XVth Quark Confinement and the Hadron Spectrum Conference

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Exotic states production in relativistic heavy ion collisions

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on behalf of

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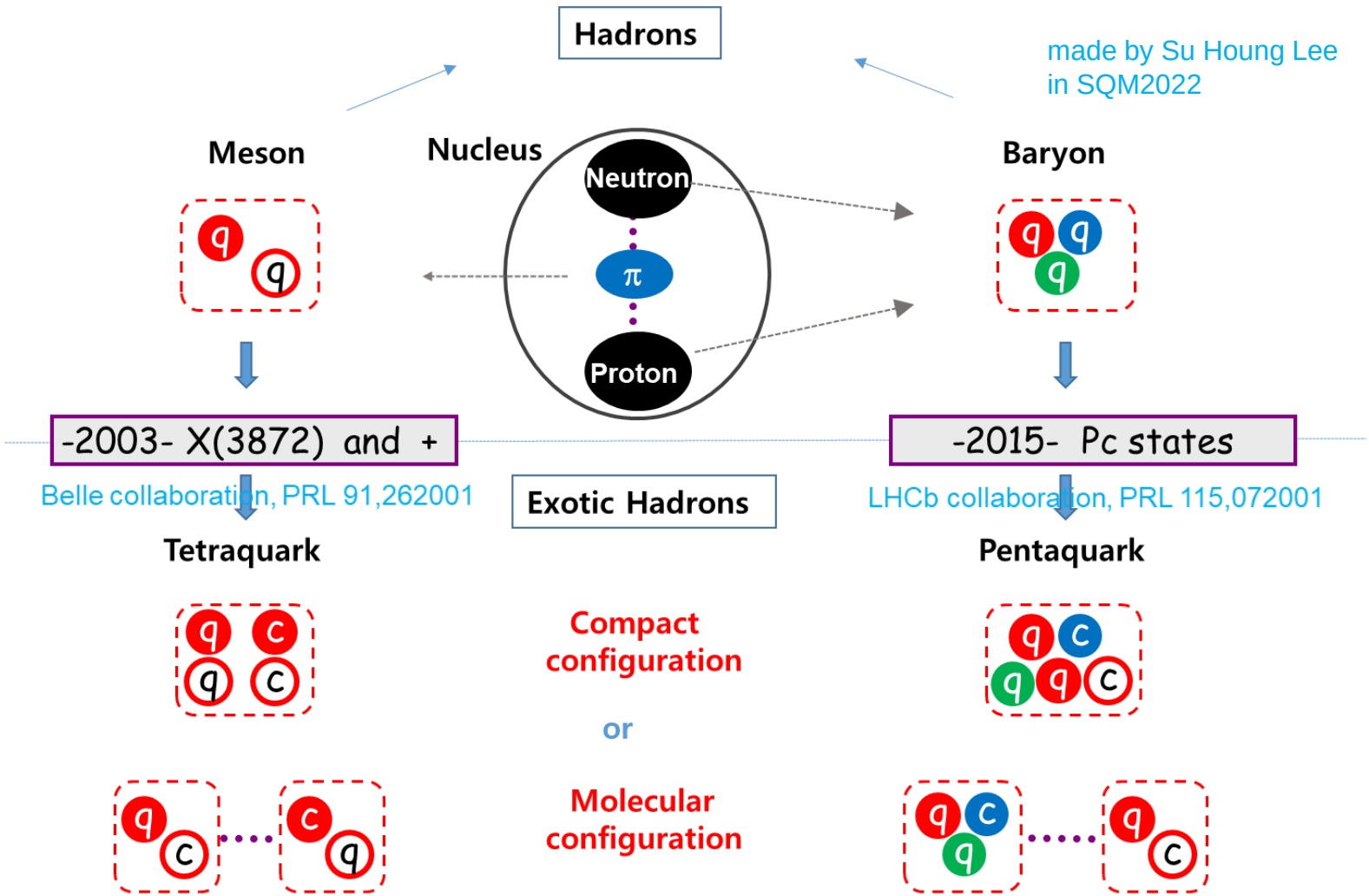
C.H. Chen, G. Chen*, X.L. Kang, B.H. Sa, Z.L. She, H.G. Xu, Y.L. Xie, Z. Zhang, L. Zheng, D.M. Zhou

August 5th, 2022, Stavanger, Norway

Outline

- Introduction
- Thermal model results on Sexaquarks
- Coalescence model results on Exotic States
- Summary and Outlook

Exotic Hadrons



Sexaquark states exist or not?

Which structure? ⟶ short distance *or* long distance interaction

H-dibaryon and Sexaquark

The H-dibaryon (uuddss) state, initially proposed by Robert L. Jaffe who used a bag model and predicted the unstable H-dibaryon with a mass about 2150 MeV.

R. L. Jaffe, Phys. Rev. Lett. 38, 195 (1977).

However, several experiments have searched for such a state and did not find it.

B. H. Kim et al. [Belle], Phys. Rev. Lett. 110, 222002 (2013).
J. Badier et al. [NA3], Z. Phys. C 31, 21 (1986).
R. H. Bernstein et al, Phys. Rev. D 37, 3103 (1988).
J. Belz et al. [BNL-E888], Phys. Rev. Lett. 76, 3277 (1996).
A. Alavi-Harati et al. [KTeV], Phys. Rev. Lett. 84, 2593 (2000).
H. R. Gustafson et al, Phys. Rev. Lett. 37, 474 (1976).

The Sexaquark (uuddss) state, recently proposed by Glennys R. Farrar, is a new hypothetical low mass (below 2 GeV), small radius (0.1-0.4 fm) multiquark state.

G. R. Farrar, arXiv:1708.08951.

This new state S-uuddss could exist and have escaped the experimental searches till now. Depending on its mass, it may be absolutely stable or almost stable with decay rate of the order of the lifetime of the Universe, therefore making it as a possible candidate for Dark Matter (assuming that DM is composed of equal number of u,d,s quarks).

G. R. Farrar, arXiv:1708.08951, 1805.03723, 2201.01334 [hep-ph].
G. R. Farrar et al, arXiv:2007.10378 [hep-ph].

S-uuddss characteristics

The S-uuddss state can be maximally bound because of its symmetry.

Due to being a flavor singlet it is expected to not couple to pions resulting in a compact configuration.

Assuming it can bind to lightest flavor singlet mesons like the f_0 a radius of 0.1-0.3 fm is estimated.

The different size between the S and baryons means that amplitudes involving the S and 2 baryons are strongly suppressed.

Lacking coupling via pions its interaction with matter is lower than that of ordinary hadrons supporting the hypothesis it can be a DM candidate.

G. R. Farrar, arXiv:1708.08951, 1805.03723, 2201.01334 [hep-ph].
G. R. Farrar et al, arXiv:2007.10378 [hep-ph].

Besides, the assumption of a light Sexaquark has been shown to be consistent with observations of neutron stars and the Bose-Einstein Condensate of light Sexaquarks has been discussed as a mechanism that could induce quark deconfindement in the core of neutron stars.

D. Blaschke et al., Phys. Rev. D 105, 103005 (2022)
D. Blaschke et al., e-Print: 2202.05061 [nucl-th]

Experiment searches

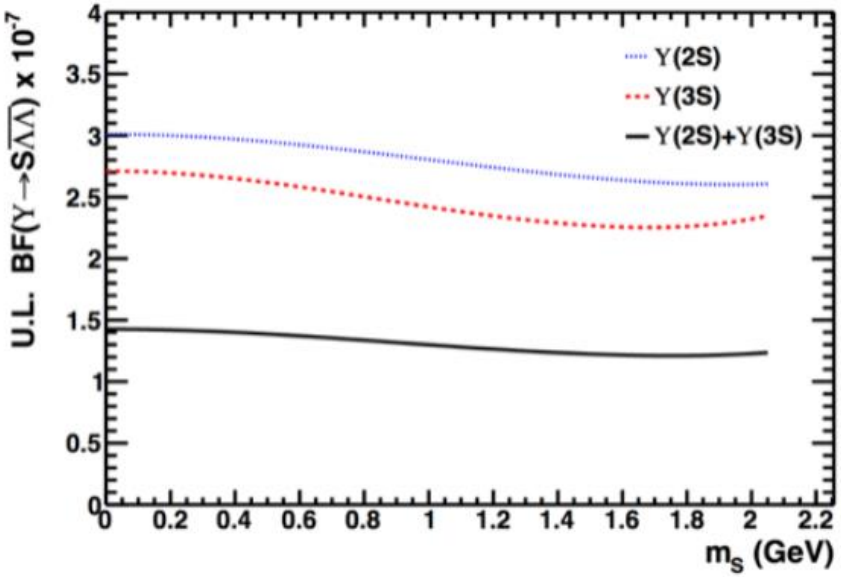
One proposed method to discover S-uuddss via the Upsilon decay in Upsilon factories

$$\Upsilon \ [\rightarrow \text{gluons}] \rightarrow S\,\bar{\Lambda}\,\bar{\Lambda} \ \text{ or } \bar{S}\,\Lambda\,\Lambda \ \ + \text{pions and/or } \gamma$$

G. R. Farrar, arXiv:1708.08951

Even though not everyone agrees [Sexaquark abundance will freeze out at Temperature of 10 MeV], its possible cosmological implications as DM candidate cannot be excluded [due to the robustness of sexaquarks in hot hadronic phase against breakup to baryons]

E. Kolb, M. Turner, PRD 99, 063519 (2019)
D. Blaschke et al, Int. J. Mod. Phys. A 36, 2141005 (2021)



S-uuddss has been recently searched in BaBar experiment, that no signal is observed and set upper limits.

BaBar Collaboration, PRL 122, 072002 (2019).

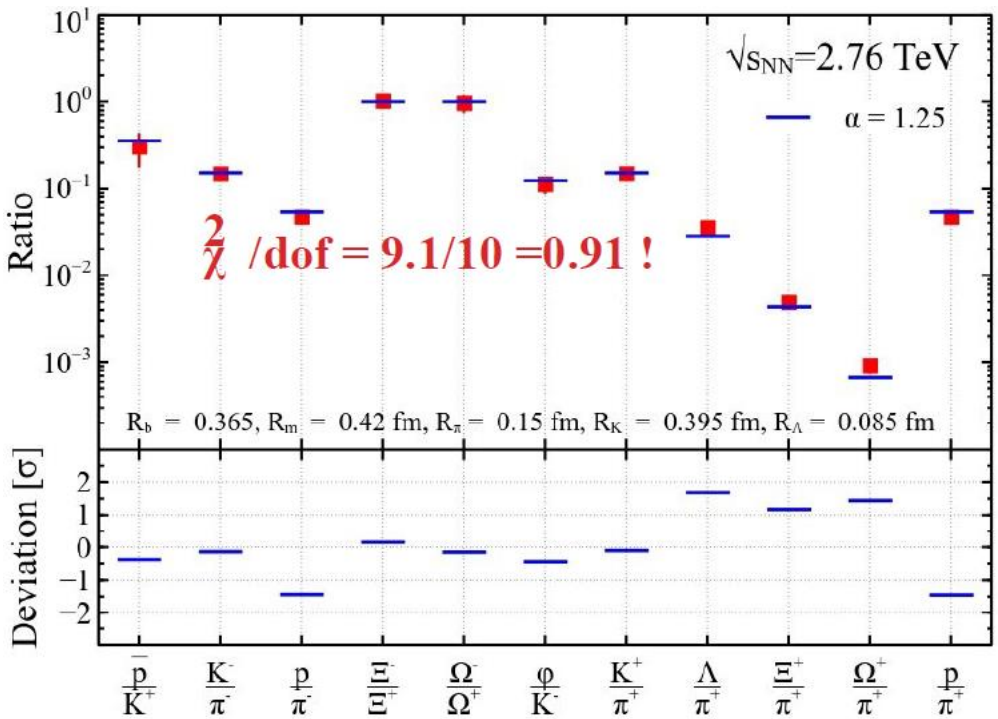
S-uuddss production in heavy ion collisions is expected to be much more favorable, and parton coalescence or thermal production give much larger rates in heavy ion collisions.

G. R. Farrar, arXiv:1708.08951, 1805.03723, 2201.01334 [hep-ph].
G. R. Farrar et al, arXiv:2007.10378 [hep-ph].
D. Blaschke et al, Int. J. Mod. Phys. A 36, 2141005 (2021).

Thermal model results on Sexaquarks

Thermal model

Hadron Resonance Gas Model with Induced Surface Tension, has successfully described hadron and nuclei production in Pb + Pb collisions at LHC energy, is employed to estimate the thermal production of Sexaquarks discussed previously rendering them DM candidates.

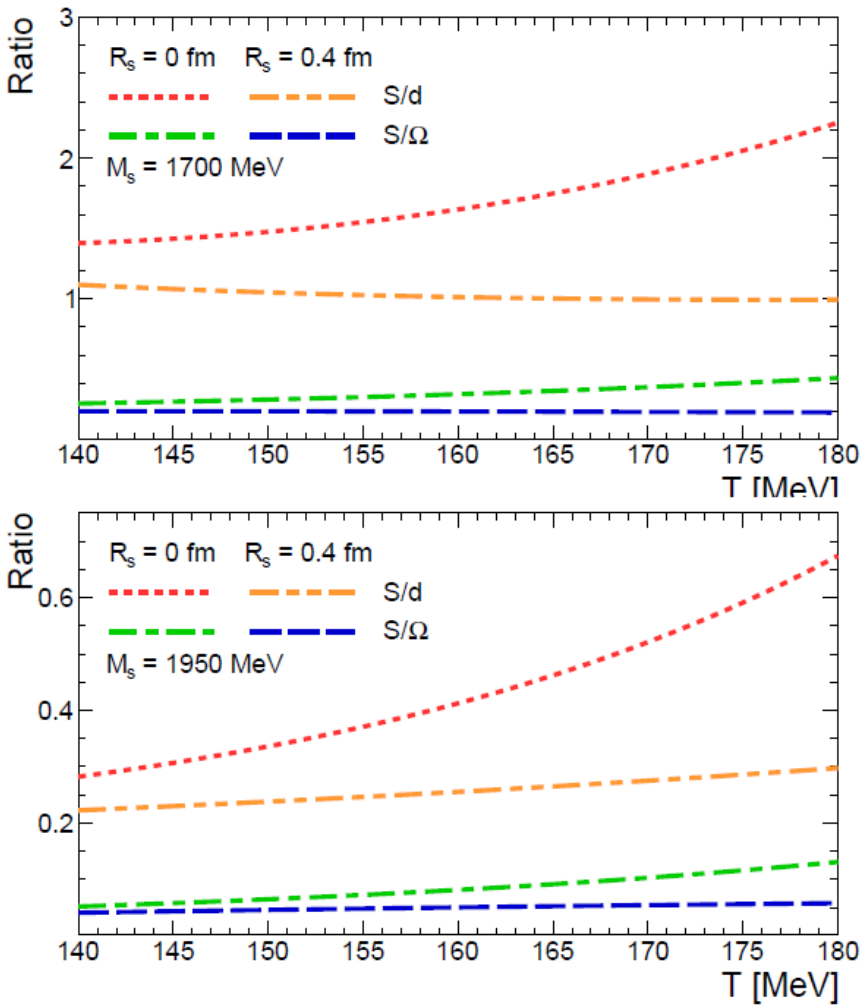


Here, hard-core radii of hadrons are taken from the fit of AGS, SPS, and RHIC data.

Single parameter, temperature of chemical freezeout $T_c = 150 \pm 4$ MeV

V. V. Sagun et al., Eur. Phys. J. A 54: 100 (2018)
K. A. Bugaev et al, Nucl. Phys. A 970, 133 (2018)

Sexaquark to hadrons ratio



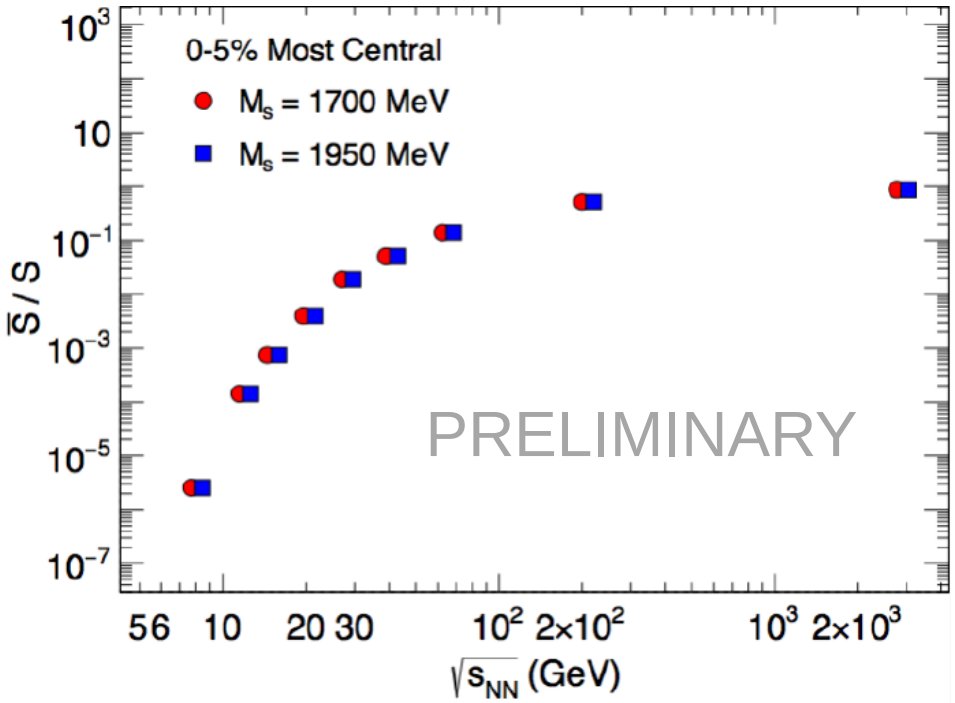
The yield ratios of S-uuddss to hadrons like deuteron and Omega in Pb + Pb collisions at the LHC.

Sexaquarks are produced for the radii both 0.0 and 0.4 fm and for masses of 1700 and 1950 MeV.

D. Blaschke et al, Int. J. Mod. Phys. A 36, 2141005 (2021)

Antisexaquark to Sexaquark ratio

The yield ratios of $\bar{S} - \overline{uuddss}$ to $S - uuddss$ with collision energy in Au + Au collisions for masses of 1700 and 1950 MeV.



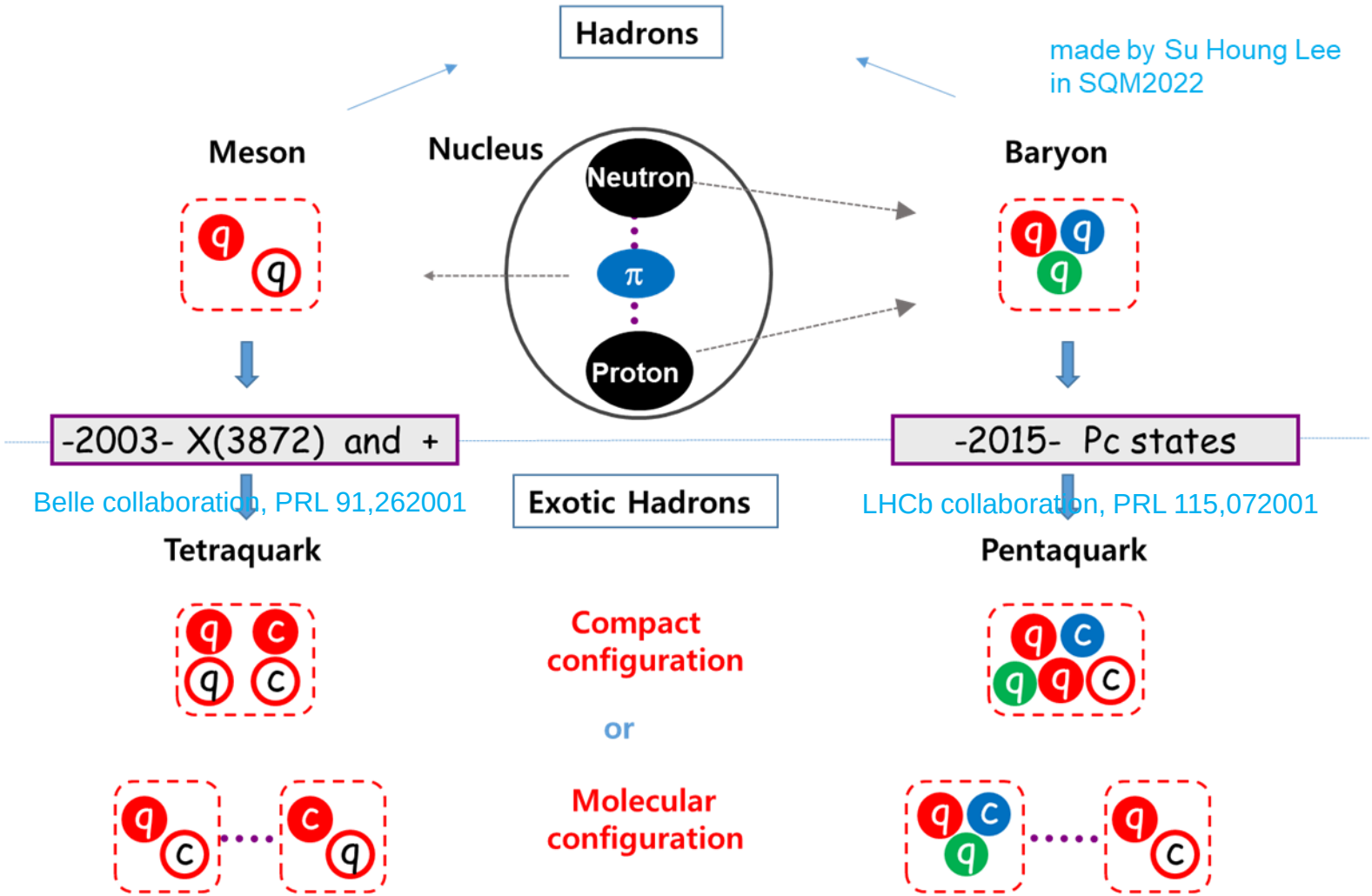
Apparently, the ratios are maximal at top RHIC energy and similar with LHC energy.

Here, another thermal model is employed, based on

S. Kabana, P. Minkowski, New J. Phys. 3, 4 (2001).

Coalescence model results on Exotic States

Exotic Hadrons

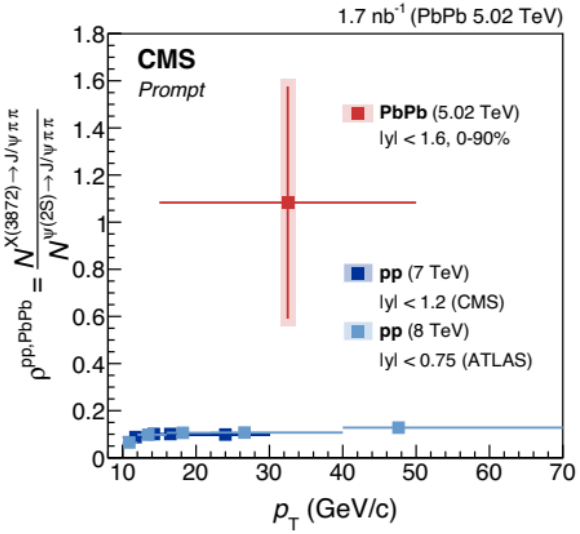


Sexaquark states exist or not?

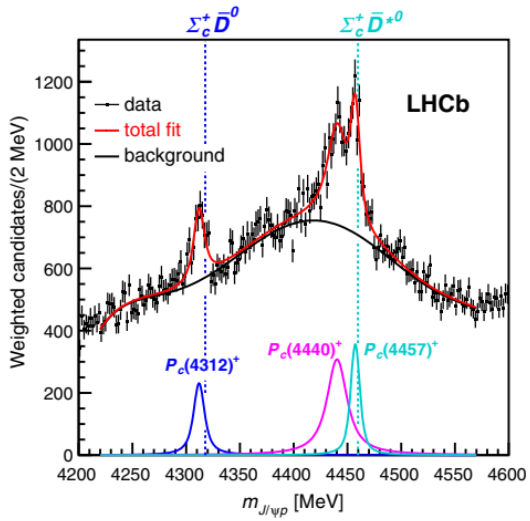
Which structure? ⟶ short distance *or* long distance interaction

X(3872) and Pc production in heavy ion collisions

Experiment measurement

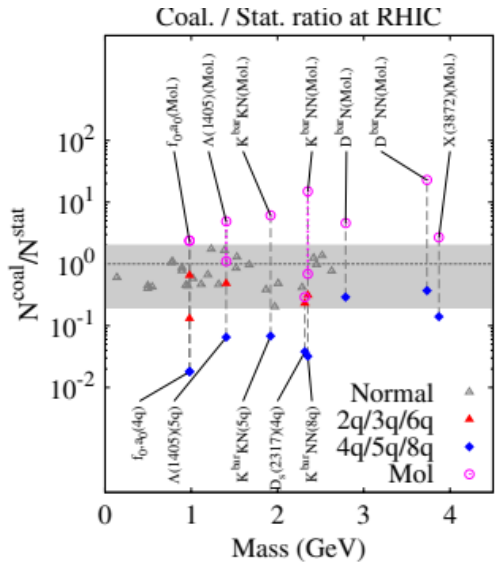


CMS collaboration, PRL 128, 032001 (2022).

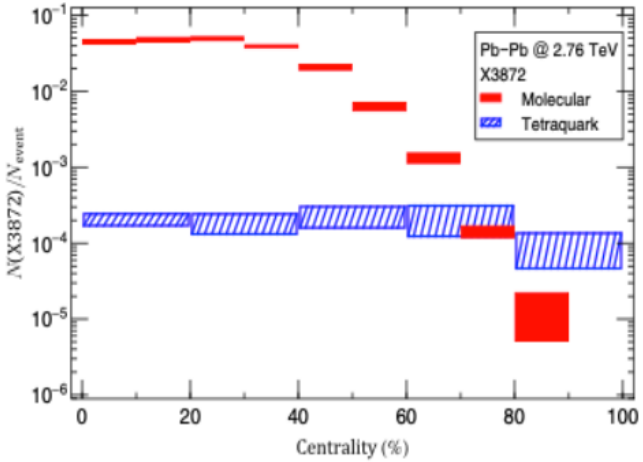


LHCb collaboration, PRL 122, 222001 (2019).

Theory prediction
(Coalescence and Thermal-statistical model)



ExHIC collaboration, PRL 106, 212001 (2011).

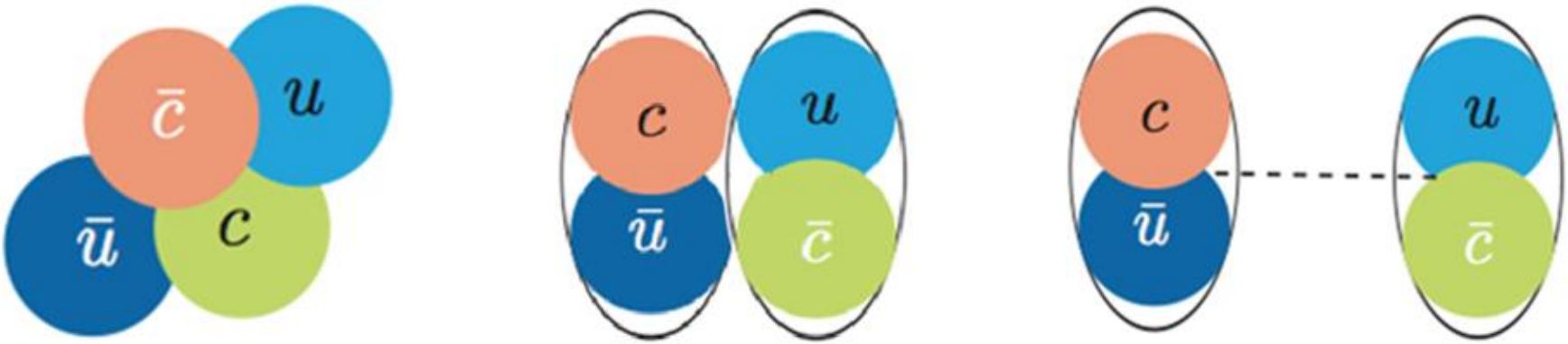


H. Zhang et al, PRL 136, 012301 (2021).

Three possible scenarios of Exotics

The exotic state is assumed to be a combination of three scenarios according to the different distances between the components: the multiquark state for short distances, nucleuslike state for intermediate distances, and molecular state for large distances.

In this case, e.g., X(3872) could be described as



tetraquark state nucleus-like state molecular state

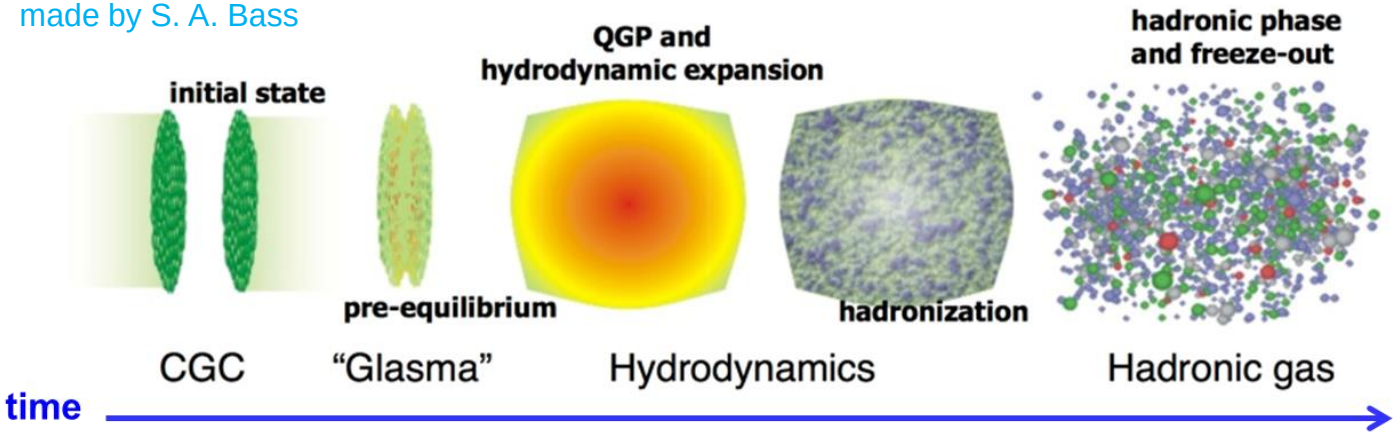
H.G. Xu et al., Eur. Phys. J. C 81, 784 (2021).

Transport model and Coalescence model

Parton and hadron cascade (PACIAE) model, which is based on PYTHIA 6.4, is a Monte-Carlo event generator in high energy collisions, including parton initial state, parton rescattering, hadronization and hadronic rescattering.

B.H. Sa et al, Comput. Phys. Commun. 183, 333 (2012).

made by S. A. Bass



Dynamically constrained phase-space coalescence (DCPC) model, is developed to estimate nuclei production in high energy collisions, by

Y.L. Yan et al, Phys. Rev. C 85, 024907(2012).

$$Y_N = \int \cdots \int_{E_A \le H \le E_B} \frac{d\vec{q}_1 d\vec{p}_1 \cdots d\vec{q}_N d\vec{p}_N}{(h)^{3N}}.$$

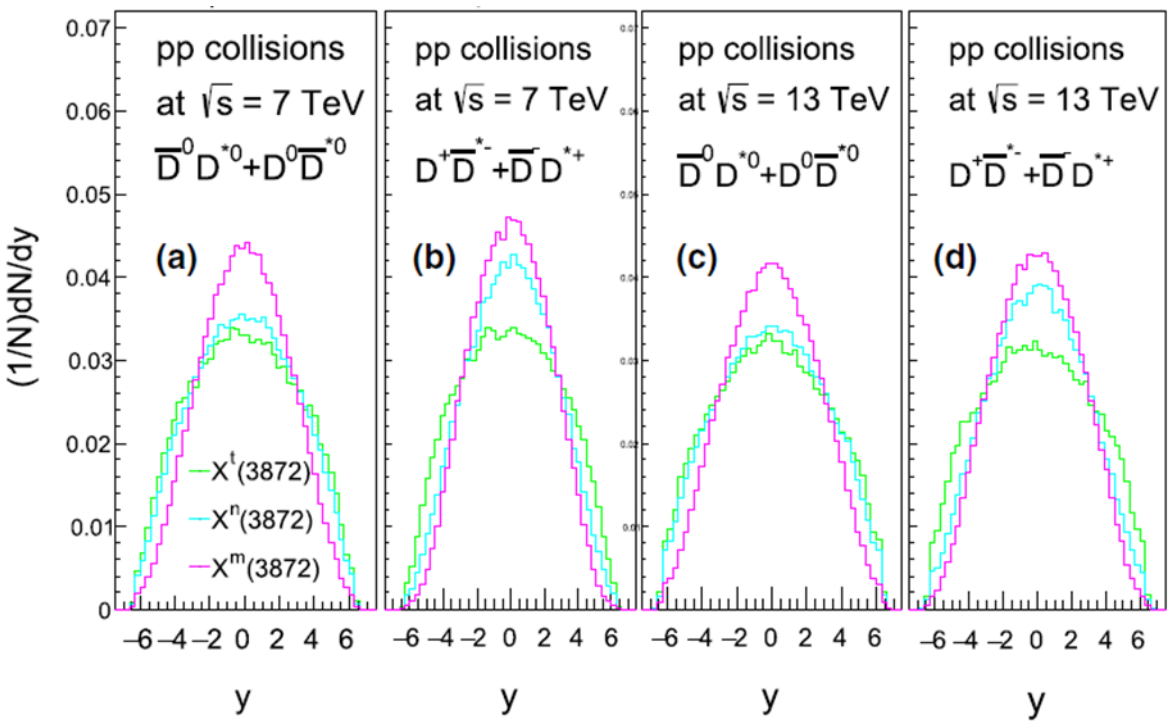
with two common constraints: mass m and radius of nuclei R.

PACIAE+DCPC model has successfully described hadron and nuclei production in high energy collisions at RHIC and LHC energies.

Z.L. She et al., Phys. Rev. C 103, 014906 (2021), Eur. Phys. J. A 58, 15 (2022).

X(3872) production in pp collisions

X(3872), assumed to consist of bound state $D\bar{D}^*$, is calculated in pp collisions at $\sqrt{s}$ = 7,13 TeV within PACIAE+DCPC model for the aforementioned scenarios. The yield, transverse momentum distribution, and rapidity distribution are predicted.



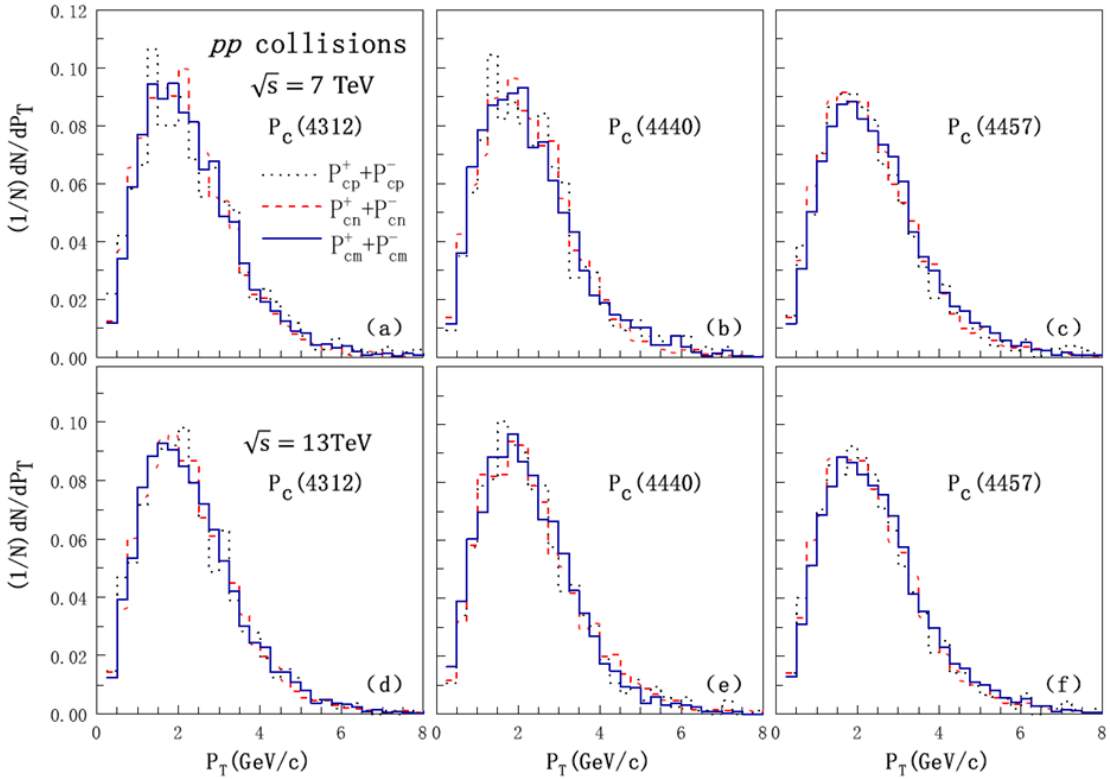
Rapidity distribution of X(3872) with three scenarios.

Sizable differences can be found in the transverse momentum and rapidity distributions for the three different scenarios.

H.G. Xu et al., Eur. Phys. J. C 81, 784 (2021).

Pc states production in pp collisions

Pc(4312), Pc(4440), Pc(4457) are considered to be three possible scenarios based on $P_c^{\pm} \rightarrow J/\Psi p(\bar{p})$ bound state, and their productions are predicted by PACIAE+DCPC model in pp collisions at $\sqrt{s}$ = 7,13 TeV.



Normalized p_T-differential yield of Pc state with three scenarios (P_{cp}, P_{cn}, P_{cm}).

The calculated results indicate a hierarchy of the yields for different possible scenarios; and they are all on the order of 10^{-6}.

C.H. Chen et al, Phys. Rev. D 105, 054013 (2022).

Summary & Outlook

Thermal production of sexaquarks(uuddss) are calculated in different statistical models.

The yield ratios of Sexaquarks to deuteron and Omega, Anti-Sexaquarks to Sexaquarks are estimated in heavy ion collisions at LHC and RHIC energies.

Coalescence model results on Exotics (X(3872) and Pc states) in pp collisions are shown, and three different scenarios are taken into account, i.e., pentaquark state, nucleus-like state and molecular state.

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

Thank you for your attention!