Production of Sexaquark state in high-energy nuclear collisions

An-Ke Lei (雷安科)

Central China Normal University, China

University of Oslo, Norway

On behalf of:

Z. L. She, D. M. Zhou, L. Bravina, E. Zabrodin, S. Kabana, V. Bairathi

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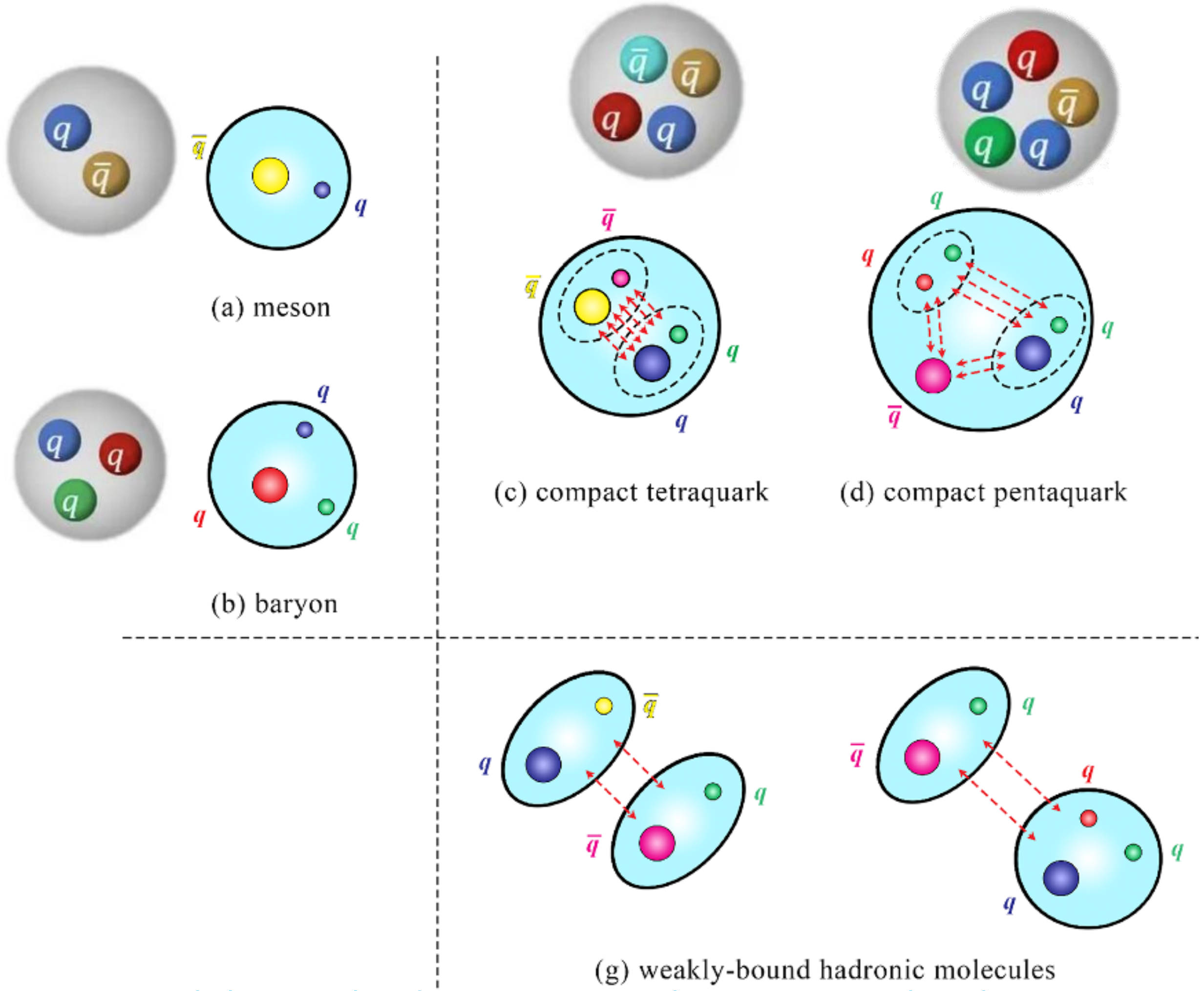
Outline

- Introduction
- Sexaquark from thermal model
- Sexaquark from coalescence model
- Summary and Outlook

Exotic Hadrons

The quantum chromodynamics (QCD) permits the existence of other types of hadrons (color-neutral / colorless) beyond ordinary mesons and baryons.



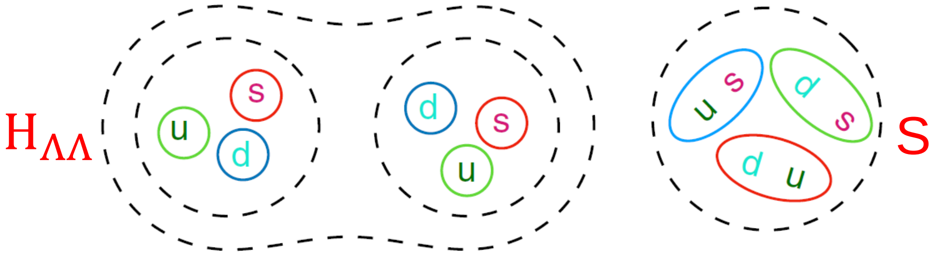
Made by H.X Chen from Rept. Prog. Phys. 86, 026201 (2023)

H-dibaryon and Sexaquark states

The Hexaquark-dibaryon (H-uuddss) state, with a mass about 2150 MeV.

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

Several experiments have been searching for it but have not yet been found.



D. Blaschke et al., Phys. Rev. D 105, 103005 (2022)

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).
Y. Kamiya et al, Phys. Rev. C 195, 014915 (2022)

The Sexaquark (S-uuddss) state, recently proposed by G. 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.

Depending on its mass, it may be absolutely stable or almost stable .

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.

Lacking coupling via pions, its interaction with matter is weaker than that of ordinary hadrons, supporting the hypothesis it can be a Dark Matter 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, it has been discussed as a mechanism that could induce quark deconfinement in the core of neutron stars.

D. Blaschke et al., Phys. Rev. D 105, 103005 (2022)

Experiment searches

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

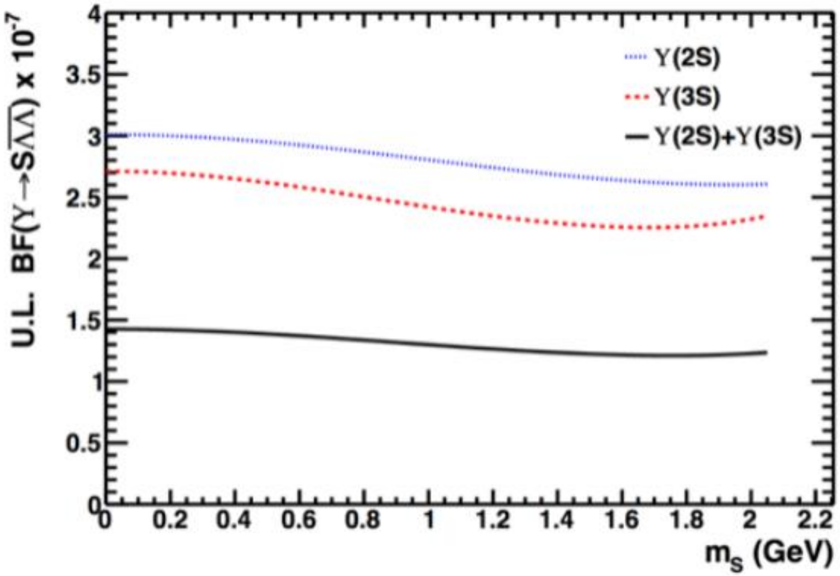
$$\Upsilon\ [\to \text{gluons}] \to S\,\bar{\Lambda}\,\bar{\Lambda}\ \text{ or } \bar{S}\,\Lambda\,\Lambda\ + \text{pions and/or } \gamma$$

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. No signal is observed but just 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.

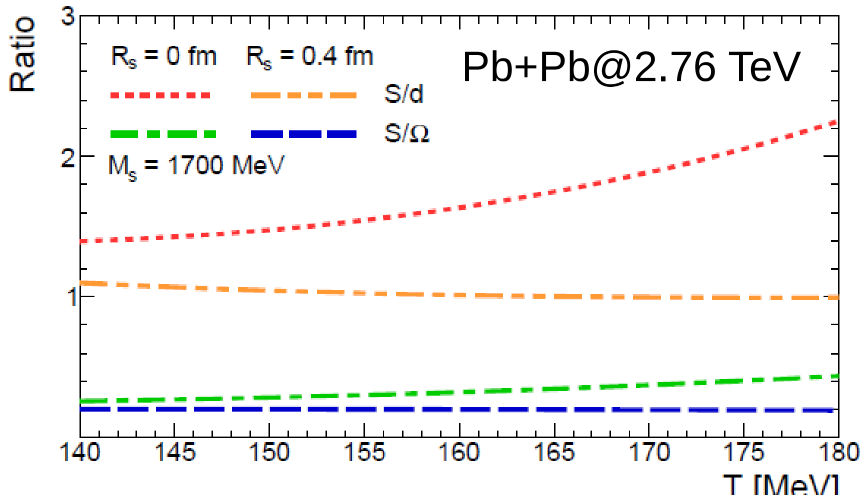
G. R. Farrar, arXiv:1708.08951, 1805.03723, 2201.01334 [hep-ph].

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

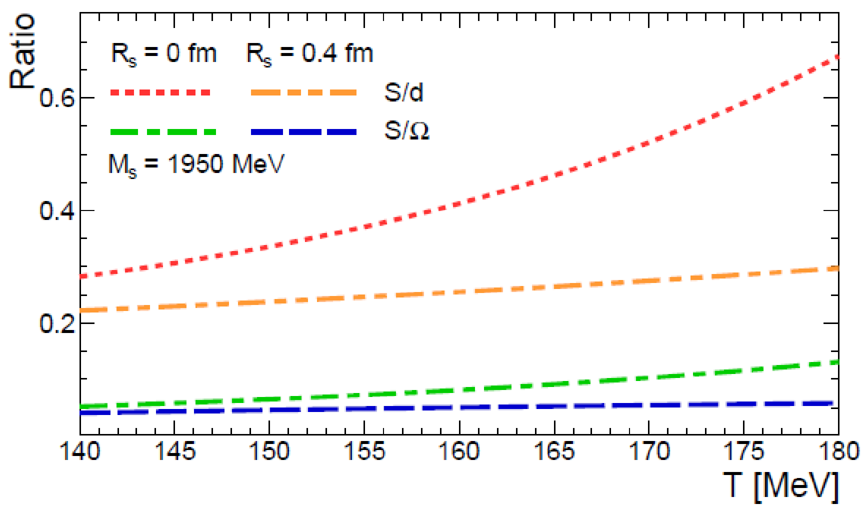
Sexaquark from thermal model

Thermal production (1)

Hadron Resonance Gas Model has been employed to estimate the thermal production of Sexaquarks in Pb + Pb collisions.



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

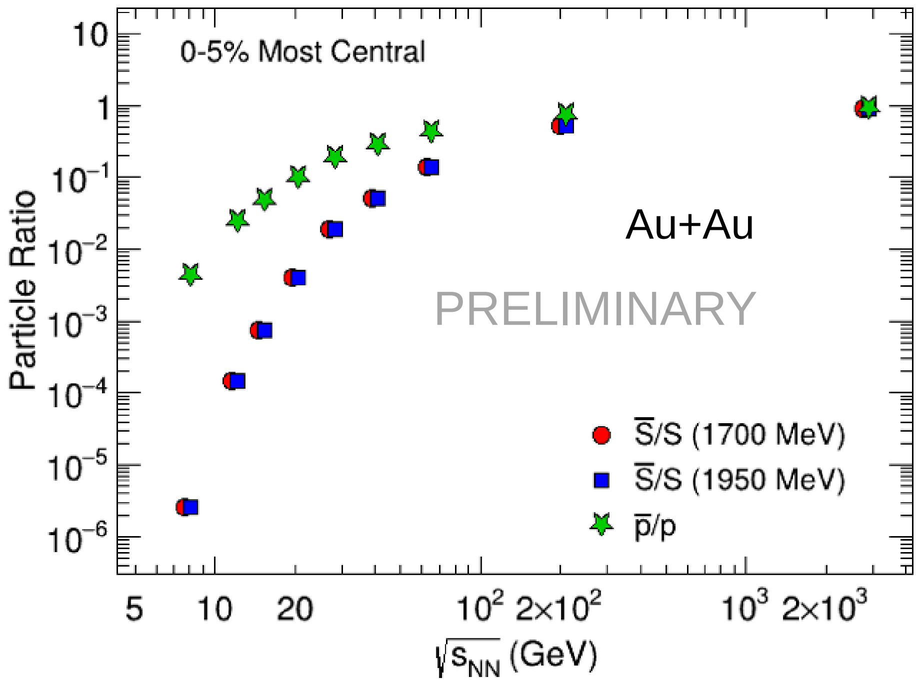


Sexaquarks are produced for the radii both 0.0 and 0.4 fm and for masses of 1700 and 1950 MeV.

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

Thermal production (2)

The yield ratios of $\bar{S} - \overline{\mathrm{uuddss}}$ to $S - \mathrm{uuddss}$ 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.

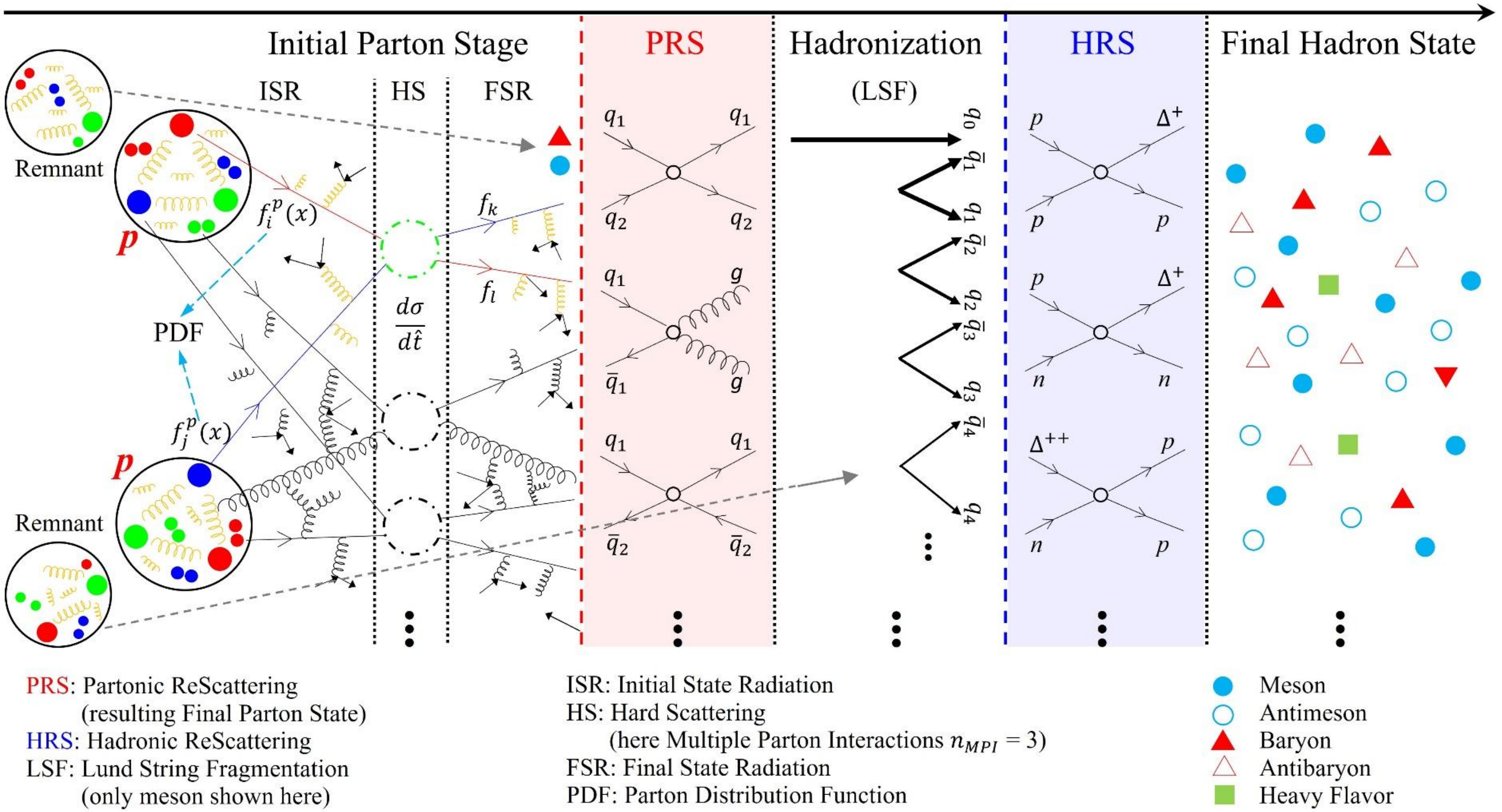
The thermal model based on

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

Sexaquark from coalescence model

PACIAE model

Parton and hadron cascade (PACIAE) model, based on PYTHIA model, is a Monte-Carlo event generator in elementary particles and nuclear collisions.



A sketch for physical routines in a high energy pp simulation

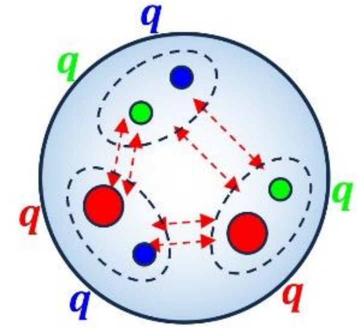
PRC 108, 064909 (2023), arXiv:2411.14255v1

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

Coalescence mechanism

- DCPC model: 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



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

We assumed that if the cluster is possible to exist naturally, e.g. three-diquark cluster of $ud - ds - us$, should be calculated by

$$Y_{cluster} = \int \cdots \int \delta_{123} \frac{\prod_{i=1}^{i=3} d\vec{q}_i d\vec{p}_i}{h^9}$$

with constraints:

component constraint   if [$1 \equiv ud, 2 \equiv ds, 3 \equiv us$], $\delta_{123} = 1$; otherwise $\delta_{123} = 0$

spatial coordinate constraint $|\vec{q}_{ij}| = |\vec{q}_i - \vec{q}_j| \leq R_0, (i \neq j;\ i,j = 1,2,3)$

momentum constraint $m_{low} \leq m_{inv} \leq m_{high}$, where $m_{inv} = \sqrt{(\sum_{i=1}^{i=3} E_i)^2 - (\sum_{i=1}^{i=3} \vec{p}_i)^2}$

PRC 85, 024907(2012)

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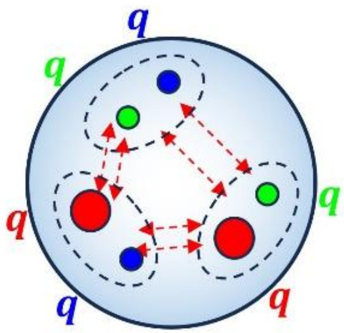

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The relative distance of two quarks (~0.2 fm based on qq/q ratio in PYTHIA8 Monash 2013 tune)

with constraints:

component constraint u, u, d, d, s, s ➡ diquark structure: ud, ds, us

spatial coordinate constraint $0.1 \le R_0 \le 0.4$ fm

G. R. Farrar, arXiv:1708.08951.

momentum constraint $1885 \le m_{inv} \le 2054\ \mathrm{MeV/c^2}$

D. Blaschke et al., Phys. Rev. D 105, 103005 (2022)

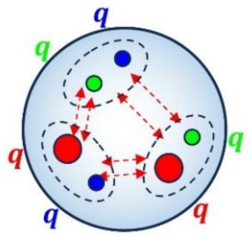
Coalescence production (1)

The yield of Sexaquark by PACIAE + DCPC model in *pp* collisions at $\sqrt{s} = 7$ TeV

D(diquark)	R(S-uuddss)	Y(S)	Y(Sbar)
0.2 fm	0.1 ≤ R ≤ 0.4	7.5×10^{-6}	2.5×10^{-6}
0.2 fm	0.1 ≤ R ≤ 0.35	2.0×10^{-6}	6.5×10^{-7}
0.2 fm	0.1 ≤ R ≤ 0.3	1.5×10^{-6}	5.0×10^{-7}

PRELIMINARY

Here D is the distance of two quarks in a diquark; R is the radius of S-uuddss; Y is the yield of (anti)S-uuddss.



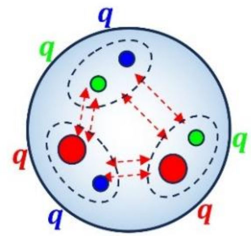
D(diquark)	R(S-uuddss)	Y(S)	Y(Sbar)
0.18 fm	0.1 ≤ R ≤ 0.4	3.0×10^{-6}	2.0×10^{-6}
0.2 fm	0.1 ≤ R ≤ 0.4	7.5×10^{-6}	2.5×10^{-6}
0.3 fm	0.1 ≤ R ≤ 0.4	2.0×10^{-5}	1.5×10^{-5}

Coalescence production (2)

The yield ratios in *pp* collisons at $\sqrt{s}$ = 7 TeV
(Here the D = 0.2 fm and 0.1 ≤ R ≤ 0.4 fm are chosen)

PRELIMINARY

Particle type	Ratio value
S/Λ	0.83×10^{-4}
S/d	3.71×10^{-2}
$\bar{S}/S$	0.33



More data will be updated!

Summary & Outlook

Production of Sexaquarks(uuddss) via the thermal approach.

Production of Sexaquarks(uuddss) via the coalescence approach.
The compact diquark-containing configuration of S-uuddss is assumed.

The yields of S, yield ratios of S to light nuclei, strange hadrons, and anti-S to S are estimated preliminarily.

Next :

pp, *p*A, AA collisions at different energies.

Other models (PHSD, AMPT…) and interior structures to compare …

Thank you for your attention!