陕西师範大学
SHAANXI NORMAL UNIVERSITY

第十一届XYZ研讨会

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

Exotic hadron productions in high energy nuclear collisions with the parton and hadron cascade model PACIAE

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arXiv: 2607.01075, Phys. Rev. D 113, L031501 (2026),
Phys. Lett. B 872 140068 (2026), Phys. Rev. D 112, 014033 (2025),
Phys. Rev. D 110, 054046 (2024), Phys. Rev. C 110, 014910 (2024)

2026.07.24@贵阳

Outline

1. Background and motivations
2. The PACIAE model
3. Exotic hadron productions
4. Summary

Background and motivations

- 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)

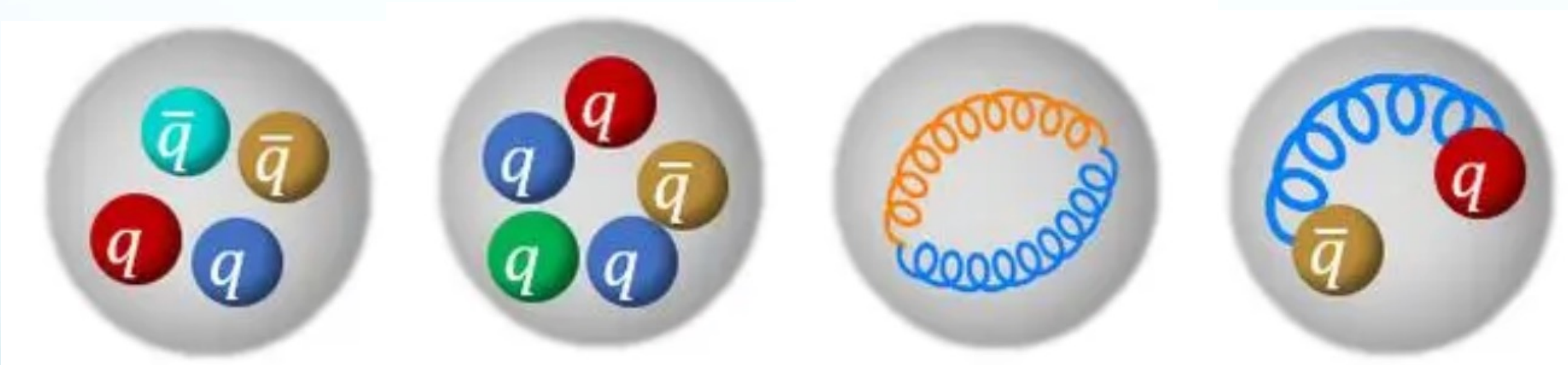
A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

Background and motivations

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

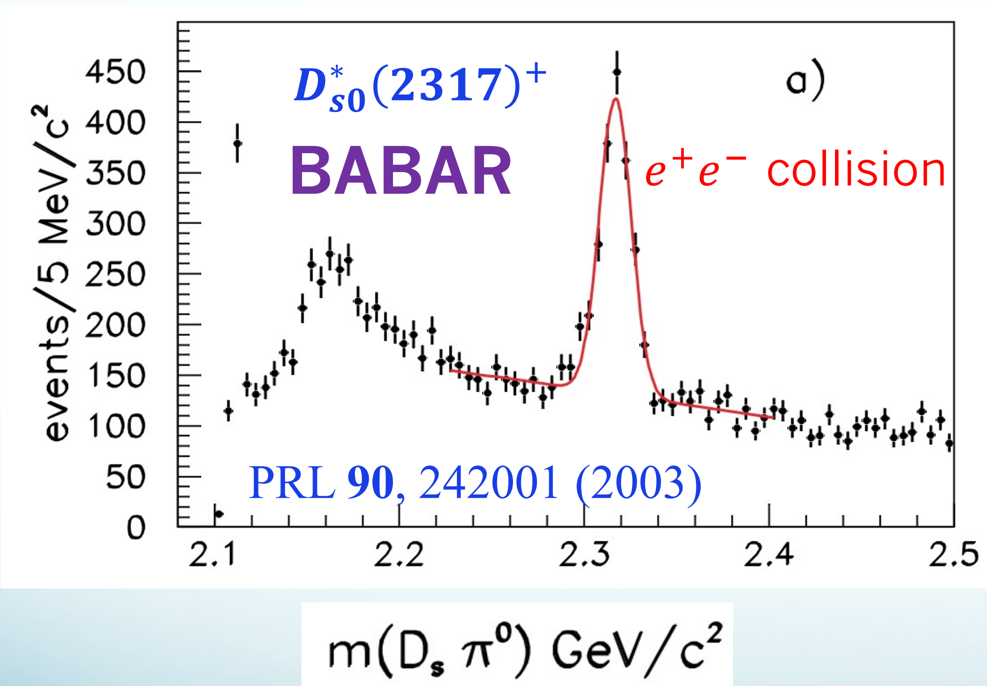


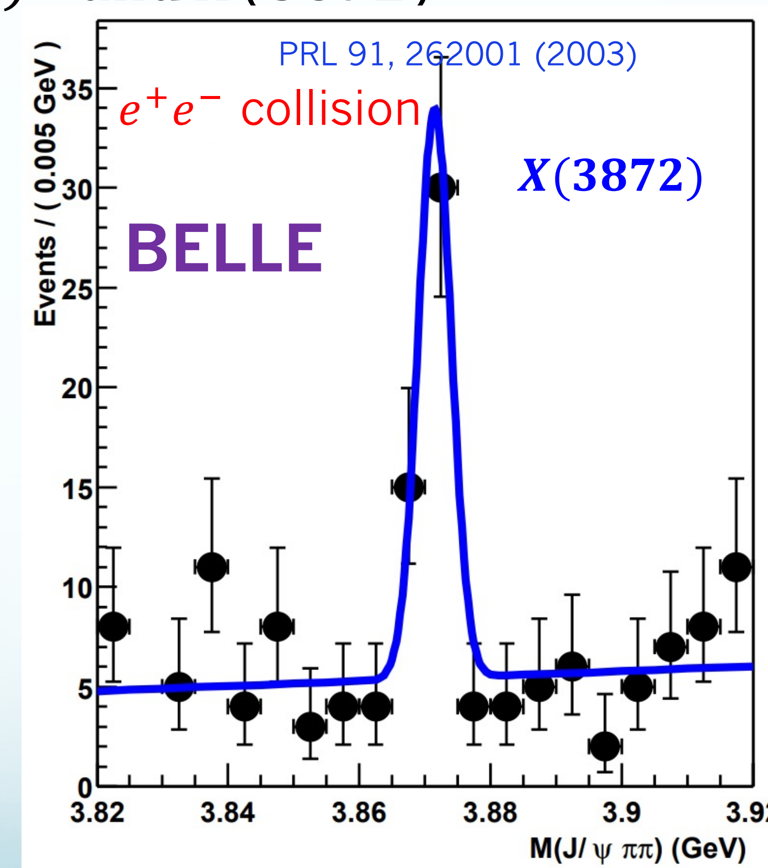
tetraquark pentaquark glueball hybrid state …

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

Background and motivations

- First exotic candidates $D_{s0}^*(2317)^+$ and $X(3872)$



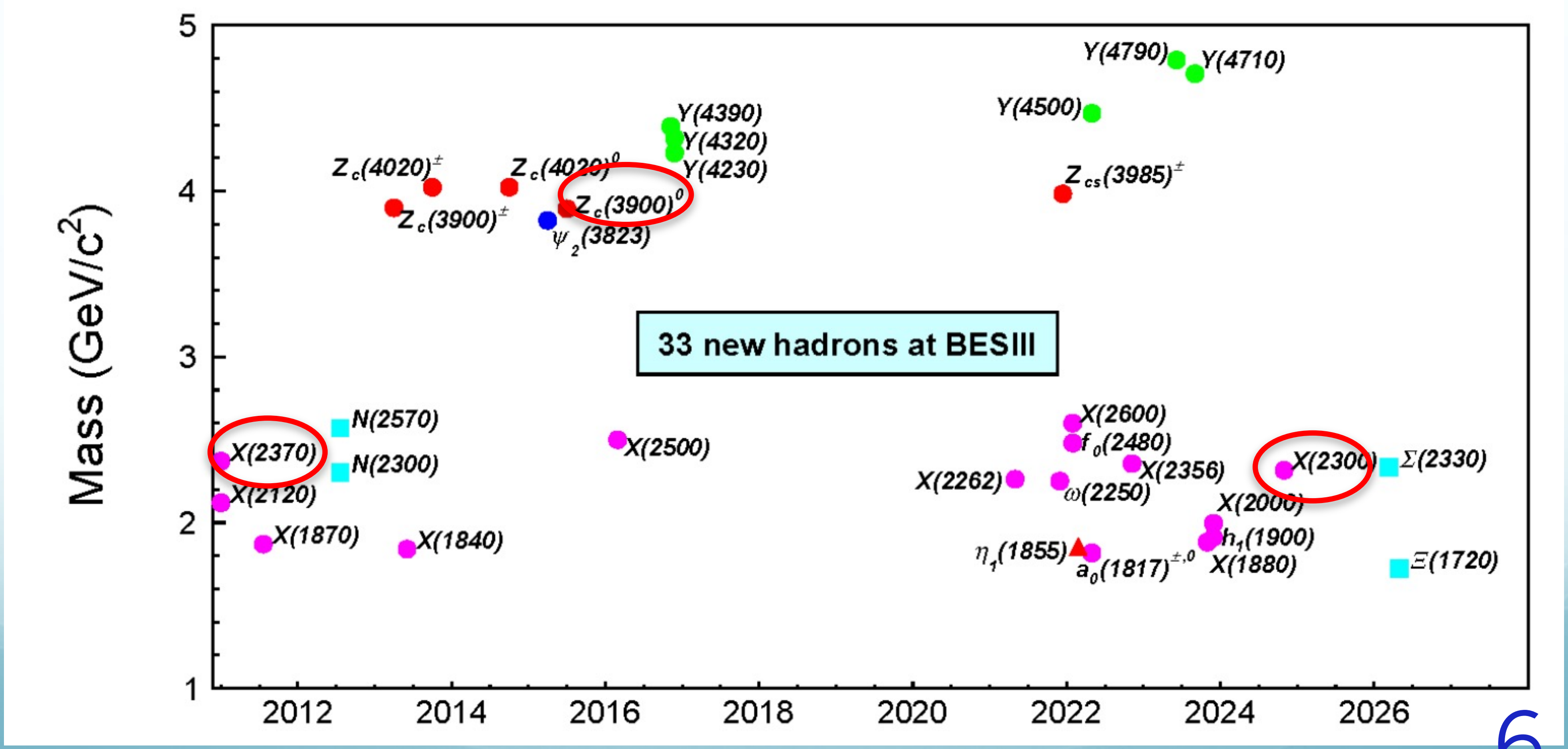


Later, more experiments have confirmed its existence and have measured its properties in both pp and Pb-Pb collisions.

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

Background and motivations

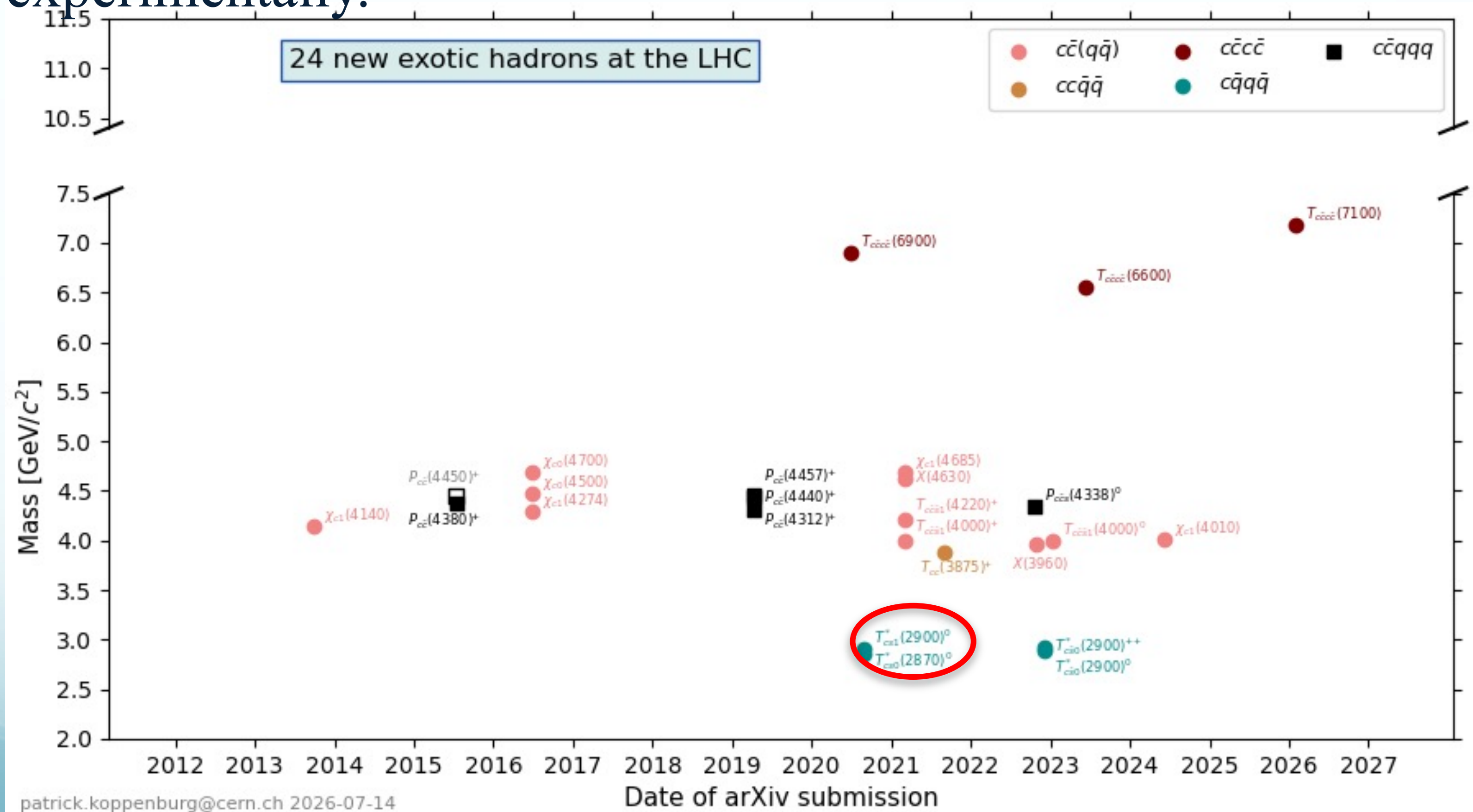
- Since then more and more exotic states have been confirmed experimentally.



Science Bulletin 68 (2023) 2148–2150

Background and motivations

- Since then more and more exotic states have been confirmed experimentally.

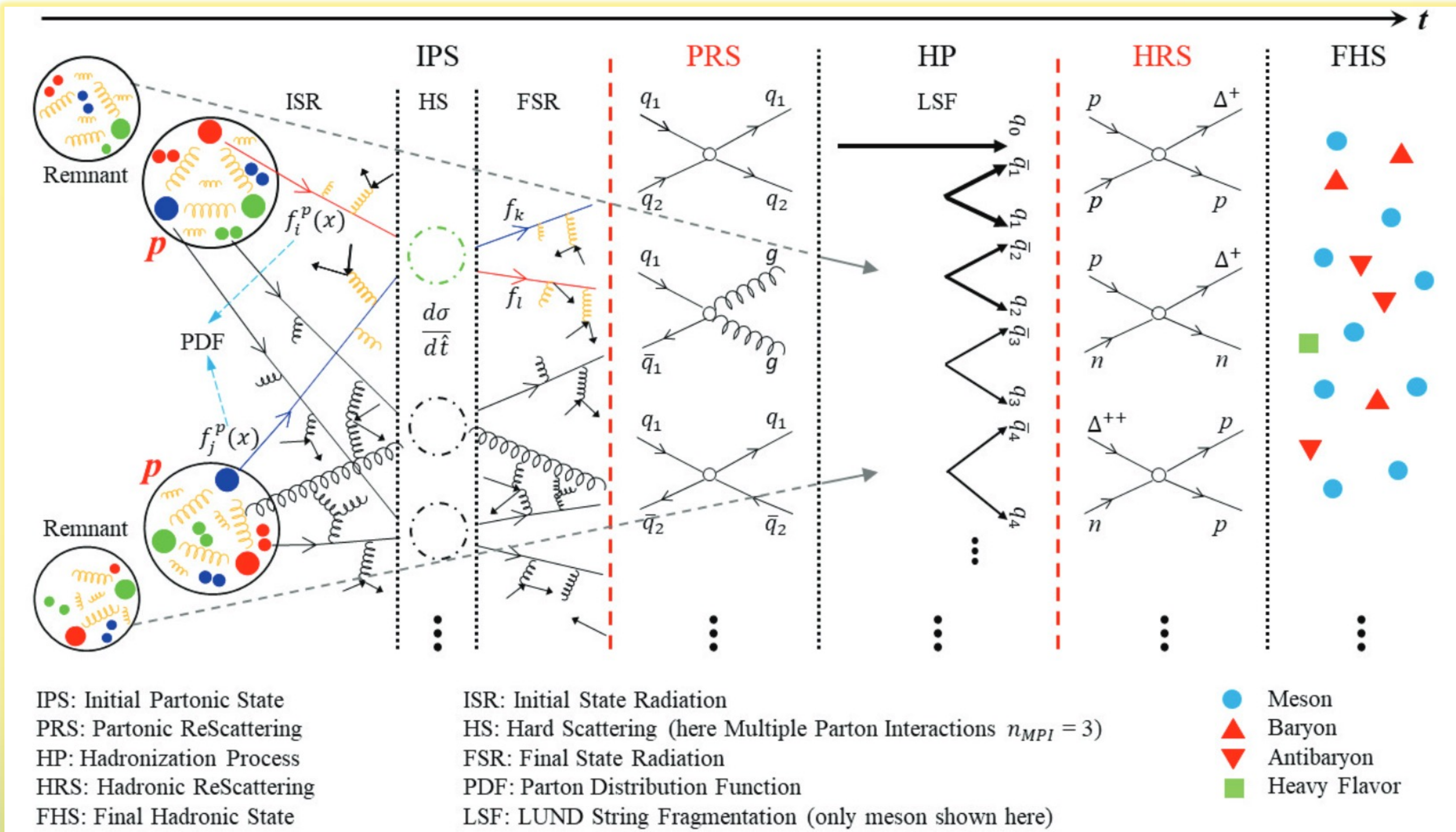


https://www.koppenburg.ch/particles.html

Background and motivations

- These exotic hadrons have been explained as tetraquark, pentaquark, molecule, hybrid, or glueball state.
- Key Question: How to distinguish different configurations experimentally?
- We use the parton and hadron cascade model PACIAE to simulate the exotic hadron productions in pp and e^+e^- collisions at the LHC and BESIII energies.
- Discrepancy between different configurations of the exotic hadrons in the yield, rapidity distributions and p_T spectra can be served as a criterion for deciphering the nature of them.

The PACIAE Model



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

Initialization (PYTHIA with string fragmentation off) → Parton rescattering → Hadronization (Lund string fragmentation/coalescence) → Hadron rescattering → Kinetic freeze-out

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

The PACIAE Model

Order	Process	$\overline{\|\mathcal{M}\|^2}$
1	$q_1q_2 \to q_1q_2$ $\bar{q}_1\bar{q}_2 \to \bar{q}_1\bar{q}_2$	$\frac{4}{9}\frac{s^2+u^2}{t^2} \approx \frac{8}{9}\frac{s^2}{t^2}$
2	$q_1q_1 \to q_1q_1$ $\bar{q}_1\bar{q}_1 \to \bar{q}_1\bar{q}_1$	$\frac{4}{9}(\frac{s^2+u^2}{t^2}+\frac{s^2+t^2}{u^2})-\frac{8}{27}\frac{s^2}{ut} \approx \frac{8}{9}\frac{s^2}{t^2}$
3	$q_1\bar{q}_2 \to q_1\bar{q}_2$	$\frac{4}{9}\frac{s^2+u^2}{t^2} \approx \frac{8}{9}\frac{s^2}{t^2}$
4	$q_1\bar{q}_1 \to q_2\bar{q}_2$	$\frac{4}{9}\frac{t^2+u^2}{s^2} = \frac{4}{9}\frac{t^2+(t+s)^2}{s^2}$
5	$q_1\bar{q}_1 \to q_1\bar{q}_1$	$\frac{4}{9}(\frac{s^2+u^2}{t^2}+\frac{t^2+u^2}{s^2})-\frac{8}{27}\frac{u^2}{ts} \approx \frac{8}{9}\frac{s^2}{t^2}$
6	$q\bar{q} \to gg$	$\frac{32}{27}\frac{u^2+t^2}{ut}-\frac{8}{3}\frac{u^2+t^2}{s^2} \approx -\frac{32}{27}\frac{s}{t}$
7	$gg \to q\bar{q}$	$\frac{1}{6}\frac{u^2+t^2}{ut}-\frac{3}{8}\frac{u^2+t^2}{s^2} \approx -\frac{1}{3}\frac{s}{t}$
8	$qg \to qg$ $\bar{q}g \to \bar{q}g$	$-\frac{4}{9}\frac{u^2+s^2}{us}+\frac{u^2+s^2}{t^2} \approx \frac{2s^2}{t^2}$
9	$gg \to gg$	$\frac{9}{2}(3-\frac{ut}{s^2}-\frac{us}{t^2}-\frac{st}{u^2}) \approx \frac{9}{2}\frac{s^2}{t^2}$

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

The PACIAE Model

$$\pi N \rightleftharpoons \pi\Delta, \qquad \pi N \rightleftharpoons \rho N,$$
$$NN \rightleftharpoons N\Delta, \qquad \pi\pi \rightleftharpoons K\bar{K},$$
$$\pi N \rightleftharpoons KY, \qquad \pi\bar{N} \rightleftharpoons \bar{K}\bar{Y},$$
$$\pi Y \rightleftharpoons K\Xi, \qquad \pi\bar{Y} \rightleftharpoons \bar{K}\bar{\Xi},$$
$$\bar{K}N \rightleftharpoons \pi Y, \qquad K\bar{N} \rightleftharpoons \pi\bar{Y},$$
$$\bar{K}Y \rightleftharpoons \pi\Xi, \qquad K\bar{Y} \rightleftharpoons \pi\bar{\Xi},$$
$$\bar{K}N \rightleftharpoons K\Xi, \qquad K\bar{N} \rightleftharpoons \bar{K}\bar{\Xi},$$
$$\pi\Xi \rightleftharpoons K\Omega, \qquad \pi\bar{\Xi} \rightleftharpoons \bar{K}\bar{\Omega},$$
$$K\bar{\Xi} \rightleftharpoons \pi\bar{\Omega}, \qquad \bar{K}\Xi \rightleftharpoons \pi\Omega,$$
$$N\bar{N} \text{ annihilation}, \qquad N\bar{Y} \text{ annihilation},$$

$$J/\psi + N \rightleftharpoons Y_c + \bar{D},$$
$$J/\psi + \pi \rightleftharpoons D + \bar{D}^*,$$
$$J/\psi + \rho \rightleftharpoons D + \bar{D},$$
$$D + \pi \rightleftharpoons D^* + \rho,$$
$$D + N \rightleftharpoons D^* + N,$$

$$\psi' + N \rightleftharpoons Y_c + \bar{D},$$
$$\psi' + \pi \rightleftharpoons D + \bar{D}^*,$$
$$\psi' + \rho \rightleftharpoons D + \bar{D},$$
$$D^* + \pi \rightleftharpoons D + \rho,$$
$$D^* + \bar{N} \rightleftharpoons D + \bar{N},$$

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

$X(3872)$

- The nature of $X(3872)$ is still unclear.
- The loose molecule state and compact tetraquark state are of most interest.

Tetraquark

Charmonium

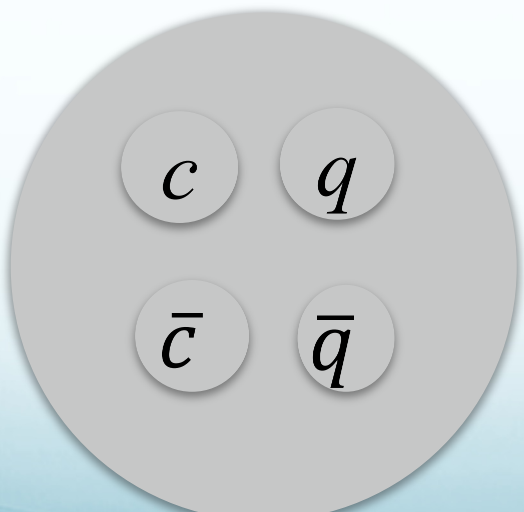
Hybrid

Hadronic molecule

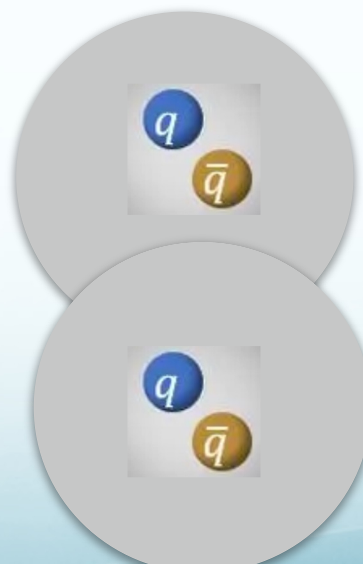
Reviews: Phys. Rep. 668, 1 (2017); Rev. Mod. Phys. 90, 015004 (2018); Phys. Rep. 873, 1 (2020); Phys. Rept. 1001, 1 (2023); Rept. Prog. Phys. 86, 026201 (2023)...

$X(3872)$

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



tetraquark



molecular state

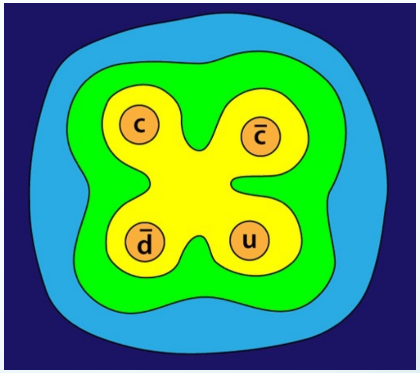
$X(3872)$

- 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 $c\bar{c}\bar{d}u$ tetraquark, its yield reads as

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



PPNP, 107 (2019) 237-320

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

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

$X(3872)$

- 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

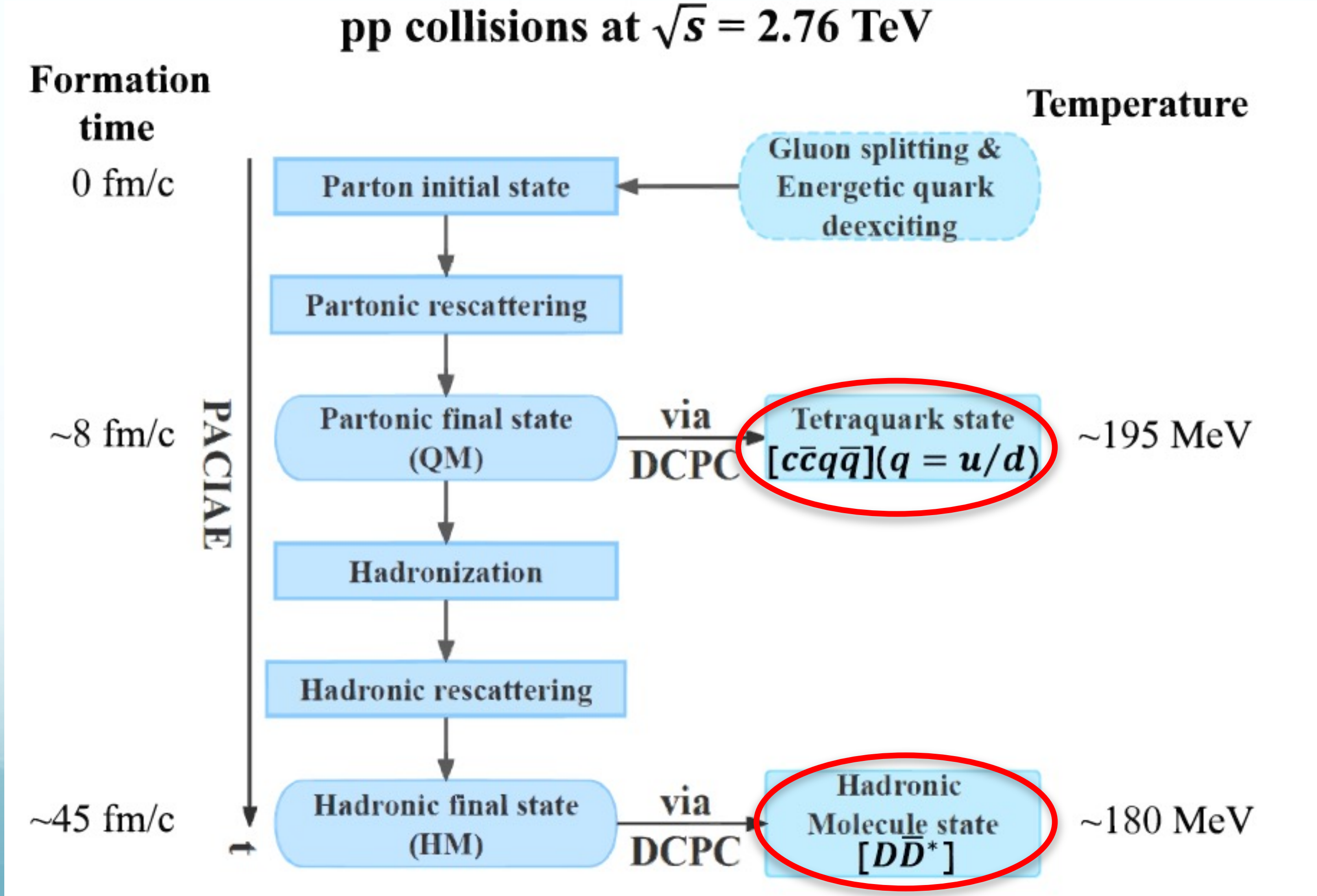
$$Y_{molecule} = \int \cdots \int \delta_{12} \frac{d\vec{q}_1 d\vec{p}_1 d\vec{q}_2 d\vec{p}_2}{h^6}$$

$$\delta_{12} = \begin{cases} 1. & if\ 1 = D, 2 = \bar{D}^* \\ & m_{X(3872)} - \Delta m < m_{inv} < m_{X(3872)} - \Delta m, 1fm \le R \le 10fm \\ 0. & otherwise \end{cases}$$

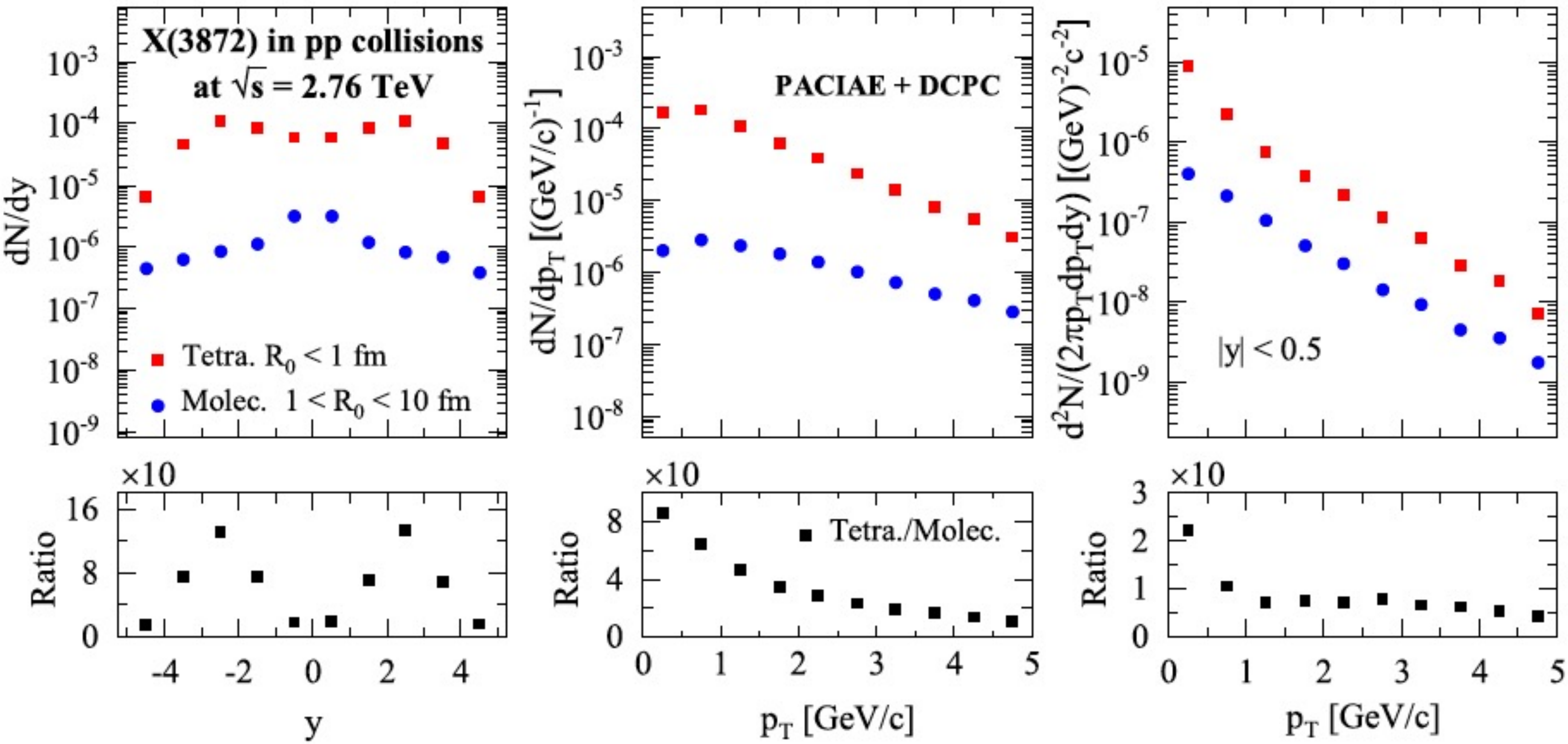
$\Delta m = \frac{\Gamma}{2} = 1.95\mathrm{MeV}/c^2$, R is the radius of the cluster.

$X(3872)$

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

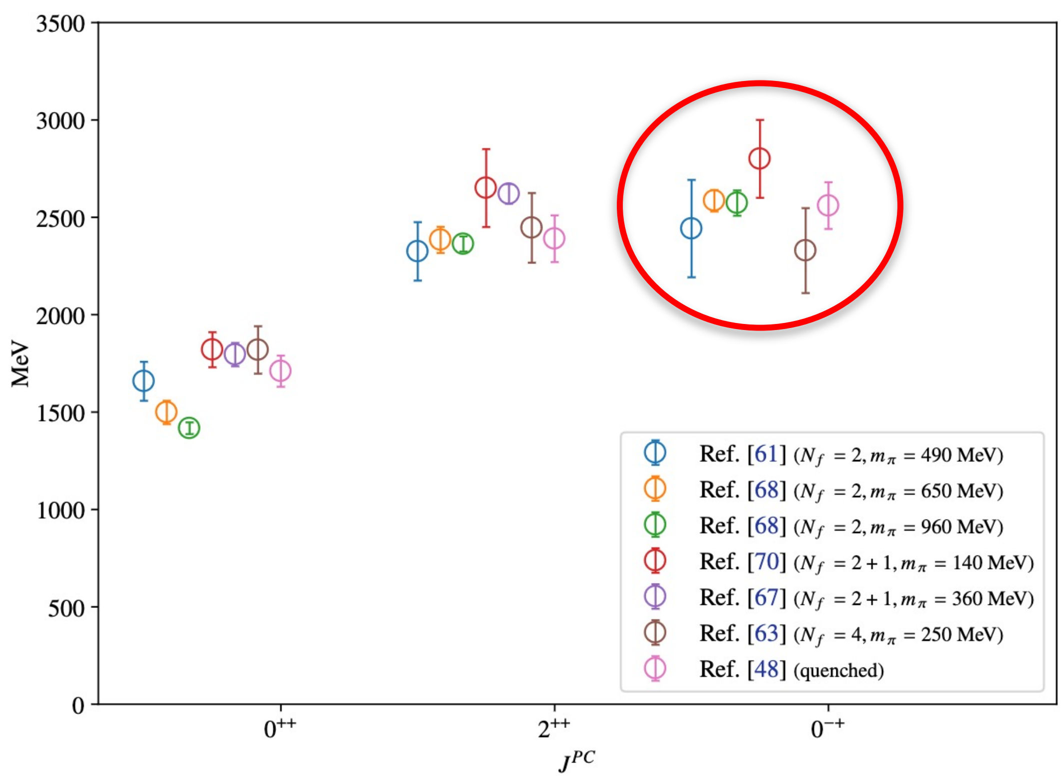


$X(3872)$



Z. L. She*, A. K. Lei, Y. L. Yan, D. M. Zhou*, **W. C. Zhang**, H. Zheng, L. Zheng, Y. L. Xie, G. Chen, and B.H. Sa*, ***PRC*** 110, 014910 (2024)

$X(2370)$



Lattice QCD predictions

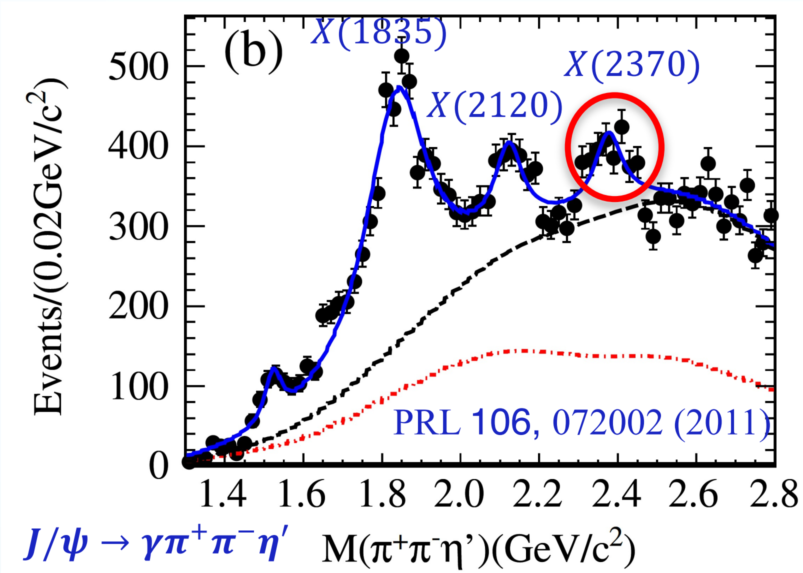
0^{++} ground state: 1.5 - 1.7 GeV/c^2

2^{++} ground state: 2.3 - 2.4GeV/c^2

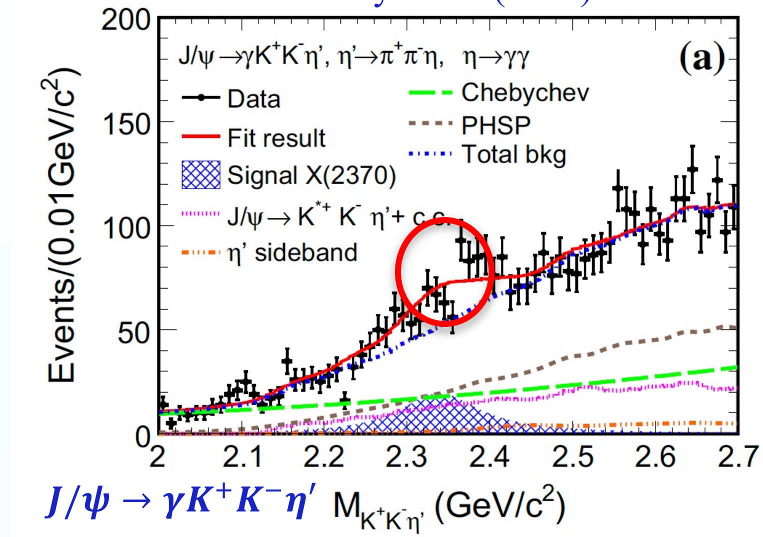
0^{-+} ground state: 2.3 - 2.6GeV/c^2

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)

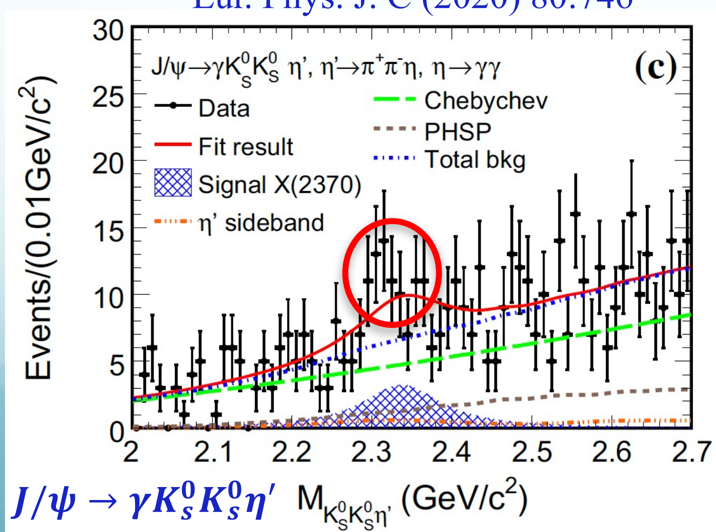
$X(2370)$

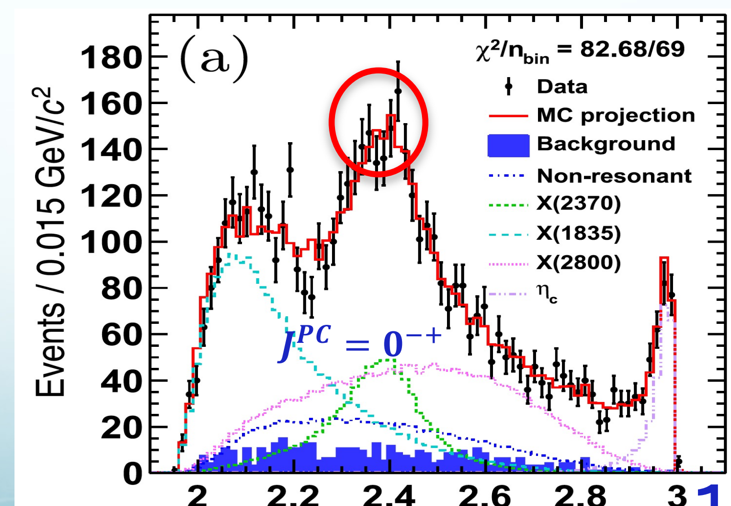


Eur. Phys. J. C (2020) 80:746



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





PRL 132, 181901 (2024)

$X(2370)$

- 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)

$X(2370)$

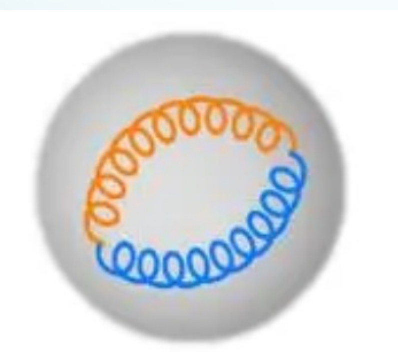
- Among the theoretical studies, one of the intriguing explanations is a pseudoscalar glueball

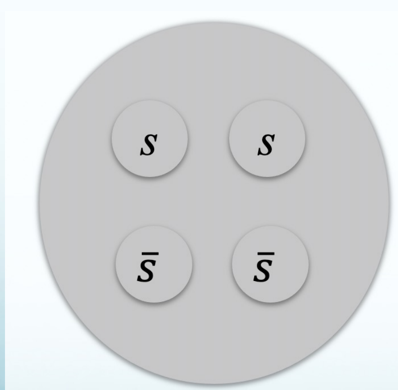
PRD 100, 054511 (2019); PRD 82, 074026 (2010); PRD 87, 054036 (2013); PLB 827, 136960 (2022); NPA 728 (2003) 165–181; PLB 642 (2006) 53–61

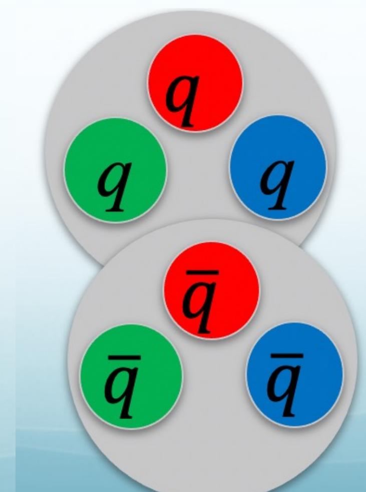
$X(2370)$

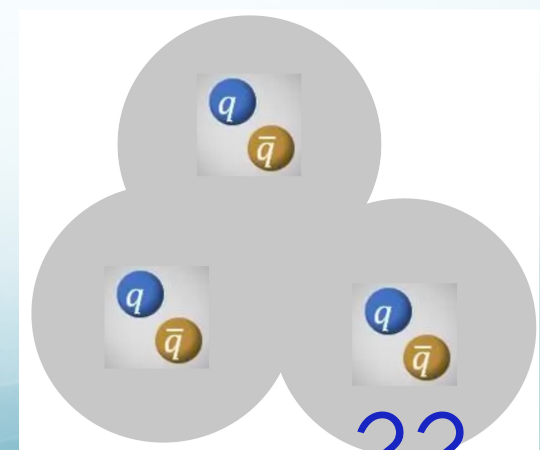
- In our work, we will investigate the glueball-like particle (X(2370)) production in pp collisions at $\sqrt{s} = 13$ TeV with PACIAE model.

- Three sicarios are considered: the glueball states containing two valence gluons, the tetraquark state $ss\bar{s}\bar{s}$, the molecular state $\Lambda-\bar{\Lambda}$ /Σ-$\bar{\Sigma}$, or $\pi^+\pi^-\eta'/K^+K^-\eta'/K_S^0K_S^0\eta'$.









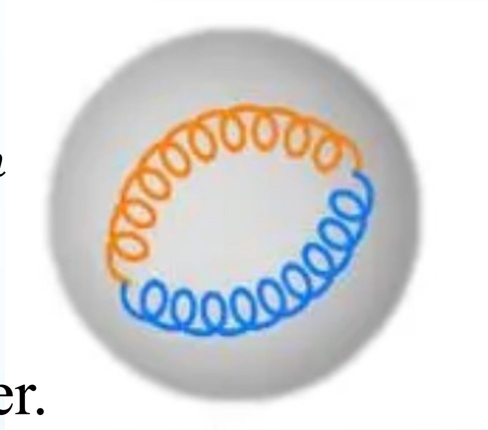
$X(2370)$

Phys. Rev. C 85, 024907 (2012).

- In DCPC model, for the two-gluon glueball, its yield reads as

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

$$\delta_{12} = \begin{cases} 1. & if\ 1 = g, 2 = g' \\ & m_{X(2370)} - \Delta m < m_{inv} < m_{X(2370)} - \Delta m, R_0 \leq 1fm \\ 0. & otherwise \end{cases}$$

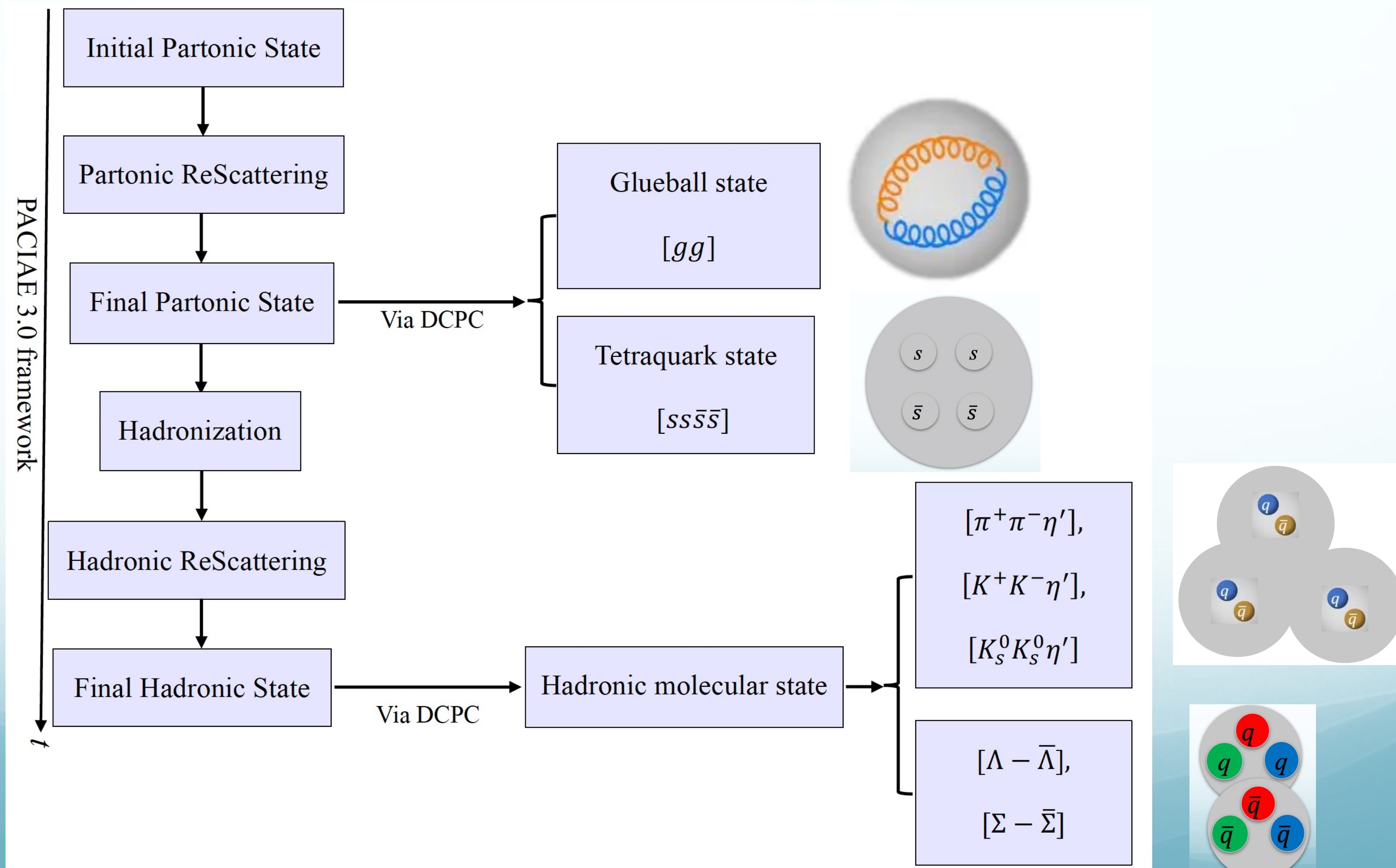


$\Delta m = \frac{\Gamma}{2} = 94 \mathrm{MeV}/c^2$, R_0 is the radius of the cluster.

	Glueball	Tetraquark	Molecular	
			B-$\bar{B}$	3-mesons
Δm (MeV/c^2)	94	94	94	94
R_0 (fm)	1.0	1.0	1.0–2.0[a]	1.0–2.0[b]

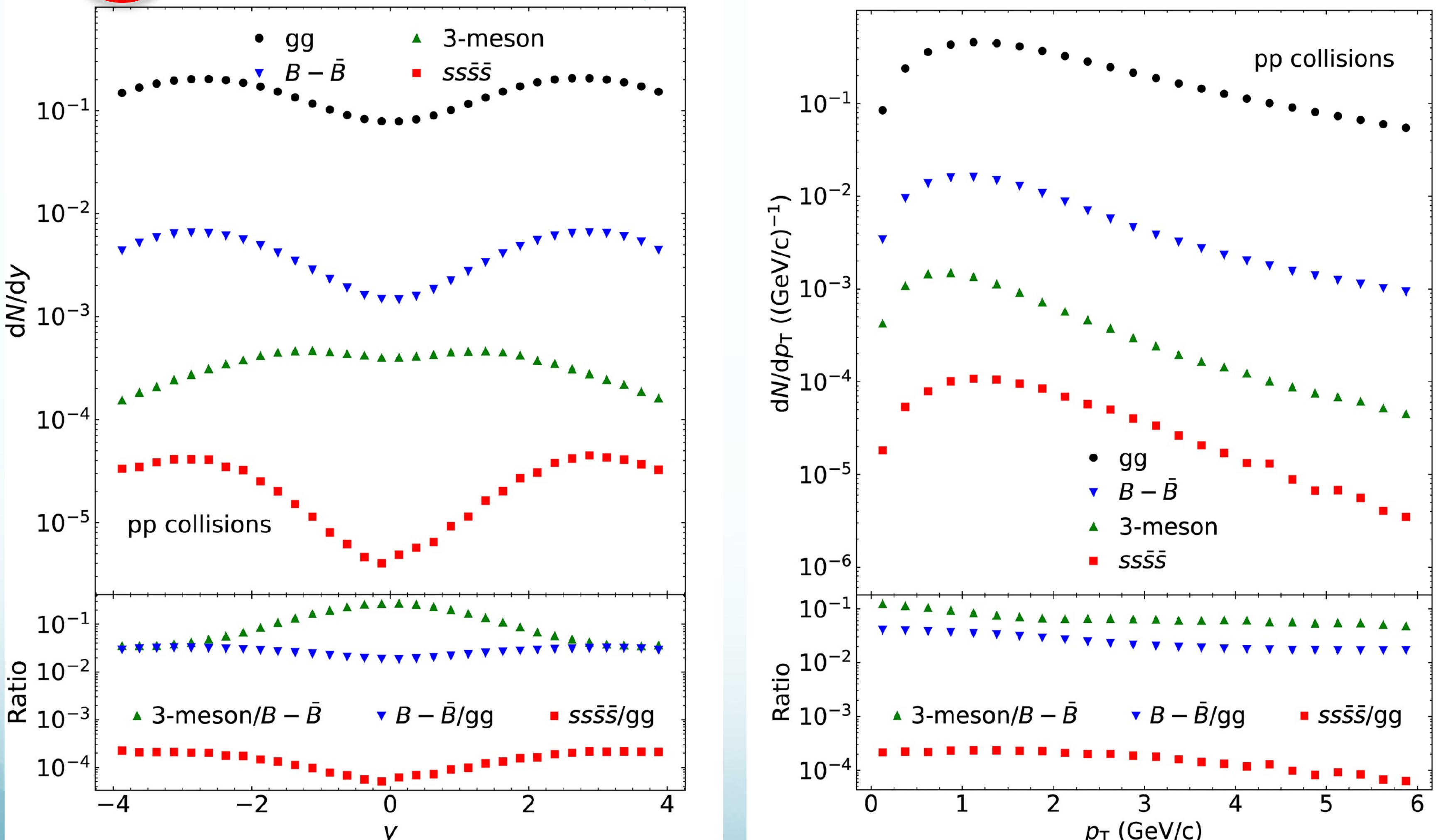
$X(2370)$

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



	Glueball	Tetraquark	Molecular	
			B-$\bar{B}$[a]	3-mesons[b]
pp	1.50	2.63×10^{-4}	4.12×10^{-2}	3.13×10^{-3}

$X(2370)$



J. Cao, Z. L. She*, J. P. Zhang, J. H. Shi, Z. Y. Qin, **W. C. Zhang***, H. Zheng, A. K. Lei, D. M. Zhou*, Y. L. Yan, and B. H. Sa*, ***PRD*** 110, 054046 (2024).

$T_{cs0}^{*}(2870)^{0}$

- In 2020, the LHCb Collaboration reported two new exotic states in the $D^{+}K^{-}$ final state of the $B^{-} \to D^{-}D^{+}K^{-}$ decays: $T_{cs0}^{*}(2870)^{0}$ and $T_{cs1}^{*}(2900)^{0}$.
- They are the first two manifestly observed opencharm tetraquark exotic states containing one single charm quark.
- In 2025, the LHCb collaboration confirmed the existence of $T_{cs0}^{*}(2870)^{0}$ in the $D^{0}K_{S}^{0}$ invariant mass spectrum from the new decay mode of $B^{-} \to D^{-}D^{0}K_{S}^{0}$ in pp collisions at $\sqrt{s}$ = 7, 8, and 13 TeV.
- Unfortunately, there is no evidence for $T_{cs1}^{*}(2900)^{0}$ in the mass spectrum of $D^{0}K_{S}^{0}$.

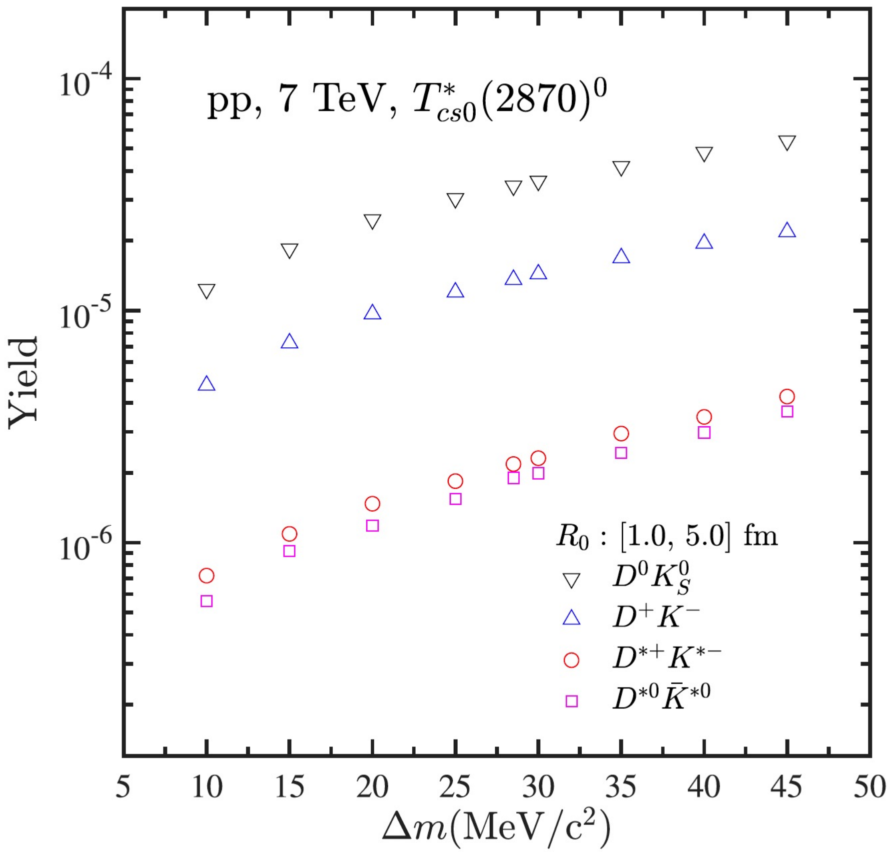
$T_{cs0}^{*}(2870)^{0}$

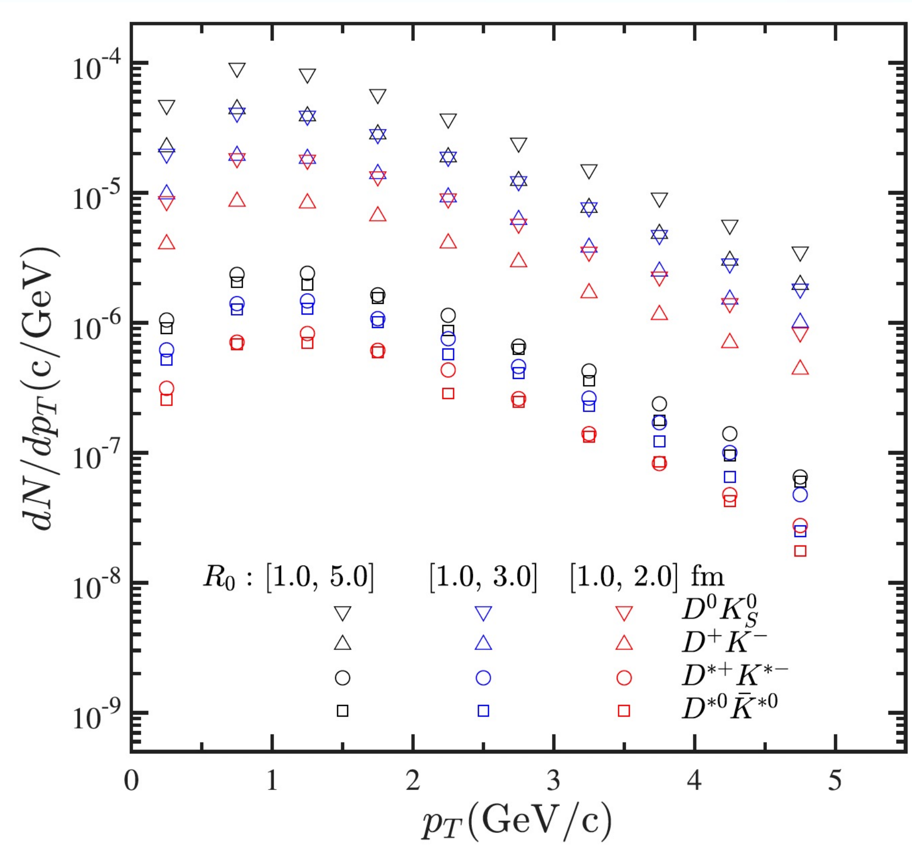
- $T_{cs0}^{*}(2870)^{0}$ has been explained as a compact tetraquark state $cs\bar{u}\bar{d}$ or hadronic molecular state.
- We assume $T_{cs0}^{*}(2870)^{0}$ as a hadronic molecular state and investigate its production in pp collisions at $\sqrt{s}=7$ TeV with PACIAE.

$$D^{+}K^{-}, D^{0}K_{S}^{0}, D^{*+}K^{*-}, \text{and } D^{*0}\bar{K}^{*0}$$

Eur. Phys. J. C 80 (2020) 1026. Phys. Rev. D 105 (2022) 54018. Phys. Rev. D 103 (2021) 74011.
Eur. Phys. J. C 81 (2021) 188. Chin. Phys. C 45 (2021) 21003. Int. J. Mod. Phys. A 35 (2020) 2050187.
Phys. Rev. D 102 (2020) 91502. Phys. Rev. D 104 (2021)94012. Eur. Phys. J. C 82 (2022) 419.
Phys. Rev. D 103 (2021) 34004. Chin. Phys. Lett. 37 (2020) 101201. Eur. Phys. J. C 80 (2020) 973.
Commun. Theor. Phys 74 (2022) 125201 Phys. Rev. D 94 (2016) 14023 and …

$T^*_{cs0}(2870)^0$

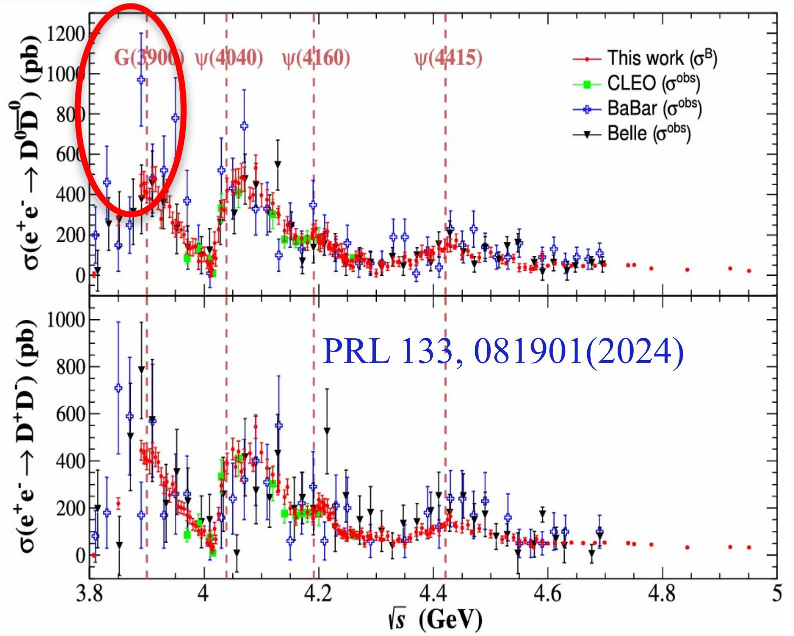


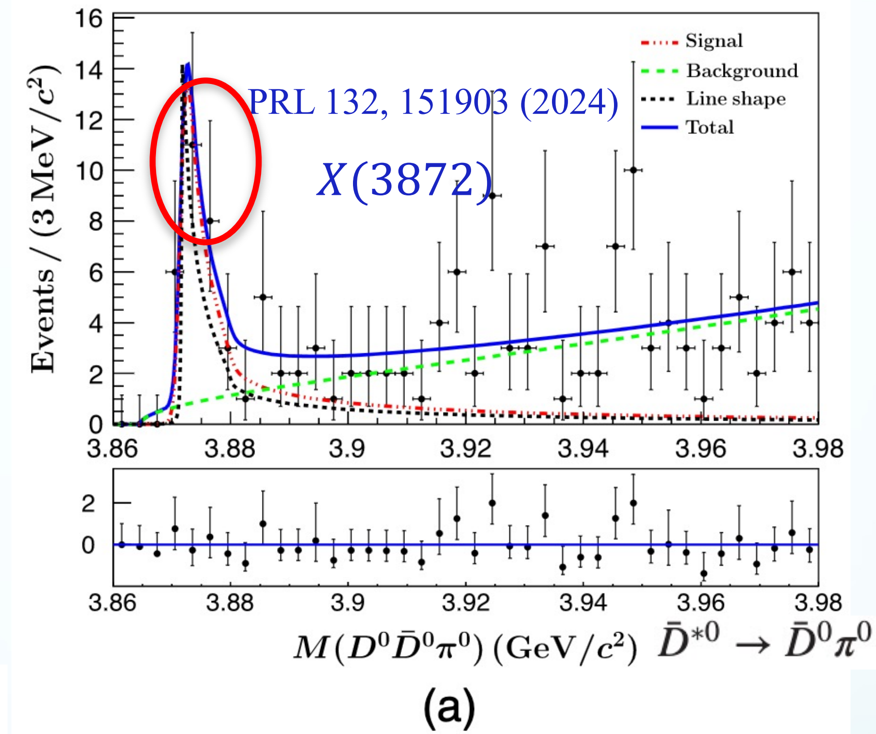


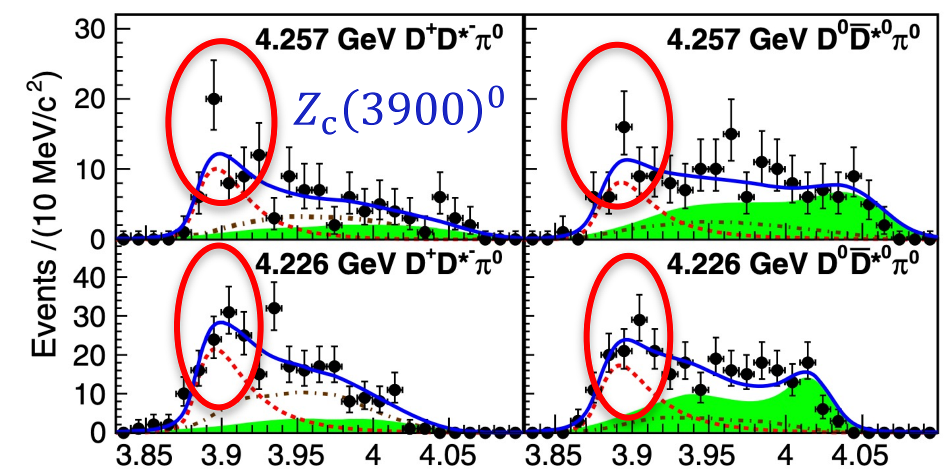
yield hierarchy: $D^0K^0_S > D^+K^- > D^{*+}K^{*-} \sim D^{*0}\bar{K}^{*0}$

Q. Wang, Z. L. She, A. K. Lei, D. M. Zhou*, **W. C. Zhang**, H. Zheng, Y. L. Yan*, and B. H. Sa*, ***Phys. Lett. B*** 872 (2026) 140068

$G(3900)/Z_c(3900)^0/X(3872)$







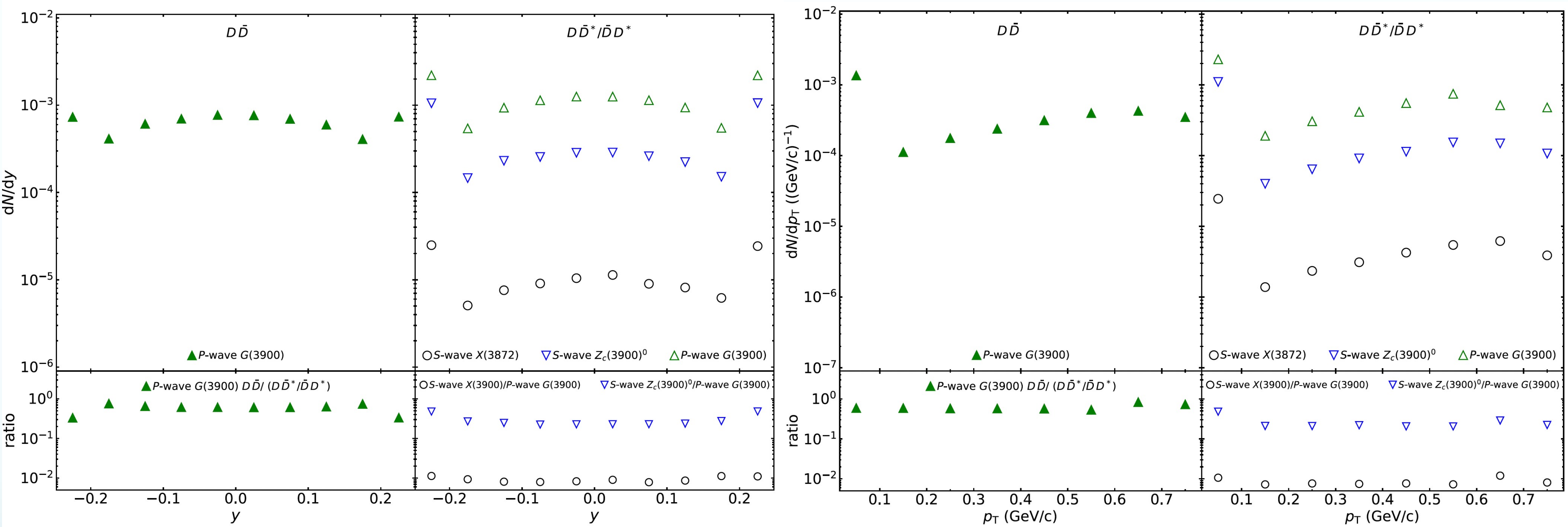
PRL 115, 222002 (2015)

	$X(3872)$	$Z_c(3900)^0$	$G(3900)$
m_0 (MeV/c^2)	3872.9	3893.0	3872.5
Δm (MeV/c^2)	1.95	22.1	89.85

	$G(3900)$	$Z_c(3900)^0$	$X(3872)$
J^{PC}	1^{--}	1^{+-}	1^{++}
$D\bar{D}^*/\bar{D}D^*$	P-wave	S-wave	S-wave

$G(3900)/Z_c(3900)^0/X(3872)$

$D\bar{D}$ [for $G(3900)$] or $D\bar{D}^*/\bar{D}D^*$ [for $X(3872)$, $Z_c(3900)^0$, and $G(3900)$]



	P-wave $D\bar{D}$ $G(3900)$	P-wave $D\bar{D}^*/\bar{D}D^*$ $G(3900)$	S-wave $D\bar{D}^*/\bar{D}D^*$ $X(3872)$	S-wave $D\bar{D}^*/\bar{D}D^*$ $Z_c(3900)^0$
Yield	3.87×10^{-4}	6.08×10^{-4}	5.81×10^{-6}	1.97×10^{-4}

J. Cao, **W. C. Zhang***, Z. L. She, A. K. Lei, J. P. Zhang, H. Zheng, D. M. Zhou*, Y. L. Yan, Z. Q. Wang, and B. H. Sa, ***PRD*** 112, 014033 (2025).

$X(2300)$

- In 2025, the BESIII collaboration reported the observation of an axial-vector particle $X(2300)$ in the $\phi\eta$ and $\phi\eta'$ invariant mass spectra for the $\psi(3686) \to \phi\eta\eta'$ process. PRL 134, 191901 (2025)
- Its mass and width are, respectively, 2316 MeV/c^2 and 89 MeV. Its spin and parity are determined as 1^{+-}.
- There are several theoretical speculations for the nature of the $X(2300)$, including the excited strangeonium state, the tetraquark state ($ss\bar{s}\bar{s}$).

PRD 112, 036006 (2025). PRD 111, 054005 (2025).

PRD 103, 016016 (2021). *CPC* **50** 043104 (2026) and …

$X(2300)$

- In this work, we simulate the production of the $X(2300)$ in e^+e^- collisions at $\sqrt{s} = 4.95$ GeV with PACIAE 4.0.
- The U(1) anomaly coupling permits nonstrange quarks to couple to a vector $s\bar{s}$ component via soft-gluon interactions.
- This motivates us to propose that the $X(2300)$ could also be a $q\bar{q}s\bar{s}$ $(q = u/d)$ state.
- Furthermore, we suggest another novel possibility that the $X(2300)$ may be a hadro-strangeonium state, i.e., a bound system of a strangeonium (ϕ) and a light hadron (η/η').

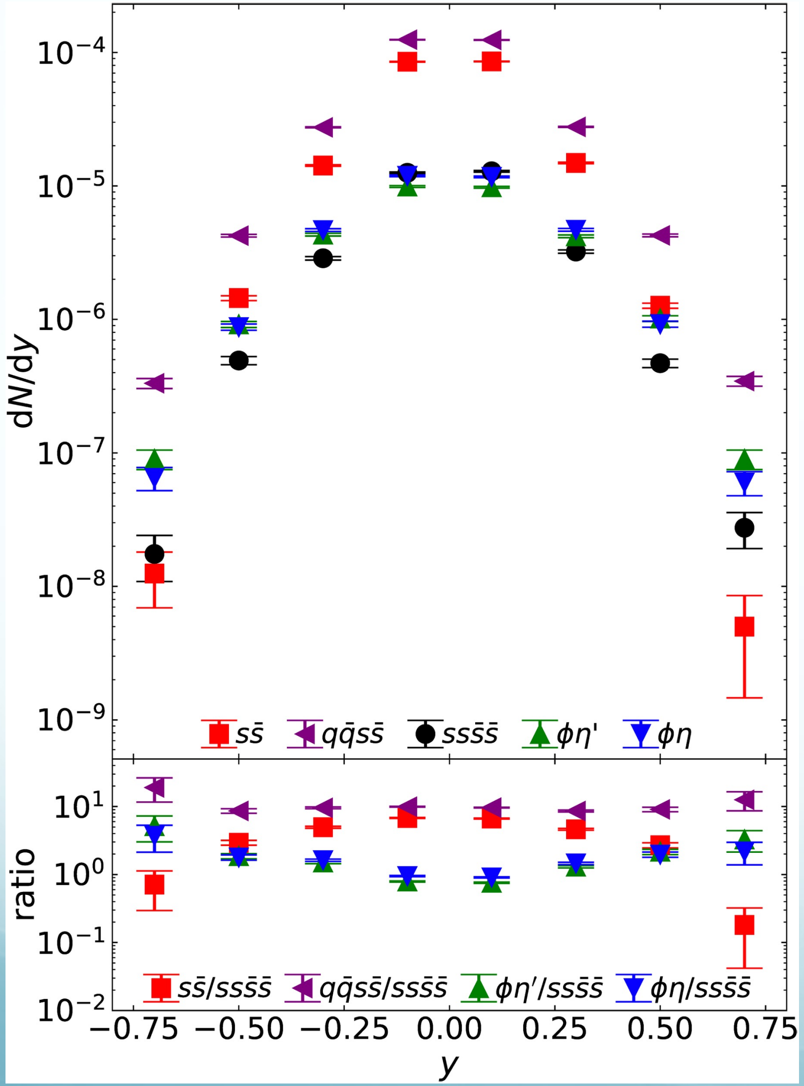
$X(2300)$

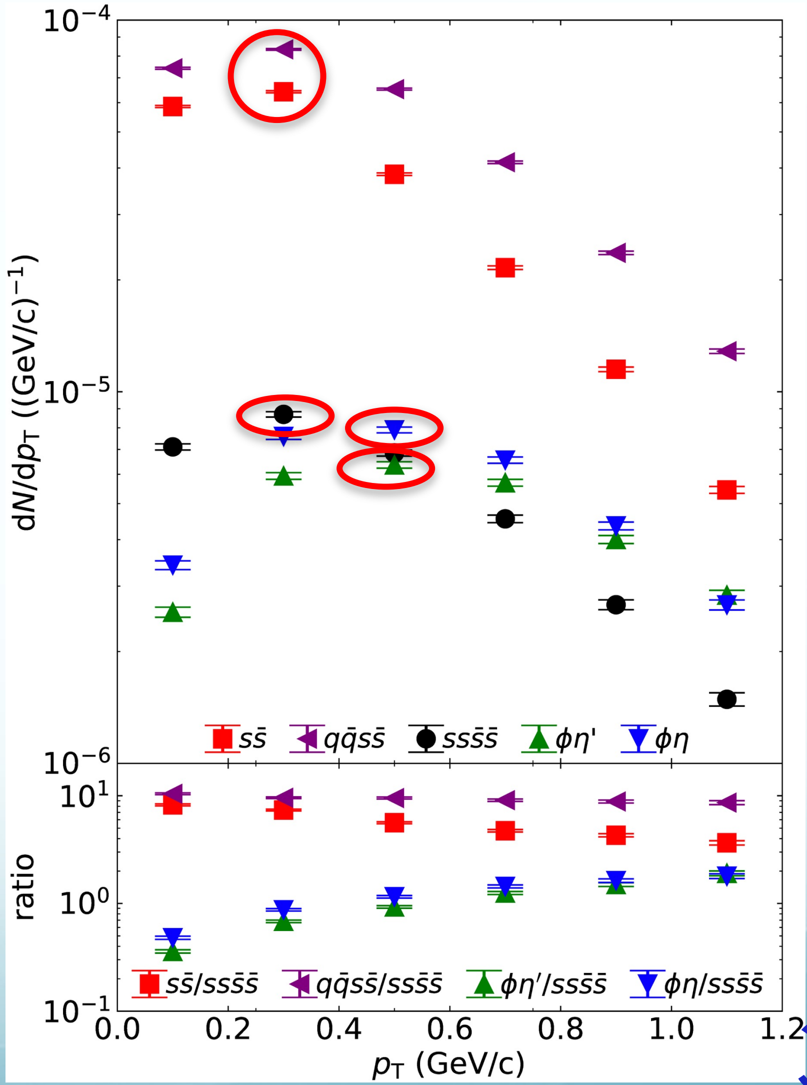
	Excited $s\bar{s}$	$q\bar{q}s\bar{s}$	$ss\bar{s}\,\bar{s}$	$\phi\eta'$	$\phi\eta$
Δm (MeV$/c^2$)	44.5	44.5	44.5	44.5	44.5
R_0 (fm)	1.0	1.0	1.0	1.0–2.0	1.0–2.0

TABLE III. The event-average yields of the P-wave $s\bar{s}$ strangeonium state, the S-wave $q\bar{q}s\bar{s}/ss\bar{s}\,\bar{s}$ tetraquark state, and the S-wave $\phi\eta'/\phi\eta$ hadro-strangeonium state for the $X(2300)$ candidates in e^+e^- collisions at $\sqrt{s} = 4.95$ GeV. The uncertainties quoted are statistical errors.

		S-wave		S-wave	
	P-wave $s\bar{s}$	$q\bar{q}s\bar{s}$	$ss\bar{s}\,\bar{s}$	$\phi\eta'$	$\phi\eta$
Yield	$(4.05 \pm 0.01) \times 10^{-5}$	$(8.43 \pm 0.02) \times 10^{-5}$	$(6.50 \pm 0.06) \times 10^{-6}$	$(6.06 \pm 0.06) \times 10^{-6}$	$(6.97 \pm 0.06) \times 10^{-6}$

X(2300)





J. Cao, **W. C. Zhang***, J. P. Zhang, B. Feng, A. K. Lei, Z. L. She, H. Zheng, D. M. Zhou*, Y. L. Yan, and B. H. Sa*,, ***PRD*** 113, L031501 (2026).

$\phi(2170)$

- $\phi(2170)$ was first observed by the BaBar Collaboration in 2006 via the initial-state radiation (ISR) process $e^+e^- \to \gamma_{ISR}\phi f_0(980)$ in the $\phi f_0(980)$ channel.

- Its observation was subsequently confirmed by the Belle, BES and BESIII Collaborations, and further supported by later BaBar analyses.

- It has been explained an excited $s\bar{s}$ state with the 2^3D_1 or 3^3S_1 configuration, an $s\bar{s}g$ hybrid state, an $ss\bar{s}\bar{s}$ or a $u\bar{u}s\bar{s}$ tetraquark state, a $\bar{\Lambda}\Lambda$ $(^3S_1)$ bound state, and a $\phi K\bar{K}$ resonance state.

PRD 99, 074015 (2019) CPC 45, 023116 (2021) PRD 85, 074024 (2012)
PLB 650, 390 (2007) JHEP 03, 087 (2026) NPA 791 106 (2007)
PRD 78, 034012 (2008) PRD 99, 036014 (2019) PRD 103, 016016 (2021)
PRD 87, 054034 (2013) PRD 88, 074007 (2013) PRD 78, 074031 (2008)
PRD 96, 074027 (2017) and …

$\phi(2170)$

- In this work, we simulate the production of the $\phi(2170)$ in e^+e^- collisions at $\sqrt{s} = 4.95$ GeV with PACIAE 4.0.

- The U(1) anomaly coupling permits nonstrange quarks to couple to a vector $s\bar{s}$ component via soft-gluon interactions.

- This motivates us to explore the $d\bar{d}s\bar{s}$ tetraquark configuration in addition to the previously proposed $ss\bar{s}\bar{s}$ and $u\bar{u}s\bar{s}$ scenarios.

- Given that $\phi(2170)$ has quantum numbers $J^{PC} = 1^{--}$, several interpretations are possible: a D-wave $s\bar{s}$ state, a P-wave $s\bar{s}g$ hybrid, a P-wave $u\bar{u}s\bar{s}/d\bar{d}s\bar{s}/ss\bar{s}\bar{s}$ tetraquark, an S-wave $\bar{\Lambda}\Lambda$ bound state, or an S-wave ϕK^+K^- resonance state.

$\phi(2170)$

	excited $s\bar{s}$	$s\bar{s}g$	$u\bar{u}s\bar{s}/d\bar{d}s\bar{s}/ss\bar{s}\bar{s}$	$\bar{\Lambda}\Lambda$	ϕK^+K^-
Δm (MeV/c^2)	106	106	106	106	106
R_0 (fm)	1.0	1.0	1.0	1.0-2.0	1.0-2.0

	$D-$wave $s\bar{s}$	$P-$wave $s\bar{s}g$
yield	$(1.223 \pm 0.002) \times 10^{-4}$	$(1.718 \pm 0.003) \times 10^{-4}$
	$P-$wave $u\bar{u}s\bar{s}$	$P-$wave $d\bar{d}s\bar{s}$
yield	$(1.595 \pm 0.003) \times 10^{-4}$	$(1.313 \pm 0.002) \times 10^{-4}$
	$P-$wave $ss\bar{s}\bar{s}$	$S-$wave $\bar{\Lambda}\Lambda$
yield	$(7.888 \pm 0.060) \times 10^{-6}$	$(6.575 \pm 0.017) \times 10^{-5}$
	$S-$wave ϕK^+K^-	
yield	$(6.426 \pm 0.017) \times 10^{-5}$	

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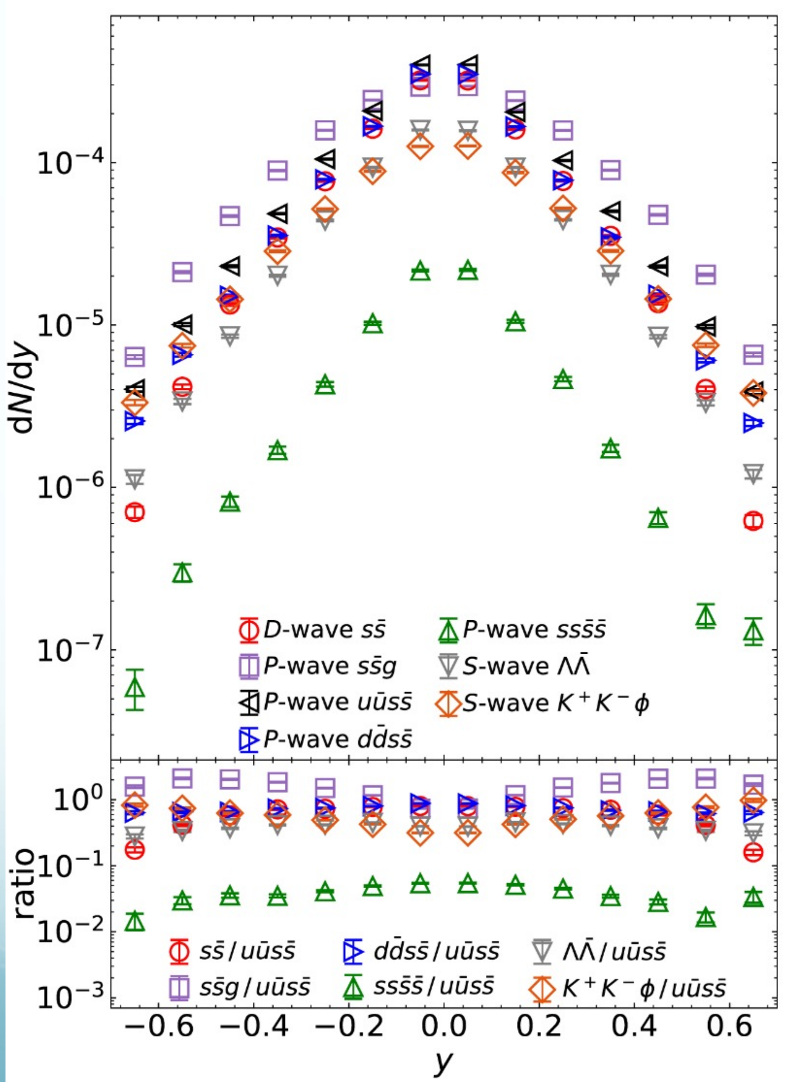
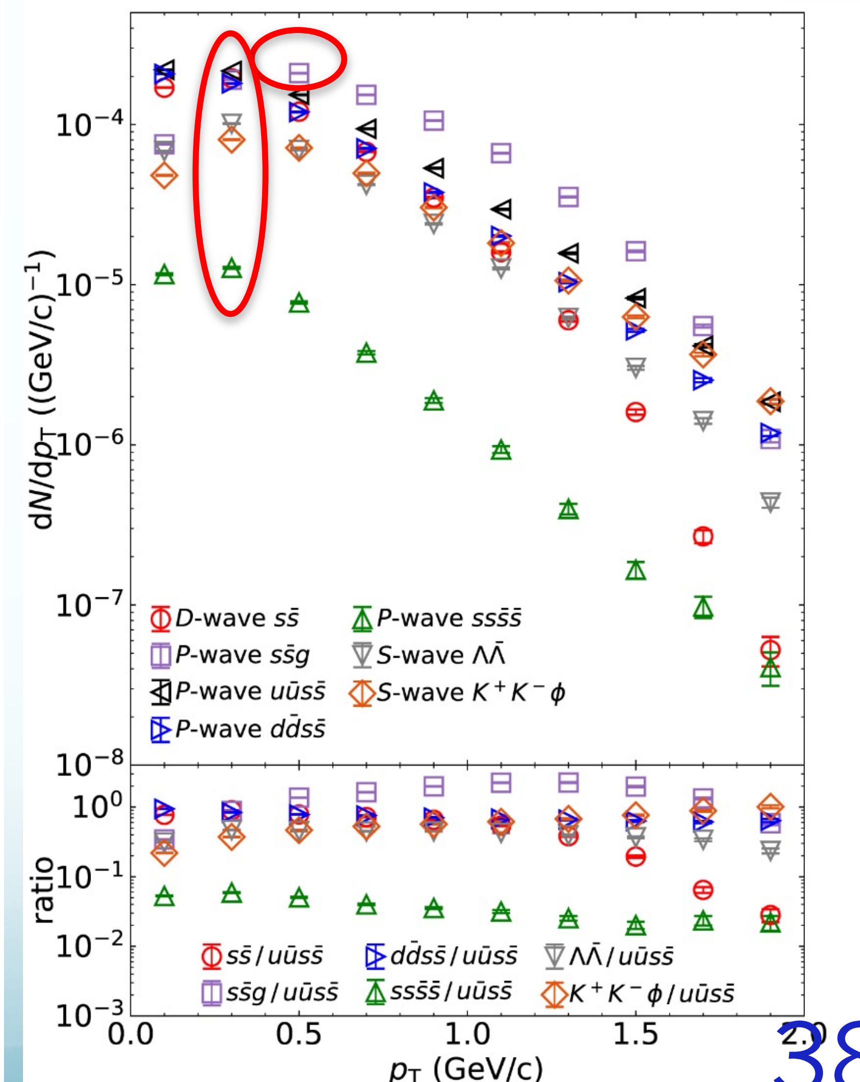
$\phi(2170)$





J. Cao, **W.-C. Zhang***, B. Feng, Y.-H. Hou, A.-K. Lei, Z.-L. She, H. Zheng, L.-L. Zhu, D.-M. Zhou*, Y.-L. Yan, B.-H. Sa*, **arXiv:2607.01075**

Conclusions

- We have investigated the exotic hadron productions in pp collisions at the LHC energy and in e^+e^- collisions at the BESIII energy with PACIAE 4.0.
- Discrepancies between the different configurations of the $X(3872)$, $X(2370)$, $X(2300)$, and $\phi(2170)$ in the yield, rapidity distributions and p_T spectra can be served as a criterion for deciphering the nature of them.
- Discrepancies in the yield, the rapidity and p_T distributions among the $G(3900)$, $Z_c(3900)^0$, and $X(3872)$ could serve as effective criteria to identify them in the $D\bar{D}^*/\bar{D}D^*$ channel from each other.
- For $T^*_{cs0}(2870)^0$, the yields of different hadronic molecular state candidates follow the magnitude order of $D^0K^0_S > D^+K^- > D^{*+}K^{*-} \sim D^{*0}\bar{K}^{*0}$.

Backup

- In the rest frame of the exotic hadron candidate, its orbital angular momentum

$$\boldsymbol{l}^* = \sum_{i=1}^{N} \boldsymbol{x}_i^* \times \boldsymbol{p}_i^*$$

- According to quantum mechanics, the orbital angular momentum is quantized, satisfying the relation

$$\boldsymbol{l}^{*2} = L(L+1)\hbar^2$$

- *L* denotes the orbital angular momentum quantum number of the exotic hadron candidate

$$L = \text{round}\left(\frac{-1 + \sqrt{1 + 4\boldsymbol{l}^{*2}/\hbar^2}}{2}\right)$$

Backup

0.25]. Moreover, in the upper panels of Fig. 2, there is a peak in the first p_{T} bin of 0–0.1 GeV/c. This is because among our simulated final state events of e^+e^- annihilations, aimed on the $D\bar{D}$ production for instance, there are not only two-hadron events of $D+\bar{D}$ but also more than two-hadron events of $D+\bar{D}+\pi^+ + \pi^-$. In the former events, the transverse momentum of D is just opposite to that of $\bar{D}$ leading to the zero transverse momentum of the charmonium-like candidate if the final state photons are neglected, which is responsible for the peaks mentioned in the above rapidity and transverse momentum distributions. The latter events are responsible for the rest of the p_{T} distribution. So far, there is no experimental results of the $X(3872)$, $Z_c(3900)^0$, and $G(3900)$ productions in the $e^+ + e^- \to \pi^+ + \pi^- + D + \bar{D}$ and $e^+ + e^- \to \pi^+ + \pi^- + D + \bar{D}^*$ [56]. Thus, our results could serve as a prediction of these exotic hadron productions in the e^+e^- annihilation processes with four-hadron final states containing a pair of charmed mesons.

Backup

the process of hadronization. Moreover, the peak in the p_{T} distribution for the $\phi\eta'/\phi\eta$ configuration is observed at approximately 0.5 GeV/c, which is notably higher than that of the compact $q\bar{q}s\bar{s}/ss\bar{s}\,\bar{s}\,/s\bar{s}$ state, peaking at around 0.3 GeV/c. This difference is consistent with theoretical expectations based on their distinct internal structures and production mechanisms. ϕ and η'/η are both heavy mesons. Their coproduction as a hadro-strangeonium state requires substantial transverse momentum transfer from the parton shower. As a result, the resulting $X(2300)$ candidate retains this collective transverse boost, shifting its p_{T} peak to a higher value. In contrast, the $q\bar{q}s\bar{s}/ss\bar{s}\,\bar{s}\,/s\bar{s}$ state is assembled directly via the quark recombination in the FPS. Its production does not involve the independent formation and kinematic coordination of two preexisting heavy mesons. It acquires the transverse momentum from the global kick of the parton shower. Although its mass is similar to the hadro-strangeonium state, the absence of the additional coproduction constraint prevents their p_{T} spectrum from being biased toward higher values. Hence,

Backup

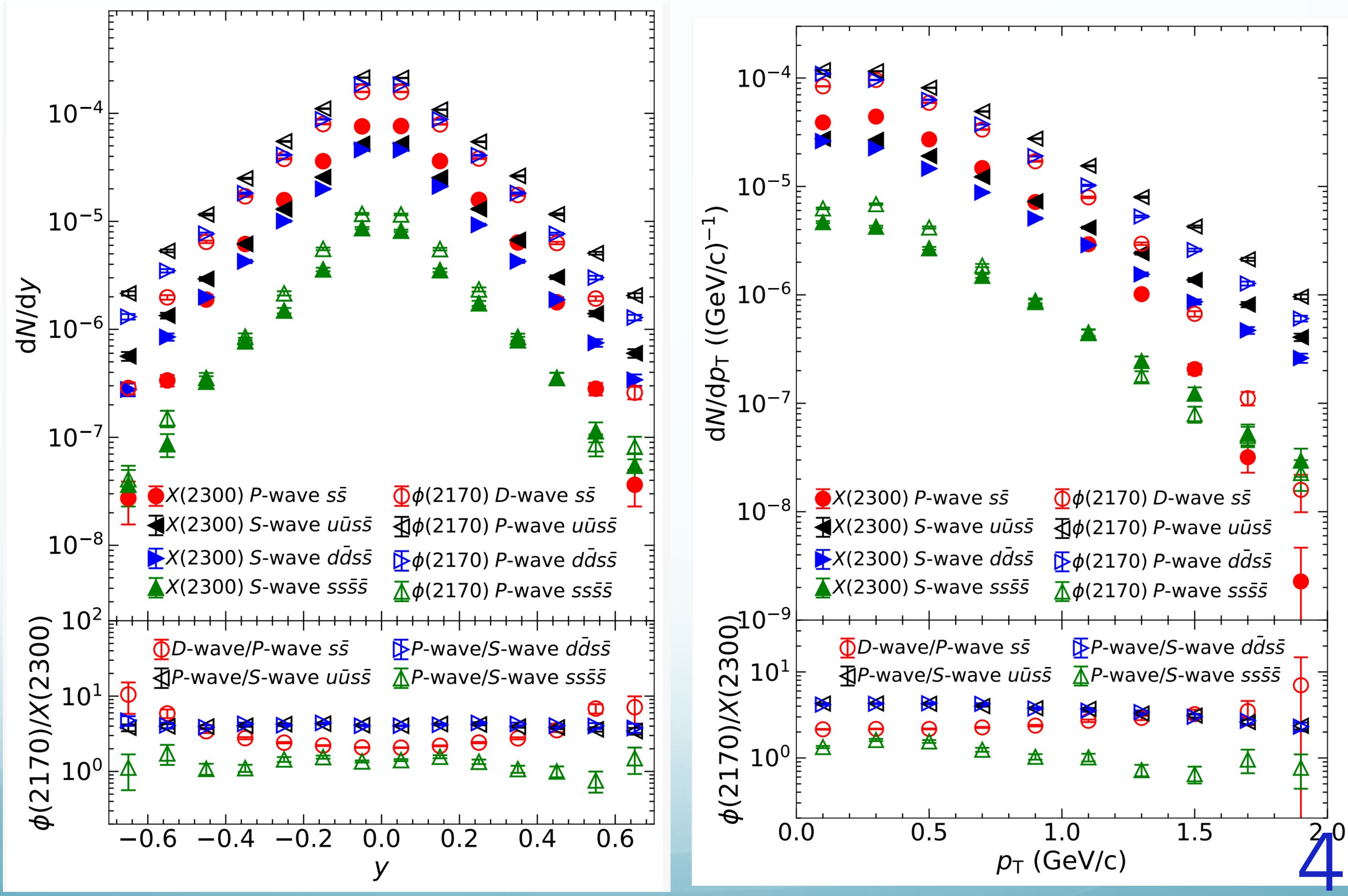
	$s\bar{s}$ $P-wave$	$ss\bar{s}\bar{s}$ $S-wave$	$d\bar{d}s\bar{s}$ $S-wave$	$u\bar{u}s\bar{s}$ $S-wave$
产额	$2.727(\pm 0.011)\times 10^{-5}$	$2.973(\pm 0.037)\times 10^{-6}$	$1.668(\pm 0.009)\times 10^{-5}$	$2.048(\pm 0.010)\times 10^{-5}$

X2300 产额

	$s\bar{s}$ $D-wave$	$ss\bar{s}\bar{s}$ $P-wave$	$d\bar{d}s\bar{s}$ $P-wave$	$u\bar{u}s\bar{s}$ $P-wave$
产额	$6.021(\pm 0.017)\times 10^{-5}$	$4.171(\pm 0.044)\times 10^{-6}$	$6.905(\pm 0.018)\times 10^{-5}$	$8.458(\pm 0.020)\times 10^{-5}$

phi2170 产额（Δm=53MeV）

Backup


dN/dy
X(2300) P-wave $s\bar{s}$
X(2300) S-wave $u\bar{u}s\bar{s}$
X(2300) S-wave $d\bar{d}s\bar{s}$
X(2300) S-wave $s\bar{s}s\bar{s}$
ϕ(2170) D-wave $s\bar{s}$
ϕ(2170) P-wave $u\bar{u}s\bar{s}$
ϕ(2170) P-wave $d\bar{d}s\bar{s}$
ϕ(2170) P-wave $s\bar{s}s\bar{s}$
ϕ(2170)/X(2300)
D-wave/P-wave $s\bar{s}$
P-wave/S-wave $u\bar{u}s\bar{s}$
P-wave/S-wave $d\bar{d}s\bar{s}$
P-wave/S-wave $s\bar{s}s\bar{s}$
y
dN/dp_T ((GeV/c)$^{-1}$)
p_T (GeV/c)

Backup

$D^{*+}K^{*-}$, and $D^{*0}\bar{K}^{*0}$ component meson pairs. It is observed that the yield of $T^{*}_{cs0}(2870)^{0}$ composed of $D^{0}K^{0}_{S}$ is larger than the one composed of $D^{+}K^{-}$, which is consistent with the yields of the constituent particles of $T^{*}_{cs0}(2870)^{0}$ in Table 1. The yields of $T^{*}_{cs0}(2870)^{0}$ composed of $D^{*+}K^{*-}$ and $D^{*0}\bar{K}^{*0}$ are nearly equal, which is attributed to the similar yields of their constituent mesons D^{*+} and D^{*0} as reported in Ref. [59]. The yields of $T^{*}_{cs0}(2870)^{0}$ composed of $D^{*+}K^{*-}$ and $D^{*0}\bar{K}^{*0}$ are lower than the former two. It can be understood by the fact that the productions of inclusive D^{+} (D^{0}) and K^{-} (K^{0}_{S}) are larger than those of D^{*+} (D^{*0}) and K^{*-} ($\bar{K}^{*0}$). Meanwhile, the yield of $T^{*}_{cs0}(2870)^{0}$ increases with the increasing of the R_0 range from $1.0\,\text{fm} < R_0 < 2.0$ to $1.0\,\text{fm} < R_0 < 3.0\,\text{fm}$, and to $1.0\,\text{fm} < R_0 < 5.0\,\text{fm}$, as expected.

Backup

cedure described in Section II. Given that $\phi(2170)$ has quantum numbers $J^{PC} = 1^{--}$ [27], several interpretations are possible: a D-wave $s\bar{s}$ state, a P-wave $s\bar{s}g$ hybrid, a P-wave $u\bar{u}s\bar{s}/d\bar{d}s\bar{s}/s\bar{s}s\bar{s}$ tetraquark, an S-wave $\bar{\Lambda}\Lambda$ bound state, or an S-wave ϕK^+K^- resonance state. For the excited strangeonium interpretation, an S-wave 3^3S_1 configuration has also been proposed [38–40]. However, as pointed out in Refs. [29, 37], this 3^3S_1 assignment is disfavored because it predicts a rather large width of about 380 MeV [38], which exceeds the experimental upper limit of about 100 MeV [28, 35]. In contrast, the 2^3D_1 assignment yields a total width of approximately 186 MeV, which is consistent with the estimate in Ref. [29]. Therefore, for the excited strangeonium scenario, we retain only the D-wave configuration. For the $\bar{\Lambda}\Lambda$ bound state and the ϕK^+K^- resonance, D-wave configurations could also yield $J^{PC} = 1^{--}$. Nevertheless, as discussed in Refs. [51–55], $\phi(2170)$ is most favorably interpreted as a $^3S_1$ $\bar{\Lambda}\Lambda$ bound state or an S-wave ϕK^+K^- resonance. Consequently, D-wave configurations for these two scenarios are not considered in this work.