





Exotic hadrons-X(3872)

- The naive **constituent quark model** has been the basic framework within which most of the hadronic states could be understood.

Volume 8, number 3

PHYSICS LETTERS

1 February 1964

Phys. Lett. 8, 214 (1964)

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

California Institute of Technology, Pasadena, California

Received 4 January 1964



Exotic hadrons-X(3872)

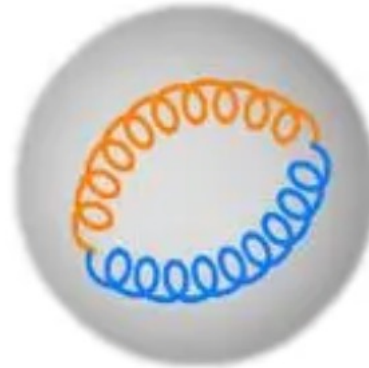
- The non-Abelian property of quantum chromodynamics (QCD) permits the existence of new types of hadrons.



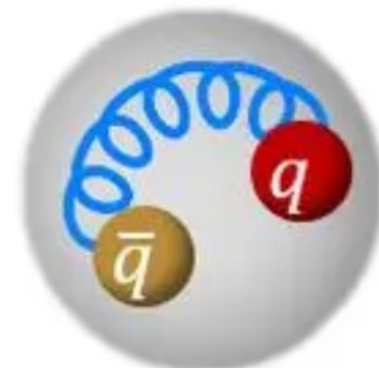
tetraquark



pentaquark



glueball



hybrid state

...

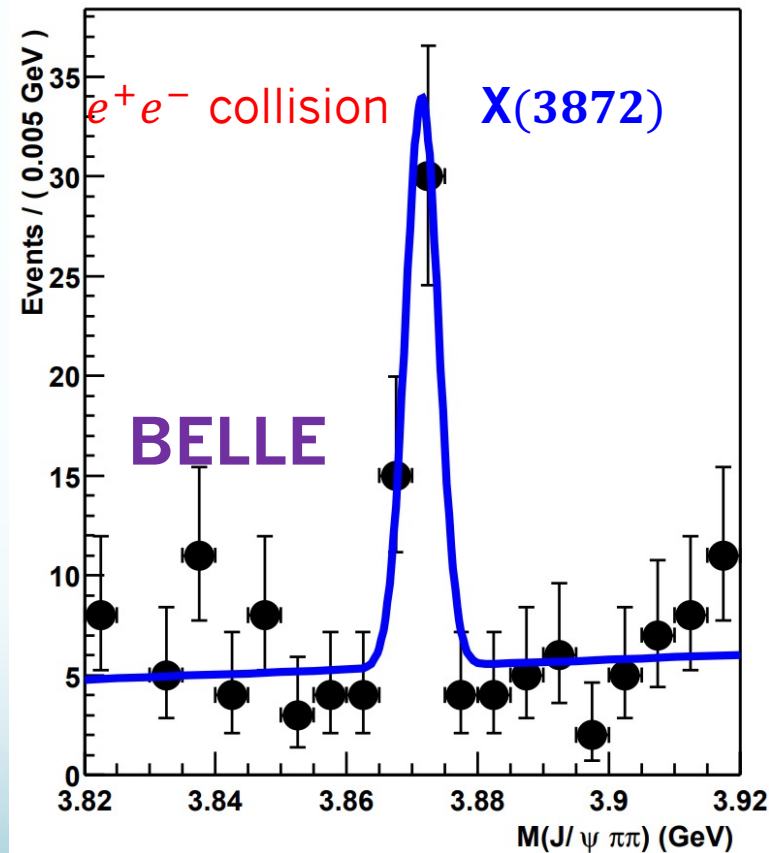
Phys. Rep. 389, 61 (2004); Phys. Rep. 454, 1 (2007); Prog. Part. Nucl. Phys. 63, 74 (2009).



Exotic hadrons-X(3872)

- First exotic candidate X(3872)

PRL 110, 222001 (2013);
JHEP 04, 154 (2013);
JHEP 01, 117 (2017);
PRL 126, 092001 (2021);
PRL 128, 032001 (2022) ...



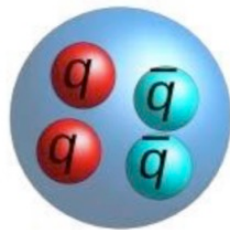
PRL 91, 262001 (2003)

Later, more experiments have confirmed its existence and have measured its properties in both pp and Pb-Pb collisions.



Exotic hadrons-X(3872)

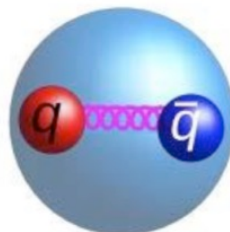
- However, the exact nature of X(3872) is still unclear.
- The loose molecular state and compact tetraquark state are of most interest.



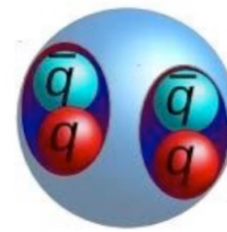
Tetraquark



Charmonium



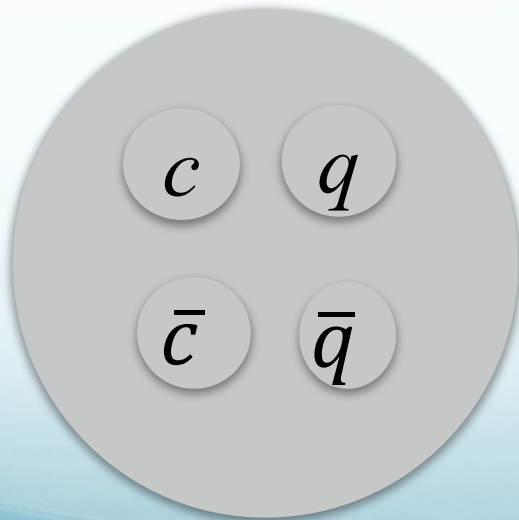
Hybrid



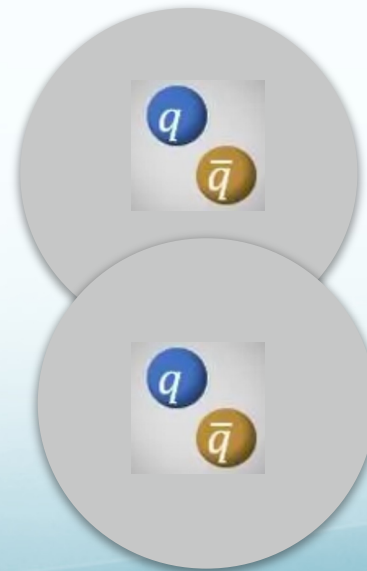
Hadronic molecule

Exotic hadrons-X(3872)

- In our work, we will investigate the X(3872) production in pp collisions at $\sqrt{s} = 2.76$ TeV with PACIAE model.
- Two scenarios are considered: the tetraquark state and the molecular state containing $D\bar{D}^*$.



tetraquark



molecular state



Exotic hadrons-X(3872)

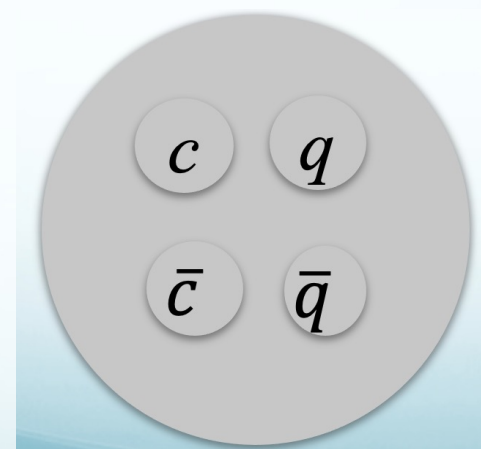
- In the quantum statistical mechanics inspired dynamically constrained phase-space coalescence (DCPC) model, the yield of N -particle cluster in six-dimensional phase space can be estimated by [Phys. Rev. C 85, 024907 \(2012\)](#).

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

- For the $c\bar{c}q\bar{q}$ tetraquark, its yield reads as

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

$$\delta_{1234} = \begin{cases} 1. & \text{if } 1 = c, 2 = \bar{c}, 3 = q, 4 = \bar{q} \\ 0. & m_{X(3872)} - \Delta m < m_{inv} < m_{X(3872)} + \Delta m, R \leq 1fm \\ & \text{otherwise} \end{cases}$$



$$\Delta m = \frac{\Gamma}{2} = 1.95 \text{ MeV}/c^2, R \text{ is the radius of the cluster.}$$



Exotic hadrons-X(3872)

- 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 $D\bar{D}^*$ molecular state, its yield reads

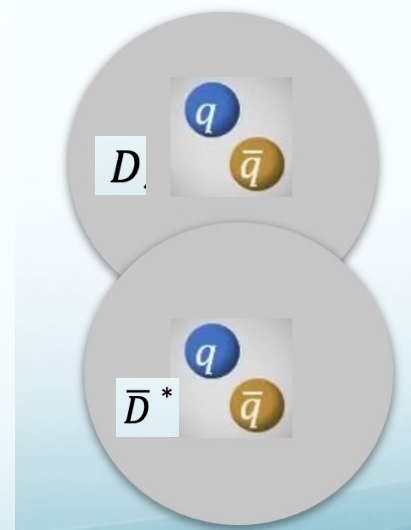
as

$$Y_{molecule} = \int \cdots \int \delta_{12} \frac{d\vec{q}_1 d\vec{p}_1 d\vec{q}_2 d\vec{p}_2}{h^6}$$

$$\delta_{12} = \begin{cases} 1. & \text{if } 1 = D, 2 = \bar{D}^* \\ 0. & \text{otherwise} \end{cases}$$

$m_{X(3872)} - \Delta m < m_{inv} < m_{X(3872)} - \Delta m, 1 \leq R \leq 2fm$

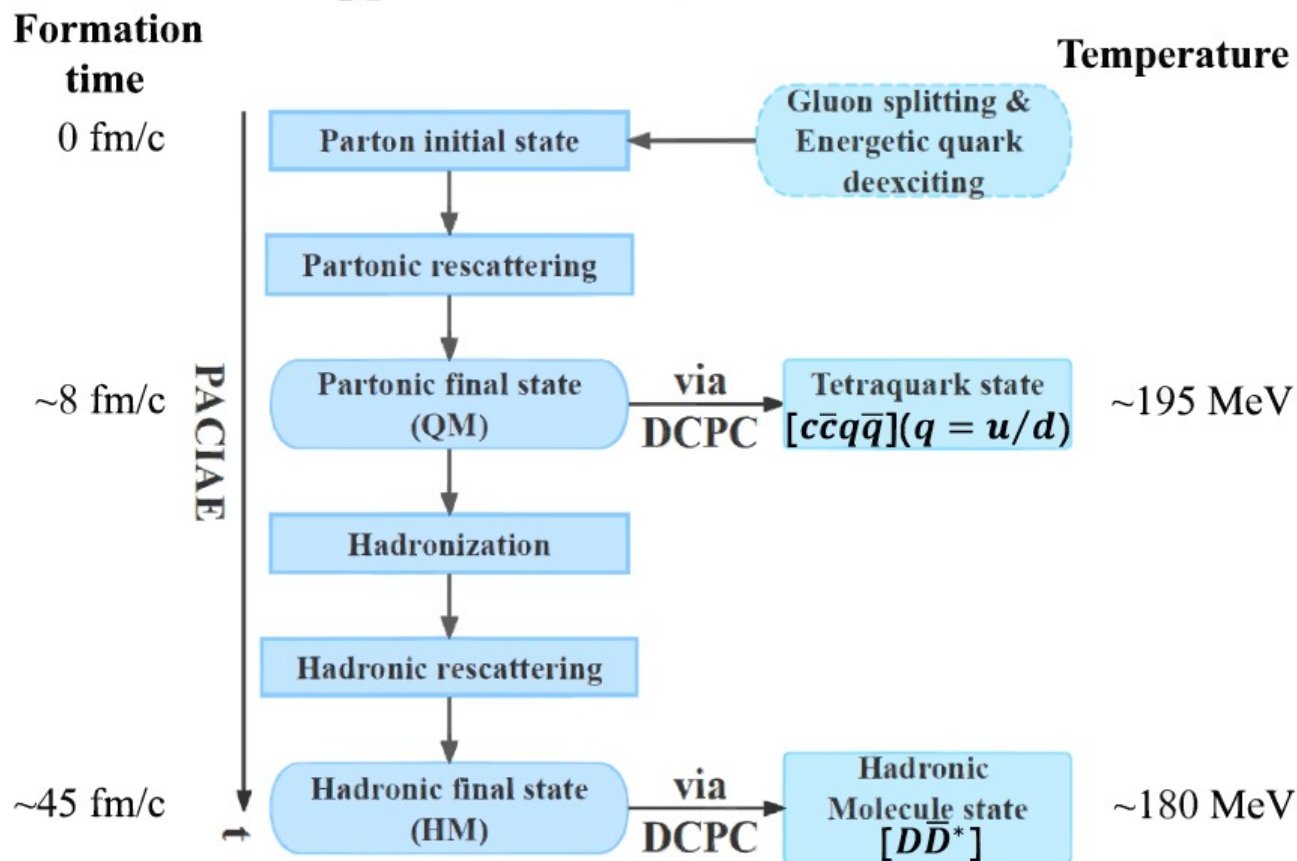
$$\Delta m = \frac{\Gamma}{2} = 1.95 \text{ MeV}/c^2, R \text{ is the radius of the cluster.}$$



Exotic hadrons-X(3872)

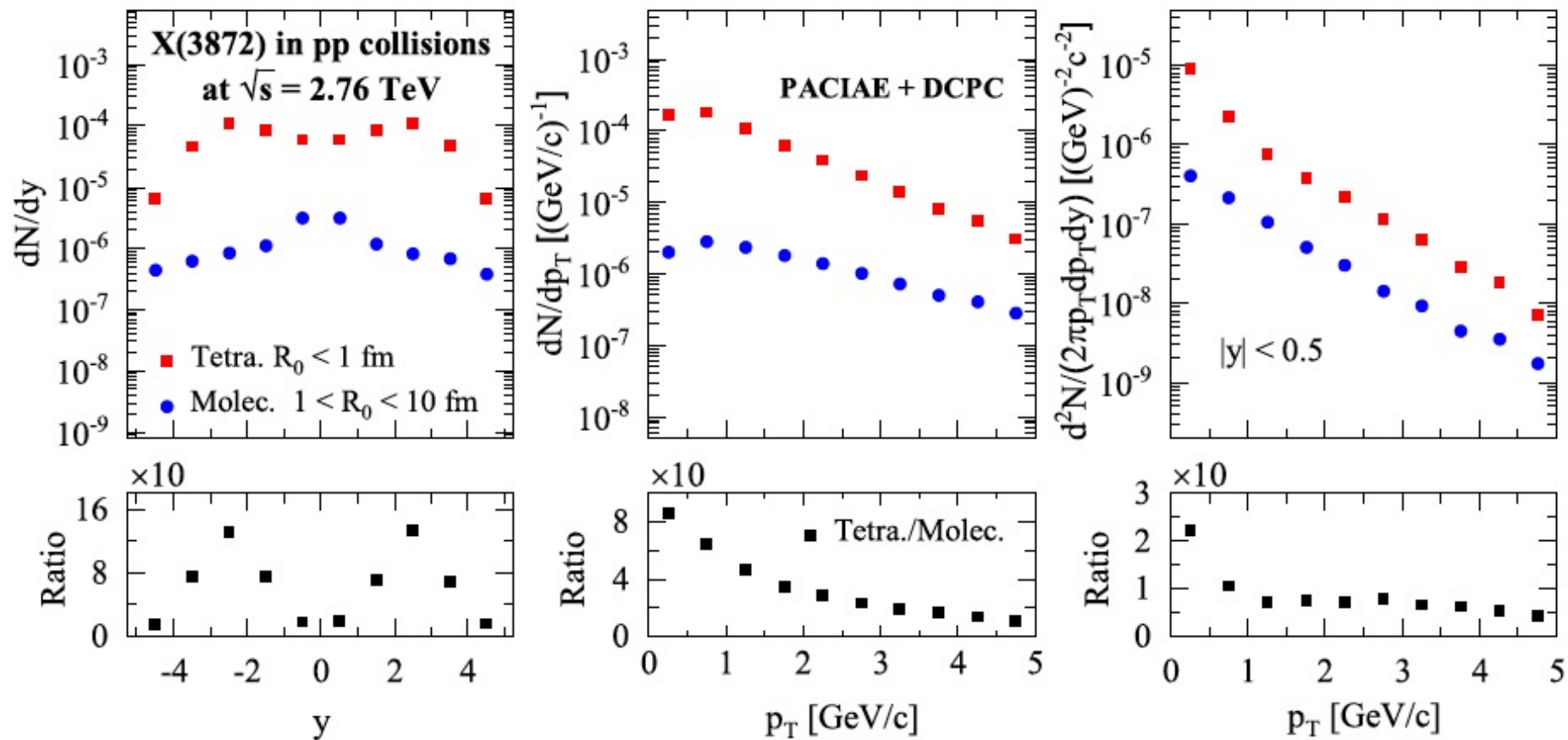
- In this work, tetraquark- and molecule-state of X(3872) are assumed to be coalesced in PFS and HFS, respectively.

pp collisions at $\sqrt{s} = 2.76$ TeV



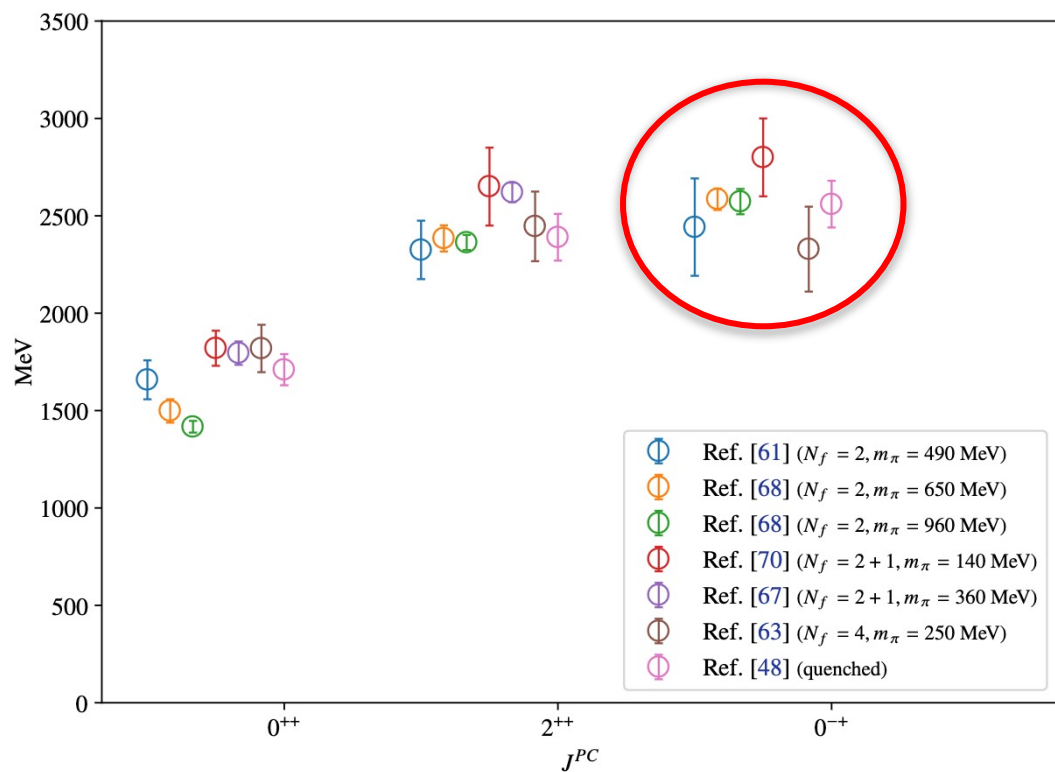
Exotic hadrons-X(3872)

Phys. Rev. C 110, 014910 (2024)





Exotic hadrons-X(2370)



Lattice QCD predictions

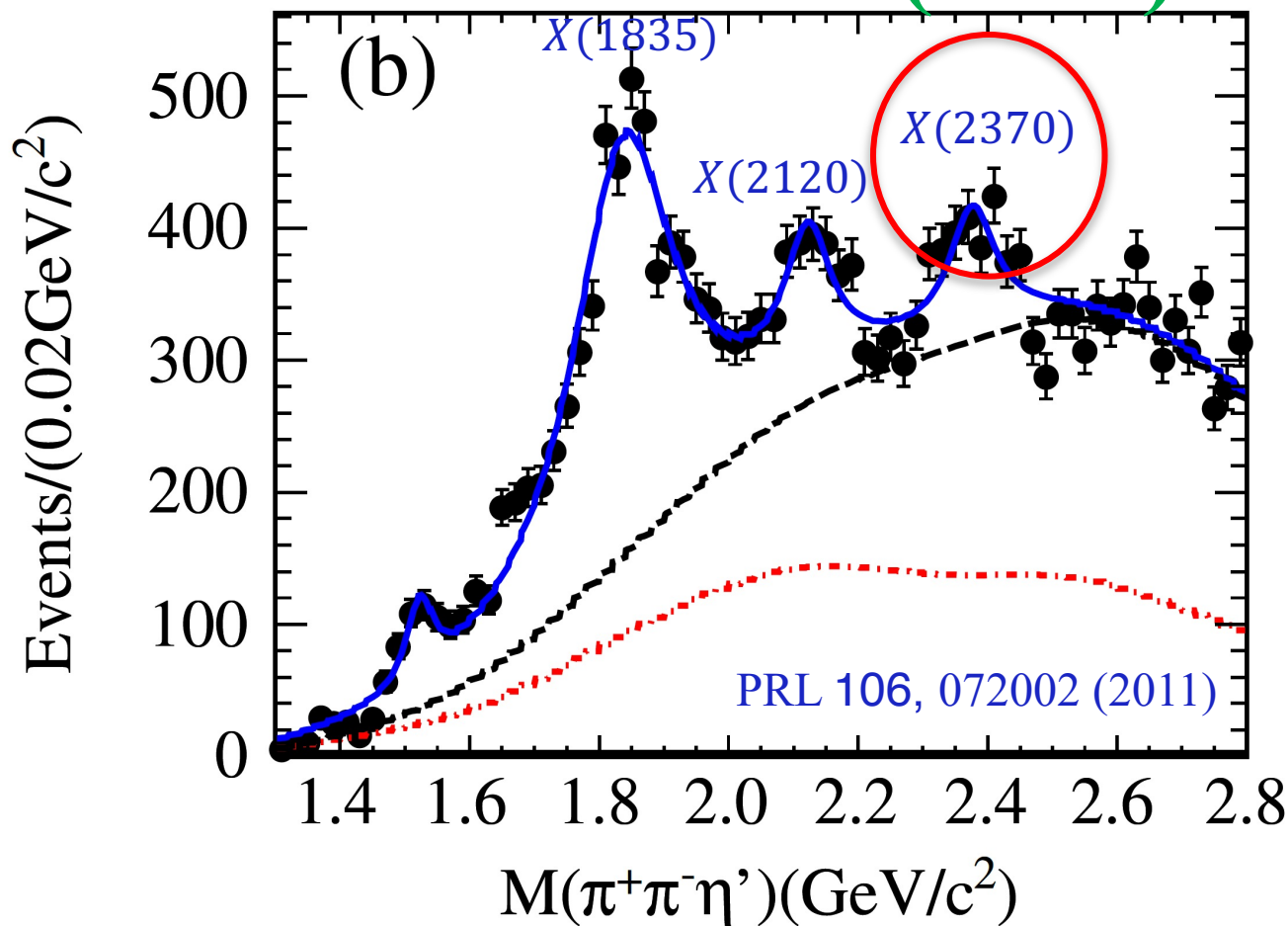
0^{++} ground state: 1.5 - 1.7 GeV/c²

2^{++} ground state: 2.3 - 2.4 GeV/c²

0^{-+} ground state: 2.3 - 2.6 GeV/c²

Phys. Lett. B 309, 378 (1993); Phys. Rev. D 60, 034509 (1999); Phys. Rev. D 73, 014516 (2006); J. High Energy Phys. 10 (2012) 170; Phys. Rev. D 100, 054511 (2019)

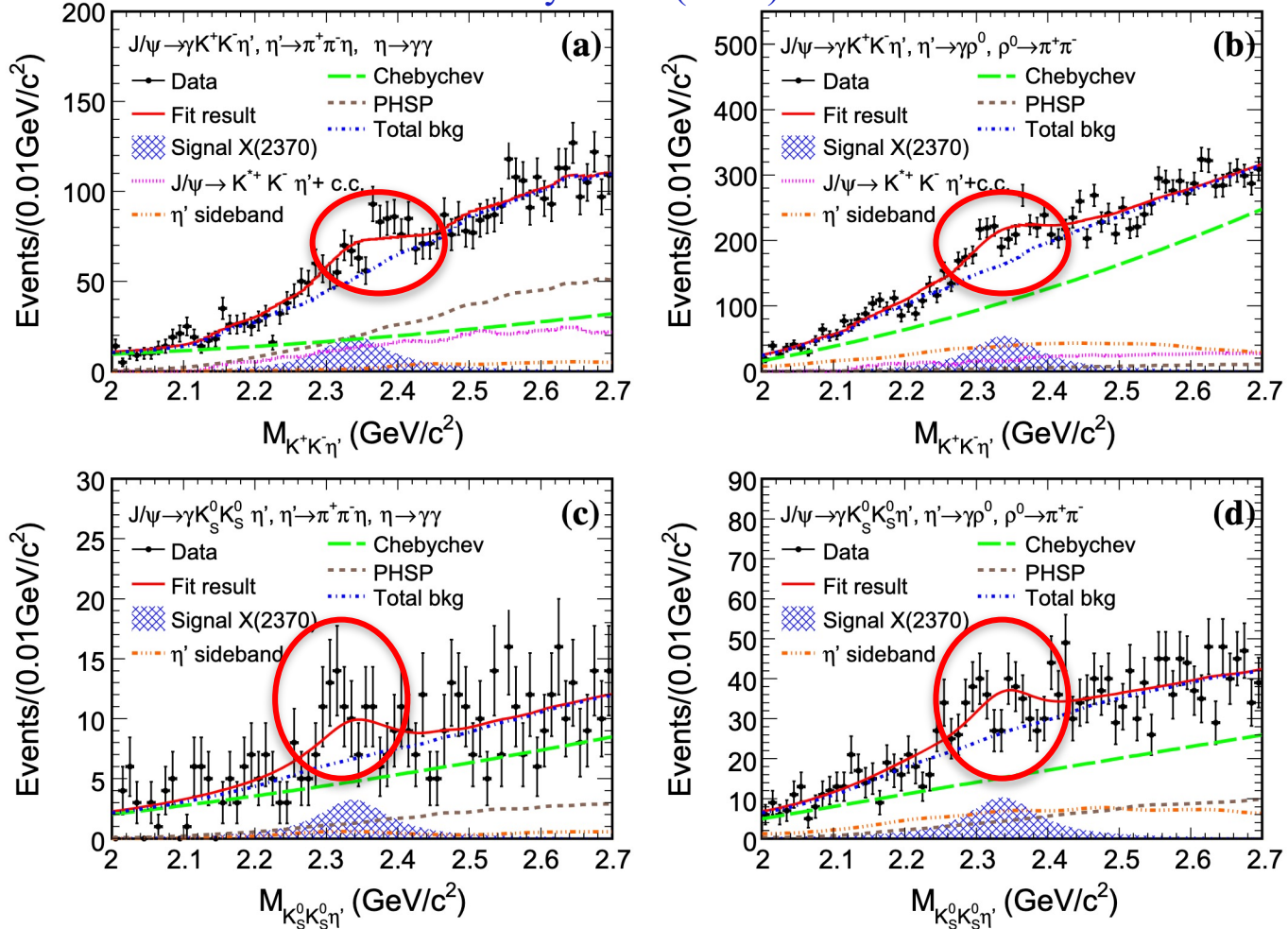
Exotic hadrons-X(2370)



$X(2370)$ was observed in $J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$ decays with a statistical significance of 6.4σ by the BESIII experiment

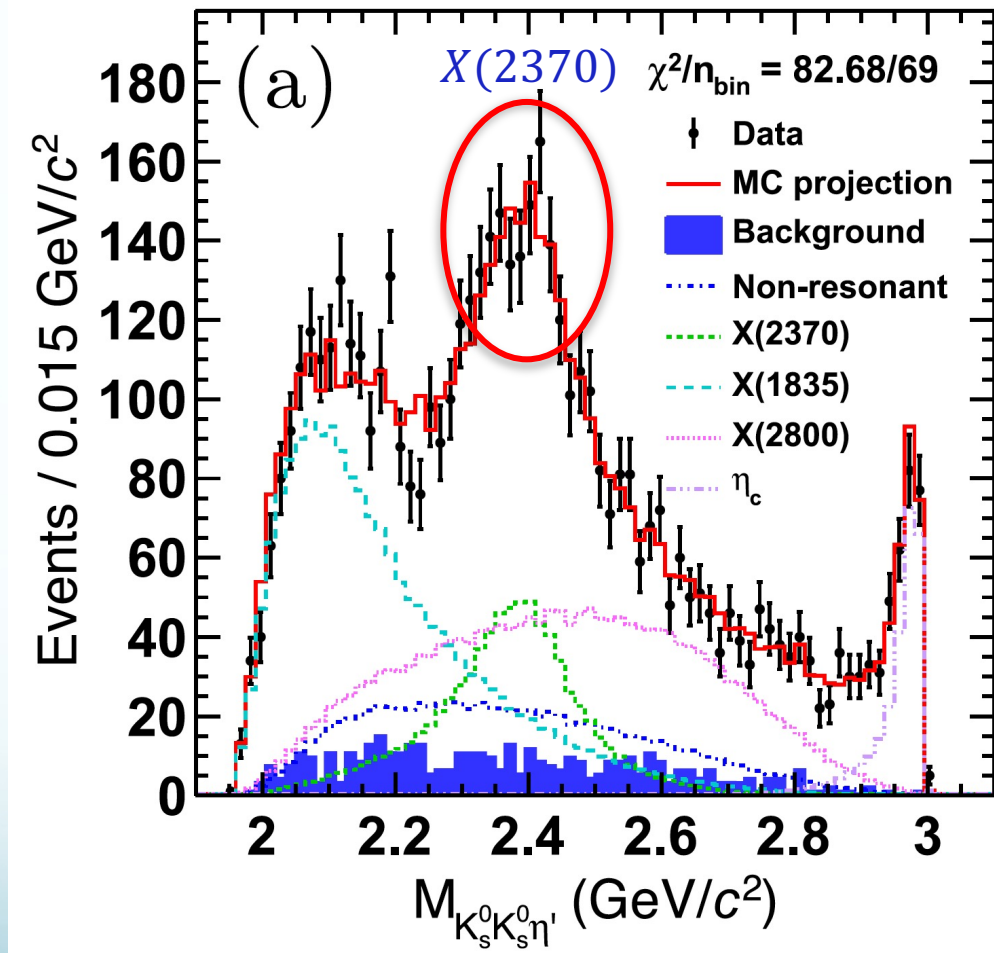
Exotic hadrons-X(2370)

Eur. Phys. J. C (2020) 80:746



It was further observed from the combined measurement of $J/\psi \rightarrow \gamma K^+ K^- \eta'$ and $J/\psi \rightarrow \gamma K_S^0 K_S^0 \eta'$ with a statistical significance of 8.3σ by BESIII

Exotic hadrons-X(2370)



PRL 132, 181901 (2024)

The statistical significance of the $X(2370)$ is greater than 6.4σ and the spin parity is determined to be 0^{-+} for the first time



Exotic hadrons- $X(2370)$

- Some theoretical studies interpret $X(2370)$ states as the fourth radial excitation of η/η' . PRD 83, 114007 (2011); PRD 102, 114034 (2020)
- Some theoretical studies also suggest that the $X(2370)$ states are the P -wave $ss\bar{s}\bar{s}$ tetraquark states of $J^{PC} = 0^{-+}$. PRD 106, 014023 (2022)
- Some theoretical studies indicate that $X(2370)$ states can be explained as light baryonium states $\Lambda - \bar{\Lambda}$ and $\Sigma - \bar{\Sigma}$ with quantum numbers of 0^{-+} and 1^{--} . PRD 105, 014016 (2022)



Exotic hadrons-X(2370)

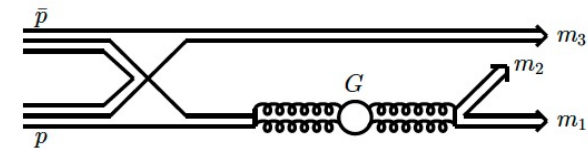
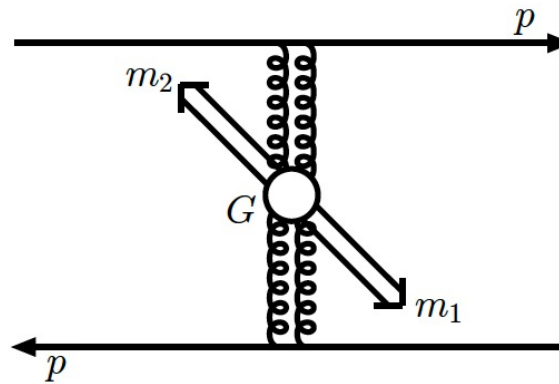
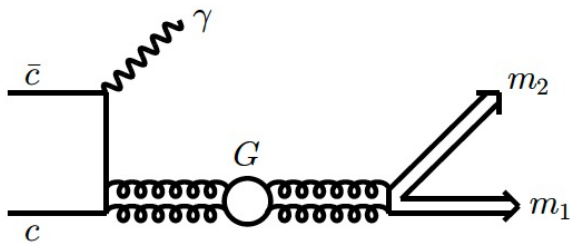
- Among the theoretical studies, one of the intriguing explanations is a **pseudoscalar glueball**



Phys. Rev. D 100, 054511 (2019); PRD 82, 074026 (2010); PRD 87, 054036 (2013);
Phys. Lett. B 827, 136960 (2022); Nucl. Phys. A 728 (2003) 165–181; Phys. Lett. B
642 (2006) 53–61

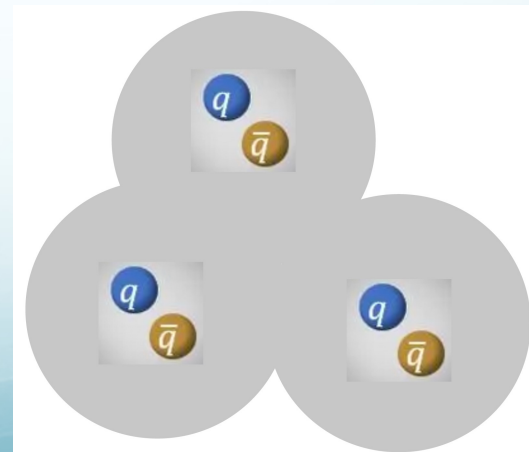
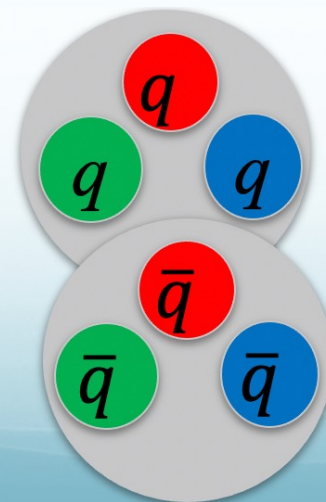
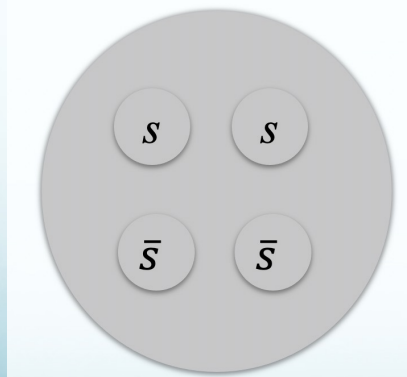
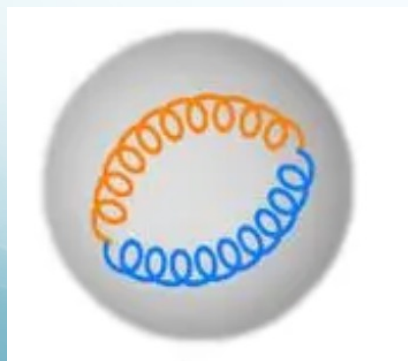
Exotic hadrons-X(2370)

- Glueball productions: [Int J Mod Phys E , 18, 1-49 \(2009\)](#)
- J/ψ decays
- Double pomeron exchange in pp collisions
- $p\bar{p}$ annihilation



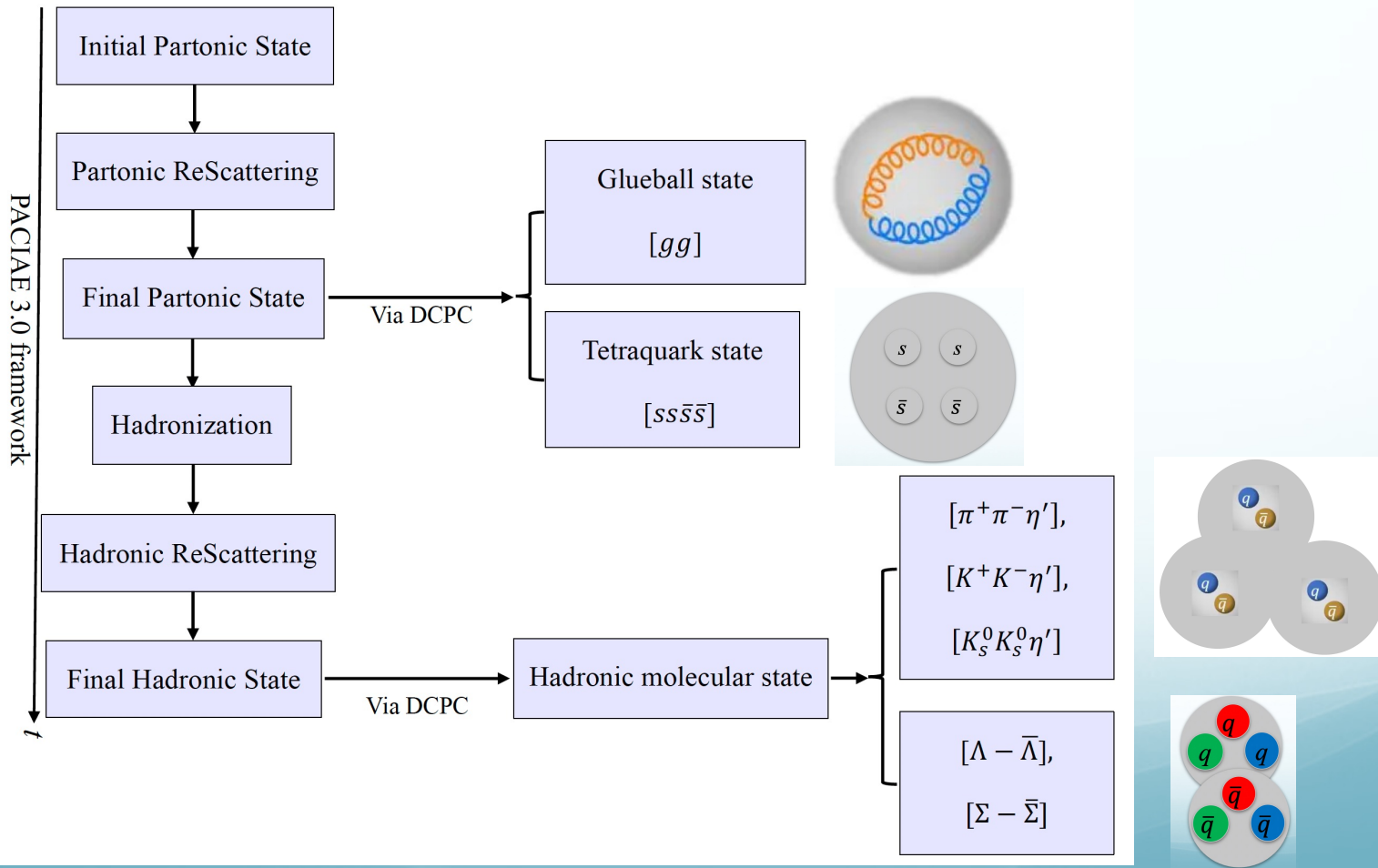
Exotic hadrons-X(2370)

- In our work, we will investigate the glueball-like particle (X(2370)) production in pp collisions at $\sqrt{s} = 13$ TeV with PACIAE model.
- Three scenarios are considered: the glueball states containing two valence gluons, the tetraquark state $ss\bar{s}\bar{s}$, the molecular state $\Lambda - \bar{\Lambda} / \Sigma - \bar{\Sigma}$, or $\pi^+ \pi^- \eta' / K^+ K^- \eta' / K_S^0 K_S^0 \eta'$.



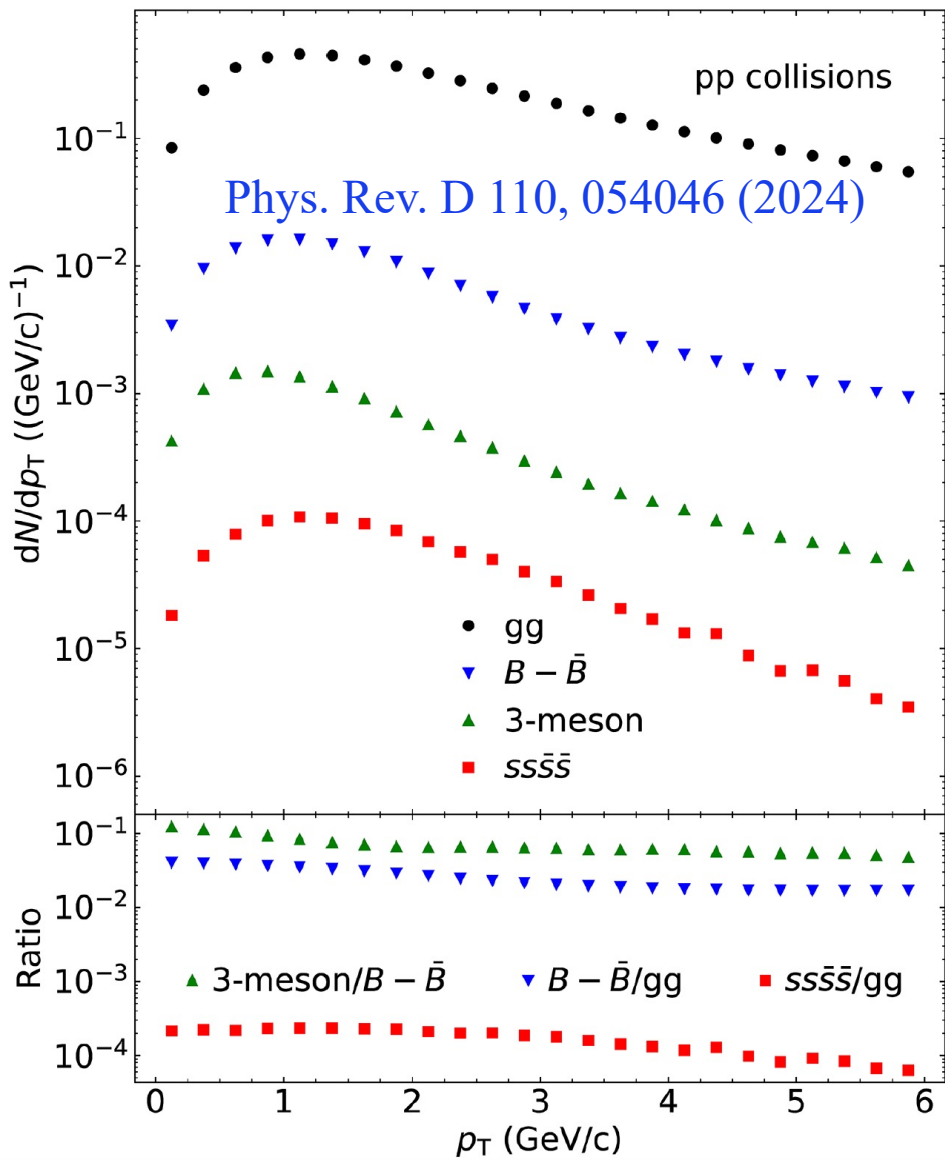
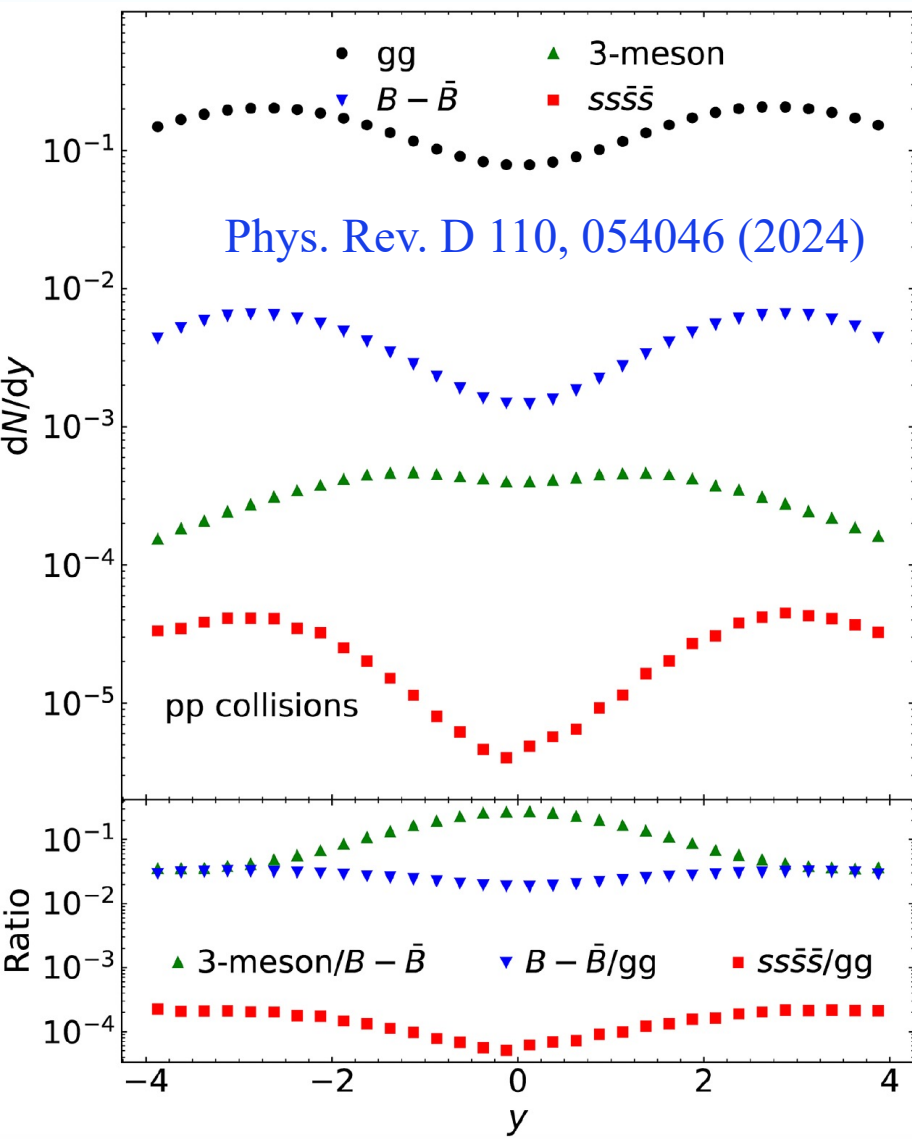
Exotic hadrons-X(2370)

- In this work, glueball-like state, tetraquark- and molecule-state of $X(2370)$ are assumed to be coalesced in PFS and HFS, respectively.

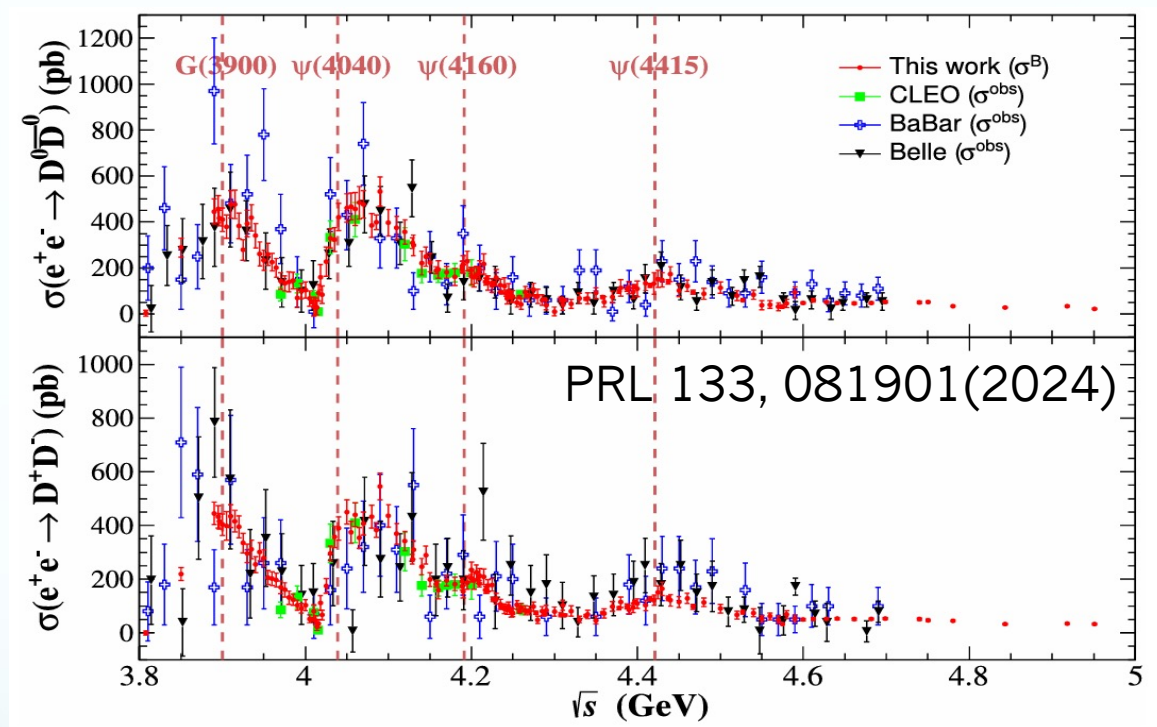




Exotic hadrons-X(2370)



Exotic hadrons-G(3900)



在BESIII能区下利用PACIAE模型研究类粲偶素奇特强子的产生

Phys. Rev. D 112, 014033 (2025)



(3+1)-D nonextensive hydrodynamics

PHYSICAL REVIEW D **111**, 036010 (2025)

Nonextensive (3 + 1)-dimensional hydrodynamics for relativistic heavy-ion collisions

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QCD phase transition

QCD phase transition at finite temperature and chemical potential with the non-extensive statistics

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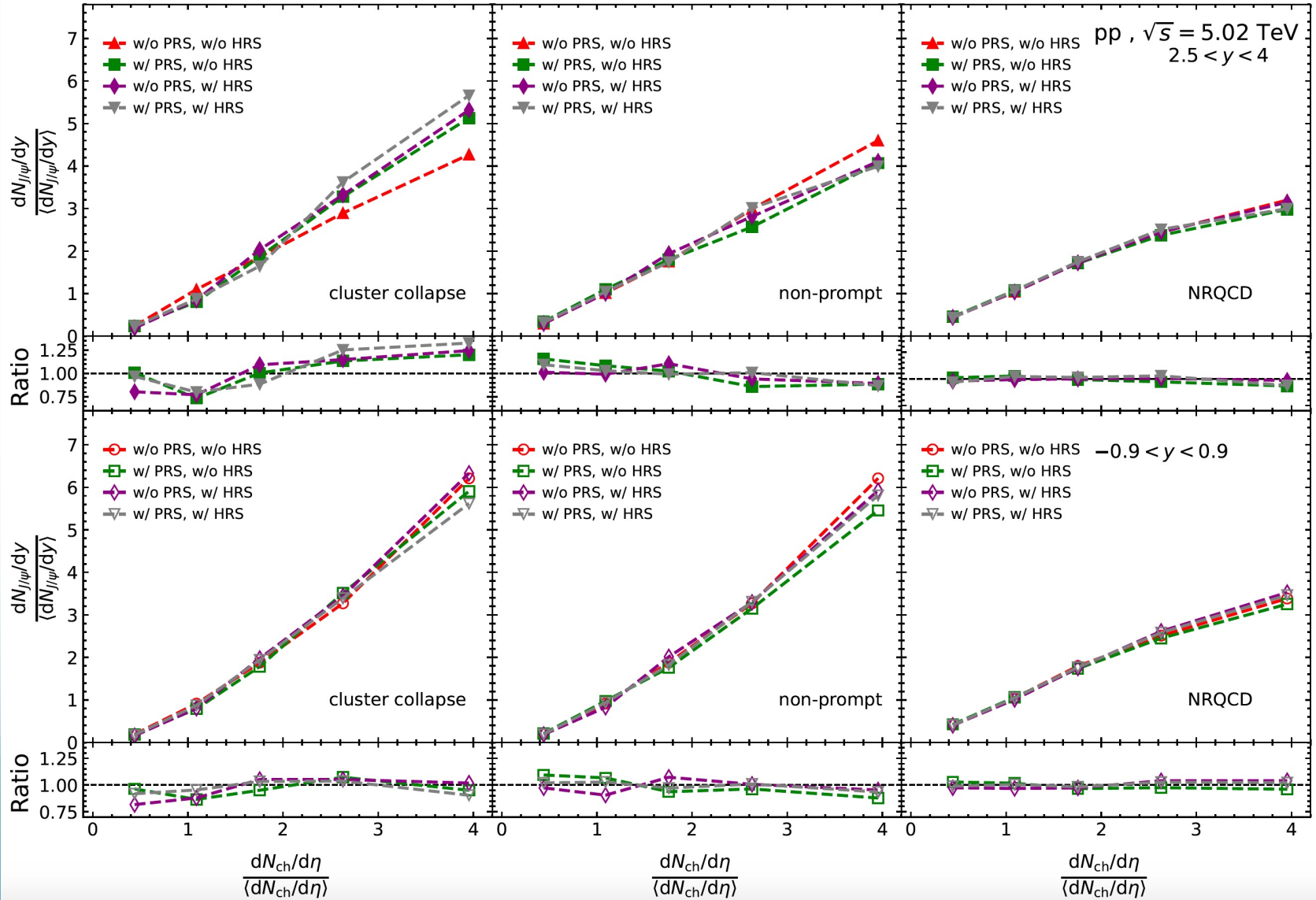
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Conclusions

- 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.
- The hadronization process has an obvious effect on the J/ψ energy correlator.
- Discrepancy between the glueball-, tetraquark- or molecule-state of the exotic hadrons in the rapidity and p_T distributions can be served as a criterion for identifying the configuration.

Back up





Back up

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

$N_{J/\psi}^i$ and N_{evt}^i are the number of J/ψ and number of events in i^{th} 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.