APCTP workshop on “Exotics and Exotic phenomena in Heavy Ion Collision ExHIC III”

Period: 2022-9-29 ~ 2022-10-1

Location: Pohang APCTP Headquarter or Online

Organizer: Su Houng Lee 이수형(연세대),

Akira Ohnishi (YITP, Kyoto)

Xu-Guang Huang (Fudan Univ.)

Sungtae Cho 조성태 (강원대)

Yongseok Oh 오용석 (경북대)

Origin of Exotics from Heavy Ion Collision (ExHIC): Theory Collaboration

- **2007.12-3 -12-14: APCTP Focus program on Hadron Physics at RHIC**
- **2010.5.17-30: Yukawa Institute (YITP) workshop on ExHIC**
- **2019.3-25 -4.5: YITP workshop on "Hadron Interactions and Polarization from High energy Collisions"**

→ Outcome:

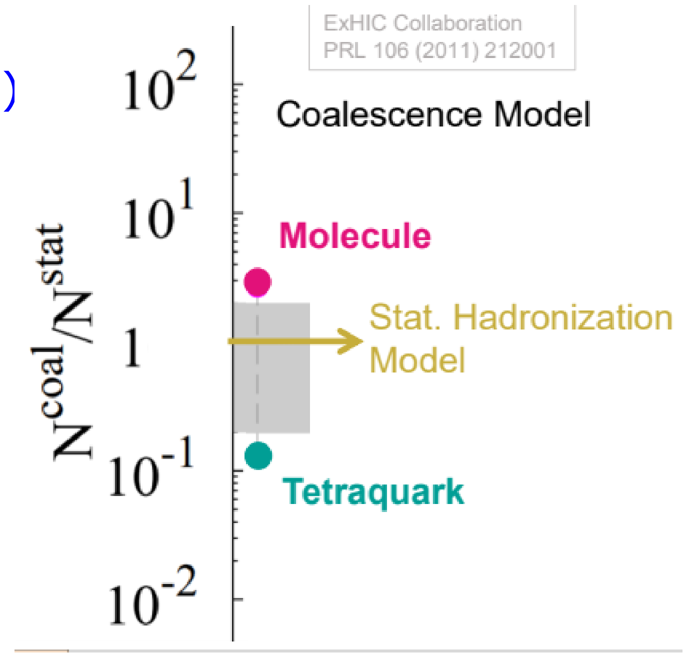
- Charmed exotics in heavy ion collision: EPJC (2008)
- ExHIC: PRL(2011), PRC(2011), PPNP(2017)

  all >100 citations

- ExHIC-p: PRD (2020)

→ Measure Exotics in Heavy Ion Collision

ex: can discriminate structure of X(3872), Tcc



Exotica production in Heavy Ion Collision

Su Houng Lee

YONSEI UNIVERSITY

Why it is interesting to measure Exotics in Heavy Ion Collision

Will use X(3872) and Tcc ($D^0D^0\pi^+$) as examples

Acknowledgements: arXiv:2208.06960

Yonsei group : W. Park, A. Park, J. Hong, S. Noh, H. Yoon, D. Park,

External: C. M. Ko, Sungtae Cho, Sanghoon Lim, Yongsun Kim

+ ExHIC collaboration

Exotics – some example

1. Tetraquark states

Tetraquark Belle	Mass	Quark content	$\bar{D}^0 D^{*0}$	$D^- D^{*+}$
X(3872)	3871.65	$(q\bar{q})(c\bar{c})$	3871.69	3879.92

Tetraquark LHCb	Mass $(u\bar{d})(c\bar{c})$	Quark content	$D^+ D^{*0}$	$\bar{D}^0 D^{*+}$	Observed mode
Tcc	3875	$(\bar{u}\bar{d})(cc)$	3876.51	3875.26	$\bar{D}^0 D^0 \pi^+$

Tetraquark LHCb,BES?	Mass +i(width)	Quark content	$\bar{D}^0 D_s^{*+}$	$\bar{D}^{0*} D_s^+$	Observed mode
Zcs(4000)	4003+i(131)	$(u\bar{d})(c\bar{c})$	3977	3978	$J/\psi K^+$

Tetraquark D0	Mass	Quark content	$B_s^0 \pi^{\pm}$	$B^0 K^+$	Observed mode
X(5568)	5568+i(21.9)	$(bu)(\bar{d}\bar{s})$	5506.49	5773	$B_s^0 \pi^{\pm}$

2. Pentaquarks: Pc …

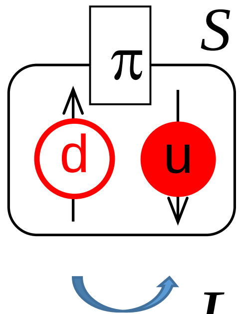
Ground state Mesons

$$J^P = (s+L)^{(-1)^{L+1}} \xrightarrow{\text{Ground states L=0}} (s)^{-1}$$

$J^P = 0^-$

$m_\pi^0 = 135$ MeV

$S = 0$

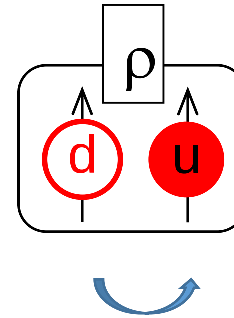


$L = 0$

$J^P = 1^-$

$m_\rho^0 = 775$ MeV

$S = 1$



$L = 0$

P-wave Mesons

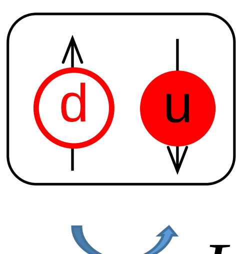
$$P = (-1)^{L+1}, \quad C = (-1)^{L+S}$$

$J^{PC} = 1^{+-}$

$m_{h_1}^{I=0} = 1166$ MeV

$m_{b_1}^{I=1} = 1229$ MeV

$S = 0$



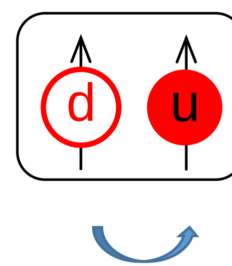
$L = 1$

$J^{PC} = 0^{++}$

$m_{a_0}^{I=0} = 980$ MeV

$m_{f_0}^{I=1} = 980$ MeV

$S = 1$



$L = 1$

P-wave Mesons

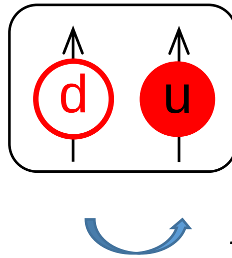
$$P=(-1)^{L+1},\quad C=(-1)^{L+S}$$

$J^{PC}=0^{++}$

$m_{a_0}^{I=0}=980\ \text{MeV}$

$m_{f_0}^{I=1}=980\ \text{MeV}$

$S=1$



$L=1$

which one ?

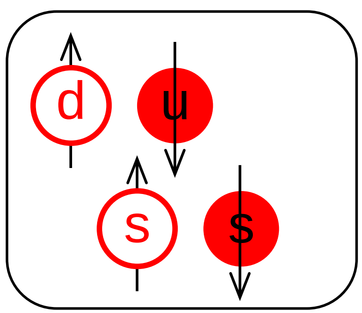
$J^{PC}=0^{++}$

$m_{a_0}^{I=0}=980\ \text{MeV}$

$m_{f_0}^{I=1}=980\ \text{MeV}$

Mass of 2 diquarks

$S=L=0$



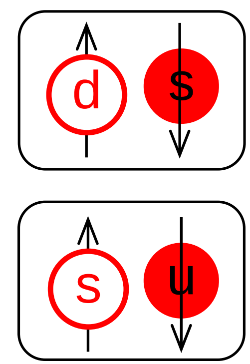
compact multiquark

$J^{PC}=0^{++}$

$m_{a_0}^{I=0}=980\ \text{MeV}$

$m_{f_0}^{I=1}=980\ \text{MeV}$

Mass of 2 Kaon



K^0

K^+

Loosely bound molecule

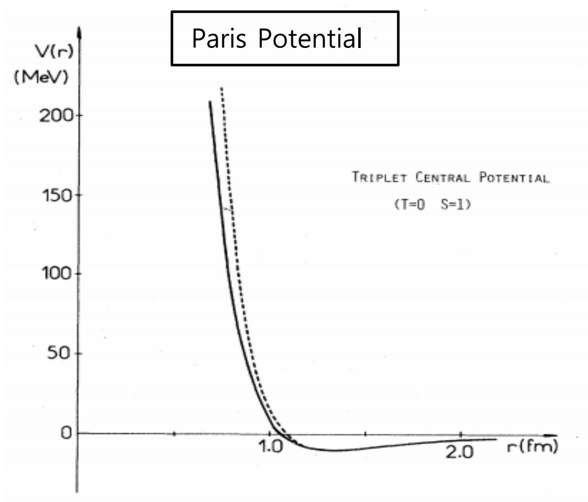
I: Short distance:

Perspectives from a quark model

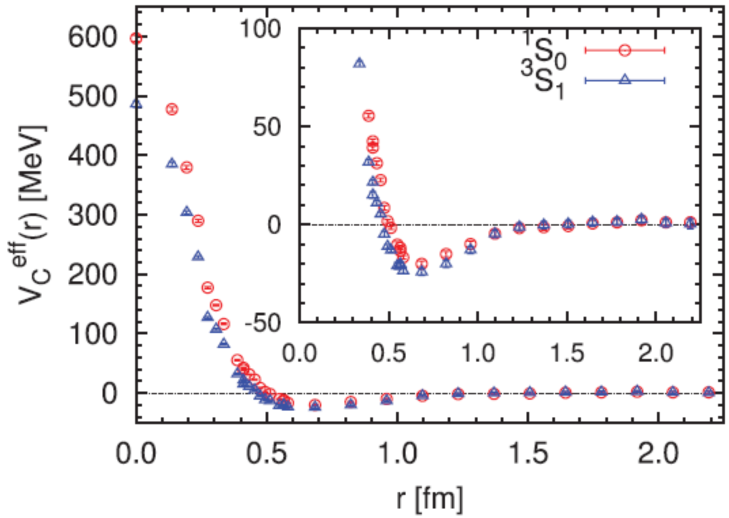
There are attractive channels

1. Nucleon-Nucleon potential at (I=0, S=1)

Paris Potential

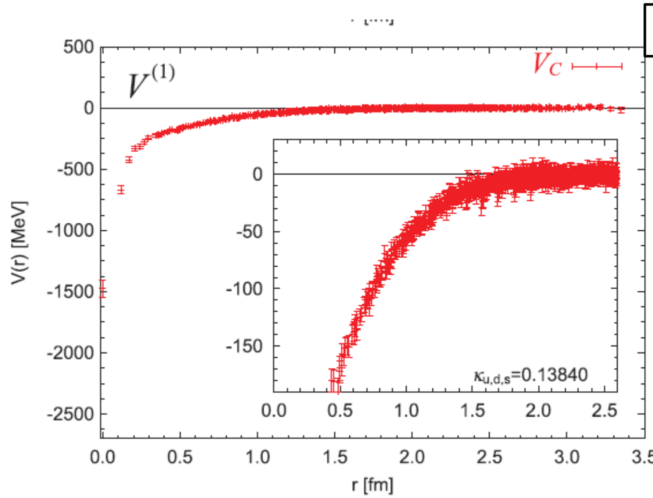


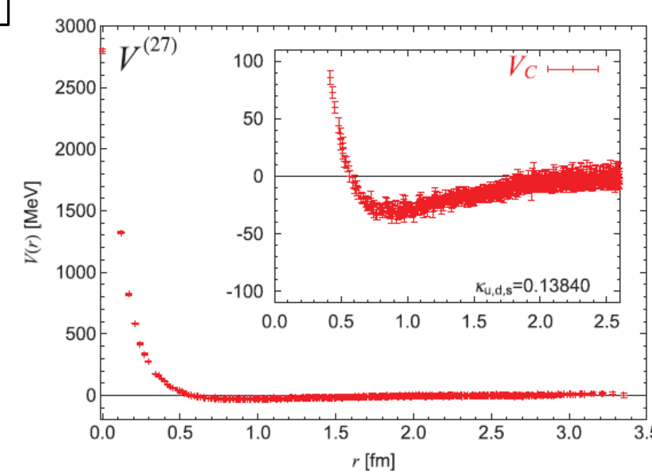
QCD HAL collaboration



2. There are attractive channels in $SU(N_F)$ when $N_F \geq 3$

QCD HAL collaboration



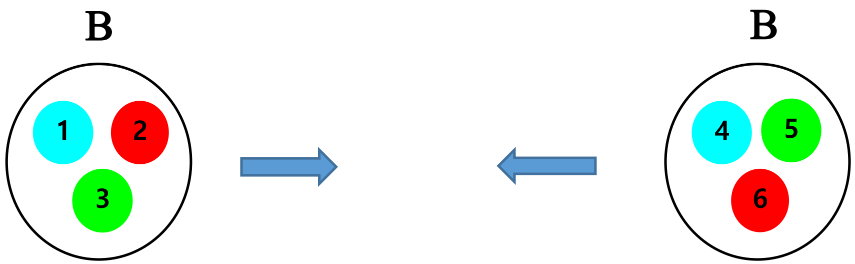


Quark model : interaction between quarks

$$H=\sum_{i=1}^{n}\left(m_i+\frac{p_i^2}{2m_i}\right)-\sum_{i<j}^{n}\left(\lambda_i^c\lambda_j^c\right)V_{ij}^{C}\left(r_{ij}\right)-\sum_{i<j}^{n}\frac{\left(\lambda_i^c\lambda_j^c\right)\left(\sigma_i\sigma_j\right)}{m_im_j}V_{ij}^{SS}\left(r_{ij}\right)$$

☞ When brought together need to overcome Additional Kinetic energy

$$\frac{p_{BB}^2}{2\mu_{BB}}\approx\frac{1}{2\mu_{BB}}\frac{1}{(0.6\text{fm})^2}\sim100\text{MeV}$$



→ To have a compact configuration, short range attraction should be larger than 100 MeV

Quark Model perspectives on Interaction at short distance – color-color interaction

Quark model

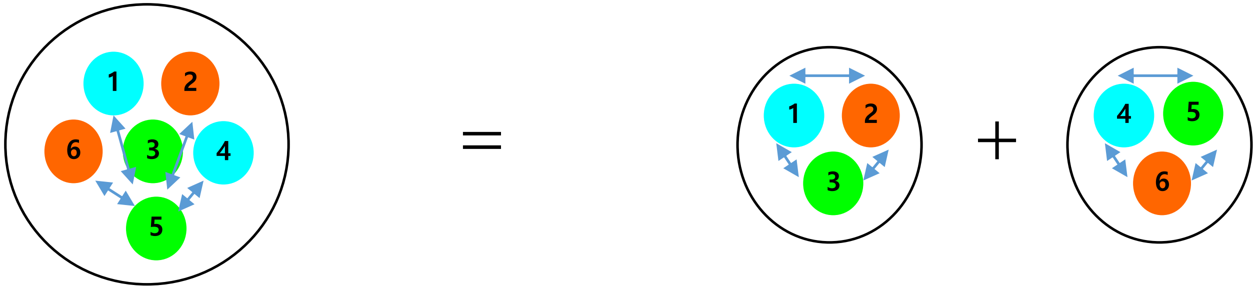
$$H=\sum_{i=1}^{n}\left(m_i+\frac{p_i^2}{2m_i}\right)-\sum_{i<j}^{n}\left(\lambda_i^c\lambda_j^c\right)V_{ij}^C\left(r_{ij}\right)-\sum_{i<j}^{n}\frac{\left(\lambda_i^c\lambda_j^c\right)\left(\sigma_i\sigma_j\right)}{m_im_j}V_{ij}^{SS}\left(r_{ij}\right)$$

☞ Color-Color interaction is not important for short range N-N interaction

$$\sum_{i<j}^{N}\left(\lambda_i^c\lambda_j^c\right)=\frac{1}{2}\left[\left(\lambda_1^c+\ldots+\lambda_N^c\right)^2-\lambda_1^2-\ldots\lambda_N^2\right]$$

$$N=N_{B_1}+N_{B_2}$$

$$=0-\frac{8}{3}\left(N_{B_1}+N_{B_2}\right)=\sum_{i<j}^{N_{B_1}}\left(\lambda_i^c\lambda_j^c\right)+\sum_{i<j}^{N_{B_2}}\left(\lambda_i^c\lambda_j^c\right)$$



Quark model

$$H=\sum_{i=1}^{n}\left(m_i+\frac{p_i^2}{2m_i}\right)-\sum_{i<j}^{n}\left(\lambda_i^c\lambda_j^c\right)V_{ij}^C\left(r_{ij}\right)-\sum_{i<j}^{n}\frac{\left(\lambda_i^c\lambda_j^c\right)\left(\sigma_i\sigma_j\right)}{m_i m_j}V_{ij}^{SS}\left(r_{ij}\right)$$

☞ Color-spin interaction for 2 body:

$$K=-\sum_{i<j}^{N}\left(\lambda_i^c\lambda_j^c\right)\left(\sigma_i^s\sigma_j^s\right)\longrightarrow$$

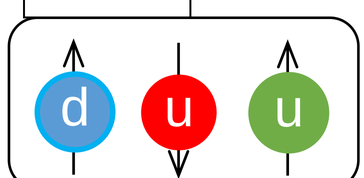
	$Q-Q$				$Q-\bar{Q}$			
Color	A	S	A	S	1	8	1	8
Flavor	A	A	S	S				
Spin	A(0)	S(1)	S(1)	A(0)	0	0	1	1
K	-8	-4/3	8/3	4	-16	2	16/3	-2/3

$K<0$ attraction; $K>0$ repulsion

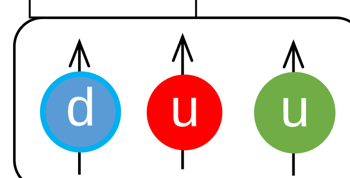
☞ $M_\Delta - M_P \approx 290\text{ MeV} \rightarrow K$ factors $3\times\left(\frac{8}{3}\right) - (-8) = 16$

K factor of $1 \rightarrow 18\text{ MeV}$

Proton $S=1/2$



Delta $S=3/2$

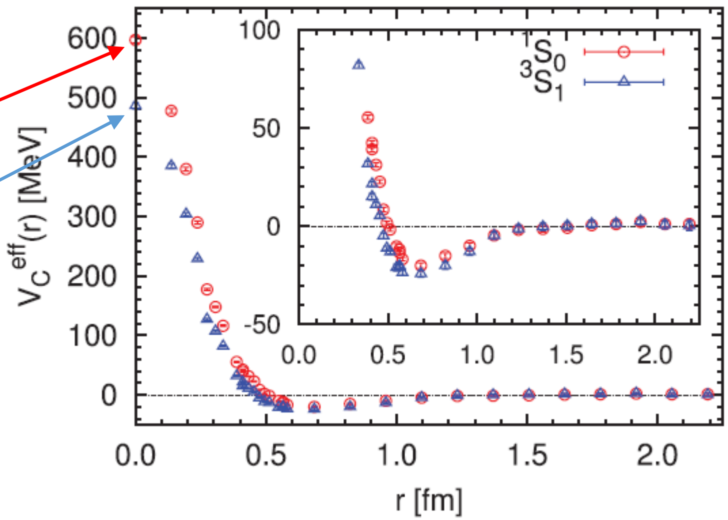


☞ NN force in SU(2) spin 1 vs spin 0 channel: comparison to lattice

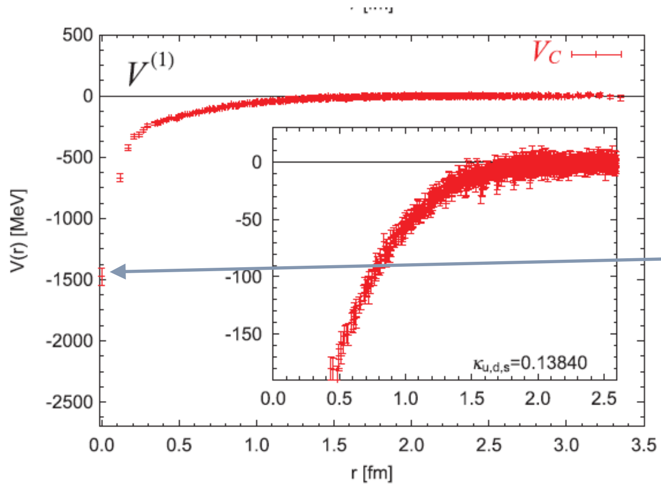
$$K_{2-N} = K_{6-quark} - \left(K_{1N} + K_{1N}\right)$$

$$\frac{K_{2-N}^{S=0}}{K_{2-N}^{S=1}} = 1.29 \quad \rightarrow \text{comparison}$$

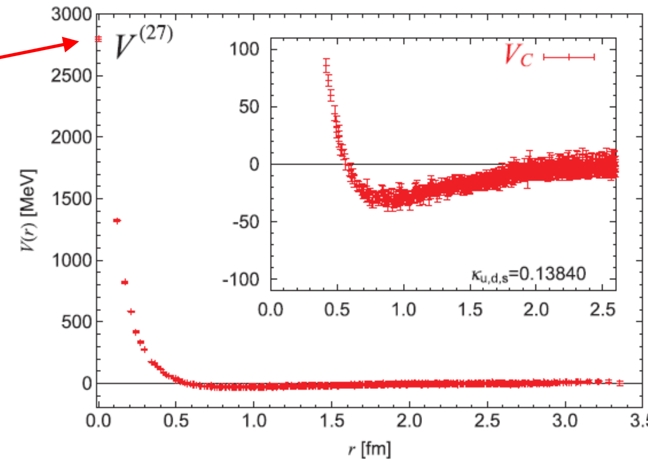
QCD HAL collaboration



☞ H dibaryon channel: Flavor 1 vs Flavor 27



$$\frac{K_{2-N}^{F=27}}{K_{2-N}^{F=1}} = -3$$

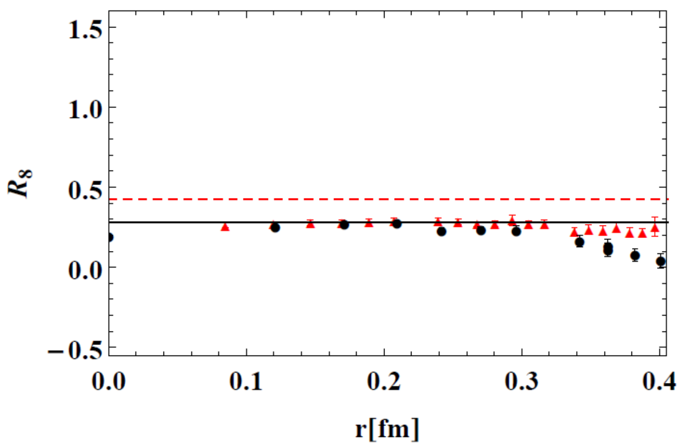


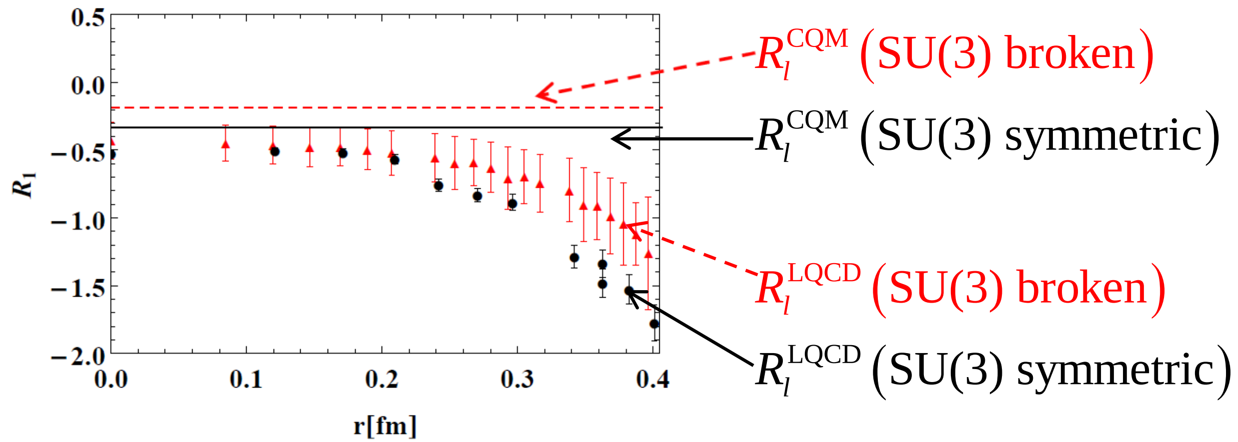
(HAL QCD Collaboration)

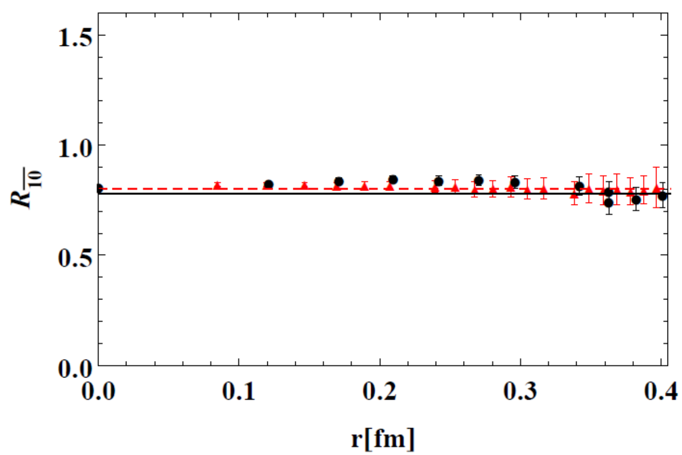
Confirmed in Full quark model calculation vs Lattice – A.Park, Lee, Inoue, Hatsuda, EPJA 56(20203,93

☞ Comparison to Lattice calculation

$$R_l^{CQM} = \frac{V_{CQM}(F_l)}{V_{CQM}(F_{27})} \quad \text{vs} \quad R_l^{LQC}(r) = \frac{V_{LQCD}(F_l)}{V_{LQCD}(F_{27})}$$







Note $\quad R_l^{CQM}(\text{SU(3) symmetric}) = \dfrac{K_{2-N}^{F=l}}{K_{2-N}^{F=27}}$

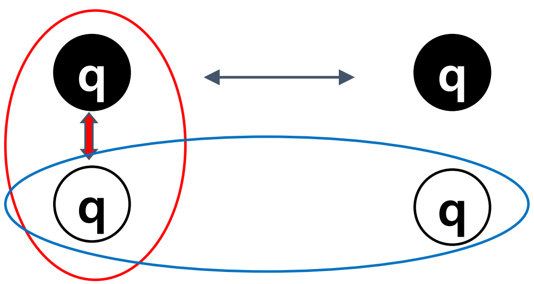
In fact, the K factors are good enough

Why heavy quarks ? (qq) vs $(\bar{q}q)$ attraction

	$Q\text{–}Q$				$Q\text{–}\bar{Q}$			
Color	A	S	A	S	1	8	1	8
Flavor	A	A	S	S				
Spin	A(0)	S(1)	S(1)	A(0)	0	0	1	1
K	-8	-4/3	8/3	4	-16	2	16/3	-2/3

Fall apart into two mesons

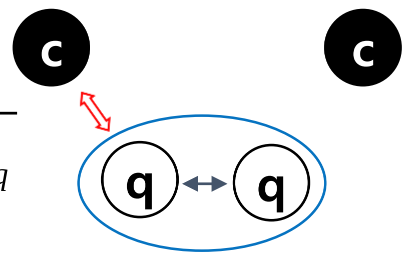
$$-16\frac{1}{m_q m_q}$$



$$-8\frac{1}{m_q m_q}$$

When heavy quarks, could be compact

$$-16\frac{1}{m_c m_q}$$



$$-8\frac{1}{m_q m_q}$$

K factor and attraction for X(3872) and Tcc : W. Park, Lee, NPA924(2014) 161

X(3872): Belle 2003

$$I^G\left(J^{PC}\right)=0^+\left(1^{++}\right) \qquad \left(c\bar{c}\right)\otimes\left(q\bar{q}\right)$$

$$K_{X(3872)}-K_D-K_{D^*}=\begin{pmatrix} \frac{16}{3}\frac{1}{m_c^2}+\frac{16}{3}\frac{1}{m_q^2}+\frac{32}{3}\frac{1}{m_cm_q} & 0 \\ 0 & -\frac{2}{3}\frac{1}{m_c^2}-\frac{2}{3}\frac{1}{m_q^2}-\frac{4}{3}\frac{1}{m_cm_q} \end{pmatrix} \begin{matrix} \left(1\otimes1\right)_{C=1}\left(V\otimes V\right)_{S=1} \\ \left(8\otimes8\right)_{C=1}\left(V\otimes V\right)_{S=1} \end{matrix}$$

Assuming typical hadron size → $\sim -20\ \mathrm{MeV}$ Too small to be compact

T_{cc}(3875): LHCb 2021

$$I^G\left(J^{P}\right)=0^+\left(1^{+}\right) \qquad \left(ud\right)\otimes\left(\overline{cc}\right)$$

$$K_{T_{cc}(3875)}-K_D-K_{D^*}=\begin{pmatrix} -8\frac{1}{m_q^2}+\frac{8}{3}\frac{1}{m_c^2}+\frac{32}{3}\frac{1}{m_cm_q} & -8\sqrt{2}\frac{1}{m_cm_q} \\ -8\sqrt{2}\frac{1}{m_cm_q} & -\frac{4}{3}\frac{1}{m_q^2}+4\frac{1}{m_c^2}+\frac{32}{3}\frac{1}{m_cm_q} \end{pmatrix} \begin{matrix} \left(\bar{3}\otimes3\right)_{C=1}\left(S\otimes V\right)_{S=1} \\ \left(6\otimes\bar{6}\right)_{C=1}\left(V\otimes S\right)_{S=1} \end{matrix}$$

Lowest Eigenvalues $\sim -100\ \mathrm{MeV}$ Note: addition Kinetic Energy -> +100 MeV

IOPscience

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Heavy-ion collisions at the LHC—Last call for predictions

N Armesto[1], N Borghini[2], S Jeon[3], U A Wiedemann[4], S Abreu[5], S V Akkelin[6], J Alam[7], J L Albacete[8], A Andronic[9], D Antonov[10] + Show full author list

Published 18 April 2008 • 2008 IOP Publishing Ltd

Journal of Physics G: Nuclear and Particle Physics, Volume 35, Number 5

Citation N Armesto *et al* 2008 *J. Phys. G: Nucl. Part. Phys.* **35** 054001

Abstract

This writeup is a compilation of the predictions for the forthcoming Heavy Ion Program at the Large Hadron Collider, as presented at the CERN Theory Institute 'Heavy Ion Collisions at the LHC—Last Call for Predictions', held from 14th May to 10th June 2007.

10.3. *Charmed exotics from heavy-ion collision*

S H Lee, S Yasui, W Liu and C M Ko

We discuss why charmed multiquark hadrons are likely to exist and explore the possibility of observing such states in heavy-ion reactions at the LHC.

Multiquark hadronic states are usually unstable as their quark configurations are energetically above those of combined meson and/or baryon states. However, constituent quark model calculations suggest that multiquark states might become stable when some of the light quarks are replaced by heavy quarks. Two possible states that could be realistically observed in heavy-ion collisions at LHC are the tetraquark $T_{cc}(ud\bar{c}\bar{c})$ [385] and the pentaquark

J. Phys. G: Nucl. Part. Phys. **35** (2008) 054001 N Armesto *et al*

Table 10. Possible decay modes of T_{cc}. Additional $(\pi^+\pi^-)$'s are possible in the bracket.

Threshold	Decay mode	Lifetime
$M_{T_{cc}} > M_{D^*} + M_D$	$D^{*-}\bar{D}^0$	Hadronic decay
$2M_D + M_\pi < M_{T_{cc}} < M_{D^*} + M_D$	$\bar{D}^0\bar{D}^0\pi^-$	Hadronic decay
$M_{T_{cc}} < 2M_D + M_\pi$	$D^{*-}(K^+\pi^-)$	0.41×10^{-12} s
	$\bar{D}^0(\pi^-K^+\pi^-)$	Weak decay

nature physics

OPEN

Observation of an exotic narrow doubly charmed tetraquark

LHCb Collaboration*

Conventional, hadronic matter consists of baryons and mesons made of three quarks and a quark-antiquark pair, respectively[1,2]. Here, we report the observation of a hadronic state containing four quarks in the Large Hadron Collider beauty experiment. This so-called tetraquark contains two charm quarks, a $\bar{u}$ and a $\bar{d}$ quark. This exotic state has a mass of approximately 3,875 MeV and manifests as a narrow peak in the mass spectrum of $D^0D^0\pi^+$ mesons just below the $D^{*+}D^0$ mass threshold. The near-threshold mass together with the narrow width reveals the resonance nature of the state.

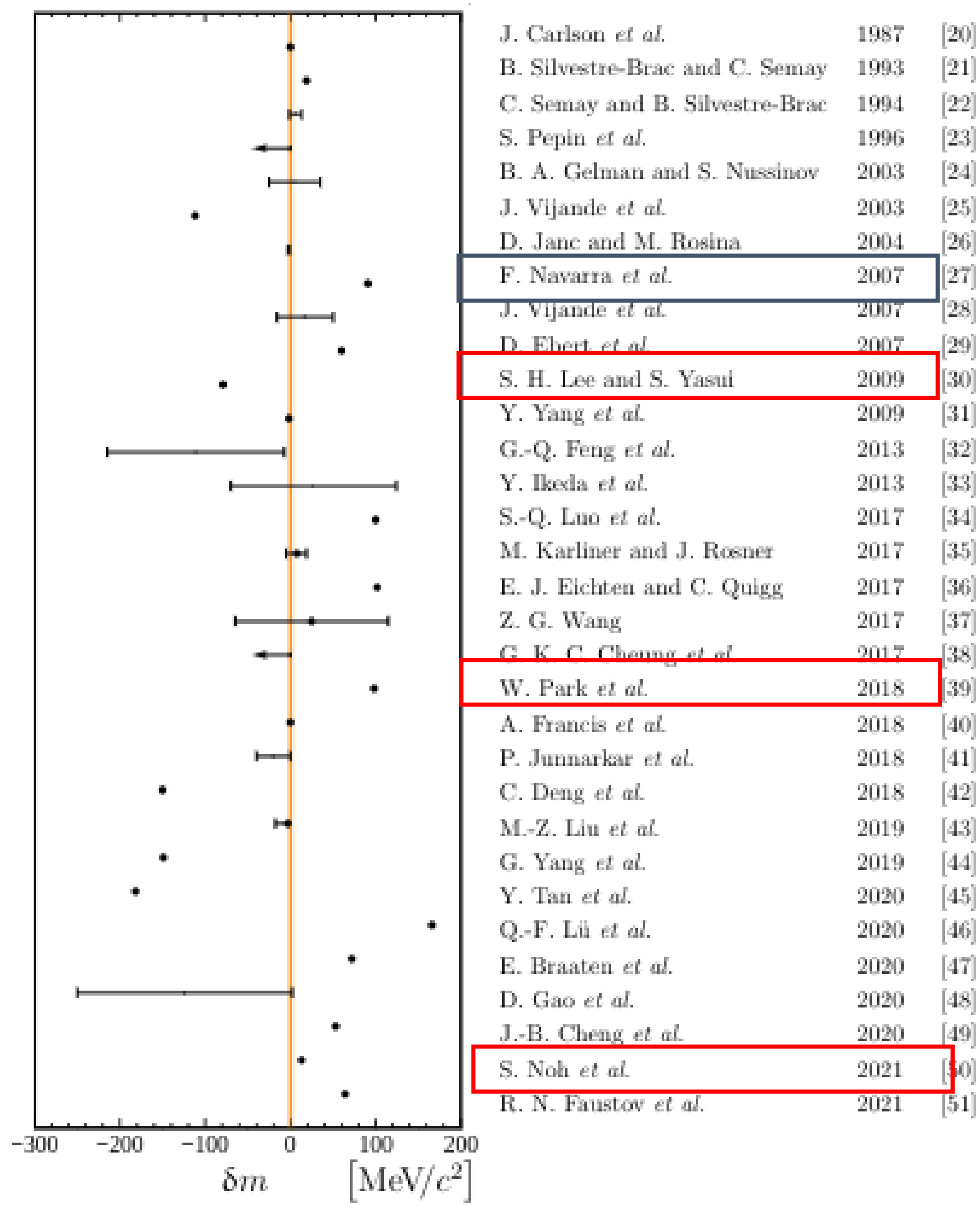
The similarity of the $cc\bar{u}\bar{d}$ tetraquark state and the Ξ_{cc}^{++} baryon containing two c quarks and a u quark leads to a relationship between the properties of the two states. In particular, the measured mass of the Ξ_{cc}^{++} baryon with quark content ccu[50–52] implies that the mass of the $cc\bar{u}\bar{d}$ tetraquark is close to the sum of the masses of the D^0 and D^+ mesons with quark content of $c\bar{u}$ and $c\bar{d}$, respectively, as suggested in ref. [53]. Theoretical predictions for the mass of the $cc\bar{u}\bar{d}$ ground state with spin-parity quantum numbers $J^P = 1^+$ and isospin $I = 0$, denoted hereafter as T_{cc}^+, relative to the $D^{*+}D^0$ mass threshold

Full Quark Model calculation suggests: ex S.Noh, W.Park, Lee, PRD10(2021)114009

-2021- Tcc(3875) LHCb coll.

☞ There is a strong short range attraction for Tcc → Could be compact, but depends sensitively on parameters:

☞ The short range attraction for X(3872) is very weak → Can not be compact



II: Measuring Exotics in Heavy Ion Collision:

Original prediction from ExHIC collaboration (Theory)

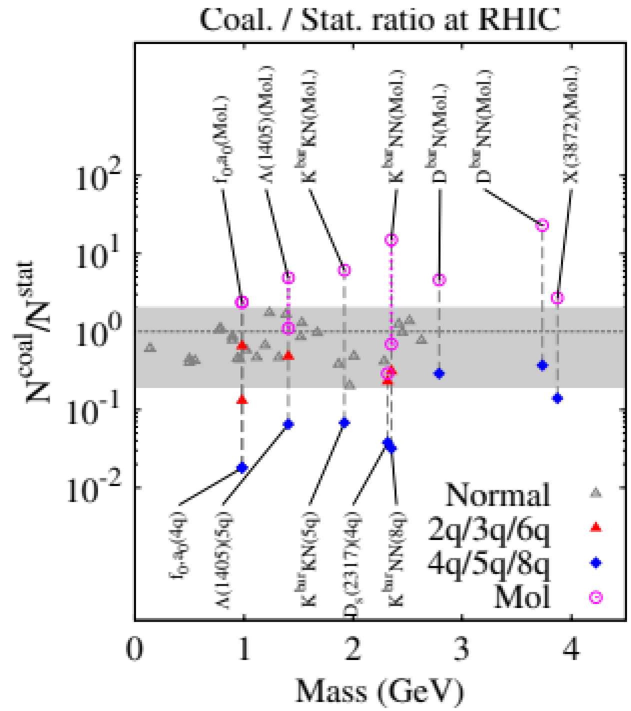
Theory prediction

PRL 106, 212001 (2011) PHYSICAL REVIEW LETTERS week ending 27 MAY 2011

Identifying Multiquark Hadrons from Heavy Ion Collisions

Sungtae Cho,[1] Takenori Furumoto,[2,3] Tetsuo Hyodo,[4] Daisuke Jido,[2] Che Ming Ko,[5] Su Houng Lee,[1,2] Marina Nielsen,[6] Akira Ohnishi,[2] Takayasu Sekihara,[2,7] Shigehiro Yasui,[8] and Koichi Yazaki[2,3]

(ExHIC Collaboration)

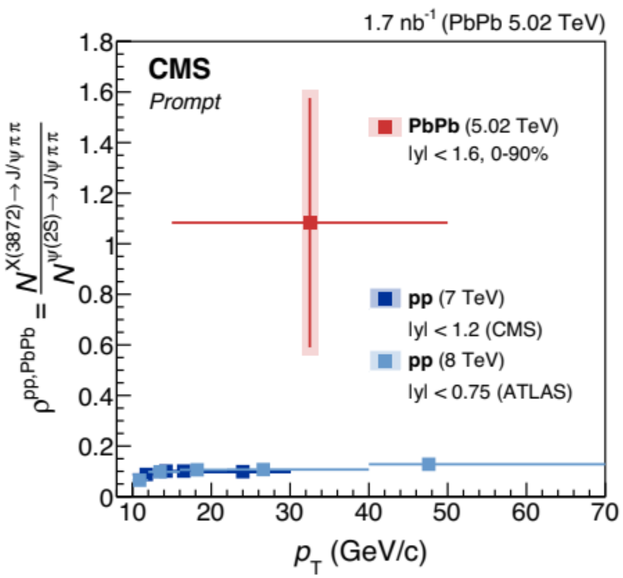


Experiment

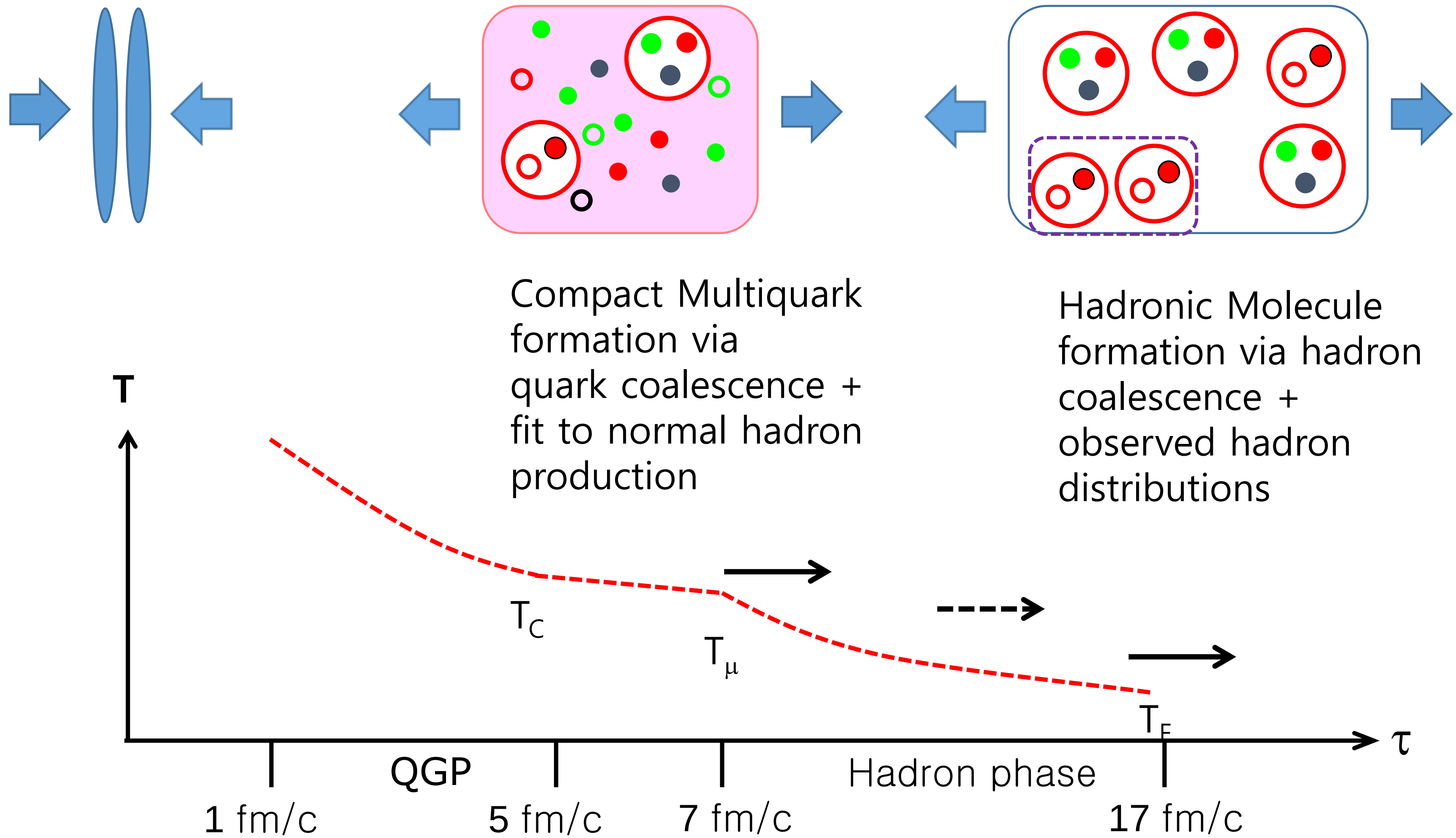
PHYSICAL REVIEW LETTERS 128, 032001 (2022)

Evidence for X(3872) in Pb-Pb Collisions and Studies of its Prompt Production at $\sqrt{s_{NN}} = 5.02$ TeV

A. M. Sirunyan *et al.**
CMS Collaboration



Hadron Production in Heavy Ion Collision



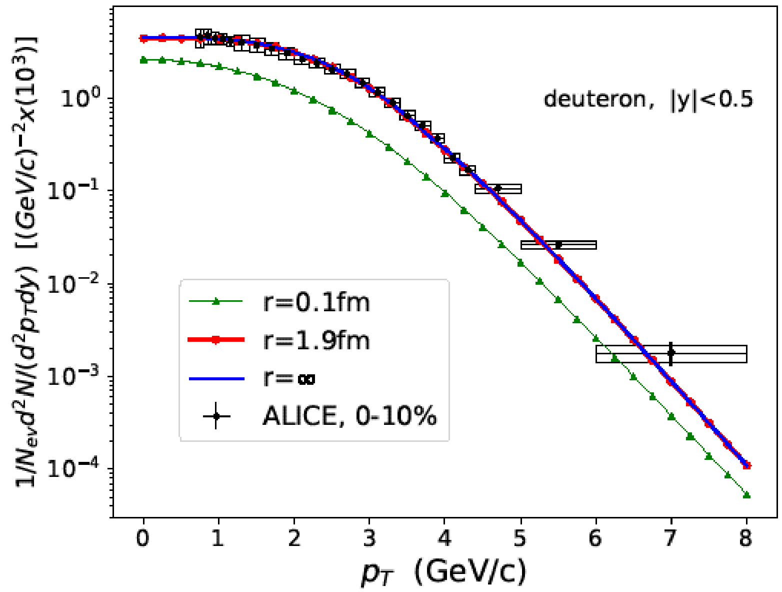
☞ Using coalescence model

$$\frac{dN_X}{dp_X} = C\int dx_1 dx_2 dp_1 dp_2 \frac{dN_1}{dp_1}\frac{dN_2}{dp_2} W\left(x_1, x_2, p_1, p_2\right)\delta\left(p_X - p_1 - p_2\right)$$

H. Yoon,… Yongsun Kim, SHL in preparation

Input: Observed proton P_T distribution

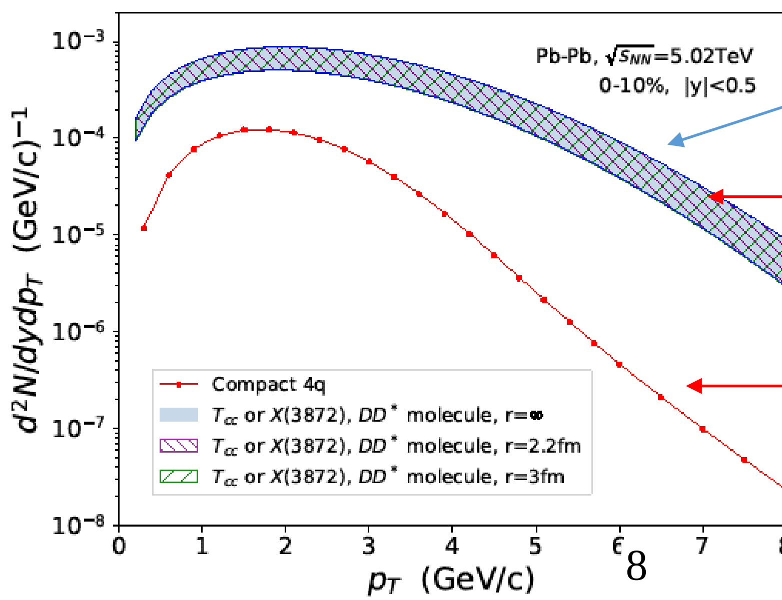
dN_d / dp_T



Output: Deuteron Pt distribution

Input: Observed D D* P_T distribution

dN / dp_T



X(3872)

Tcc if Molecular structure

Tcc if Compact multiquark

Integrated yields for loosely bound molecules

- For Deuteron and ^{3}He, results are similar SHM

hadron	$N_{SHM}^{hadron}/N_{SHM}^{p}$	$N_{coal}^{hadron}/N_{SHM}^{p}$
d	9.07×10^{-3}	8.84×10^{-3}
^{3}He	2.68×10^{-5}	2.03×10^{-5}

TABLE II. The yield ratio with proton in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76TeV. For deuteron and ^{3}He the centralities are 0-10 % and 0-20 %, respectively.

- For X(3872) and Tcc, yields for molecular configurations are larger

Tetraquark	dN_{coal}/dy	$N_{coal}/N_{SHMc}^{X(3872)}$	$N_{coal}/N_{SHMc}^{\psi(2S)}$
DD^{*} molecule	$(2.45\pm0.71)\times10^{-3}$	2.47 ± 0.716	0.806 ± 0.234
$Compact\ 4q$	6.2×10^{-4}	6.25×10^{-1}	0.204

no feed down for D*

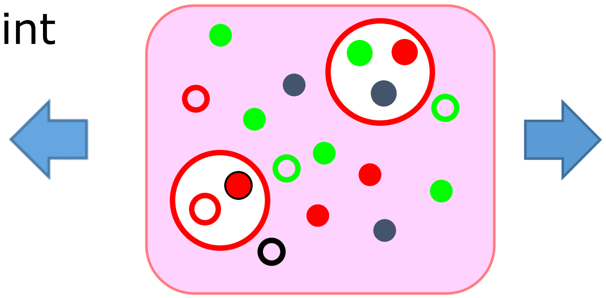
$N_{SHMc}^{X(3872)} / N_{SHMc}^{\psi(2S)} = 0.326$

TABLE III. The first column shows the total yield of the tetraquark depending on its structure calculated by the coalescence model in Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV at 0-10% centrality.. The remaining columns show their ratios to the statistical hadronization model with charm (SHMc)[28]. Here we used $dN_{\psi(2S)}/dy = 3.04\times10^{-3}$ and $N_{X(3872)}/N_{\psi(2S)} = 0.326$ obtained in SHMc.

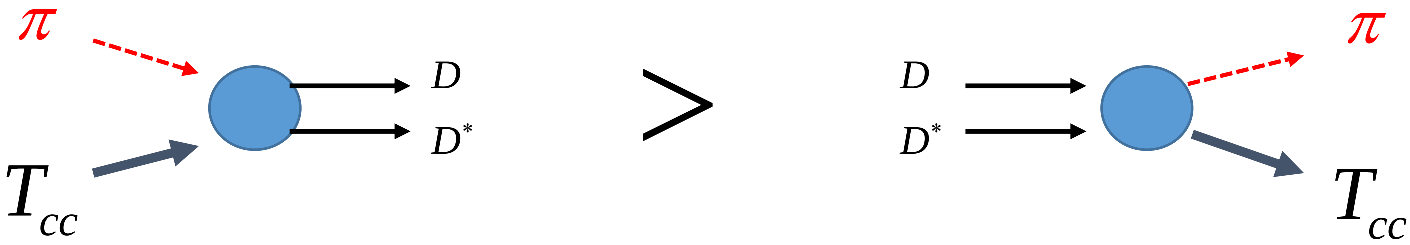
Measuring Exotics in Heavy Ion Collision I

☞ Compact configuration: When strong short attraction exists (K factor)

compact multiquarks are formed at hadronization point



Even when matrix elements are the same Harder to produce at hadronic phase



→ Large Suppression in hadronic phase

→ Can make hadronic phase shorter by looking at peripheral collision

→ Look at total yield, Pt distribution and dependence in centrality

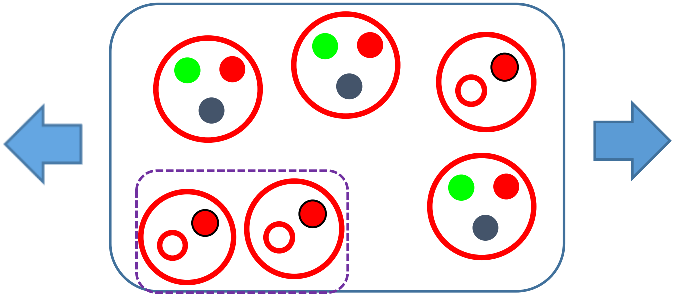
Measuring Exotics in Heavy Ion Collision II

☞ Loosely bound molecular configuration: If no short attraction but strong pion attraction exist, (Isospin is small but spin is non-zero)

molecular configurations can exist and they will form at kinetic freeze-out point

→ No suppression, even enhanced

→ Will have different production rates and Pt distribution



☞ Discriminating configuration will constraint short distance physics
→ Important step towards understanding confinement and dense matter

Additions – more tetraquarks

1. Near threshold exotics are especially interesting X, Tcc

Tetraquark Belle	Mass	Quark content	$\bar{D}^0 D^{*0}$	$D^- D^{*+}$
X(3872)	38721.65	$(q\bar{q})(c\bar{c})$	3871.69	3879.92

Tetraquark LHCb	Mass $(u\bar{d})(c\bar{c})$	Quark content	$D^+ D^{*0}$	$\bar{D}^0 D^{*+}$	Observed mode
Tcc	3875	$(\bar{u}\bar{d})(cc)$	3876.51	3875.26	$\bar{D}^0 D^0 \pi^+$

2. LHCb: PRL127 (2021) 082001: from B decay found Zcs

   predicted Lee, Nielsen, Wiedner: JKPS 55 (2009) 424, arXiv:0803.1168.

$$Z_{cs}(4003): J^P = 1^+ \quad (u\bar{s}c\bar{c}) \quad \text{width}=131 \pm 15 \pm 26 \text{ MeV}$$

$$Z_{cs}(4003) \rightarrow J/\psi + K^+$$

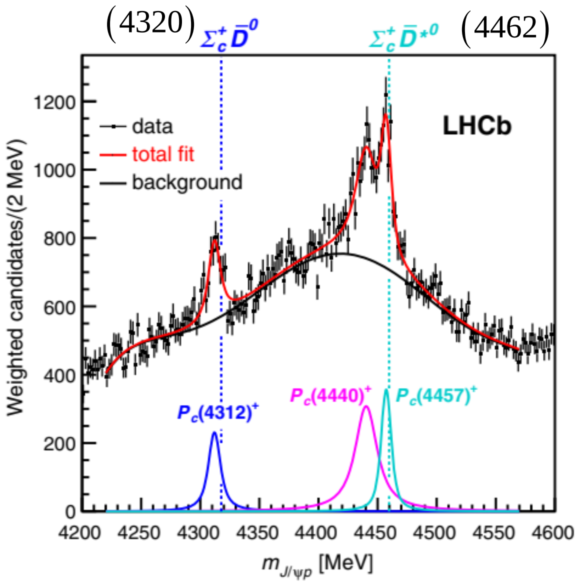
Tetraquark LHCb,BES?	Mass +i(width)	Quark content	$\bar{D}^0 D_s^{*+}$	$\bar{D}^{0*} D_s^+$	Observed mode
Zcs(4000)	4003+i(131)	$(u\bar{d})(c\bar{c})$	3977	3978	$J/\psi K^+$

Additions - Pentaquarks

1. Other Explicitly exotic state observed :

Exotic	X(3872)	Tcc(3875)	X(5568)	Pc(4312)
Quark	$(uc)(\overline{uc})$	$(ud)(\overline{cc})$	$(bu)(\overline{ds})$	$(udc)(u\bar{c})$
Threshold	$\bar{D}^0 D^{*0}$	$D^- D^{*0}$	Non near	→

$$^2H\,(\text{Deuteron}) \to p + n\,(\text{B} \sim 2.224 \text{ MeV})$$



2. Pc states could also be molecular configurations.

$$P_c(4312) \to \Sigma_c(2455) + \bar{D}^0(1865) \quad [\sim 4320]$$

$$P_c(4457) \to \Sigma_c(2455) + \bar{D}^{0*}(2007) \quad [\sim 4462]$$

3. Searched all compact pentaquark candidates: Park, Cho, Lee PRD99(2019)094023

ΔE : Expected binding with negative K factor

Quark Config.	$S=1/2$	
	ΔE	State
$uds c\bar{c}$	-124	$\Lambda\eta_c(7)$
$uds s\bar{c}$	-117	$\Lambda D_s(4)$
$udcc\bar{s}$	-135	$\Xi_{cc}K(4)$

$\mathrm{P}_{sc\bar{c}}\left(uds c\bar{c}\right)[4458]$

$\rightarrow \Lambda + J/\psi$ (LHCb 2012.10380)

$\rightarrow \Xi_c\left(2467.7\right) + D^{*-}(2010)$: (4477.7)

$\mathrm{P}_{cc\bar{s}}^{++}\left(udcc\bar{s}\right) \rightarrow \Lambda_c K^- K^+ \pi^+$ (Our prediction)

could be $\Xi_{cc}K$ molecule

Note $\Xi_{cc}^{++}\left(3621.40\right) \rightarrow \Lambda_c K^- \pi^+ \pi^+$ (LHCb 1707.01621)

Additions - 3

2. Study production of Molecule, compact states, resonance states in heavy ion collision → study and model dynamics of multiquark configuration

→ All the way to confinement and deconfinement in QCD : Need input from multiquark configurations

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Case for quarkyoniclike matter from a constituent quark model

Aaron Park,[1,*] Kie Sang Jeong,[2,†] and Su Houng Lee[1,‡]
[1]*Department of Physics and Institute of Physics and Applied Physics, Yonsei University, Seoul 03722, Korea*
[2]*Institute for Nuclear Theory, University of Washington, Seattle, Washington, D.C. 98195, USA*