Identifying X(3872) tetraquark-state or molecule-state in PACIAE model

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on behalf of

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Mainly based on papers :
arXiv:2402.16736; PRC 108, 064909 (2023)

Outline

- Introduction of exotic X(3872)
- PACIAE model studying X(3872)
- Proposed identifying criteria
- Summary and Outlook

Exotics in the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

Received 4 January 1964

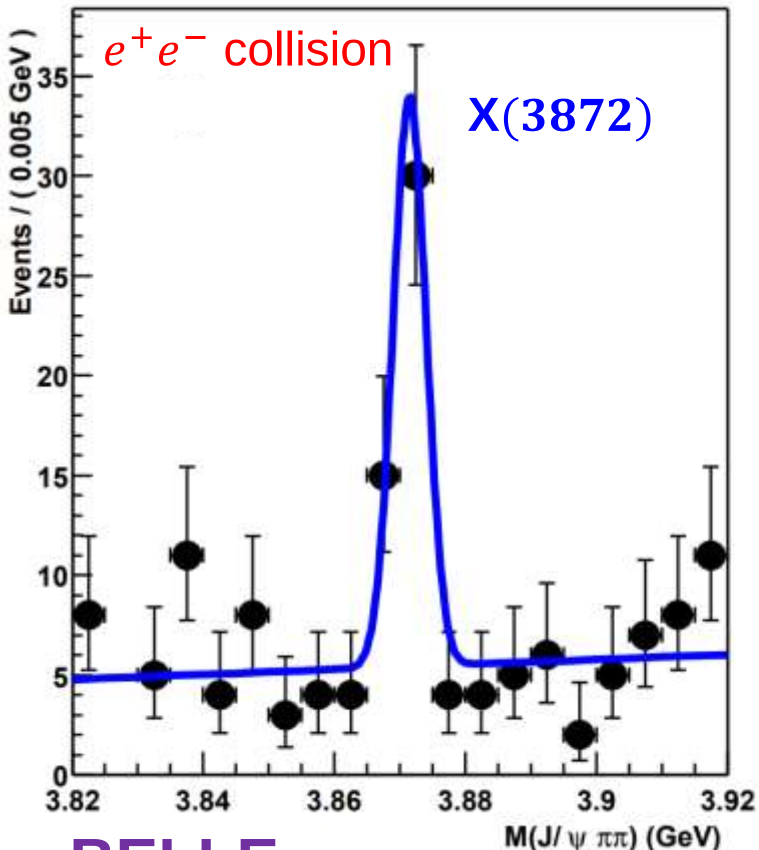
anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest

Exotic multiquark hadrons, e.g.,

- ‘tetraquarks’ with minimal four-quark content $qq\bar{q}\bar{q}$;
- ‘pentaquarks’ with minimal five-quark content $qqqq\bar{q}$;
- …

Phys. Lett. 8, 214 (1964)

First exotic candidate X(3872)



BELLE

PRL 91, 262001 (2003)

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

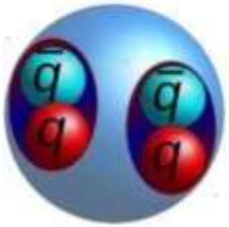
PRL 110, 222001 (2013); JHEP 04, 154 (2013); JHEP 01, 117 (2017); PRL 126, 092001 (2021); PRL 128, 032001 (2022) …

Interpretations of X(3872)

Tetraquark

Charmonium

Hybrid



Hadronic molecule

However, the exact nature of X(3872) is still unclear.

The loose molecule state and compact tetraquark state are of most interest.

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)...

Existed observables to distinguish X(3872)

Yield ratio in coalescence model to statistical model (N^{coal}/N^{stat}), PRL 106, 212001 (2011)

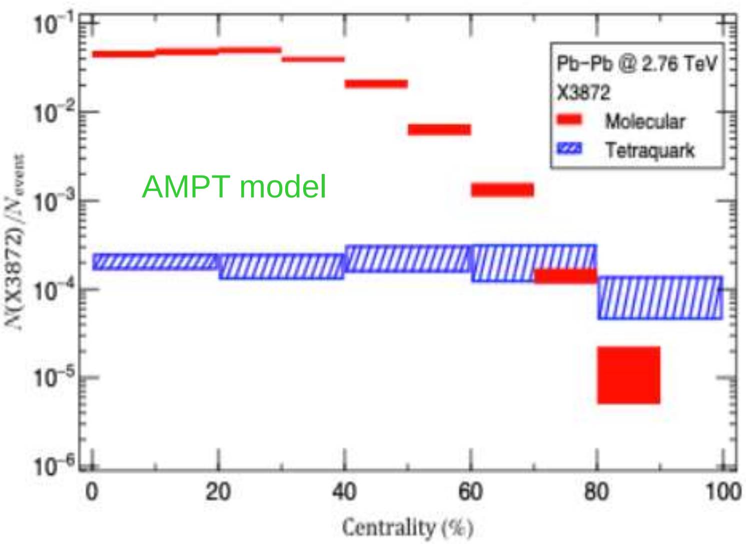
Spatial structure parameter (R_0), Phys. Rep. 639, 1 (2016); EPJC 81, 784 (2021) …

Rapidity distribution (dN/dy), PRL 126, 012301 (2021); EPJA 57, 122 (2021); PRC 105, 054901 (2022) …

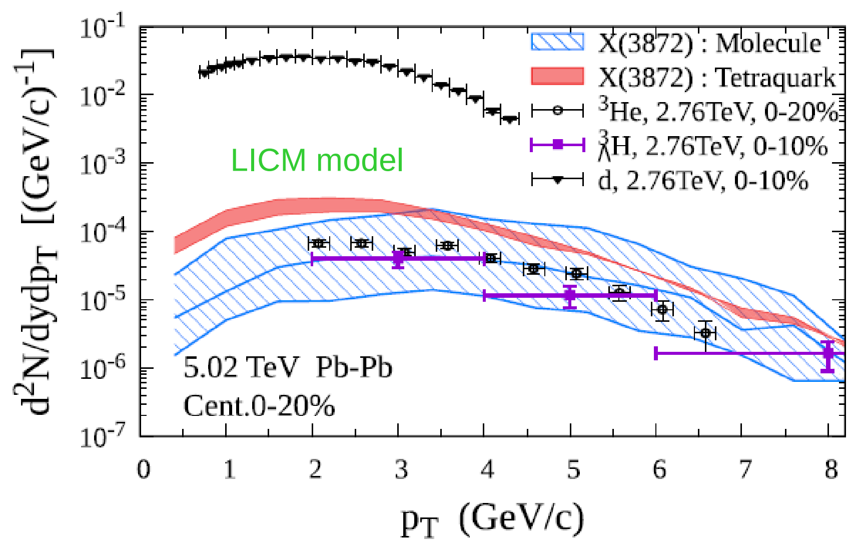
Transverse momentum spectrum (dN/dp_T), PRL 126, 012301 (2021); PRC 105, 054901 (2022) …

Cross-section ratio ($X(3872)/\psi(2S)$) EPJC 81, 669 (2021); PRL 126, 092001 (2021); PRL 128, 032001 (2022)

Radiative decay ratio ($\mathrm{X} \to \psi'(2S)\gamma)/(\mathrm{X} \to \psi(1S)\gamma$)… 2401.11623 …



PRL 136, 012301 (2021)



PRC 105, 054901 (2022)

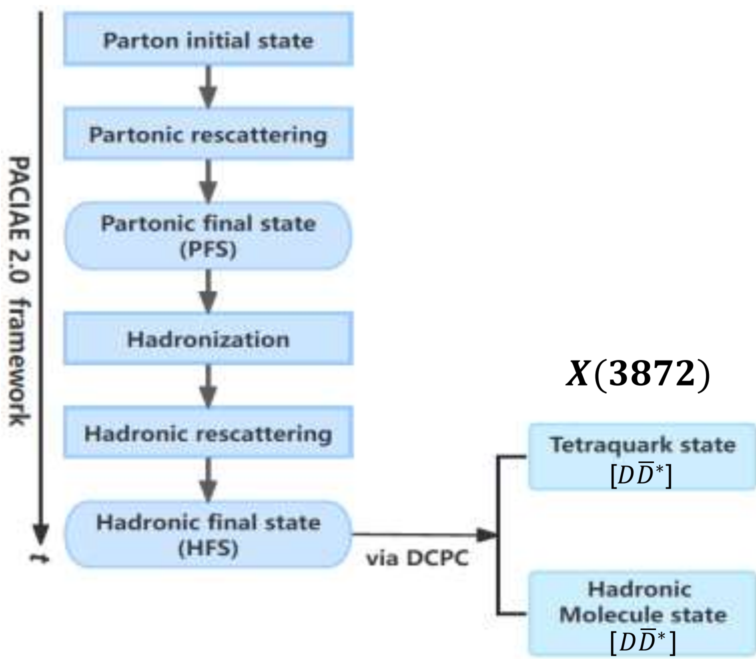
PACIAE model studying X(3872)

PACIAE Model

◆ Successes obtained and improvement introduced

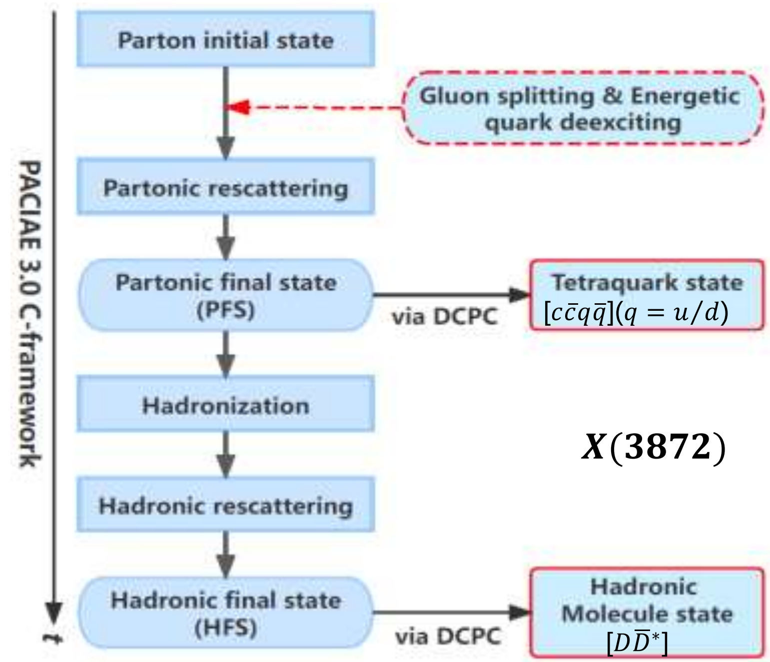
PACIAE+DCPC model has successfully described hadrons, light nuclei, and exotics ($X(3872)$, $Z_c(3900)$, P_c states, $\chi_{c1}(3872)/\psi(2S)$, etc.) production in high energy collisions at RHIC and LHC energies. PRC 103, 014906 (2021); EPJC 81,198 (2021); EPJC 81, 784 (2021); PRD 105, 054013 (2022); PRD 107,114022 (2023) …

- Previous work



Key: spatial structure parameter (R_0)

- Present work

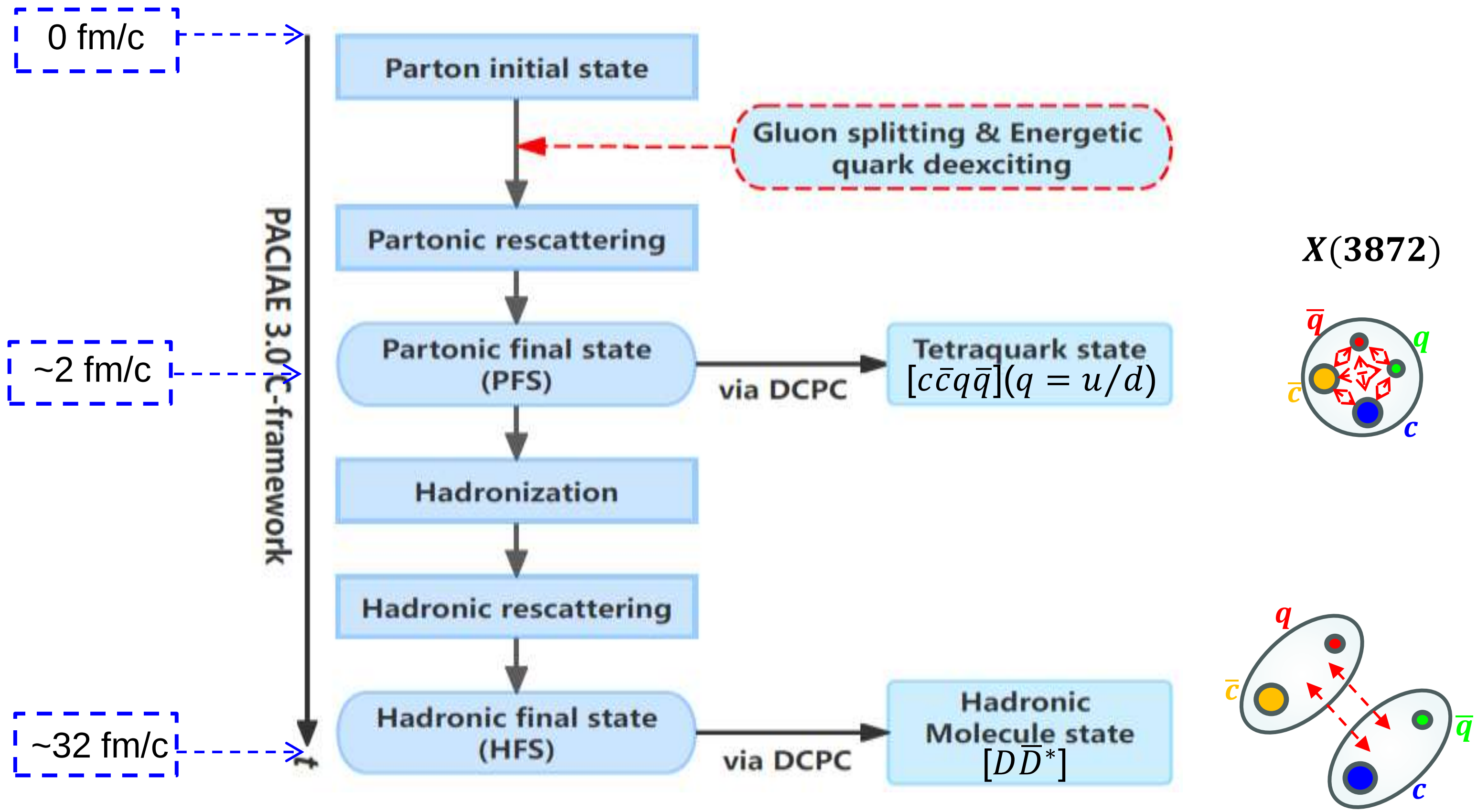


PACIAE Model

Compact tetraquark-state and loose hadronic molecule-state of X(3872) are assumed to be coalesced in PFS and HFS, respectively.

arXiv:2402.16736

Time (pp collision)



PRC 108, 064909 (2023)

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

PACIAE Model

- DCPC model

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

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

We assumed that if the cluster is possible to exist naturally, four-particle cluster of $c\bar{c}u\bar{u}$ for instance, should be calculated by

$$Y_{cluster} = \int \cdots \int \delta_{1234} \frac{\prod_{i=1}^{i=4} d\vec{q}_i d\vec{p}_i}{h^{12}}$$

with constraints:

component constraint if [$1 \equiv c, 2 \equiv \bar{c}, 3 \equiv u, 4 \equiv \bar{u}$], $\delta_{1234} = 1$; otherwise $\delta_{1234} = 0$

spatial coordinate constraint $\left|\vec{q}_{ij}\right| = \left|\vec{q}_i - \vec{q}_j\right| \le R_0, (i \neq j;\ i,j = 1,2, \dots, 4)$

Momentum constraint $m_0 - \Delta m \le m_{inv} \le m_0 + \Delta m,$ where $m_{inv} = \sqrt{(\sum_{i=1}^{i=4} E_i)^2 - (\sum_{i=1}^{i=4} \vec{p}_i)^2}$

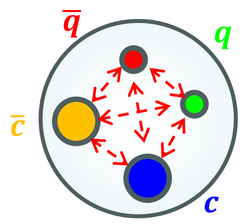
PRC 85, 024907(2012)

PACIAE Model

- Framework

<table>
<tr><td>

- Tetraquark state



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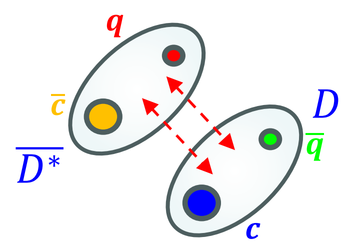
- Hadronic molecule state



</td></tr>
<tr><td>component: $c,\ \bar{c},\ q,\ \bar{q}\ (q = u/d)$</td><td>component: $D,\ \overline{D^*}\ (D = D^0, \bar{D}^0, D^+, D^-)$</td></tr>
<tr><td>mass: $m_{X(3872)} = 3871.69\ \mathrm{MeV/c^2}$</td><td>$m_{X(3872)} = 3871.69\ \mathrm{MeV/c^2}$</td></tr>
<tr><td>free parameter: $\Delta m = 1.95\ \mathrm{MeV/c^2}$</td><td>$\Delta m = 1.95\ \mathrm{MeV/c^2}$</td></tr>
<tr><td>spatial structure parameter: $R_0 < 1\ \mathrm{fm}$</td><td>$1 < R_0 < 10\ \mathrm{fm}$</td></tr>
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PRD 98, 030001 (2018)
PRL 126, 012301 (2021)

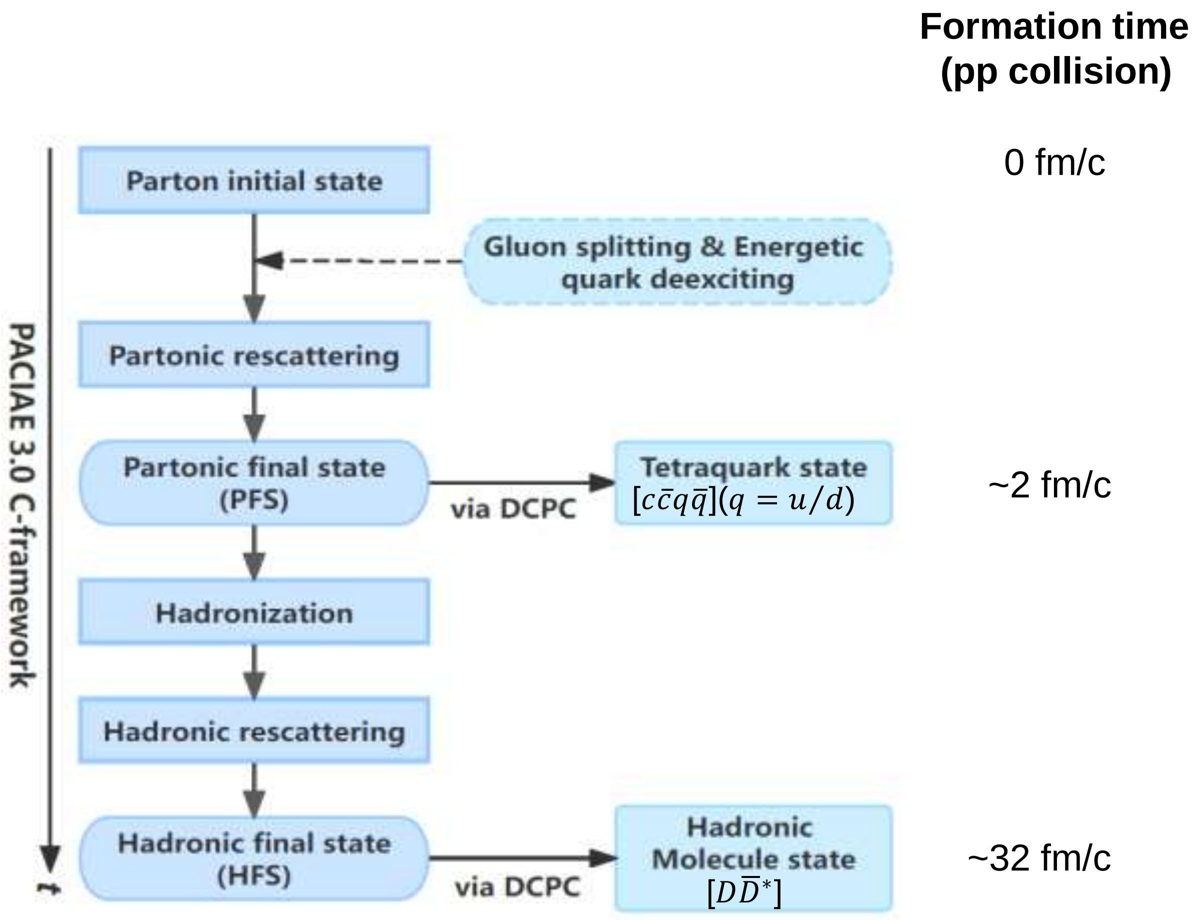
EPJC 73, 2351 (2013)

Proposed identifying criteria

Proposed identifying criteria(1)

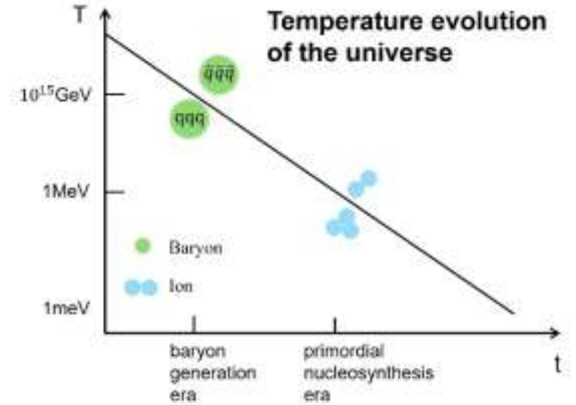
1, Discrepancy in formation times of two states:

Two formation times of multiquark- and molecule- state are suggested as a criterion and to be measured experimentally.

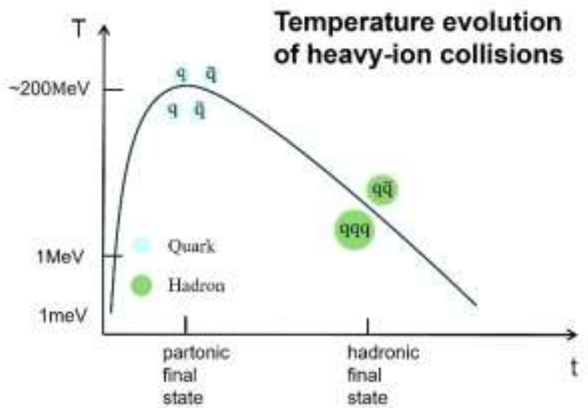


Proposed identifying criteria(2)

2, Discrepancy in apparent hadronization temperature of two states:



NPA 418, 289c (1984)



Preliminary fitted temperature by Shannon entropy with Hagedorn distribution :

$$\mathcal{H}_{Hag} = \frac{m}{m-1} + \ln\left(\frac{m}{m-1}\right) + \ln(T_{Hag})$$

$$dN/dp_T^2 \propto (p_0/(p_0 + p_T))^m$$

Phys. Rev. C 109, 034915 (2024)

Partonic matter: $T_{PFS} = 0.195$ GeV/c

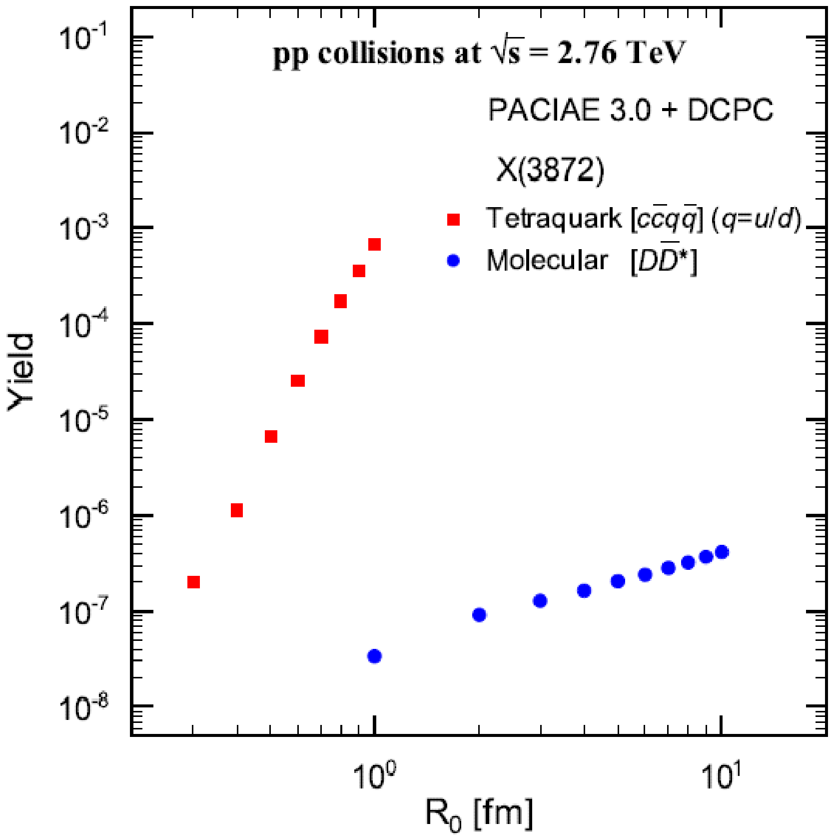
Hadronic matter: $T_{HFS} = 0.180$ GeV/c

i.e., between multiquark- and molecule-state.

The partonic- and hadronic-matter apparent temperatures here are, respectively, corresponding to the temperature of baryon generation era and temperature of primordial nucleosynthesis era in the evolution of early universe qualitatively.
An interesting physics should be studied further !

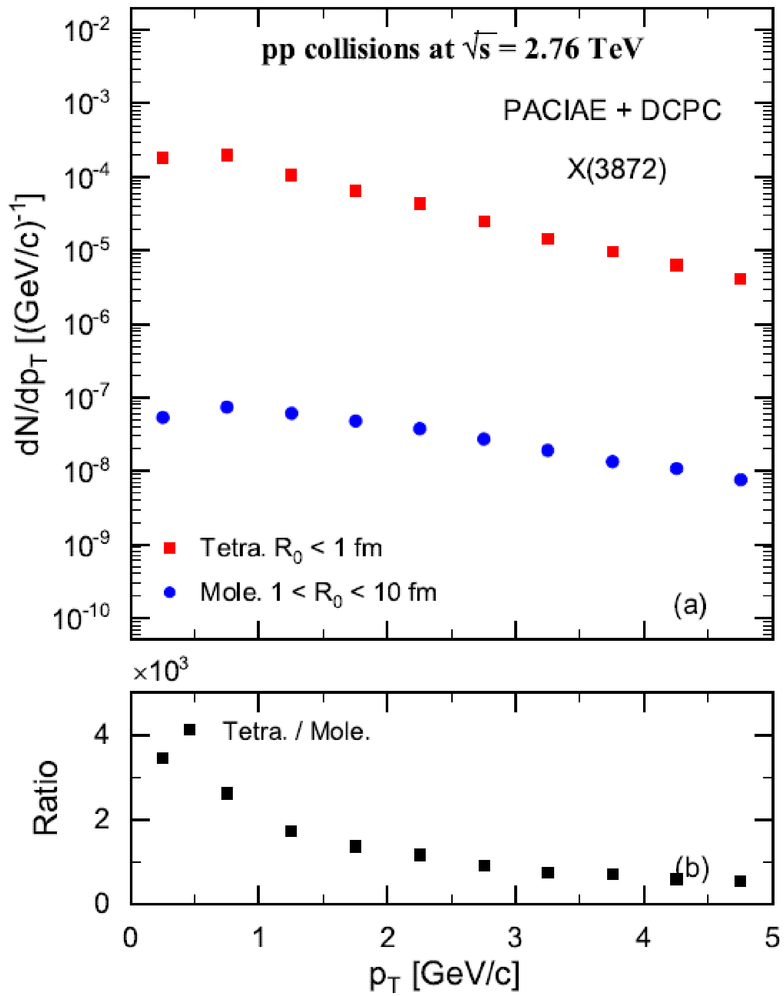
We confirm the criteria of usual observables(3) :

3.1, Discrepancy in yield:



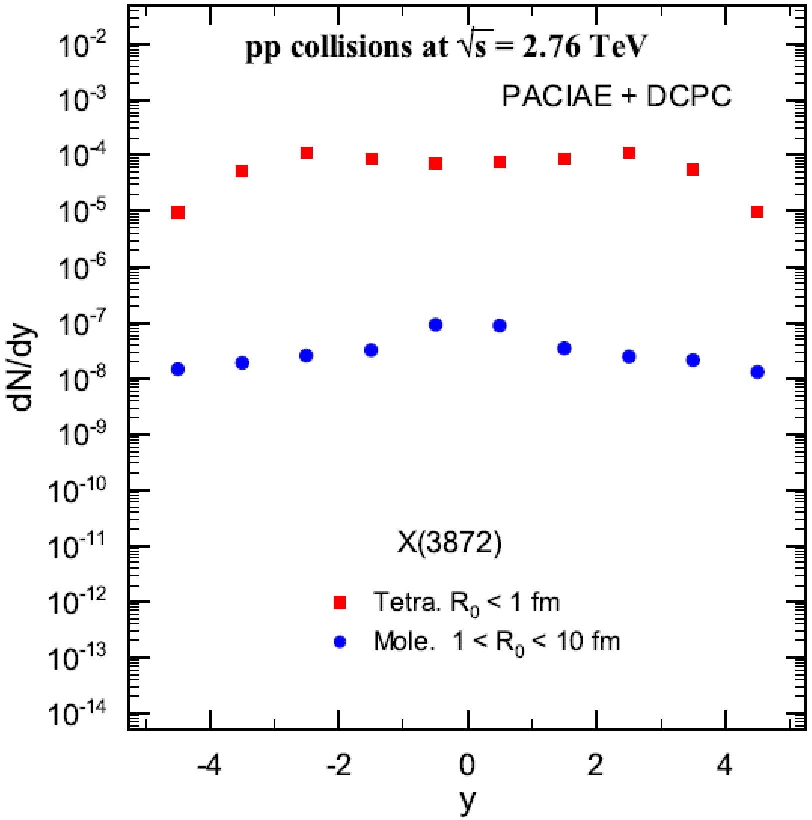
We confirm the criteria of usual observables(3):

3.2, Discrepancy in p_{T} single differential distribution:



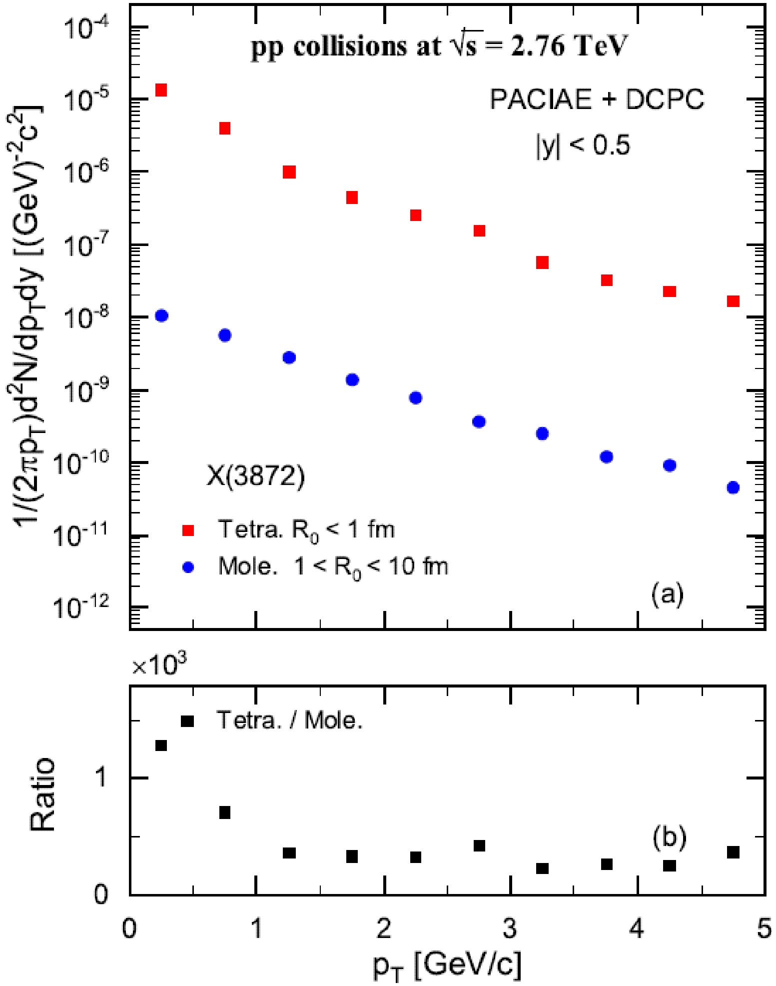
We confirm the criteria of usual observables(3):

3.3, Discrepancy in y single differential distribution:



We confirm the criteria of usual observables(3):

3.4, Discrepancy in transverse momentum spectrum:



Summary & Outlook

- ✓ PACIAE model identifies the exotic hadron compact multiquark-state or loose molecule-state successfully.

- ✓ Discrepancy in formation times between two states.

- ✓ Discrepancy in temperatures between partonic-matter and hadronic-matter, i.e., between multiquark- and molecule-state.

- ✓ We confirm the discrepancy between multiquark- and molecule-state in basic observables (yield, p_{T} spectrum, rapidity distribution, etc.).
  Each of them may serve as a distinguishing criterion.

- ✓ Next studies:
  Forward rapidity of 2<|y|<4.5;
  pp collisions at different energies;
  p-Pb collisions at different energies;
  Pb-Pb collisions at different energies;
  Other tetraquarks, pentaquarks, dibaryons, etc.

- ✓ These results are important for future experimental searches and enrich theoretical estimates in the multiquark sector.

Thank you for your attention!