Production of the glueball-like particle $X(2370)$ in e^+e^- and pp collisions with PACIAE model

An-Ke Lei (雷安科)
Central China Normal University (CCNU)

In collaboration with

Zhi-Lei She, Dai-Mei Zhou, Yu-Liang Yan,

Wen-Chao Zhang, Hua Zheng, Ben-Hao Sa

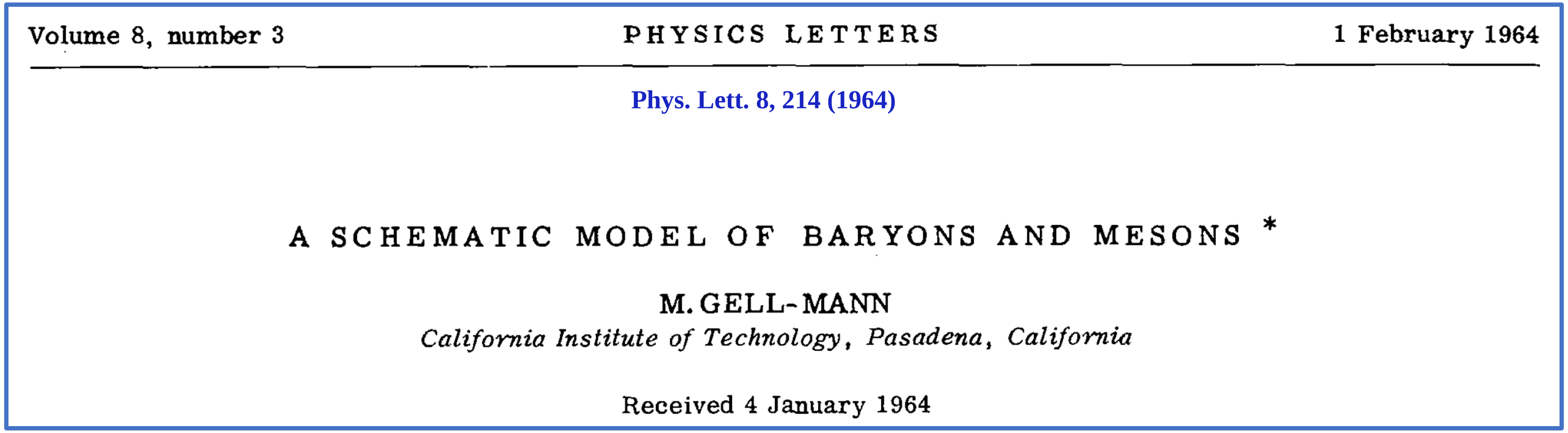
Based on
arXiv:2407.07661 and arXiv:2408.04130

OUTLINE

1. Introduction to the exotic particle $X(2370)$
2. PACIAE + DCPC model
3. Results
4. Summary

Hadrons in the naive quark model

- 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 *

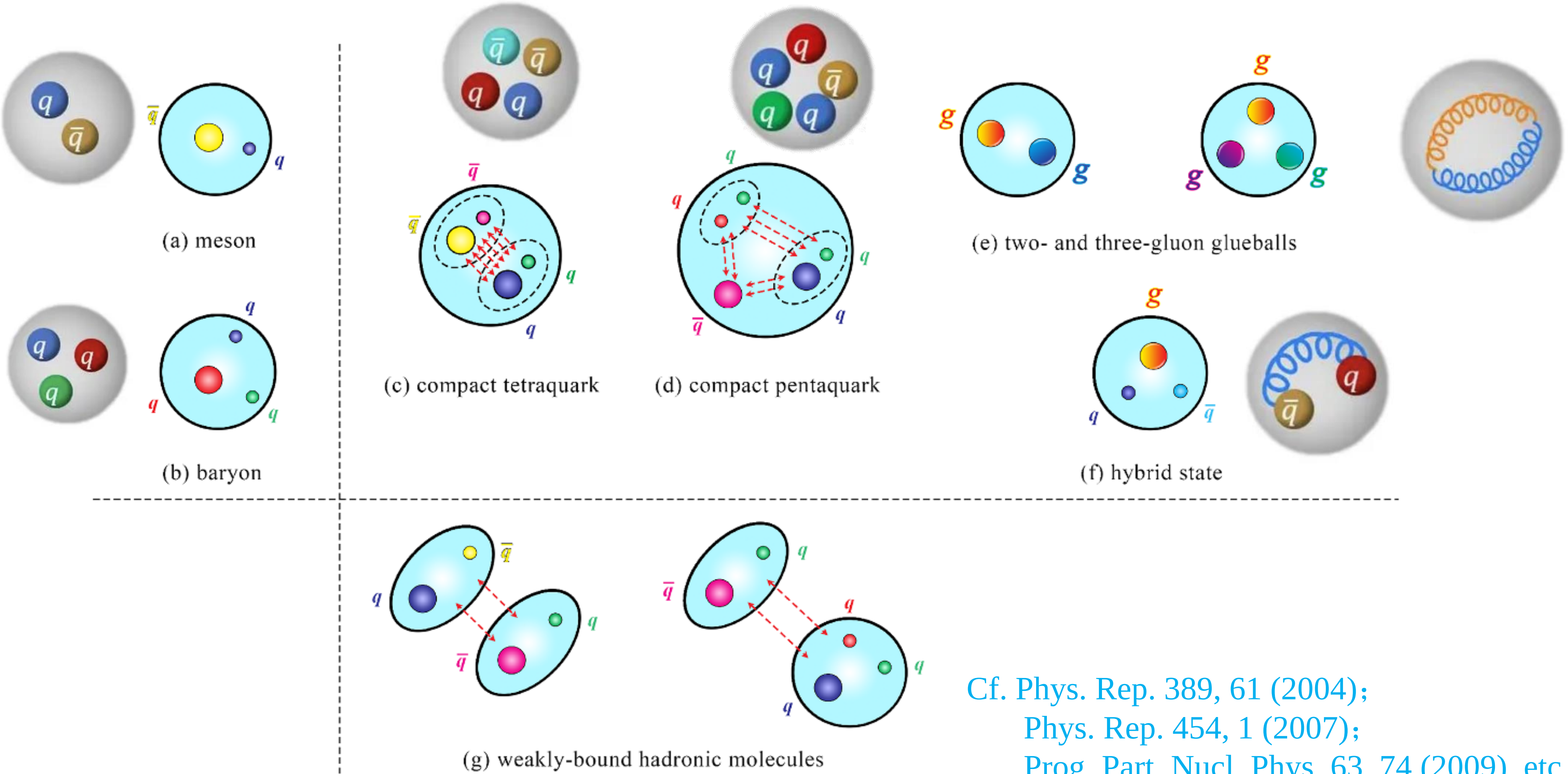
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

"Ordinary" hadrons:

Exotic Hadrons

- The quantum chromodynamics (QCD) permits the existence of other types of hadrons (color-neutral / colorless).

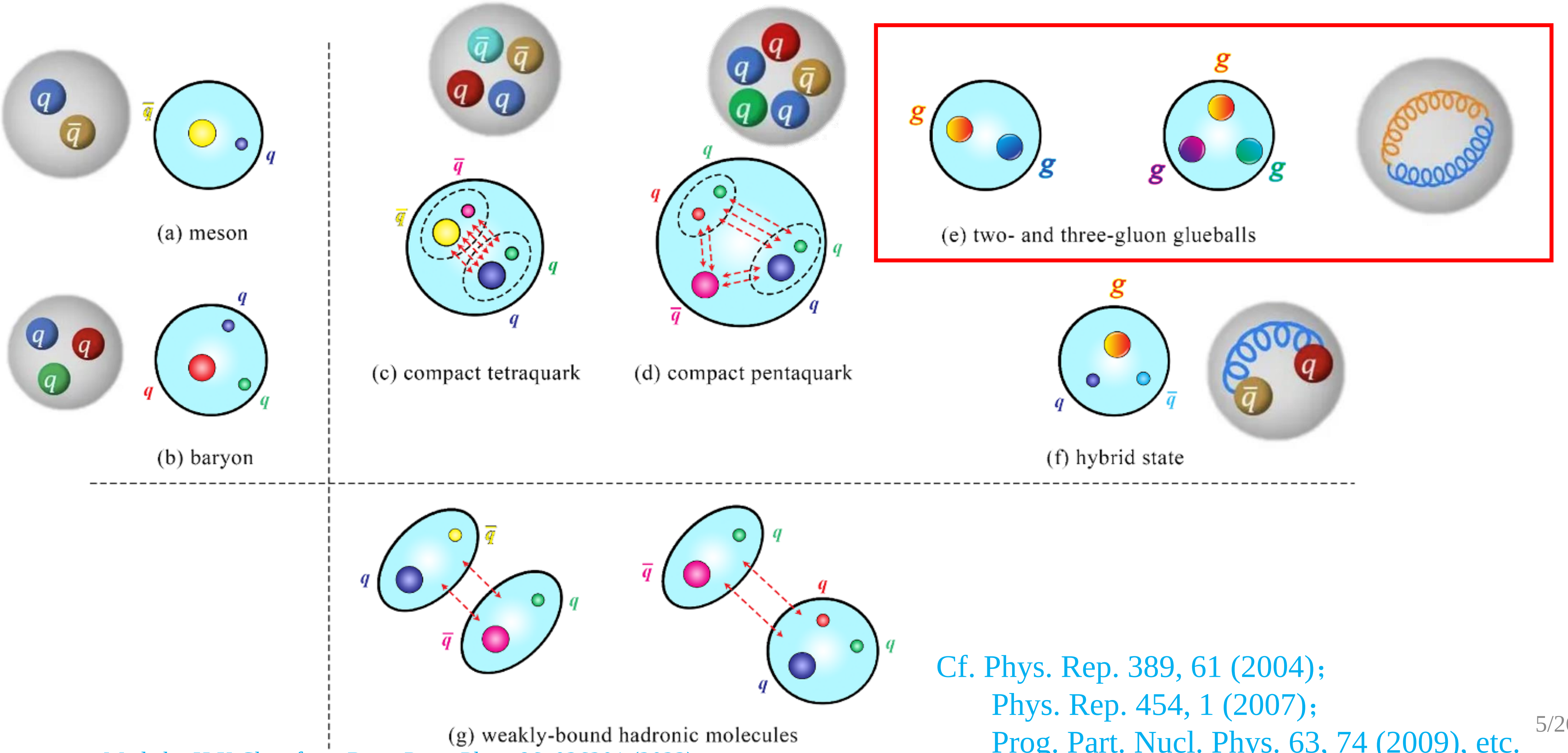


Made by H.X Chen from Rept. Prog. Phys. 86, 026201 (2023)

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

Exotic Hadrons

- The quantum chromodynamics (QCD) permits the existence of other types of hadrons (color-neutral / colorless).

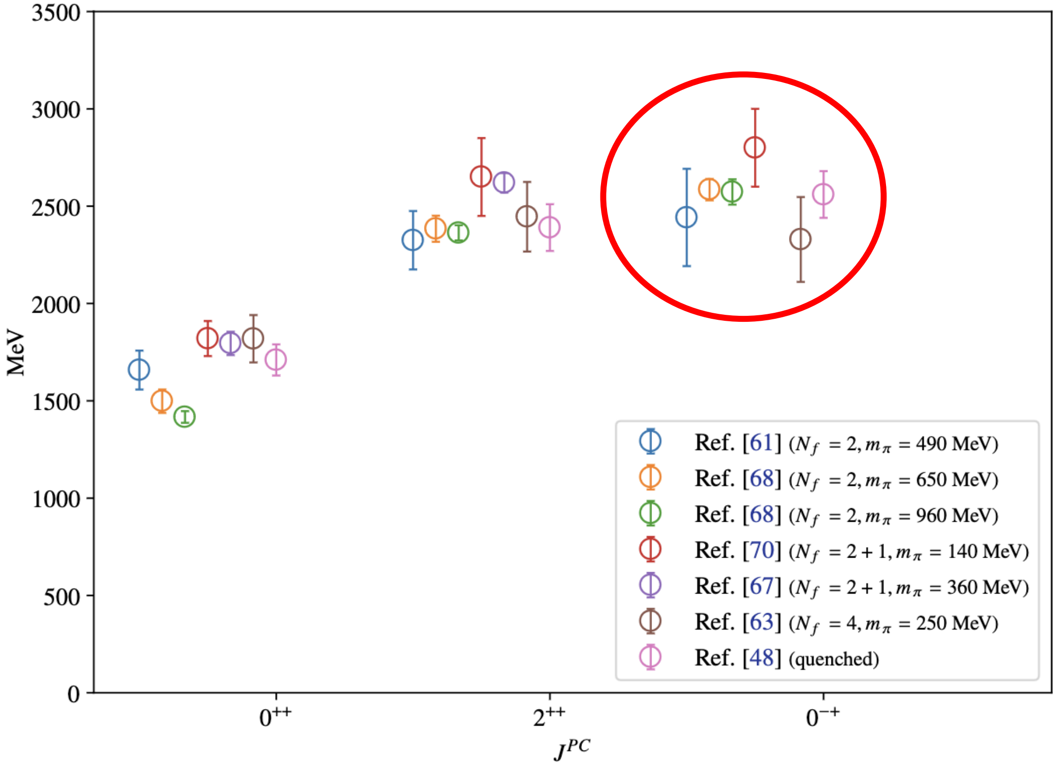


Made by H.X Chen from Rept. Prog. Phys. 86, 026201 (2023)

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

Glueball hunting

Lattice QCD predictions:



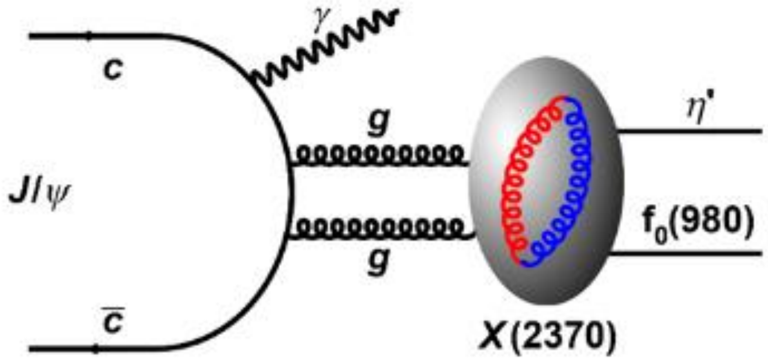
0^{++} ground state: 1.5 - 1.7 GeV/c^2

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)

Glueball hunting

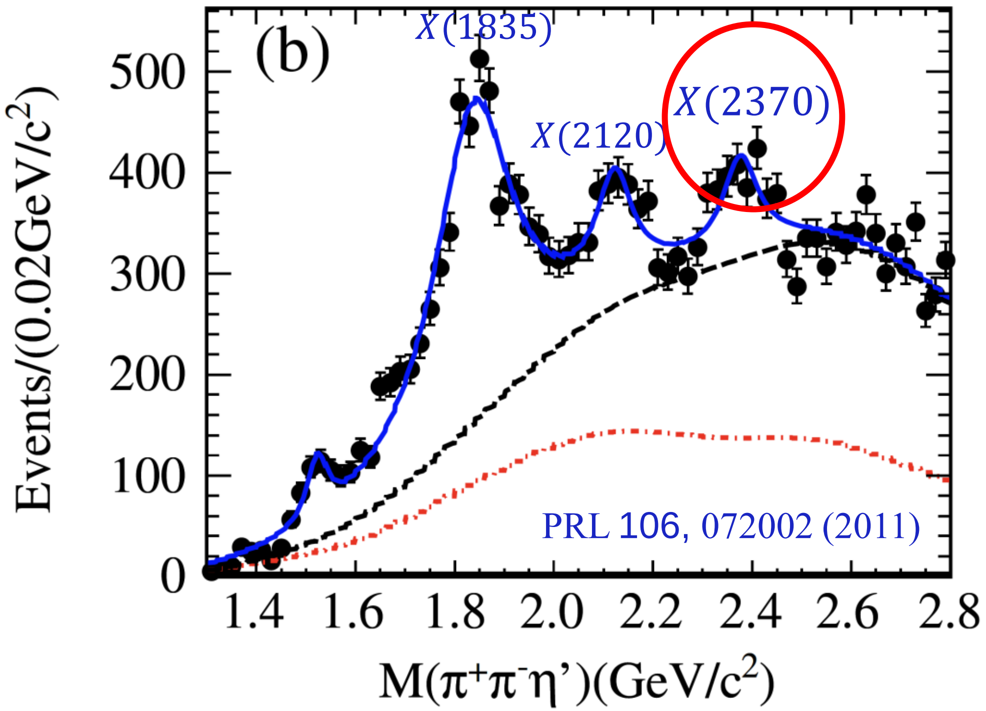


- Experimental measurements:
  mostly in *gluon-rich radiative decays* from
  J/ψ in the e^+e^- collisions.

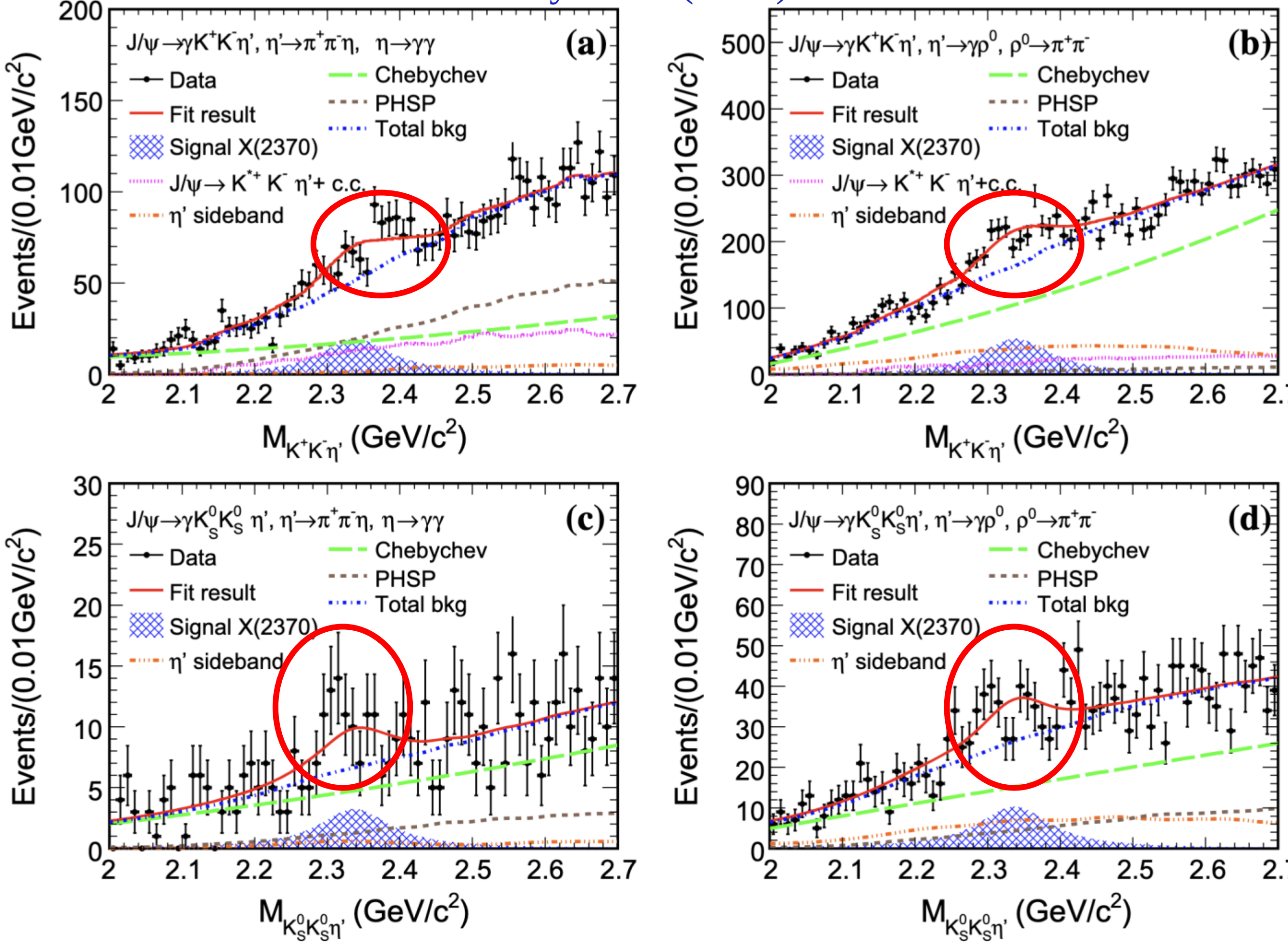
- *Glueball candidates*: the scalar mesons $f_0(1500)$ and $f_0(1710)$, the tensor meson $f_2(2340)$, and the pseudoscalar meson $X(2370)$.

- Among them, the $X(2370)$ is a good candidate for the 0^{-+} glueball, as its mass, production and decay properties are consistent with the LQCD prediction.

Glueball hunting



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



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

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

Glueball hunting

PHYSICAL REVIEW LETTERS **132,** 181901 (2024)

Editors' Suggestion

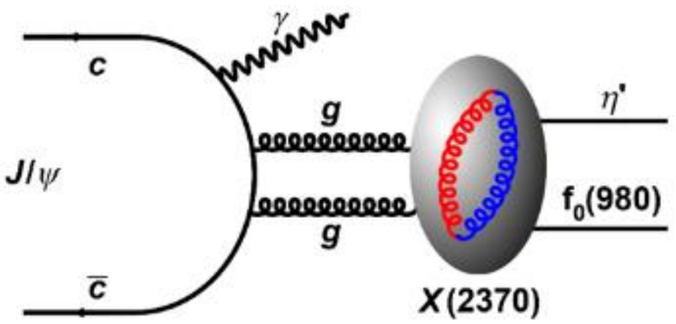
Determination of Spin-Parity Quantum Numbers of $X(2370)$ as 0^{-+} from $J/\psi \to \gamma K_S^0 K_S^0 \eta'$

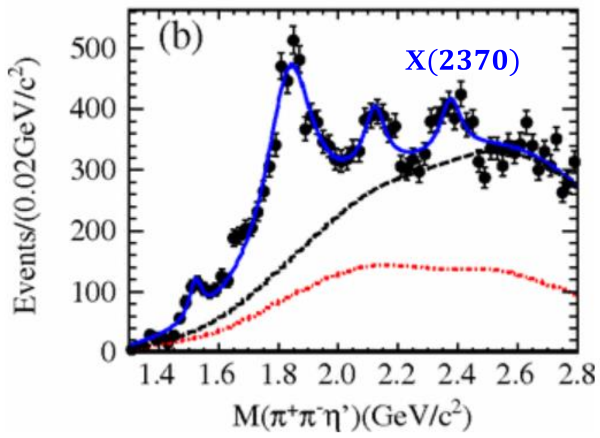
M. Ablikim *et al.*[*]
(BESIII Collaboration)

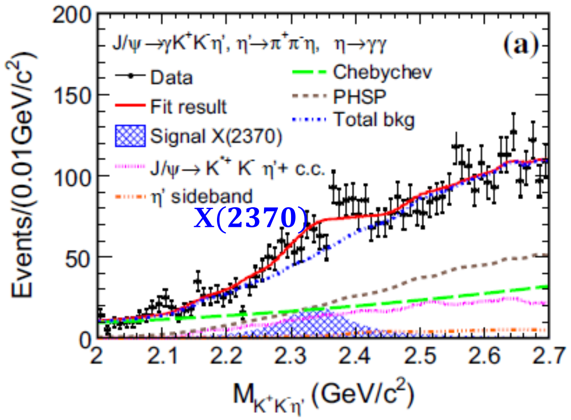
(Received 8 December 2023; revised 5 March 2024; accepted 28 March 2024; published 2 May 2024)

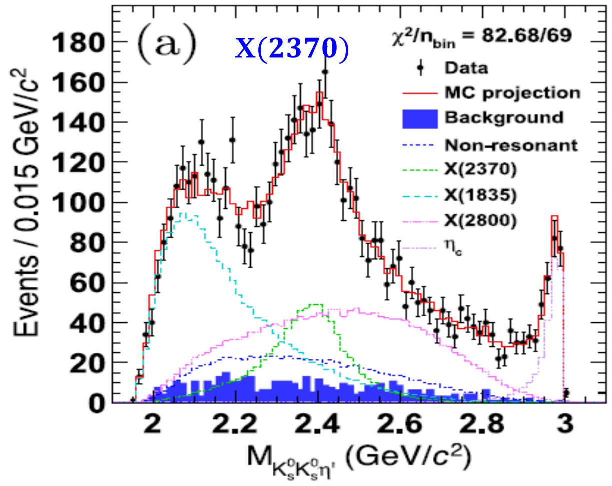
Based on $(10087 \pm 44) \times 10^6$ J/ψ events collected with the BESIII detector, a partial wave analysis of the decay $J/\psi \to \gamma K_S^0 K_S^0 \eta'$ is performed. The mass and width of the $X(2370)$ are measured to be $2395 \pm 11(\text{stat})^{+26}_{-94}(\text{syst})$ MeV$/c^2$ and $188^{+18}_{-17}(\text{stat})^{+124}_{-33}(\text{syst})$ MeV, respectively. The corresponding product branching fraction is $\mathcal{B}[J/\psi \to \gamma X(2370)] \times \mathcal{B}[X(2370) \to f_0(980)\eta'] \times \mathcal{B}[f_0(980) \to K_S^0 K_S^0] = (1.31 \pm 0.22(\text{stat})^{+2.85}_{-0.84}(\text{syst})) \times 10^{-5}$. The statistical significance of the $X(2370)$ is greater than 11.7σ and the spin parity is determined to be 0^{-+} for the first time. The measured mass and spin parity of the $X(2370)$ are consistent with the predictions of the lightest pseudoscalar glueball.

$X(2370)$ at BESIII most recently!









Interpretations of $X(2370)$

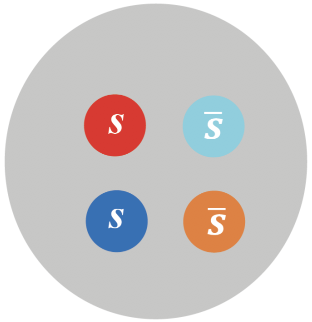
- Fourth radial excitation of η/η'.

TABLE I. The pseudoscalar nonet.

$1S$	$2S$	$3S$	$4S$	$5S$
$\eta,\ \eta'$	$\eta(1295)$	$\eta(1760)$	$X(2120)$	$X(2370)$
	$\eta(1475)$	$X(1835)$		
$K(494)$	$K(1460)$	$K(1830)$		
π	$\pi(1300)$	$\pi(1800)$		

PRD 83, 114007 (2011)； PRD 102, 114034 (2020)

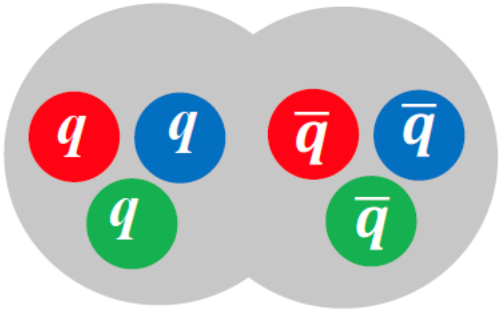
- P-wave $ss\bar{s}\bar{s}$ tetraquark states of $J^{PC} = 0^{-+}$.

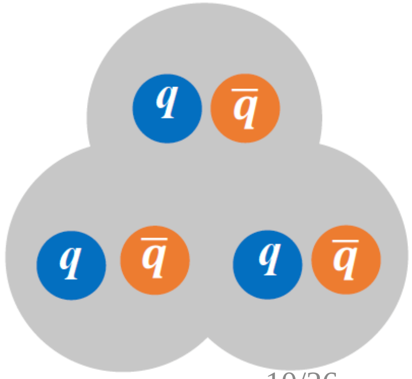


PRD 106, 014023 (2022)

- Light baryonium states $\Lambda - \bar{\Lambda}$ / $\Sigma - \bar{\Sigma}$ or three-meson states $\pi^+\pi^-\eta'$ / $K^+K^-\eta'$ / $K_s^0 K_s^0 \eta'$.

J^{PC}	$N-\bar{N}$	$\Lambda-\bar{\Lambda}$	$\Sigma-\bar{\Sigma}$	$\Xi-\bar{\Xi}$
0^{-+}	$\pi\pi\pi$ $\pi\pi\eta$ $\pi\pi\eta'$	$\Lambda\bar{\Lambda}$ $\pi\pi\eta$ $\pi\pi\eta'$ πKK	$\Sigma\bar{\Sigma}$ $\pi\pi\eta$ $\pi\pi\eta'$ πKK	$\Xi\bar{\Xi}\ \eta KK$ $\eta\eta\pi\ \eta' KK$ $\eta'\eta'\pi$ $\eta\eta'\pi$
1^{--}	$\pi\pi\omega$ $\pi\pi\phi$	$\Lambda\bar{\Lambda}$ $\pi\pi\omega$ $\pi\pi\phi$ $\pi K^* K^*$	$\Sigma\bar{\Sigma}$ $\pi\pi\omega$ $\pi\pi\phi$ $\pi K^* K^*$	$\Xi\bar{\Xi}\ \omega KK$ $\phi\phi\pi\ \phi KK$ $\omega\omega\pi$ $\omega\phi\pi$

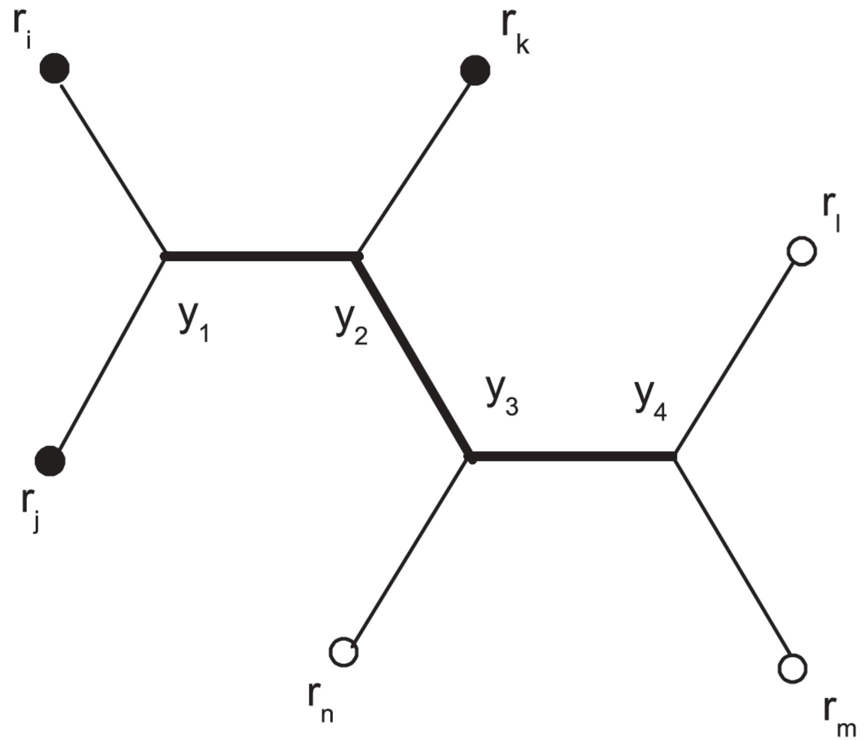




PRD 105, 014016 (2022)

Interpretations of *X*(2370)

- Nonstrange hexaquark state



PRD 86, 014008 (2012)

- Pseudoscalar glueball

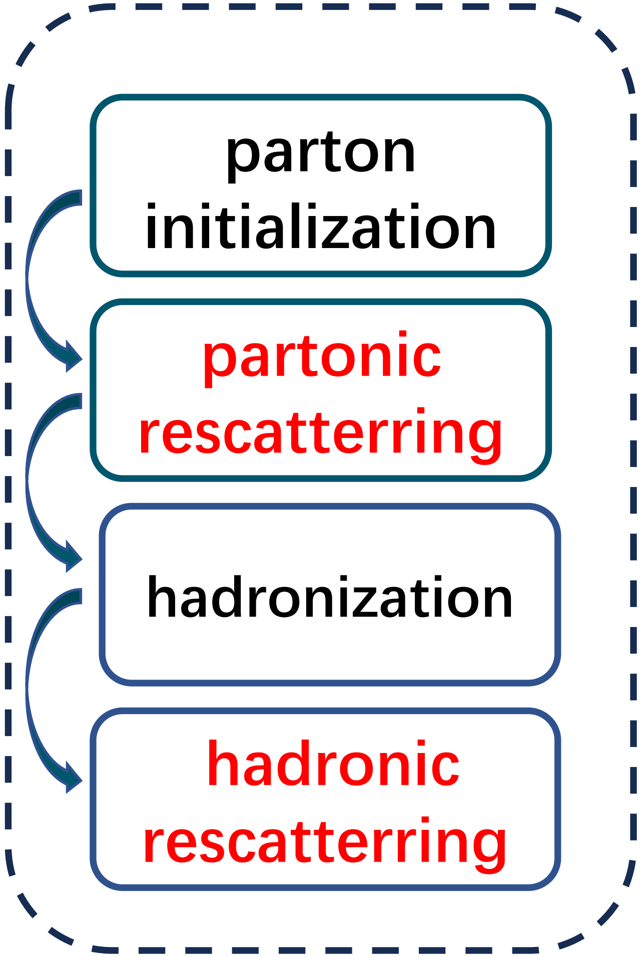
Phys. Rev. D 100, 054511 (2019); PRD 82, 074026 (2010);
PRD 87, 054036 (2013); Phys. Lett. B 827, 136960 (2022);
Nucl. Phys. A 728 (2003) 165–181;
Phys. Lett. B 642 (2006) 53–61.

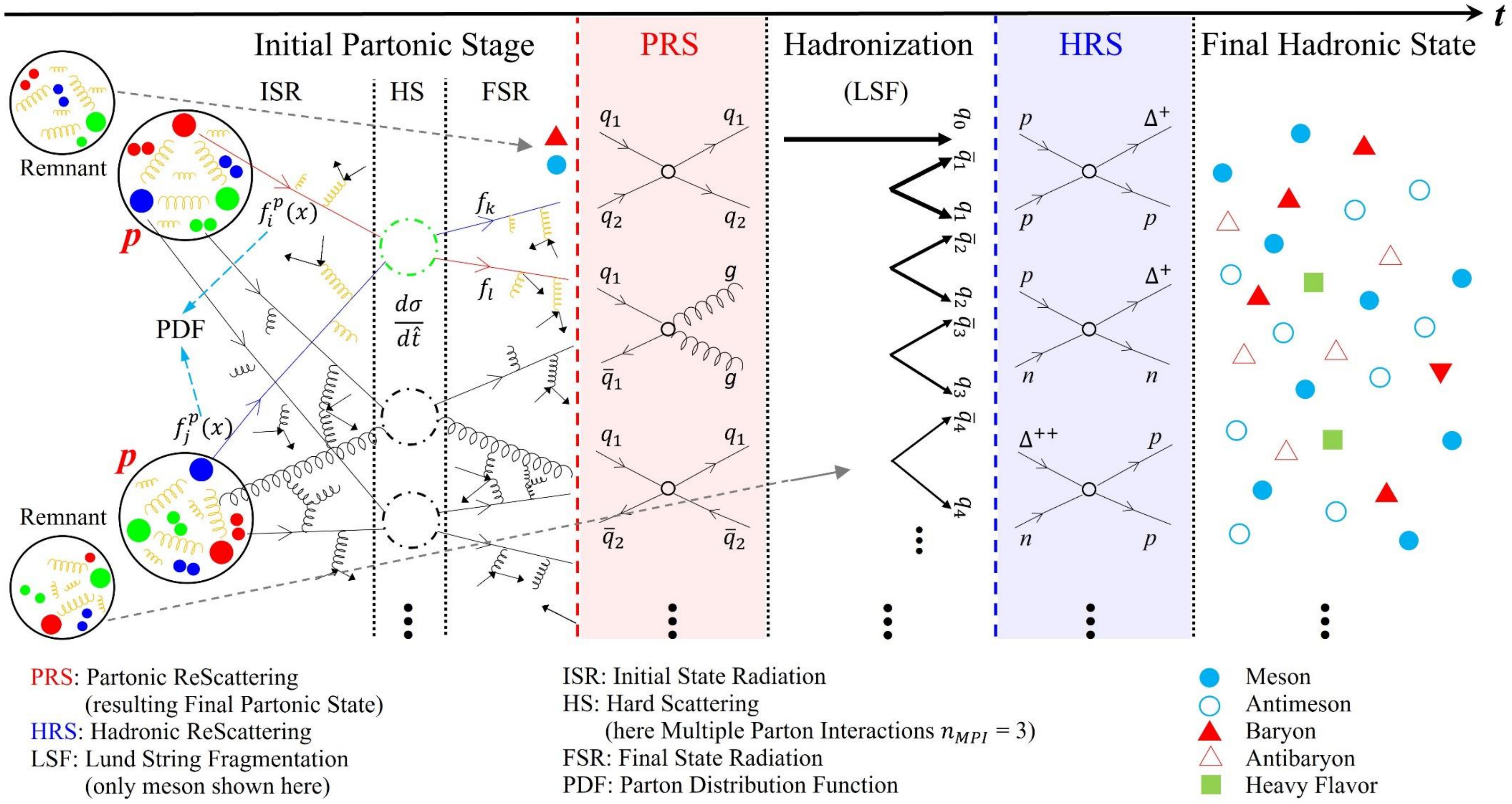
However, the consensus on its nature is still lacking indeed.

PACIAE + DCPC model

PACIAE (*Parton And-hadron China Institute of Atomic Energy*):

A microscopic parton and hadron transport model (event generator)





Open source: https://github.com/ArcsaberHep/PACIAE

PACIAE + DCPC model

DCPC: a *Dynamically Constrained Phase-space Coalescence* model

In quantum statistical mechanics, the yield of N-particle cluster in six-dimensional phase space can be estimated by

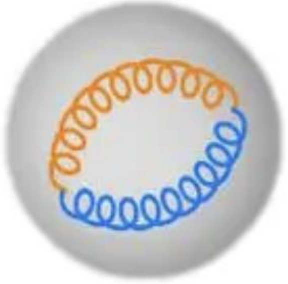
$$Y_N = \int \cdots \int \frac{d\overrightarrow{q_1}d\overrightarrow{p_1} \cdots d\overrightarrow{q_N}d\overrightarrow{p_N}}{h^{3N}}$$

If the cluster could exist naturally, two-gluon cluster of gg for instance, the yield can be calculated by

$$Y_{gg} = \frac{1}{2!}\int \cdots \int \delta_{12} \frac{\prod_{i=1}^{i=2} d\vec{q}_i d\vec{p}_i}{h^6}$$

(1/2! for identical particles)

with constraints:



component constraint if [$1 \equiv g, 2 \equiv g$], $\delta_{12} = 1$; otherwise $\delta_{12} = 0$

spatial coordinate constraint $|\vec{q}_{ij}| = |\vec{q}_i - \vec{q}_j| \le R_0, (i \ne j;\ i,j = 1,2),\ R_0 = 1$ fm

Momentum constraint $m_{X(2370)} - \Delta m \le m_{inv} \le m_{X(2370)} + \Delta m$; $m_{X(2370)} = 2395\ \mathrm{MeV/c^2}, \Delta m = \frac{\Gamma}{2} = 94\ \mathrm{MeV}/c^2$.

PACIAE + DCPC model

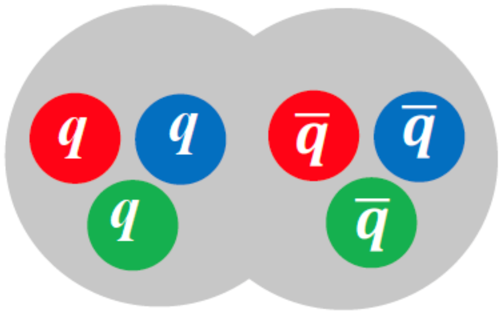
DCPC: a *Dynamically Constrained Phase-space Coalescence* model

In quantum statistical mechanics, the yield of N-particle cluster in six-dimensional phase space can be estimated by

$$Y_N = \int \cdots \int \frac{d\vec{q_1} d\vec{p_1} \cdots d\vec{q_N} d\vec{p_N}}{h^{3N}}$$

If the cluster could exist naturally, $B - \bar{B}$ molecular-state for instance, the yield can be calculated by

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



with constraints:

component constraint if $[\,1 \equiv \Lambda\,(\Sigma), 2 \equiv \bar{\Lambda}\,(\bar{\Sigma})]$, $\delta_{12} = 1$; otherwise $\delta_{12} = 0$

spatial coordinate constraint $1\ \text{fm} \leq |\vec{q}_{ij}| = |\vec{q}_i - \vec{q}_j| \leq 2\ \text{fm}$, $(i \neq j;\ i, j = 1,2)$

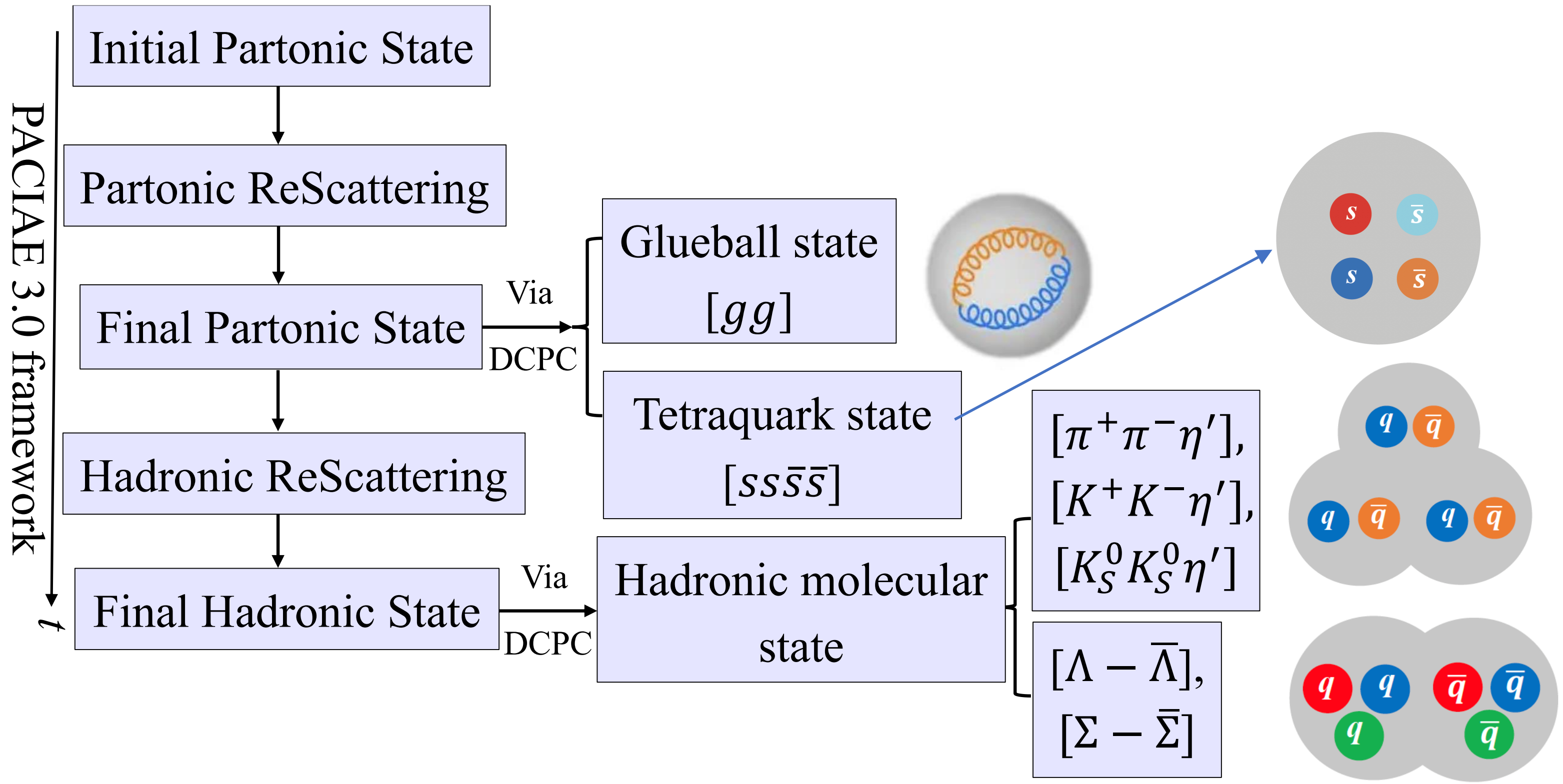
Momentum constraint $m_{X(2370)} - \Delta m \leq m_{inv} \leq m_{X(2370)} + \Delta m$; $m_{X(2370)} = 2395\ \text{MeV/c}^2$, $\Delta m = \frac{\Gamma}{2} = 94\ \text{MeV}/c^2$.

PACIAE + DCPC model

PACIAE+DCPC model has successfully described exotics production ($X(3872)$, $Z_c(3900)$, P_c states, etc.).

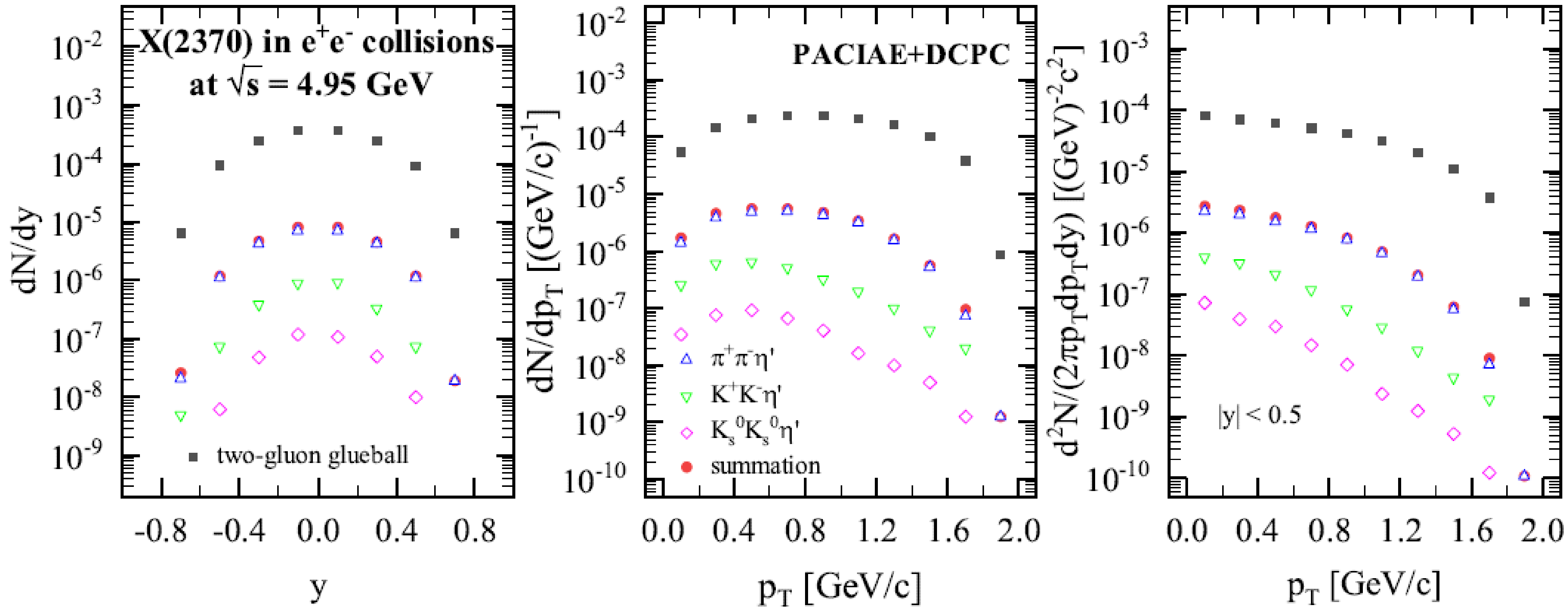
EPJC 81, 784 (2021); EPJC 81,198 (2021); PRD 105, 054013 (2022);
PRD 107,114022 (2023) , PRC 110, 014910 (2024)…

In this work, three scenarios of $X(2370)$ are considered: the two-gluon glueball-state, tetraquark-state and the molecular-states composed of baryon-antibaryon or three mesons.



$X(2370)$ production in e^+e^- at BESIII energy

y and p_T single, with p_T and y double differential distributions:

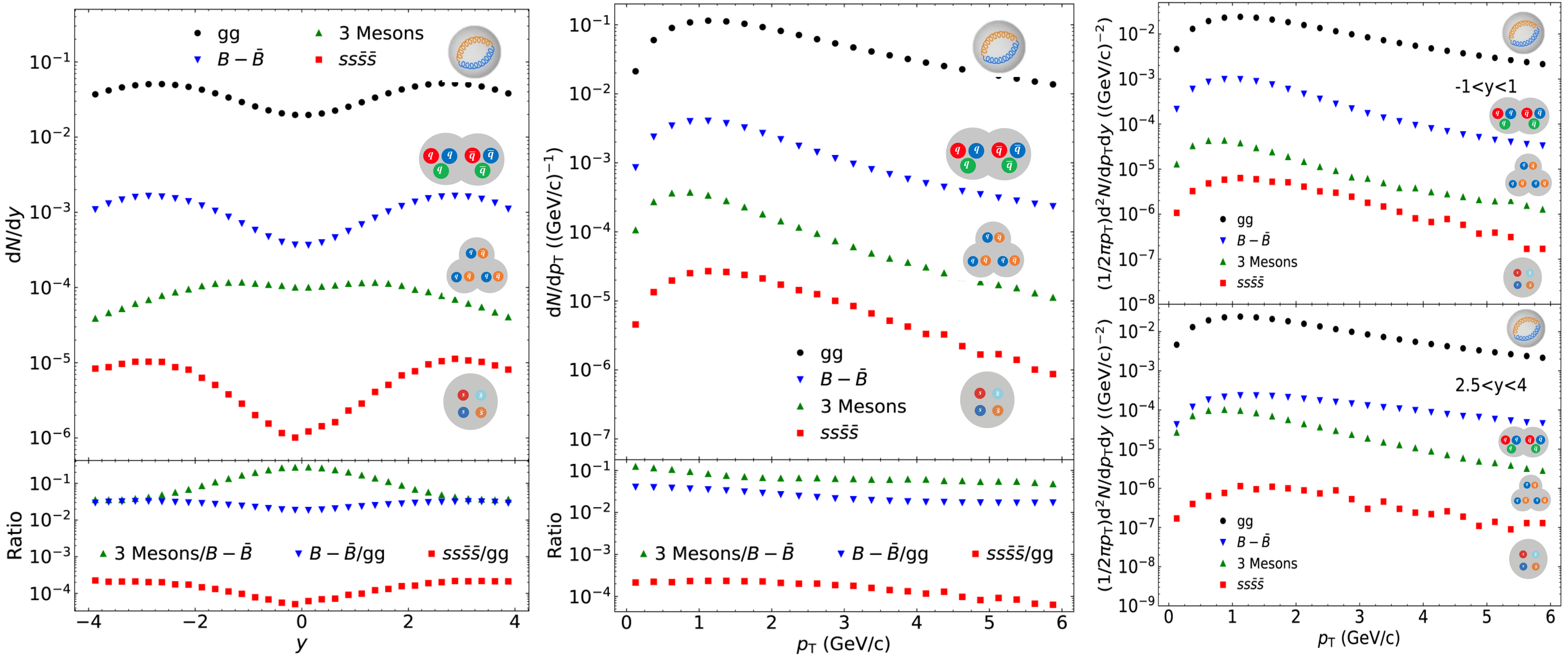


An ordering of $\pi^+\pi^-\eta' > K^+K^-\eta' > K_S^0K_S^0\eta'$, which is consistent with the ordering shown in $X(2370)$ radiative decay branching fraction.

 EPJC 80, 746 (2020); PRD 87, 054036 (2013)

$X(2370)$ production in pp at LHC energy

pp collisions at $\sqrt{s} = 13$ TeV



Summary

- Inspired by the newest BESIII observation of $X(2370)$ glueball-like particle production in e^+e^- collisions, we have studied its production in e^+e^- and pp collisions at BESIII and LHC energies.
- Discrepancies between glueball-, tetraquark- and molecular-state of the $X(2370)$ in the basic observables (yield, p_T spectra, rapidity distribution, etc.).
- They may serve as distinguishing criteria to identify the nature of the $X(2370)$.

Next: pA and AA collisions at both RHIC and LHC energies.

Other observables, R_{AA}, v_2 , correlations…

Thanks!

Backup

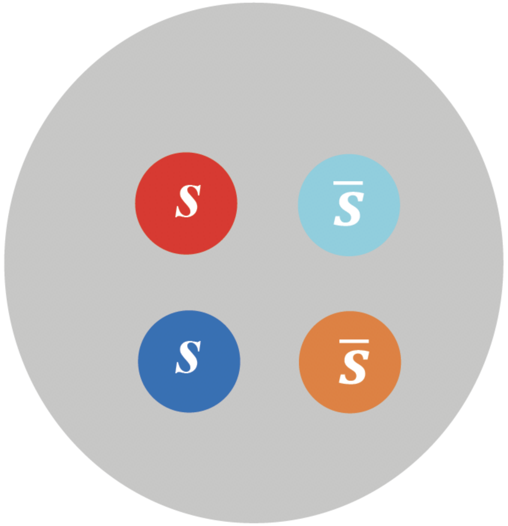
In quantum statistical mechanics, the yield of N-particle cluster in six-dimensional phase space can be estimated by

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

For the tetraquark-state, its yield reads as

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

$$\delta_{1234} = \begin{cases} 1. & if\ 1 = s, 2 = s, 3 = \bar{s}, 4 = \bar{s}, R \leq 1fm \\ & m_{X(2370)} - \Delta m < m_{inv} < m_{X(2370)} - \Delta m \\ 0. & \text{otherwise} \end{cases}$$



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

Backup

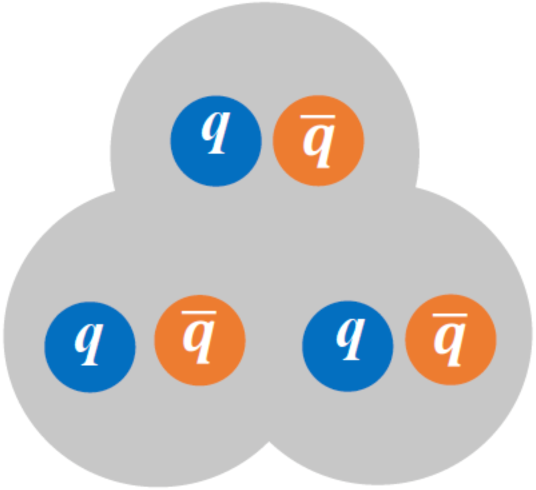
In quantum statistical mechanics, the yield of *N*-particle cluster in six-dimensional phase space can be estimated by

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

For the 3-meson molecular-state, its yield reads as

$$Y_{3-meson} = \int \cdots \int \delta_{123} \frac{d\vec{q}_1 d\vec{p}_1 d\vec{q}_2 d\vec{p}_2 d\vec{q}_3 d\vec{p}_3}{h^9}$$

$$\delta_{123} = \begin{cases} 1. & \begin{matrix} if\ 1 = \pi^+(K^+, K_S^0), 2 = \pi^-(K^+, K_S^0), 3 = \eta' \\ m_{X(2370)} - \Delta m < m_{inv} < m_{X(2370)} - \Delta m \\ 1fm \leq R \leq 2fm \end{matrix} \\ 0. & \text{otherwise} \end{cases}$$

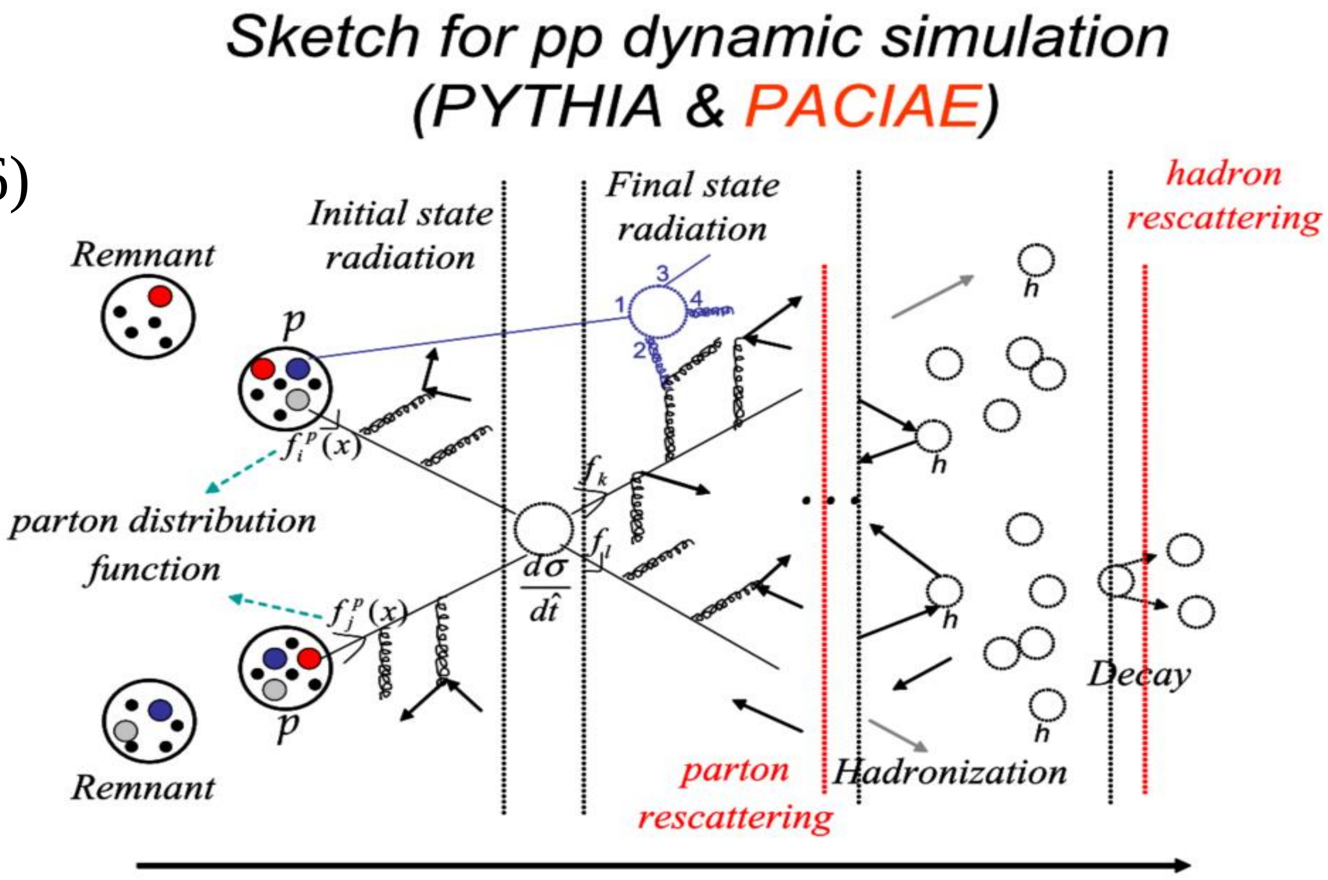


$\Delta m = \frac{\Gamma}{2} = 94\ \mathrm{MeV}/c^2$, R is the radius of the cluster.

PACIAE model: Ver. 2.0

PACIAE: *Parton And-hadron CIAE*
a microscopic parton and hadron transport model (based on PYTHIA 6)

parton initialization → *partonic rescatterring* → *hadronization* → *hadronic rescatterring*

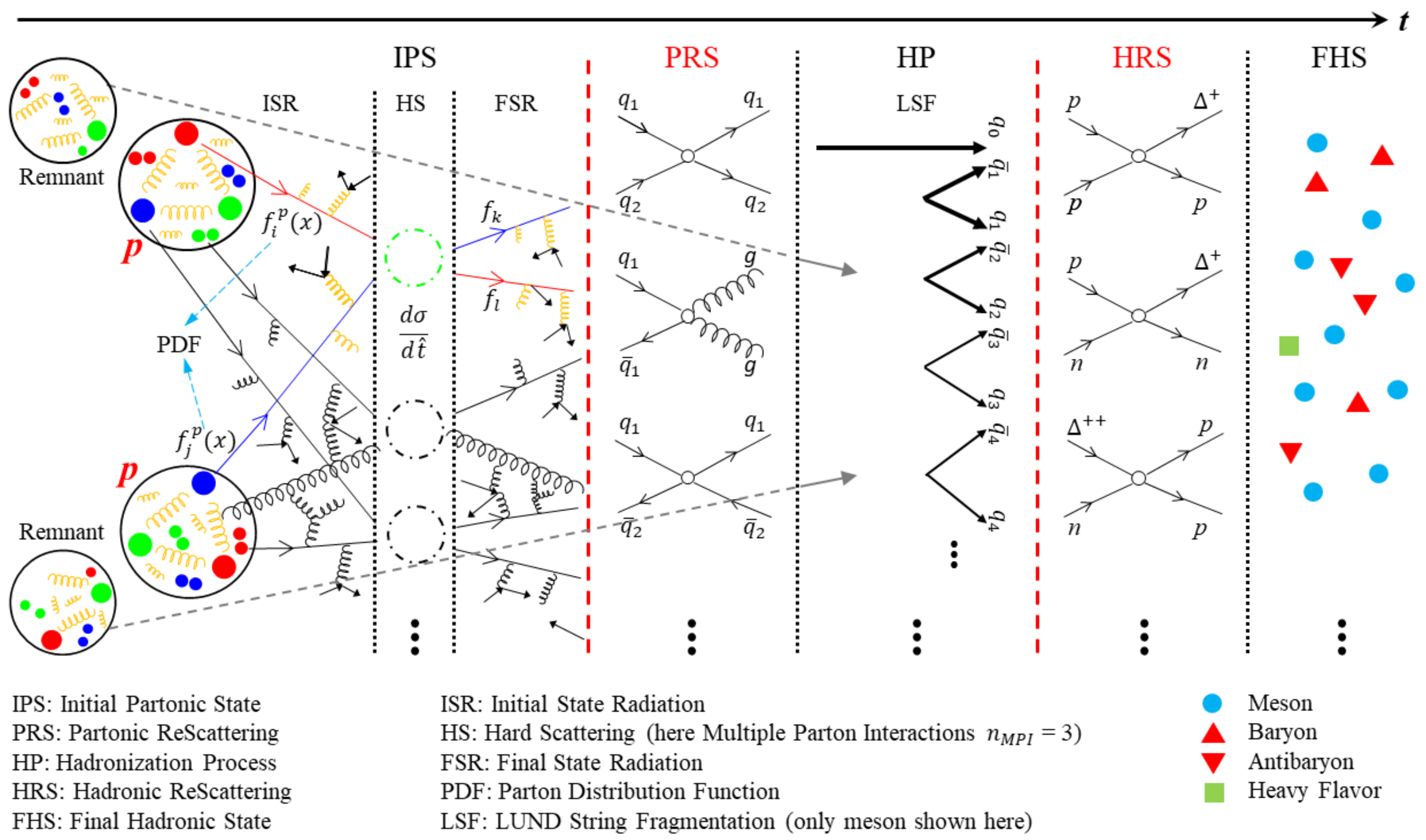


π, K, p, n, $\rho(\omega)$, Δ, Λ, Σ, Ξ, Ω, J/ψ → *hadronic rescatterring*

PACIAE model: Ver. 3.0

PACIAE: *Parton And-hadron CIAE*

a microscopic parton and hadron transport model (based on PYTHIA 6)



parton initialization

partonic rescatterring

hadronization

hadronic rescatterring

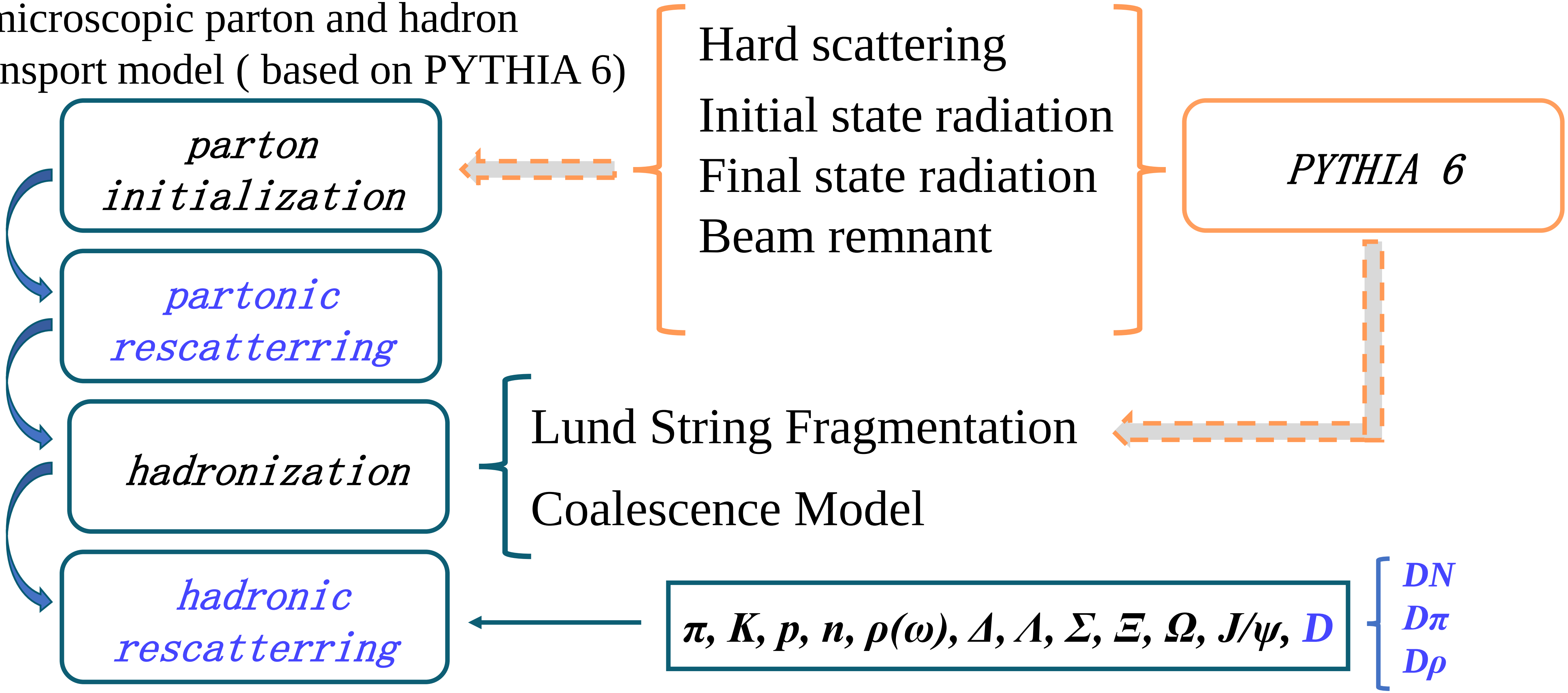
π, K, p, n, ρ(ω), Δ, Λ, Σ, Ξ, Ω, J/ψ, D

DN
Dπ
Dρ

PACIAE model: Ver. 3.0

PACIAE: *Parton And-hadron CIAE*

a microscopic parton and hadron transport model (based on PYTHIA 6)



PACIAE model: Ver. 4.0

PACIAE: *Parton And-hadron CIAE*

a microscopic parton and hadron transport model (based on PYTHIA 6/8)

- *parton initialization*
- *partonic rescatterring*
- *hadronization*
- *hadronic rescatterring*

PYTHIA 6 / 8:

- Hard scattering
- Initial state radiation
- Final state radiation
- Beam remnant
- Color reconnection

hadronization:

- Lund String Fragmentation
  - Flavor rope
  - String shoving
  - Thermodynamical string fragmentation
- Coalescence Model

hadronic rescatterring:

- ***π, K, p, n, ρ(ω), Δ, Λ, Σ, Ξ, Ω, J/ψ, D***
- ***PYTHIA 8 hadron rescattreing***

PACIAE model