Coalescence production of sexaquark (uuddss) in high-energy collisions

Sonia Kabana, Universidad de Tarapaca, Arica, Chile,

on behalf of:

Zhi-Lei She, An-Ke Lei, Dai-Mei Zhou, Larissa V. Bravina, Evgeny E. Zabrodin, Sonia Kabana and Vipul Bairathi

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Outline

Introduction

PACIAE + coalescence model

Results:
* (anti)sexaquark yields from coalescence
* comparison to thermal production
* comparison to hadrons and nuclei
* comparison to the H-dibaryon

Conclusions and outlook

Introduction

The quark model allows the existence of multiquark states like tetraquarks, pentaquarks and dibaryons.

Phys. Lett. 8, 214 (1964)

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

Received 4 January 1964

...

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the 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 baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while

10.17181/CERN-TH-401

8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING
II *)

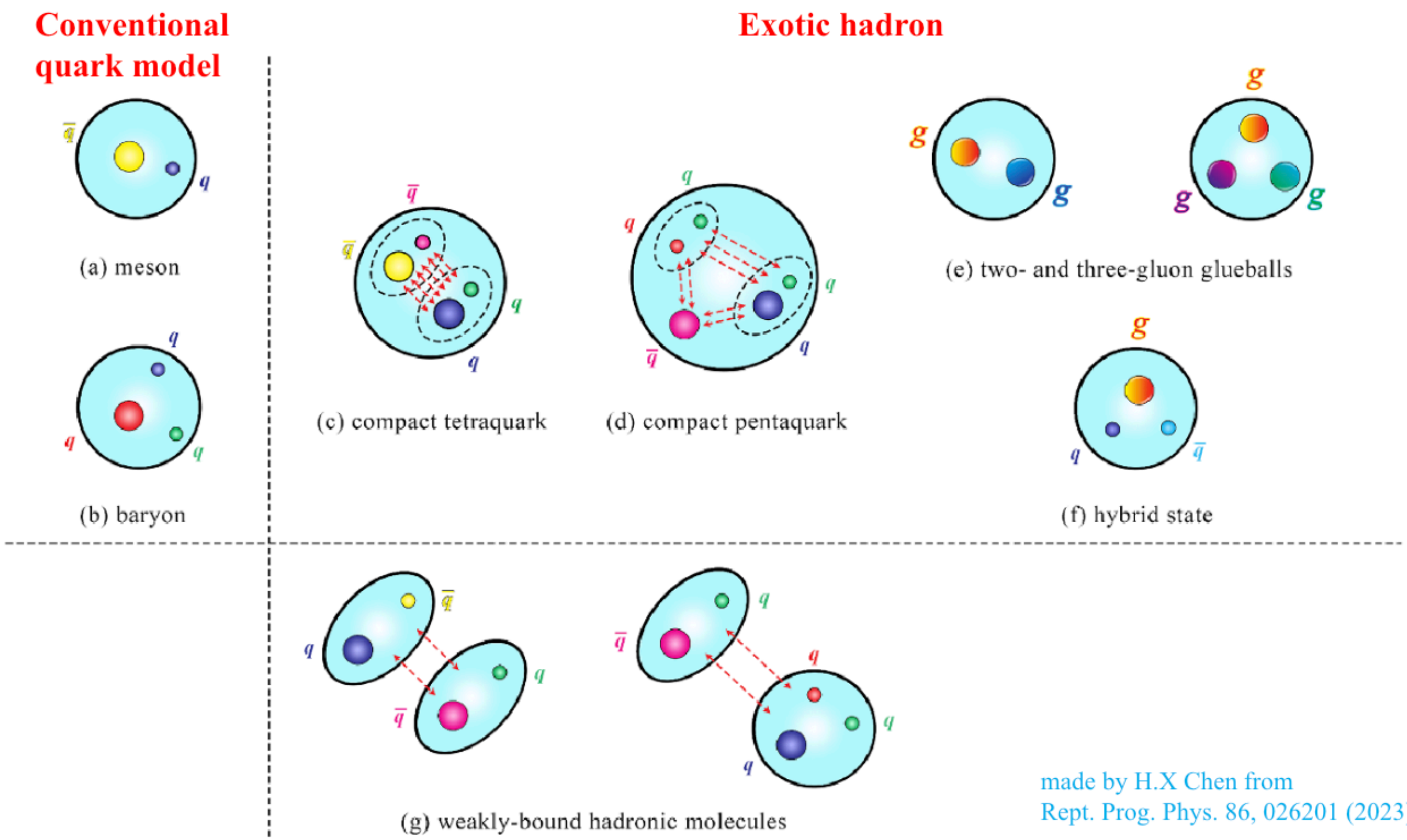
G. Zweig
CERN---Geneva

*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

...

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

Multiquark states



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

H-uuddss and S-uuddss

The uuddss dibaryon state has been initially proposed by Robert Jaffe (MIT) who predicted the so called H-dibaryon with a mass of about 2150 MeV and unstable.

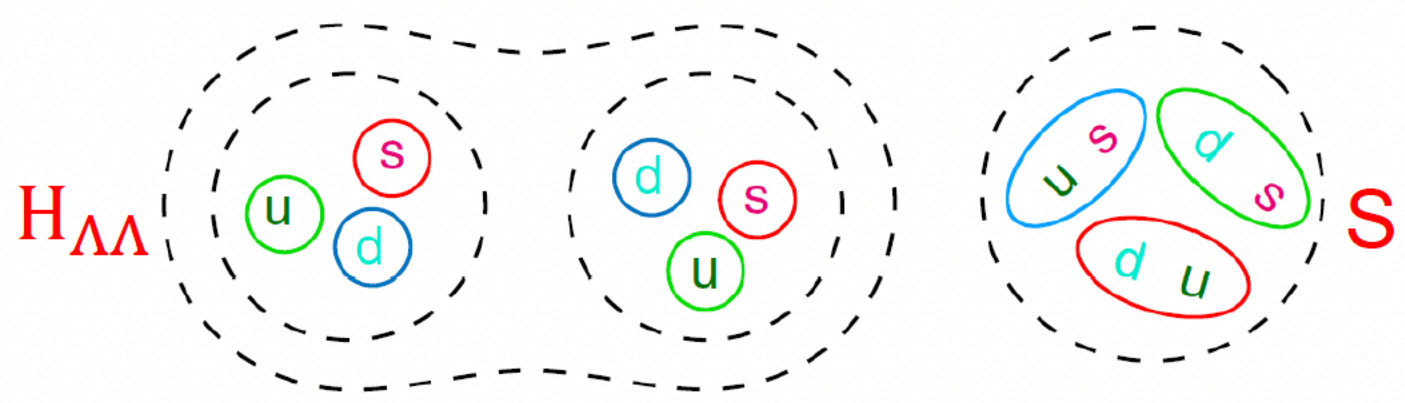
R. L. Jaffe, Phys. Rev. Lett. 38, 195 (1977).

The H-dibaryon has been searched by several experiments without finding it, e.g.:

B. H. Kim et al. [Belle], Phys. Rev. Lett. 110, 222002 (2013).
J. Badieret al. [NA3], Z. Phys. C 31, 21 (1986).
R. H. Bernstein et al, Phys. Rev. D 37, 3103 (1988).
J. Belzet al. [BNL-E888], Phys. Rev. Lett. 76, 3277 (1996).
A. Alavi-Haratiet 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, proposed by G. R. Farrar, is a new hypothetical low mass (below 2 GeV), small radius (0.1-0.4 fm) multiquark state.
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].



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

Sexaquark

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 that it can be a Dark Matter candidate.

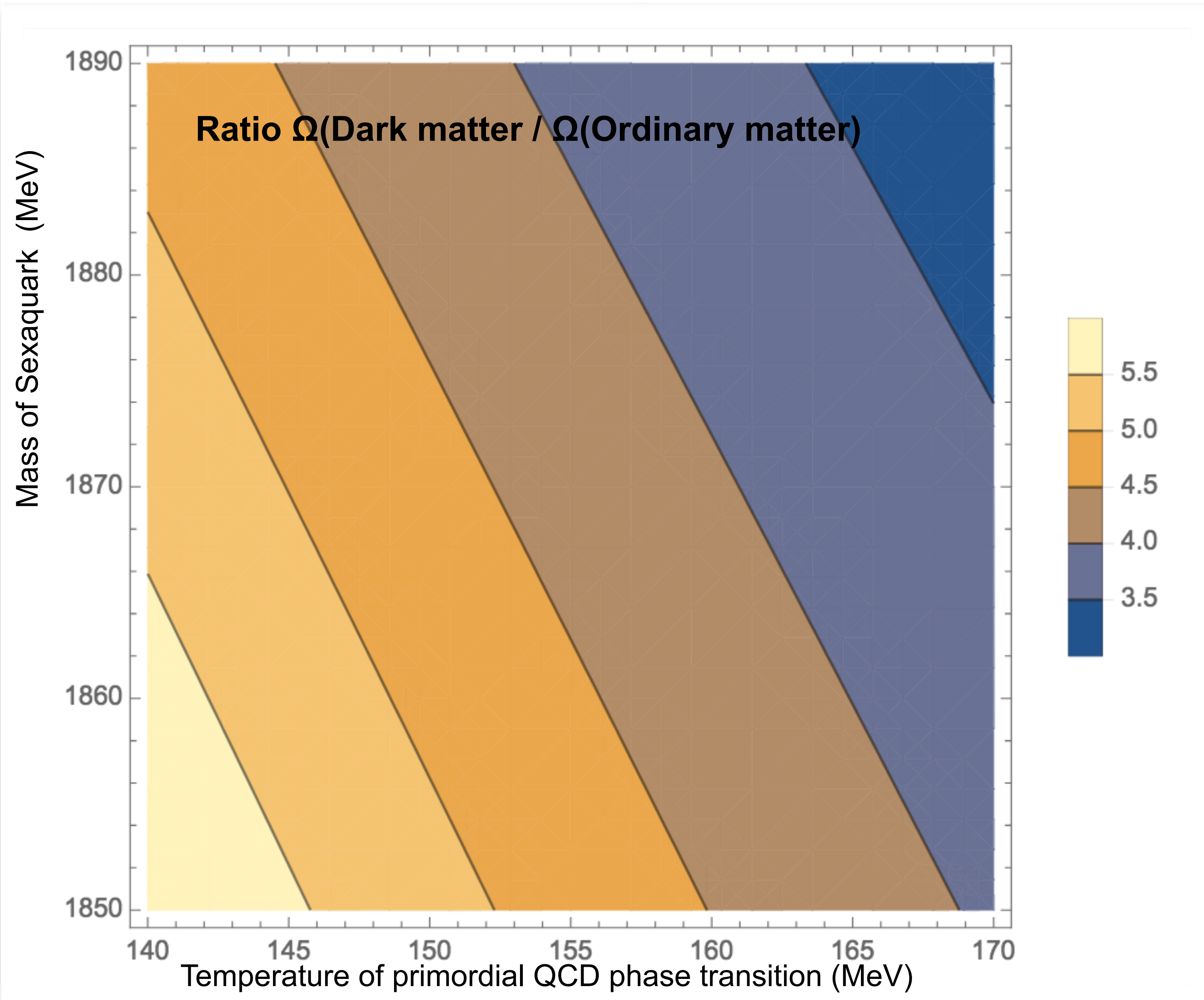
G. R. Farrar, arXiv:1708.08951, 1805.03723, 2201.01334 [hep-ph].
G. R. Farrar et al, arXiv:2007.10378 [hep-ph].

The assumption of a light Sexaquark has been shown to be consistent with observations of neutron stars.

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

S-uuddss as Dark Matter candidate

Calculation of the ratio of Dark Matter (DM) to Ordinary Matter (OM) assuming production of S(uuddss) from the Quark Gluon Plasma at the early Universe at a temperature of 140-170 MeV is shown in figure below



y-axis: m(Sexaquark) in MeV
x-axis: Freeze out Temperature

The measured value for DM/OM of 5.3+- 0.1 is in the second from lightest band.

The assumption of the Sexaquark as DM candidate leads to agreement with the measured DM/OM ratio for masses below 1885 MeV and at freeze out T below 153 MeV.

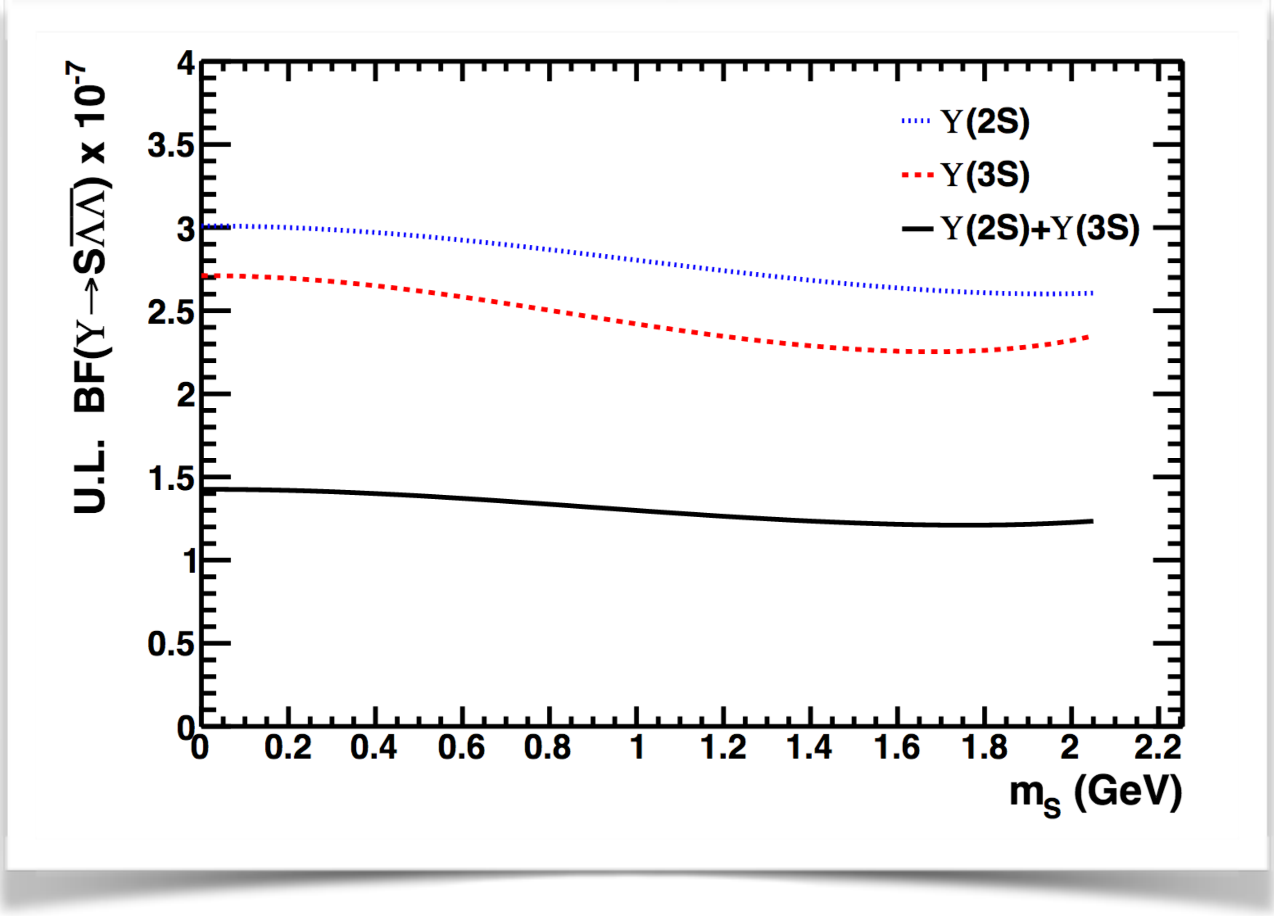
However, all values of the entire plot shown here are within factor of 2 from the measured value.

G. R. Farrar, (2017), arXiv:1708.08951 [hep-ph] and G. R. Farrar, (2018), arXiv:1805.03723 [hep-ph]

Experimental searches

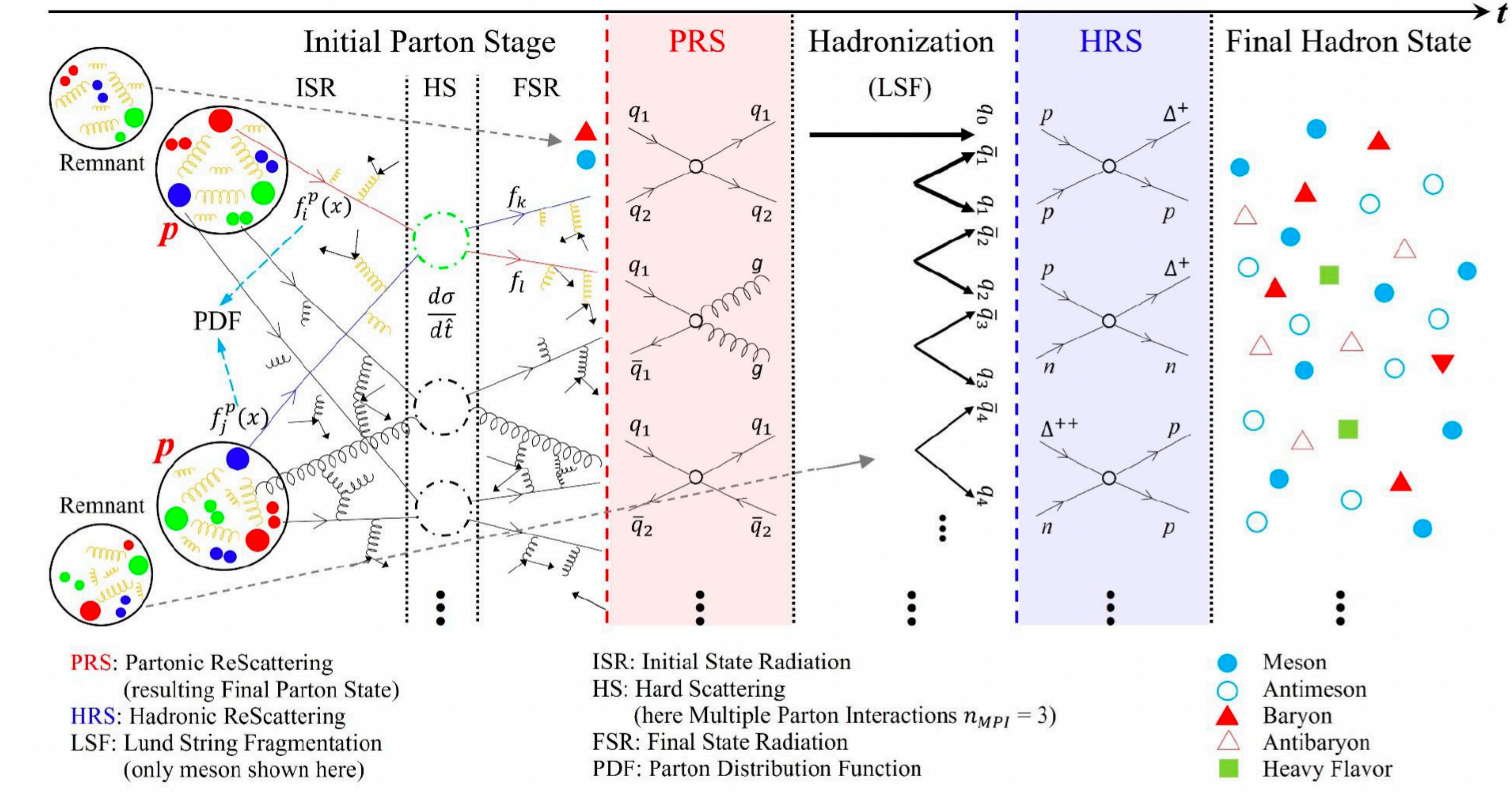
Even though not everyone agrees, (E. Kolb, M. Turner, PRD 99, 063519 (2019)) the possible cosmological implications of the sexaquark as DM candidate cannot be excluded and it has been recently searched in the BaBar experiment that set upper limits .

BABAR Coll. J. P. Lees et al, Phys.Rev.Lett. 122 (2019) no.7, 072002



The BABAR collaboration set 90% confidence level upper limits on the branching fraction Upsilon(2S,3S) —> S + antiLambda + antiLambda as well as the combined sample

Parton And-hadron China Institute of Atomic Energy (PACIAE 4.0)



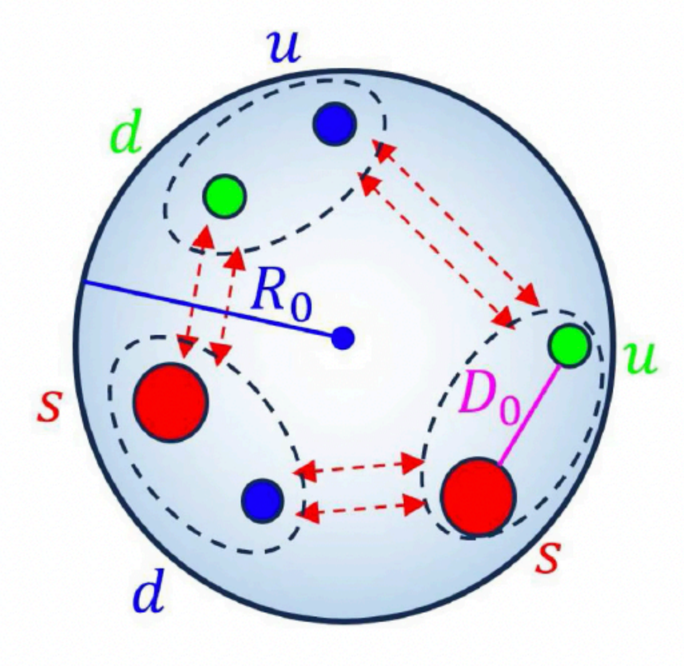
PACIAE 4.0: A. K. Lei et al Comput. Phys. Commun. 310, 109520 (2025)
An-Ke Lei et al, PRC 108, 064909 (2023),arXiv:2411.14255v1 open source: https://github.com/ArcsaberHep/PACIAE

PACIAE divides the whole collision process into four main stages: parton initiation, parton cascade, hadronization, and hadron cascade. Includes partonic and hadronic rescattering.

After the partonic freeze-out, the hadronization is implemented by the dynamically constrained phase-space coalescence (DCPC) model. PRC 85, 024907(2012)

Coalescence

Two-step approach:
- first diquarks are formed via the partonic coalescence model at partonic freeze-out
- then these diquarks are used to coalesce into the sexaquark in the Dynamically Constrained Phase-space Coalescence (DCPC) model



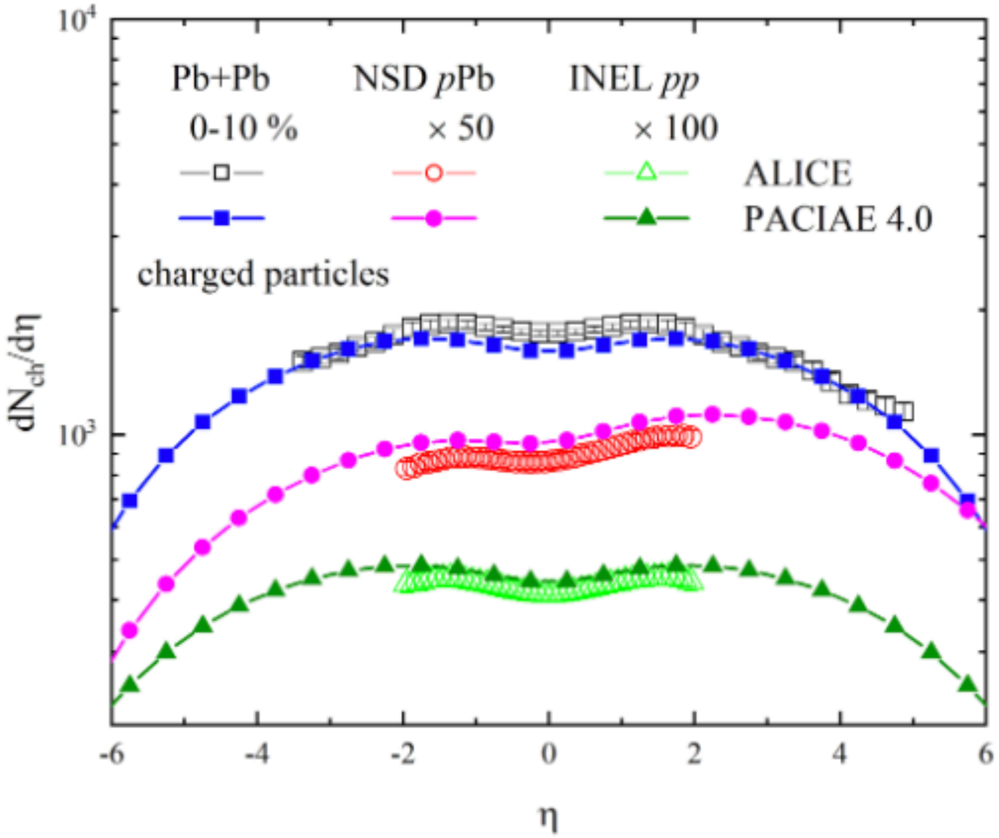
Possible structure of the sexaquark as a compact bound state of three diquarks (ud – us – ds). Here, D0 is the relative quark-quark distance in the diquark and R0 is the radius of the sexaquark.

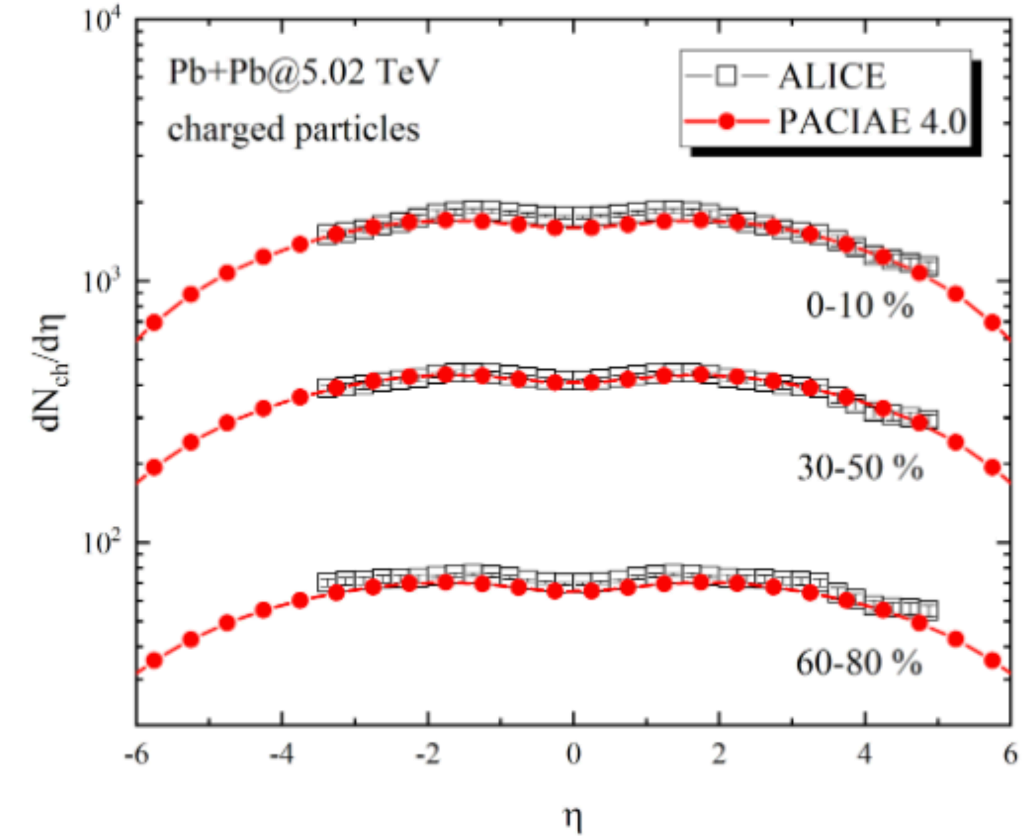
D0: 0.3-0.4 fm
R0: 0.1-0.4 fm
Assumed mass of the sexaquark: 1885-2054 MeV

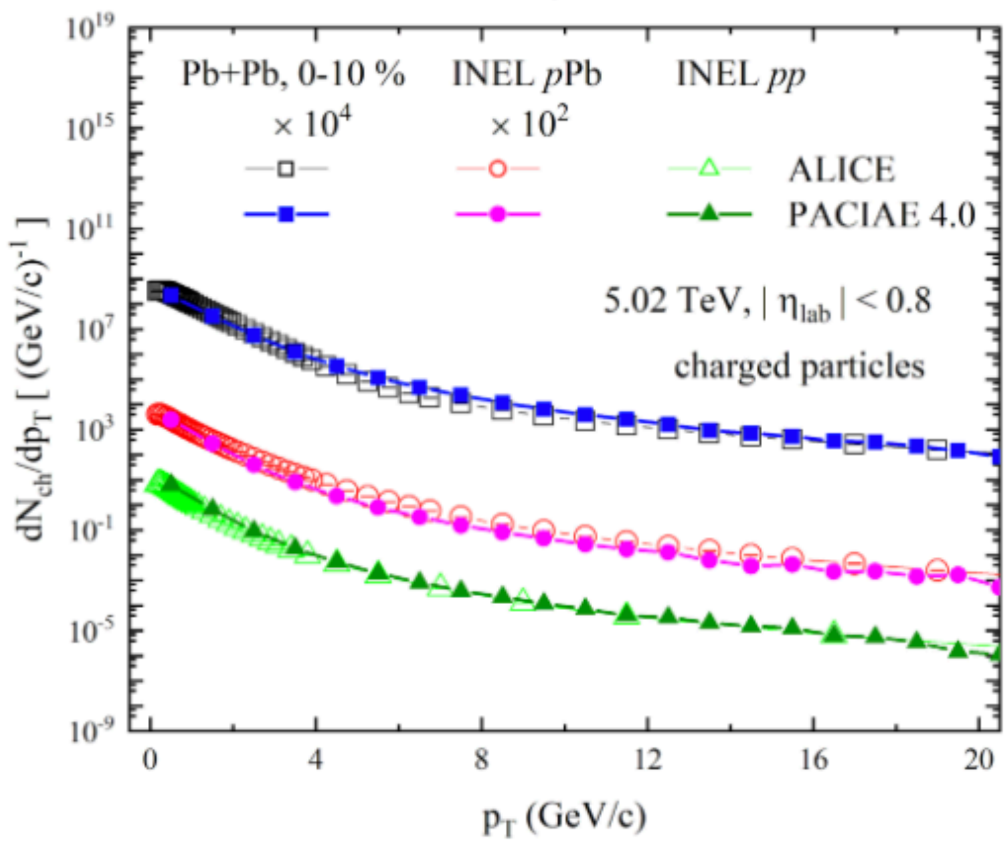
The main PACIAE 4.0 model parameters are fixed by fitting ALICE data in p+p collisions at sqrt(s)=7 TeV.

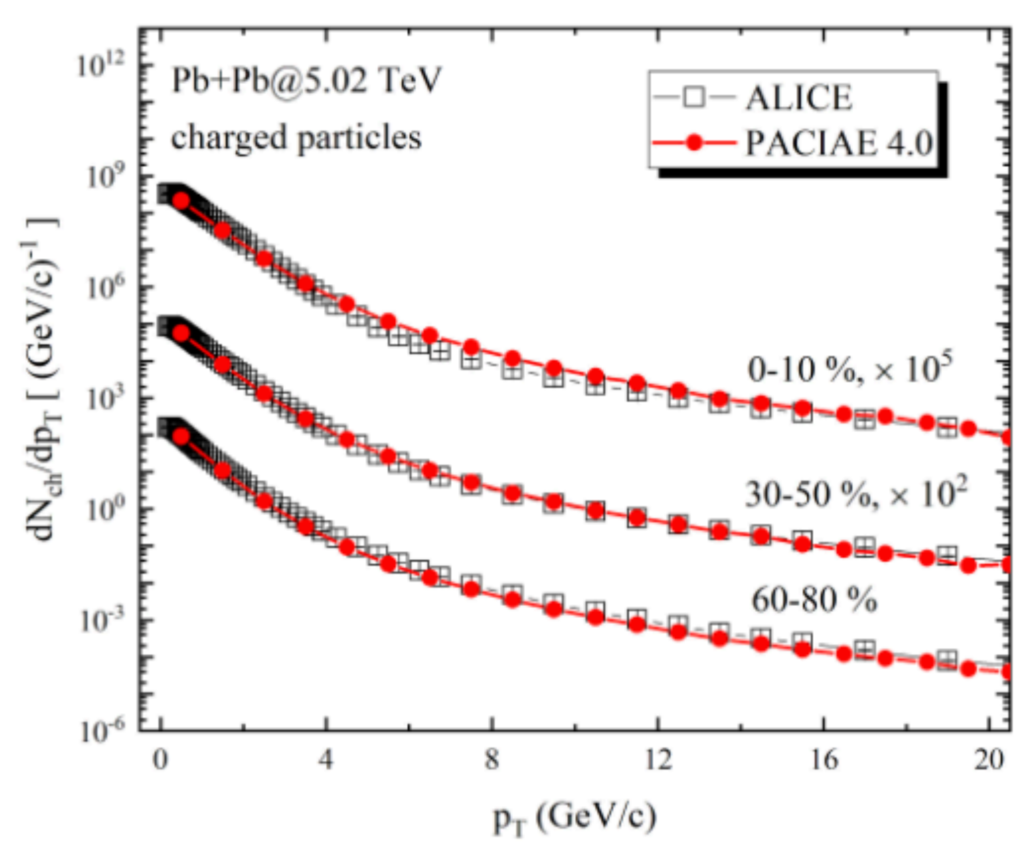
Particles	ALICE	PACIAE
$\pi^+ + \pi^-$	4.49 ± 0.20	4.49
$K^+ + K^-$	0.572 ± 0.032	0.602
$p + \bar{p}$	0.247 ± 0.018	0.265
$\Lambda + \bar{\Lambda}$	0.152 ± 0.011	0.141

PACIAE vs data

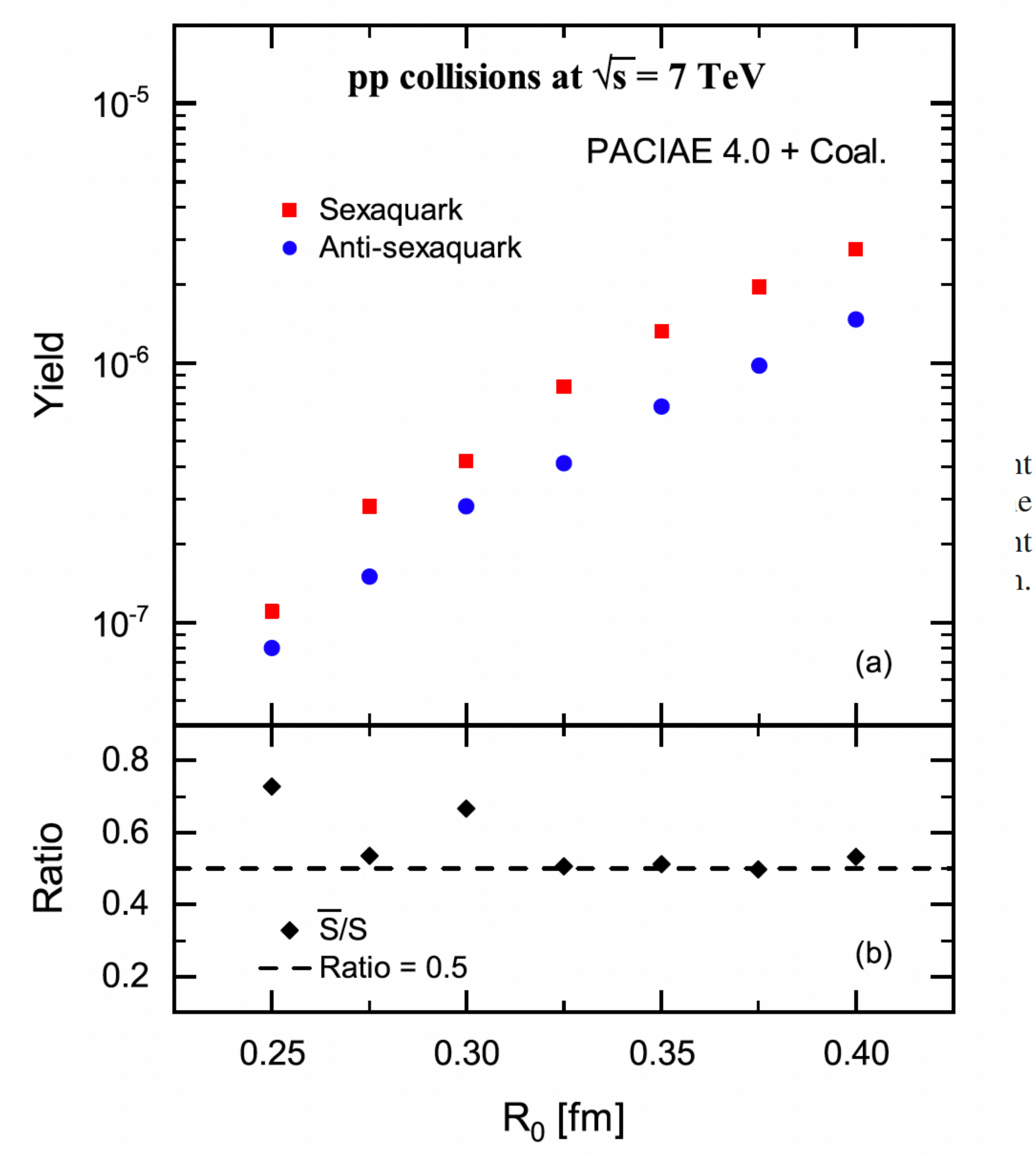








(Anti)Sexaquark predictions from PACIAE+coalescence

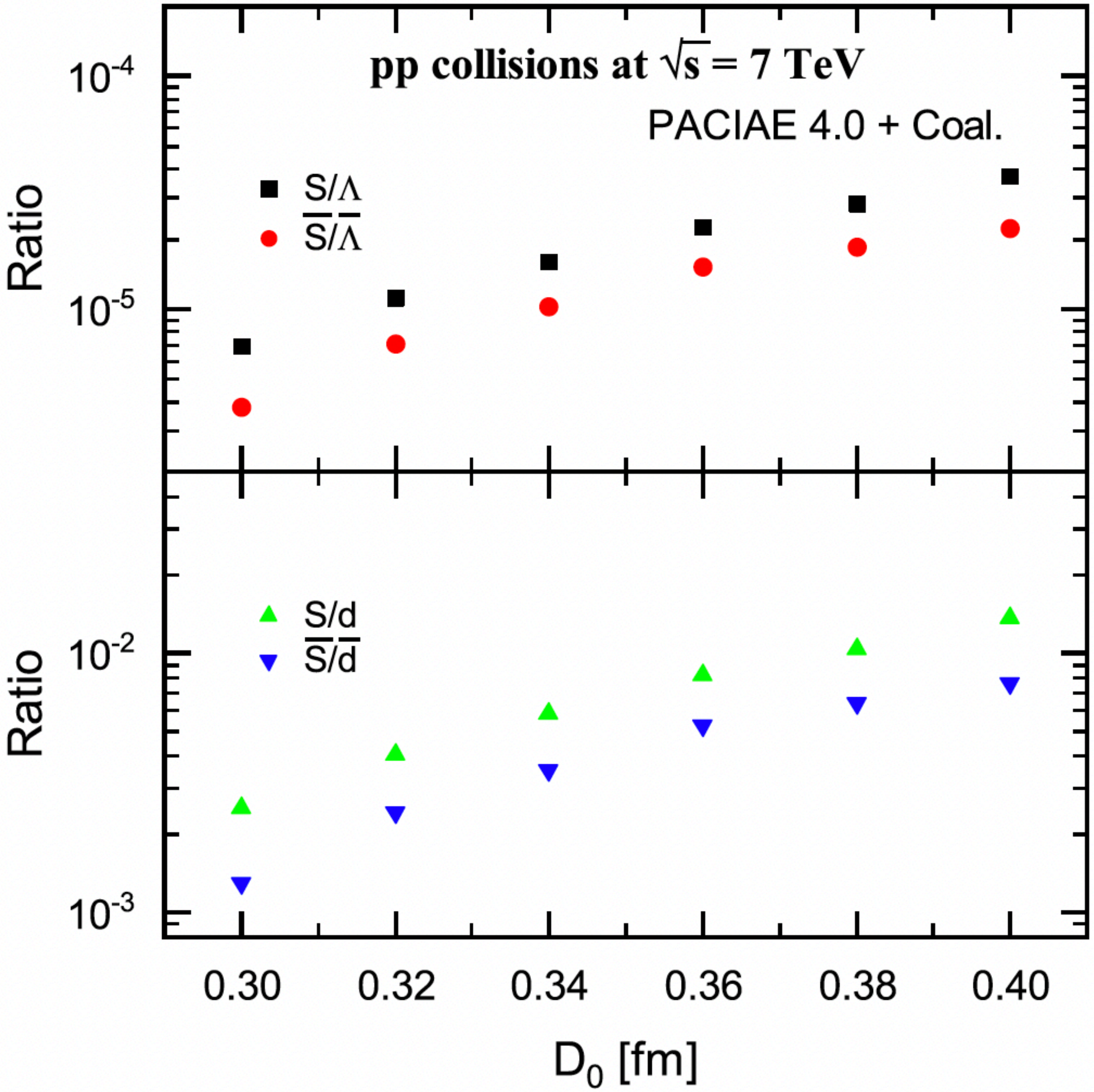


Here D0=0.4 fm is assumed.

The yields of the (anti) sexaquark increase with R0 (the relative quark-quark distance in the diquark) on a semilogarithmic plot, presenting a significant spatial parameter R0 dependence.

The ratio of anti-sexaquark to sexaquark is close to 0.5 at R0 larger than 0.3.

(Anti)sexaquark predictions from coalescence



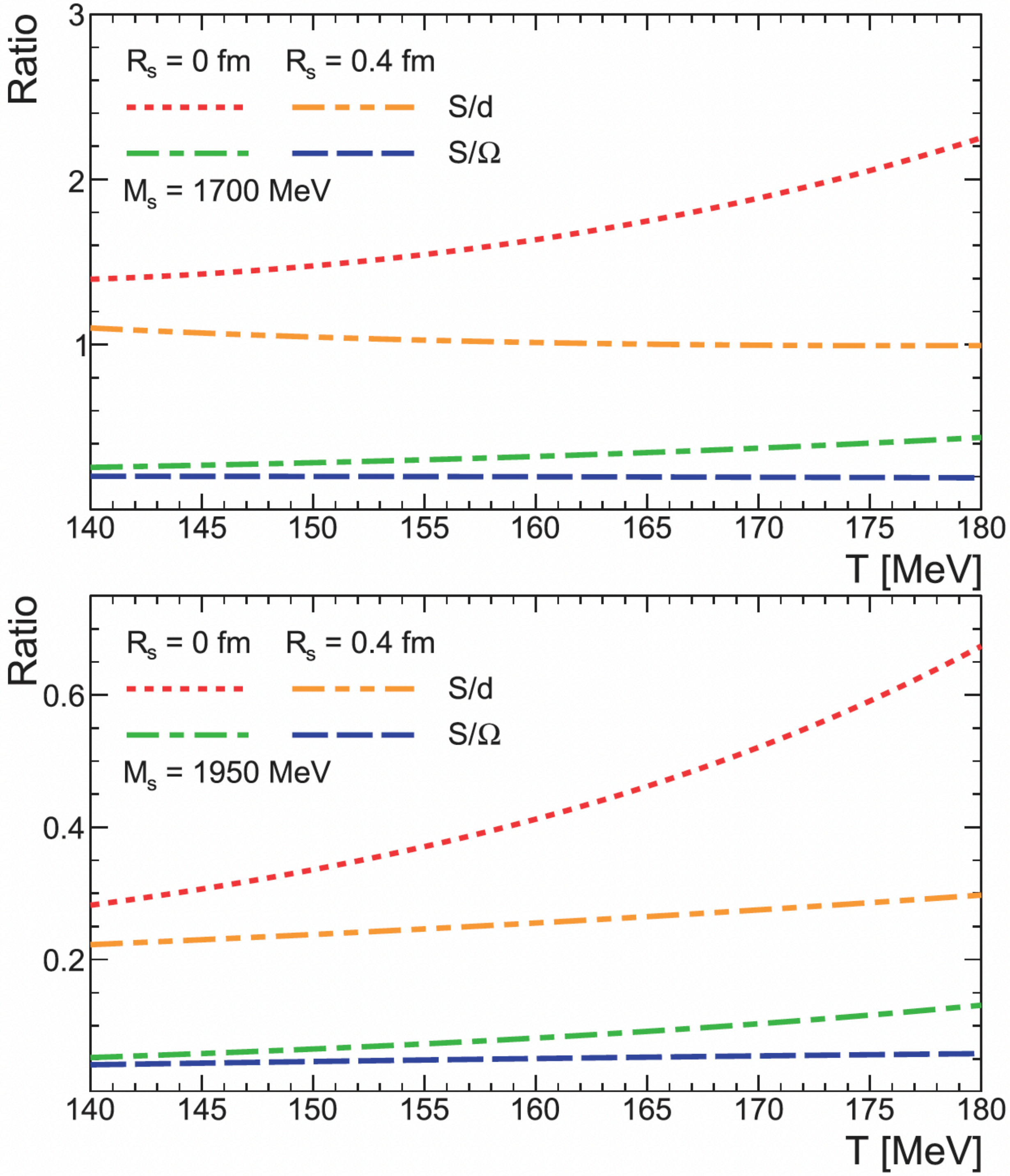
The yield-ratio oof (anti)sexaquarks to (anti)Lambdas and (anti)deuterons increase with increasing D0 (the relative quark-quark distance in the diquark).

	Ratios	
Types	$D_0 = 0.30$ fm	$D_0 = 0.40$ fm
S/Λ	6.91×10^{-6}	3.74×10^{-5}
$\bar{S}/\bar{\Lambda}$	3.77×10^{-6}	2.22×10^{-5}
S/d[a]	2.52×10^{-3}	1.35×10^{-2}
$\bar{S}/\bar{d}$[b]	1.30×10^{-3}	0.74×10^{-2}

Thermal (anti)sexaquark production

Thermal production in Pb+Pb collisions at sqrt(s_N)=2.76 TeV

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



The ratios of coalescence (anti)sexaquark to strange baryons and light nuclei in p+p collisions are much lower than that of thermal production in Pb+Pb collisions at sqrt(s_N)= 2.76 TeV

H-dibaryon compared to the S-sexaquark

The H-dibaryon is recombined using the components of two Λ hyperons using the DCPC model in the final hadronic state. The mass and radius of the H-dibaryon as a hadronic molecule are assumed to be 2055-2230 MeV and 1.0 < R0 < 4.9 fm, respectively.

The sexaquark yield is evaluated with the spatial parameters D0= 0.4 fm and 0.2 < R0 < 0.4 fm.

Yields	$S(uuddss)$	2.76×10^{-6}
	$\bar{S}(uu\bar{d}dss)$	1.47×10^{-6}
	$H(\Lambda\Lambda)$	1.65×10^{-4}
	$\bar{H}(\overline{\Lambda\Lambda})$	2.99×10^{-5}
Mixed ratios	$\bar{S}/S$	0.533
	$\bar{H}/H$	0.181
	S/H	1.67×10^{-2}
	$\bar{S}/\bar{H}$	4.92×10^{-2}

The coalescence yields of (anti)sexaquarks as a compact bound state are much less than those of (anti)H-dibaryon as a hadronic molecule.

The anti-S/S ratio (0.533) is larger than the anti-H/H ratio (0.18).

Summary and outlook

The (anti)sexaquark predicted by PACIAE+coalescence model, is assumed to be a compact state of a three-diquark configuration.

The yields of the (anti)sexaquark in p+p collisions at sqrt(s)=7 TeV are of the order of 10^{-8} to 10^{-6} for (anti)sexaquark radii of 0.25 to 0.4 fm.

The antisexaquark to sexaquark ratio is close to 0.5.

The ratios of the coalescence sexaquarks to hyperons and sexaquarks to light nuclei present a dependence on the parameter D0 (size of diquark).
The values are on the order of 10^{-6} and 10^{-3} in the D0 = 0.3 fm case and 10^{-5} and 10^{-2} in the D0 = 0.4 fm case, which are much lower than that of thermal production in heavy-ion collisions.

The coalescence yields of (anti)sexaquarks as a compact bound state are much smaller than those of (anti)H-dibaryon as a hadronic molecule.
The anti-S/S ratio (0.533) is larger than the anti-H/H ratio (0.18).

Outlook:
The study will be extended to Pb-Pb collisions at LHC energies and to other dibaryons.

Thank you very much