Heavy Exotic production in Heavy Ion Collisions

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Will discuss the structure of X(3872) and Tcc ($D^0D^0\pi^+$) and why it is interesting to measure Exotics in Heavy Ion Collision

Acknowledgements: arXiv:2208.06960

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

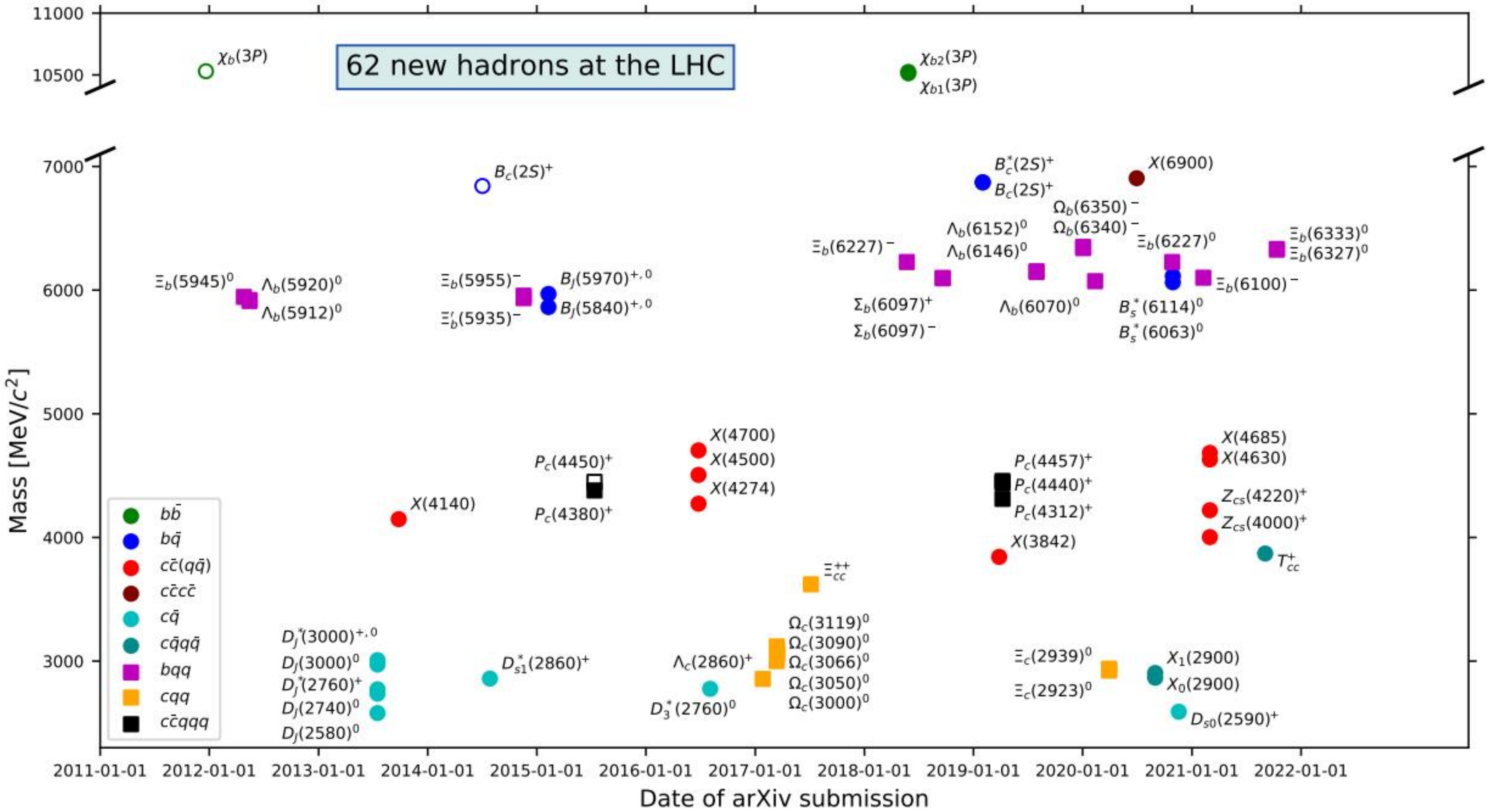
External: C. M. Ko, Sungtae Cho, Sanghoon Lim, Yongsun Kim

+ ExHIC collaboration

Exotics

1. Starting from X(3872)……….

Recent LHCb publication arXiv:2206.15233…..



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 …

We know quark model explains the ground state meson and baryon masses well

Hence, states involving similar sizes should could be understood from the quark model

What does quark model tell us about compact (typical hadrons size) multiquark states

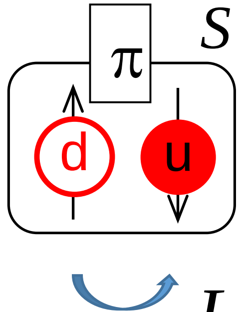
Ground state Mesons

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

$J^{P}=0^{-}$

$m_{\pi}^{0}=135\ \text{MeV}$

$S=0$

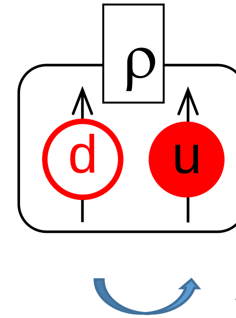


$L=0$

$J^{P}=1^{-}$

$m_{\rho}^{0}=775\ \text{MeV}$

$S=1$



$L=0$

P-wave Mesons

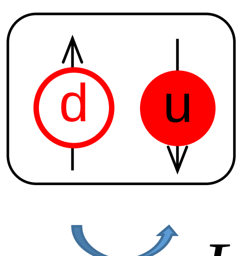
$$P=\left(-1\right)^{L+1},\quad C=\left(-1\right)^{L+S}$$

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

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

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

$S=0$



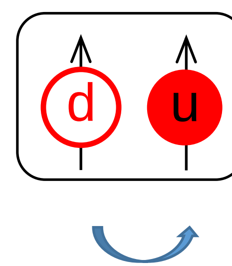
$L=1$

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

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

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

$S=1$



$L=1$

P-wave Mesons

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

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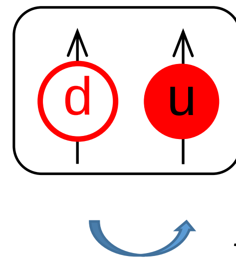
$S=1$



$L=1$

or

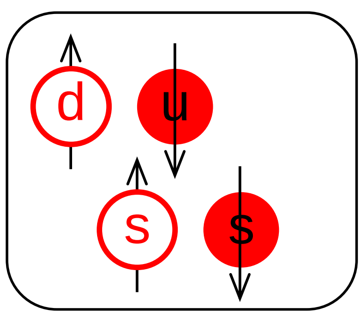
$J^{PC}=0^{++}$

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

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

Mass of 2 diquarks

$S=L=0$



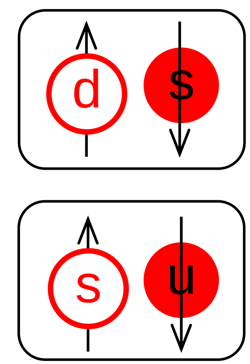
compact multiquark

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

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

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

Mass of 2 Kaon



K^0

K^+

Loosely bound molecule

ALICE measured f_0

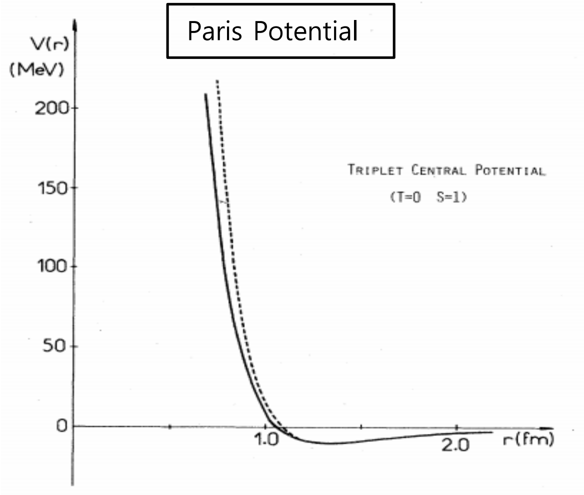
Where is the compact Exotics:

Perspectives from a quark model

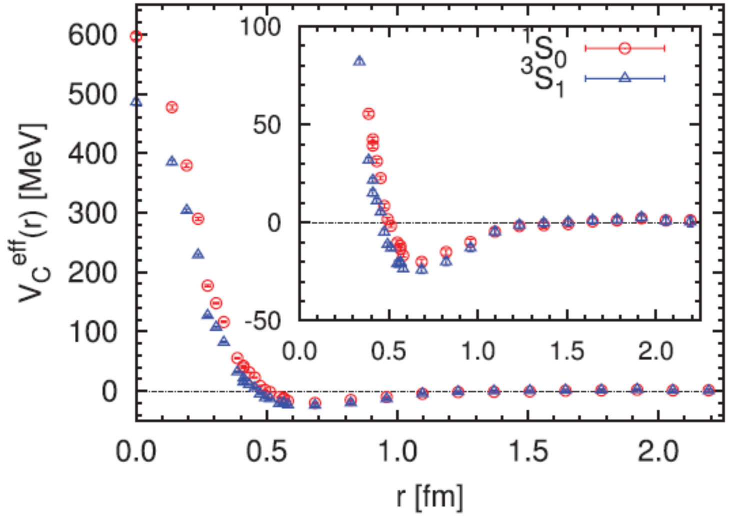
There are attractive channels

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

Paris Potential

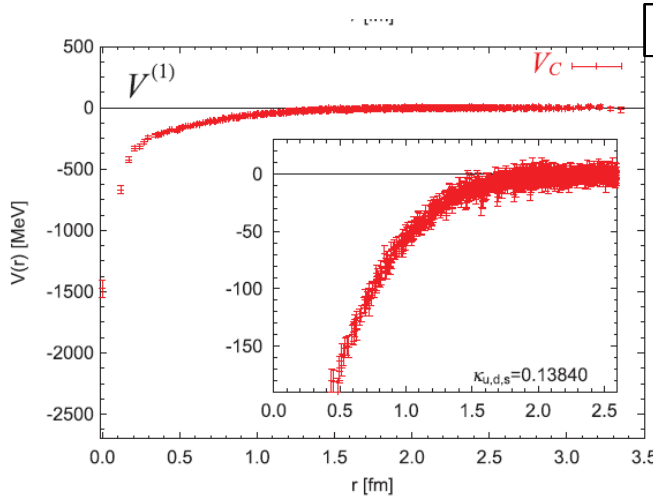


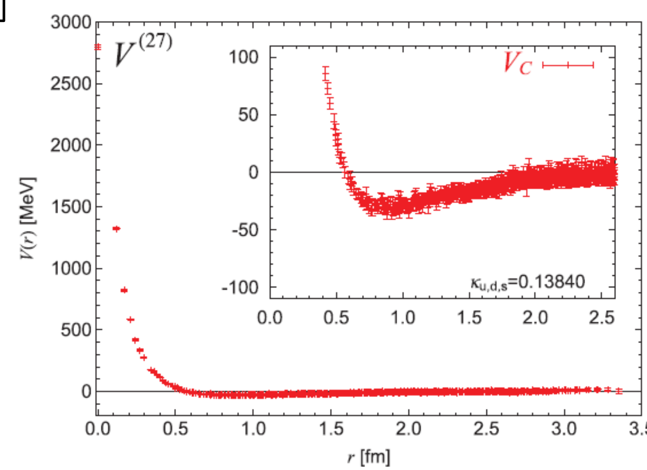
QCD HAL collaboration



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

QCD HAL collaboration





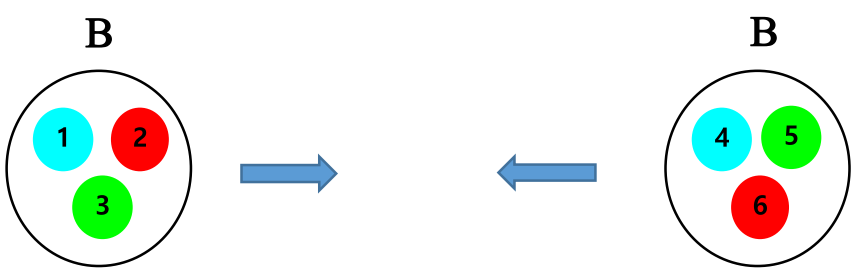
Quark Model perspectives on Interaction at short distance – Kinetic term

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

$$m_q = 300\ \text{MeV},\ m_s = 500\ \text{MeV},\ m_c = 1500\ \text{MeV}.$$

☞ When brought together need to overcome Additional Kinetic energy

$$\frac{p_{BB}^2}{2\mu_{BB}} \approx \frac{1}{2\mu_{BB}}\frac{1}{(0.6\text{fm})^2} \sim 100\text{MeV}$$



→ 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

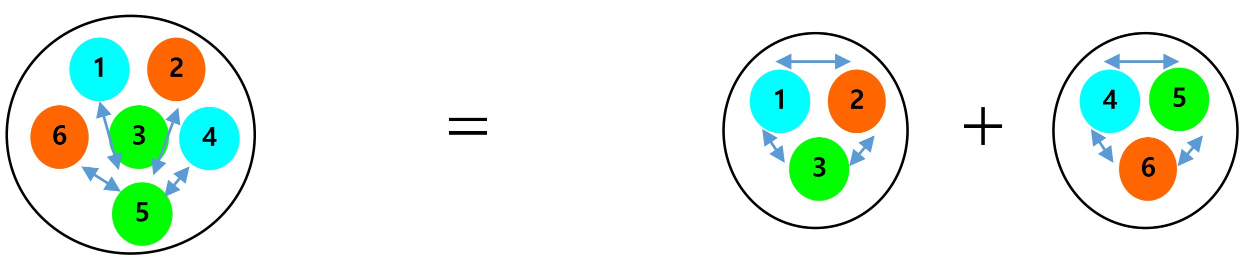
$$H=\sum_{i=1}^{n}\left(m_i+\frac{p_i^2}{2m_i}\right)-\sum_{i<j}^{n}\left(\lambda_i^c\lambda_j^c\right)V_{ij}^C\left(r_{ij}\right)-\sum_{i<j}^{n}\frac{\left(\lambda_i^c\lambda_j^c\right)\left(\sigma_i\sigma_j\right)}{m_i m_j}V_{ij}^{SS}\left(r_{ij}\right)$$

☞ Color-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 perspectives on Interaction at short distance – color-spin interaction

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

☞ Color-spin interaction for 2 body:

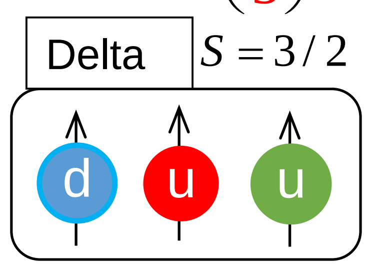
$$K = -\sum_{i<j}^{N}\left(\lambda_i^c \lambda_j^c\right)\left(\sigma_i^s \sigma_j^s\right) \longrightarrow$$

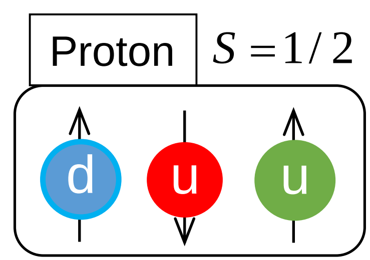
	$Q\text{–}Q$				$Q\text{–}\bar{Q}$			
Color	A	S	A	S	1	8	1	8
Flavor	A	A	S	S				
Spin	A(0)	S(1)	S(1)	A(0)	0	0	1	1
K	-8	-4/3	8/3	4	-16	2	16/3	-2/3

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

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

K factor of $1 \rightarrow 18$ MeV



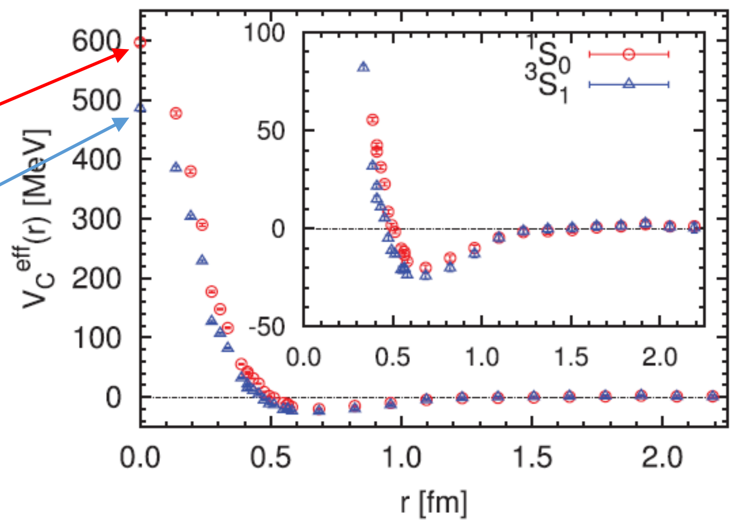


☞ NN force in SU(2) spin 1 vs spin 0 channel: comparison to lattice

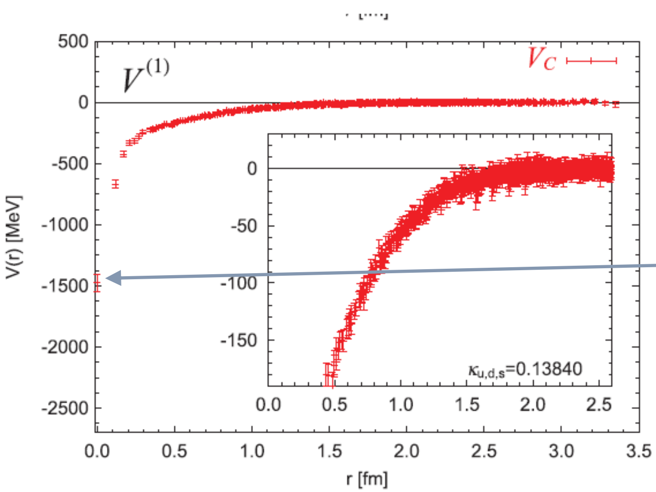
QCD HAL collaboration

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

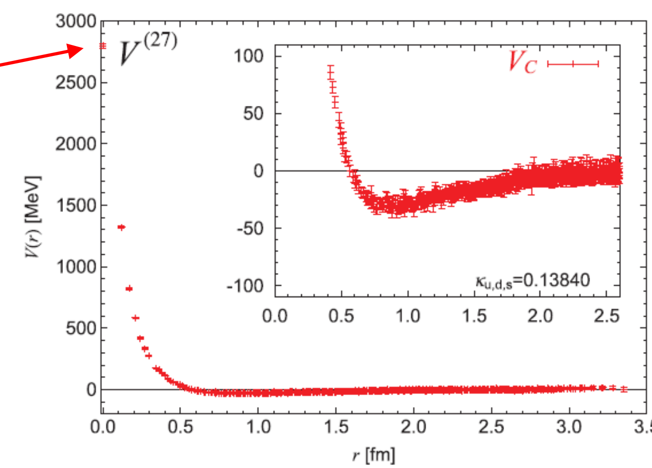
$$\frac{K_{2-N}^{S=0}}{K_{2-N}^{S=1}} = 1.29$$ → comparison



☞ H dibaryon channel: Flavor 1 vs Flavor 27



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

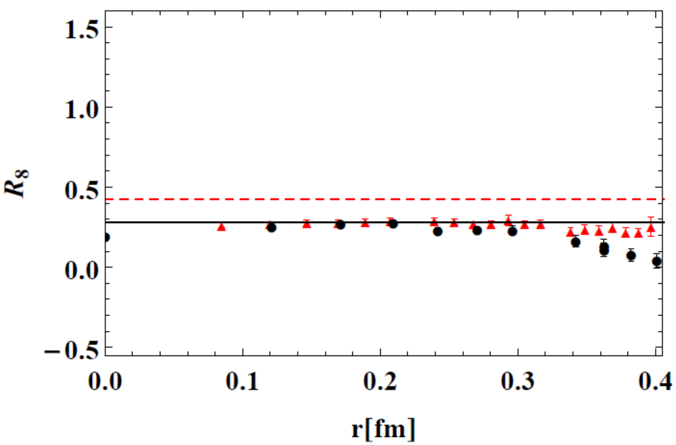


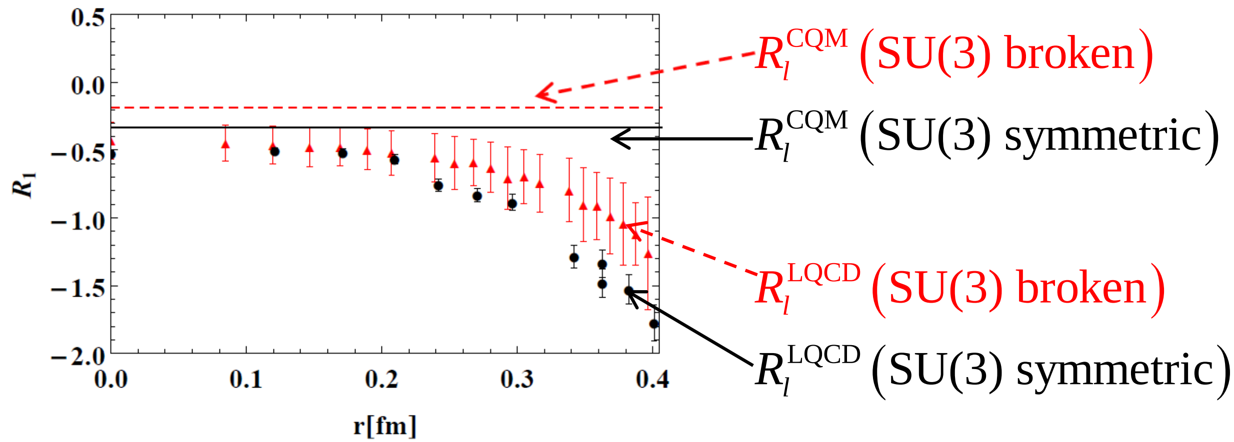
(HAL QCD Collaboration)

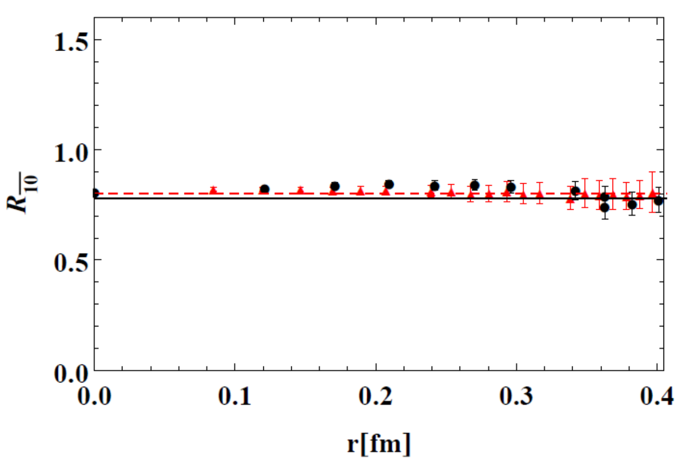
Confirmed in Full quark model calculation vs Lattice – A.Park, Lee, Inoue, Hatsuda, EPJA 56(2020)3,93

☞ Comparison to Lattice calculation

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





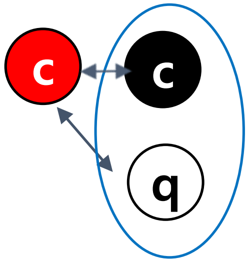


Note R_l^{CQM} (SU(3) symmetric) $= \dfrac{K_{2-N}^{F=l}}{K_{2-N}^{F=27}}$

In fact, the K factors are good enough

Why heavy quarks are needed for compact Exotics:

☞ Coulomb interaction



$$H_{cc} = \ldots + \lambda_i^c \lambda_j^c \left(\frac{g}{r_{ij}} \right) + \ldots. \qquad r \approx \frac{1}{mg^2}, \qquad E_C \approx -mg^4$$

☞ Color-Color interaction between c and color singlet $c\bar{q}$

if the color state of cc is attractive, $\lambda_c^a \left(\lambda_c^a \right) < 0$, then since $r_{cc} < r_{cq}$,

there will be attraction

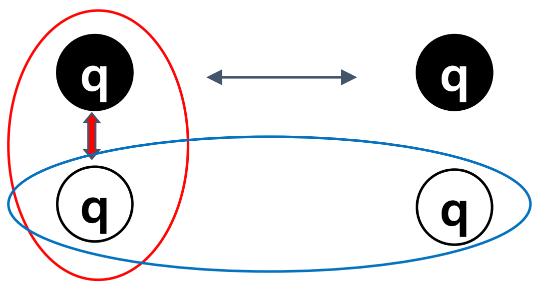
$$H_{cc} + H_{c\bar{q}} = \ldots.\lambda_c^a \left(\lambda_c^a \frac{g}{r_{cc}} + \lambda_q^a \frac{g}{r_{cq}} \right) < 0$$

Mass effect in Color-Spin interaction: Example Tcc (Ballot, Richard 83)

	$Q\!-\!Q$				$Q\!-\!\bar{Q}$			
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

Fall apart into two mesons

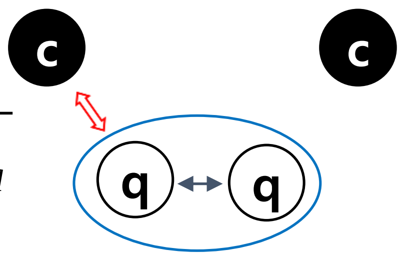
$$-16\frac{1}{m_q m_q}$$



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

When heavy quarks, could be compact

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



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

Indeed many heavy exotics were found

But still not clear about their structure

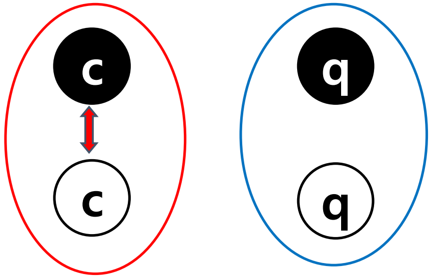
Compact multiquarks or loosely bound molecules

Will Look at X(3872) and Tcc(3875)

Can they be compact?

X(3872) : W. Park, SHLee, NPA924(2014) 161

Dominant $\left(C = \text{color}, \ S = \text{spin}\right)$ state?



$$(c\bar{c}) \otimes (q\bar{q})$$

Color-spin (K factor)

$$I^G\left(J^{PC}\right) = 0^+\left(1^{++}\right)$$

$\sim +140$ MeV

$$K_{X(3872)} - K_D - K_{D^*} = \begin{pmatrix} \frac{16}{3}\frac{1}{m_c^2} + \frac{16}{3}\frac{1}{m_q^2} + \frac{32}{3}\frac{1}{m_c m_q} & 0 \\ 0 & -\frac{2}{3}\frac{1}{m_c^2} - \frac{2}{3}\frac{1}{m_q^2} - \frac{4}{3}\frac{1}{m_c m_q} \end{pmatrix} \quad \begin{matrix} (1,1)\otimes(1,1) \\ (8,1)\otimes(8,1) \end{matrix}$$

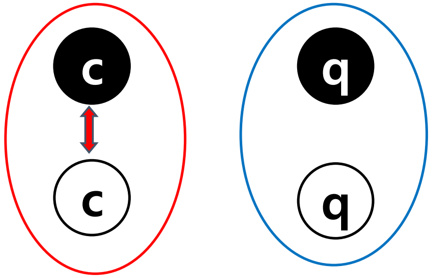
~ -20 MeV

Hence X(3872) could be in $\begin{cases} (c\bar{c}) \rightarrow (C = 8, S = 1) \\ (q\bar{q}) \rightarrow (C = 8.S = 1) \end{cases}$

X(3872) : W. Park, SHLee, NPA924(2014) 161

$$\text{X(3872)} \begin{cases} (c\bar{c}) \to (C=8, S=1) \\ (q\bar{q}) \to (C=8.S=1) \end{cases}$$

$$H_{cc} = \lambda_c^a \left(\lambda_c^a \frac{g}{r_{cc}} \right) \; ?$$



Color-Color

$$\lambda_c^a \left(\lambda_c^a\right) = \frac{1}{2}\left[\left(\lambda_c^a + \lambda_c^a\right)^2 - \lambda_c^2 - \left(\lambda_c^a\right)^2 \right]$$

$$\frac{1}{4}\lambda^2 = C = \frac{1}{3}\left(p^2 + q^2 + pq + 3(p+q)\right) \qquad C(p=1, q=1) = 3, \quad C_f(p=1, q=0) = \frac{4}{3}$$

If cc is in $(C=8, S=1)$

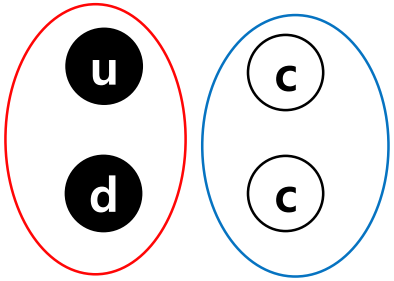
$$\lambda_c^a\left(\lambda_c^a\right) = \frac{4}{2}\left[3 - 2\frac{4}{3}\right] = \frac{2}{3} > 0$$

No additional attraction from color-color interaction

→ X(3872) can not be compact multiquark state

Tcc(3875) : W. Park, SHLee, NPA924(2014) 161

Dominant $(C=\text{color},\ S=\text{spin})$ state?



Color-spin (K factor)

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

~ -100 MeV

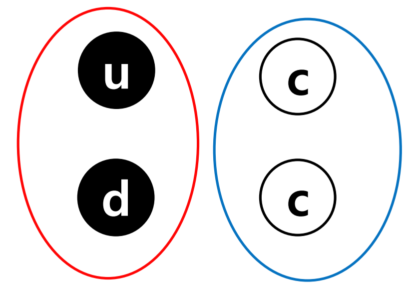
$$K_{T_{cc}(3875)}-K_D-K_{D^*}=\begin{pmatrix} -8\frac{1}{m_q^2}+\frac{8}{3}\frac{1}{m_c^2}+\frac{32}{3}\frac{1}{m_cm_q} & -8\sqrt{2}\frac{1}{m_cm_q} \\ -8\sqrt{2}\frac{1}{m_cm_q} & -\frac{4}{3}\frac{1}{m_q^2}+4\frac{1}{m_c^2}+\frac{32}{3}\frac{1}{m_cm_q} \end{pmatrix} \begin{matrix} (\bar{3},0)\otimes(3,1) \\ (6,1)\otimes(\bar{6},0) \end{matrix}$$

$\sim +17$ MeV

Hence Tcc(3875) could be in $\begin{cases} (ud)\rightarrow(C=\bar{3},S=0) \\ (\overline{cc})\rightarrow(C=3.S=1) \end{cases}$

Tcc(3875) : W. Park, SHLee, NPA924(2014) 161

$$\text{Tcc(3875)}\begin{cases}(ud)\rightarrow(C=\bar{3},S=0)\\(\overline{cc})\rightarrow(C=3.S=1)\end{cases}\qquad H_{cc}=\lambda_c^a\left(\lambda_c^a\frac{g}{r_{cc}}\right)\ ?$$



Color-Color

$$\lambda_c^a\left(\lambda_c^a\right)=\frac{1}{2}\left[\left(\lambda_c^a+\lambda_c^a\right)^2-\lambda_c^2-\left(\lambda_c^a\right)^2\right]$$

$$\frac{1}{4}\lambda^2=C=\frac{1}{3}\left(p^2+q^2+pq+3(p+q)\right)\qquad C(p=0,q=1)=\frac{4}{3},\quad C(p=1,q=0)=\frac{4}{3}$$

If $\overline{cc}$ is in $(C=3,S=1)$ $\qquad \lambda_c^a\left(\lambda_c^a\right)=\frac{4}{2}\left[\frac{4}{3}-2\frac{4}{3}\right]=-\frac{8}{3}<0$

Hence there is additional attraction

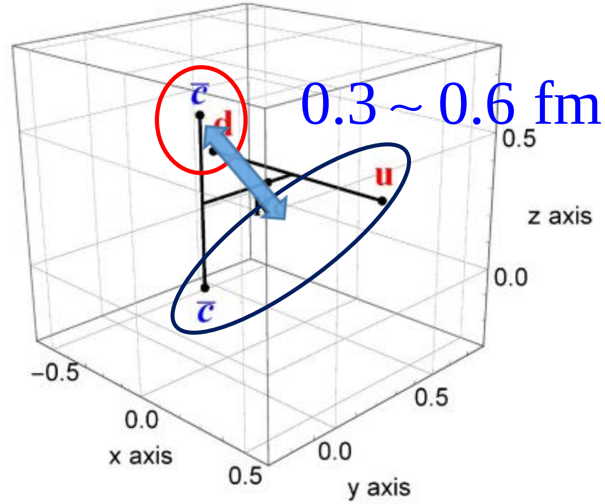
→ Tcc(3875) could be a compact multiquark state

Attraction expected from quark Model: S.Noh, A.Park, D.Park Lee (in preparation)

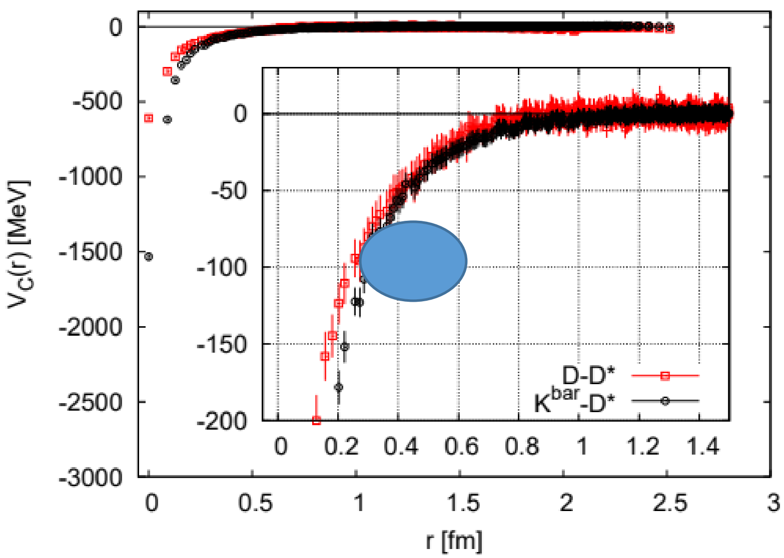
$T_{cc}(3875)$ $I^G\left(J^P\right)=0^+\left(1^+\right)$

(S. No, W. Park, SHL, PRD10 (2021)114009)

$$K_{T_{cc}(3875)} - K_D - K_{D*} \rightarrow -100 \text{ MeV}$$



☞ Consistent to Lattice (HAL QCD): Phys. Lett. B 729 (2014) 85



$m_\pi \simeq 410$ MeV

Quark Model calculation suggests: ex W. Pari, S.Noh, Lee, NPA983 (2019)1

Detailed calculation show both color-spin and color-color effects are indeed important

Still Tcc is marginal but Tbb is definitely a strongly bound compact multiquark-state

Table 4
The contribution from each term in the Hamiltonian and the relative lengths between quarks in $ud\bar{c}\bar{c}$ with $(I,S)=(0,1)$, and in the lowest threshold mesons ($\bar{D}^0 D^{*-}$). Here, V^C = Coulomb + Linear interaction, and (i, j) denotes the contribution from the i and j quark. The number is given as $i=1,2$ for the light quarks, and 3, 4 for $\bar{c}$. The contributions are in MeV unit.

	(i,j)	$ud\bar{c}\bar{c}$	2-Meson	Difference
Kinetic energy		1016.1	880.4	135.7
CS interaction		−174.3	−73.6	−100.7
V^C	(1, 2)	219.9		
	(1, 3)	93.5	229.5 ($\bar{D}^0$)	
	(1, 4)	93.5		
	(2, 3)	93.5		
	(2, 4)	93.5	308.0 (D^{*-})	
	(3, 4)	15.6		
	Subtotal	609.5	537.5	72.0
Total contribution		1451.3	1344.3	107.0
Relative lengths (fm)	(1, 2)	0.67		
	(1, 3)	0.63	0.53 ($\bar{D}^0$)	
	(1, 4)	0.63		
	(2, 3)	0.63		
	(2, 4)	0.63	0.58 (D^{*-})	
	(3, 4)	0.41		
	Average	0.60	0.56	0.04

Table 5
The contribution from each term in the Hamiltonian and the relative lengths between quarks in $ud\bar{b}\bar{b}$ with $(I,S)=(0,1)$, and in the lowest threshold mesons ($B^+ B^{*0}$). Here, V^C = Coulomb + Linear interaction, and (i, j) denotes the contribution from the i and j quark. The number is given as $i=1,2$ for the light quarks, and 3, 4 for $\bar{b}$. The contributions are expressed in MeV unit.

	(i,j)	$ud\bar{b}\bar{b}$	2-Meson	Difference
Kinetic energy		997.2	836.6	160.6
CS interaction		−176.8	−26.4	−150.4
V^C	(1, 2)	219.9		
	(1, 3)	83.5	229.5 (B^+)	
	(1, 4)	83.5		
	(2, 3)	83.5		
	(2, 4)	83.5	266.6 (B^{*0})	
	(3, 4)	−187.6		
	Subtotal	366.3	496.1	−129.8
Total contribution		1186.7	1306.3	−119.6
Relative lengths (fm)	(1, 2)	0.67		
	(1, 3)	0.60	0.53 (B^+)	
	(1, 4)	0.60		
	(2, 3)	0.60		
	(2, 4)	0.60	0.55 (B^{*0})	
	(3, 4)	0.25		
	Average	0.55	0.54	0.01

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

Also , full calculation (exact wave function) is important

TABLE XII. Contributions to the $T_{bb}(ud\bar{b}\bar{b})$ and $T_{cc}(ud\bar{c}\bar{c})$ masses from this work. (i, j) denotes the i and j quarks, where $i, j = 1, 2$ label the light quarks, and 3, 4 are for the heavy antiquarks in each configuration. $\sum V^C(i,j)$ and $\sum V^{CS}(i,j)$ cover pairs (i, j), except for the (1,2) and (3,4) pairs. D is separately added and not included in $V^C(i,j)$. m_Q is the heavy quark mass, and m'_i is defined in Eq. (13) for each configuration. $\mathbf{p}_i$ is the relative momentum corresponding to the ith Jacobi coordinate $\mathbf{x}_i$. "1 basis" is the result with only one spatial basis $\psi^{Spatial}_{[0,0,0,0,0,0]}$ and the corresponding dominant CS basis.

		T_{bb}		T_{cc}	
Overall	Contribution	Full calculation	1 basis	Full calculation	1 basis
Heavy quark	$2m_Q$	10674.0	10674.0	3844.0	3844.0
	$\frac{\mathbf{p}_2^2}{2m'_2}$	206.8	220.0	142.5	221.8
	$\frac{m_q}{m_Q+m_q}\frac{\mathbf{p}_3^2}{2m'_3}$	16.4	15.3	53.8	38.0
	$V^C(3,4)$	−188.8	−190.8	19.3	4.2
	$\frac{1}{2}\sum V^C(i,j)$	115.8	137.6	159.1	168.5
	$-D$	−917.0	−917.0	−917.0	−917.0
Subtotal		9907.2	9939.1	3301.8	3359.5
Light quark	$2m_q$	684.0	684.0	684.0	684.0
	$\frac{\mathbf{p}_1^2}{2m'_1}$	494.1	495.3	424.1	478.2
	$\frac{m_Q}{m_Q+m_q}\frac{\mathbf{p}_3^2}{2m'_3}$	255.8	239.1	302.2	213.5
	$V^C(1,2)$	171.3	181.6	91.3	188.8
	$\frac{1}{2}\sum V^C(i,j)$	115.8	137.6	159.1	168.5
	$-D$	−917.0	−917.0	−917.0	−917.0
Subtotal		804.0	820.6	743.7	816.0
CS interaction	$V^{CS}(3,4)$	7.0	6.8	5.3	9.3
	$V^{CS}(1,2)$	−195.3	−188.1	−108.6	−182.6
	$\sum V^{CS}(i,j)$	−5.7	0.0	−69.4	0.0
Subtotal		−194.0	−181.3	−172.7	−173.3
Total		10517.2	10578.4	3872.8	4002.2

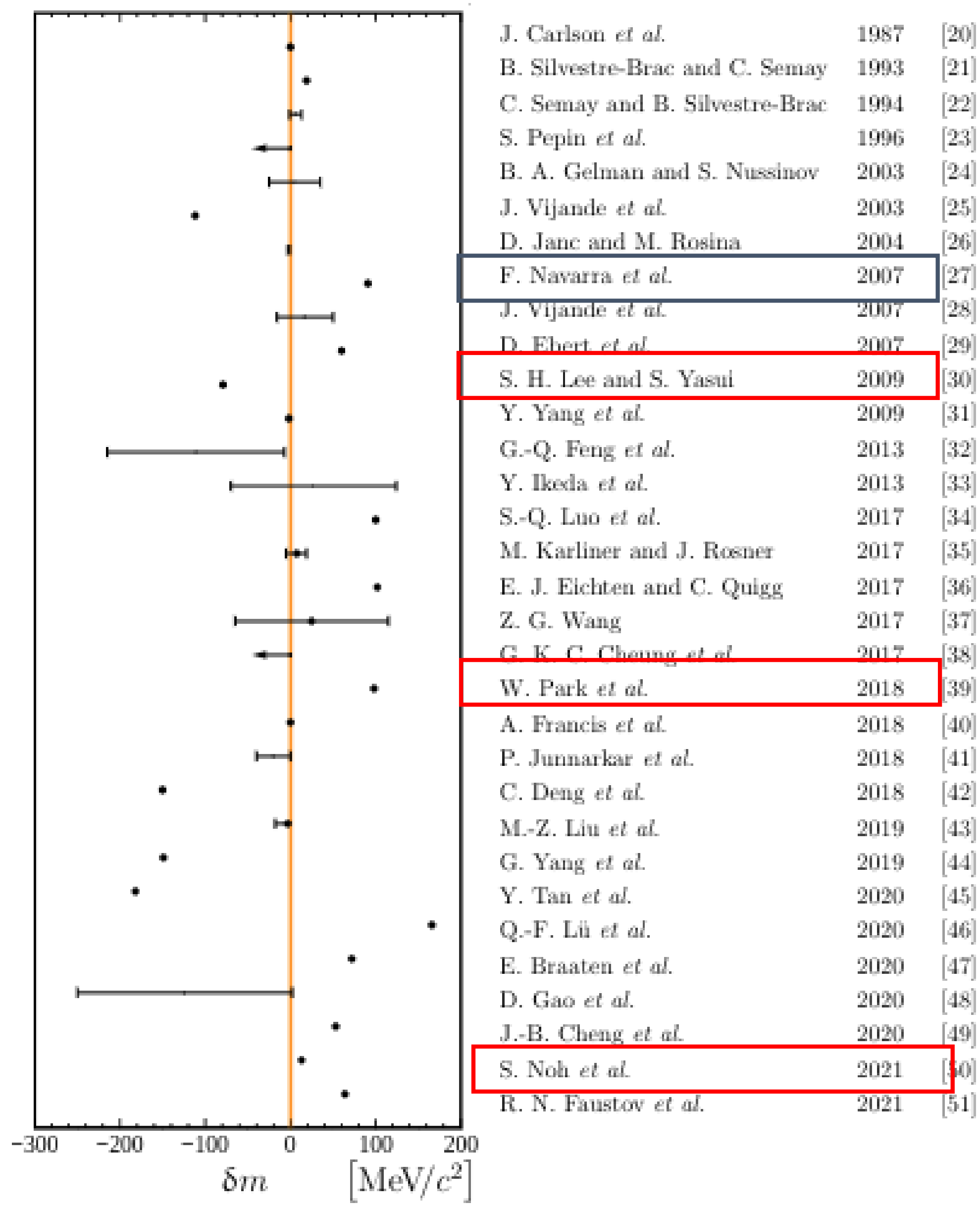
Full Quark Model calculation suggests: ex S.Noh, W.Park, Lee, PRD10(2021)114009

-2021- Tcc(3875) LHCb coll.

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

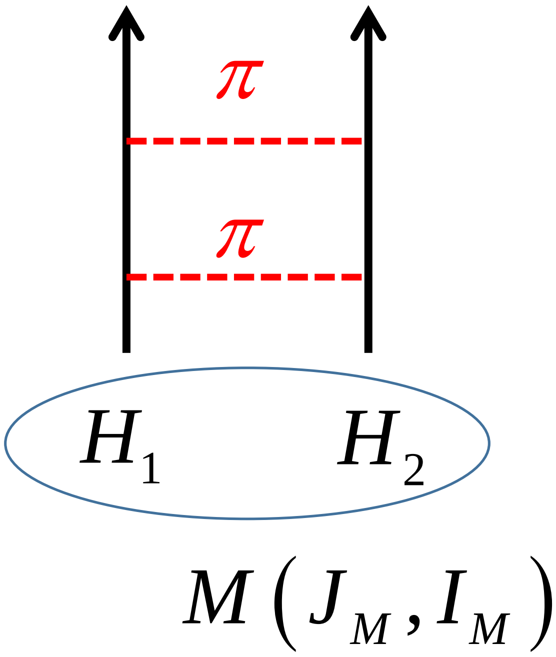
☞ The short range attraction for X(3872) is very weak

→ Can not be compact



II: Long distance:

Perspectives from the π-exchange



Especially important when

$J_M \neq 0$ Mixing with D-wave

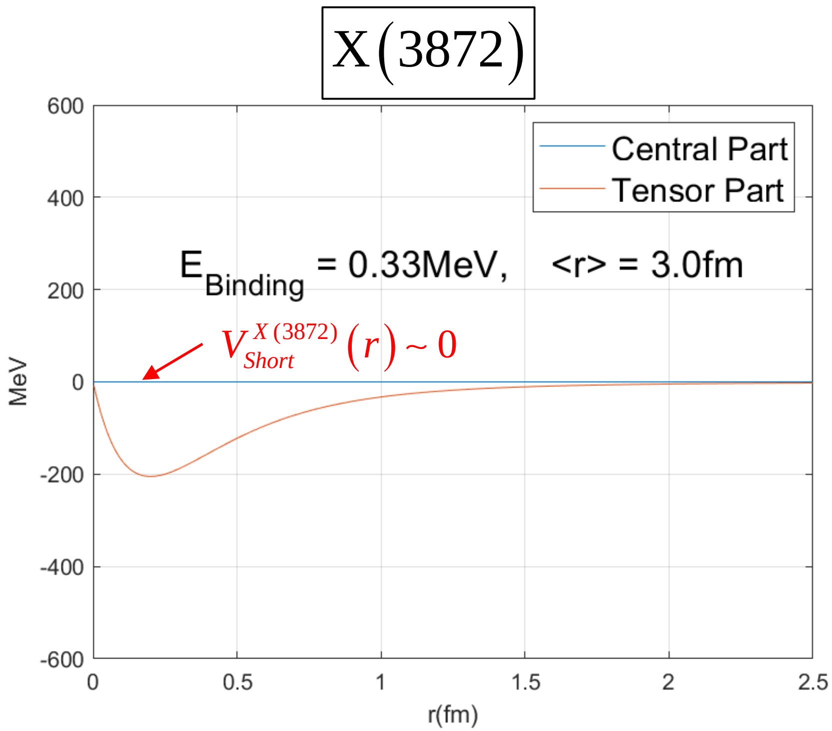
and

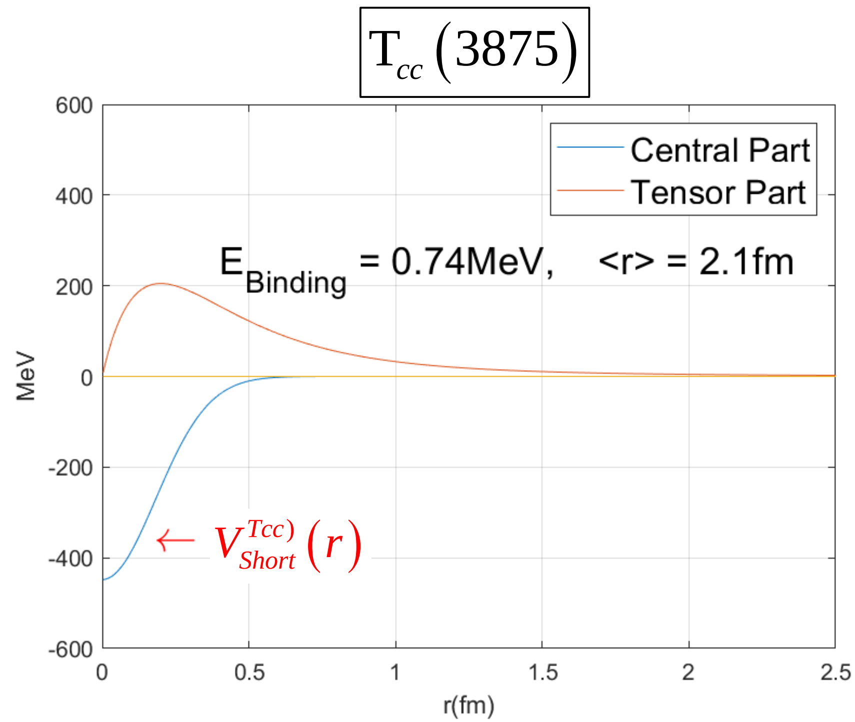
$I_M < (I_1 + I_2)$ Mixing is strong

D-wave mixing through π -exchange Tcc: N.A. Tornqvist (94) + Short range attraction (D. Park, et al)

☞ $$V(r)^{-:X(3872)}_{+:Tcc} = V_{Short}(r)\begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix} \mp 3V_0\left[\begin{pmatrix}0 & -\sqrt{2}\\ -\sqrt{2} & 1\end{pmatrix}T_\pi(r)\right]$$

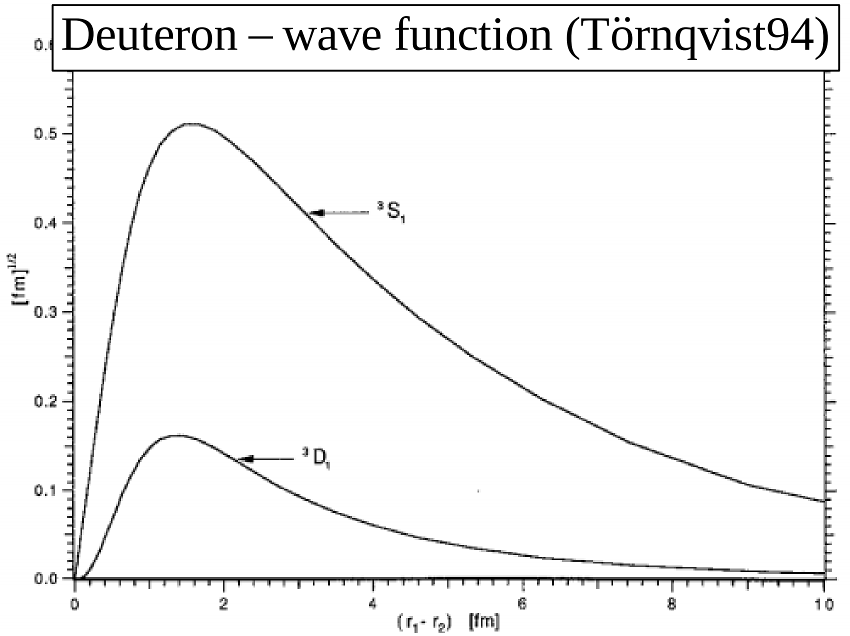
Central Part $= V_{Short}(r)$; Tensor Part $= \pm T_\pi(r)$

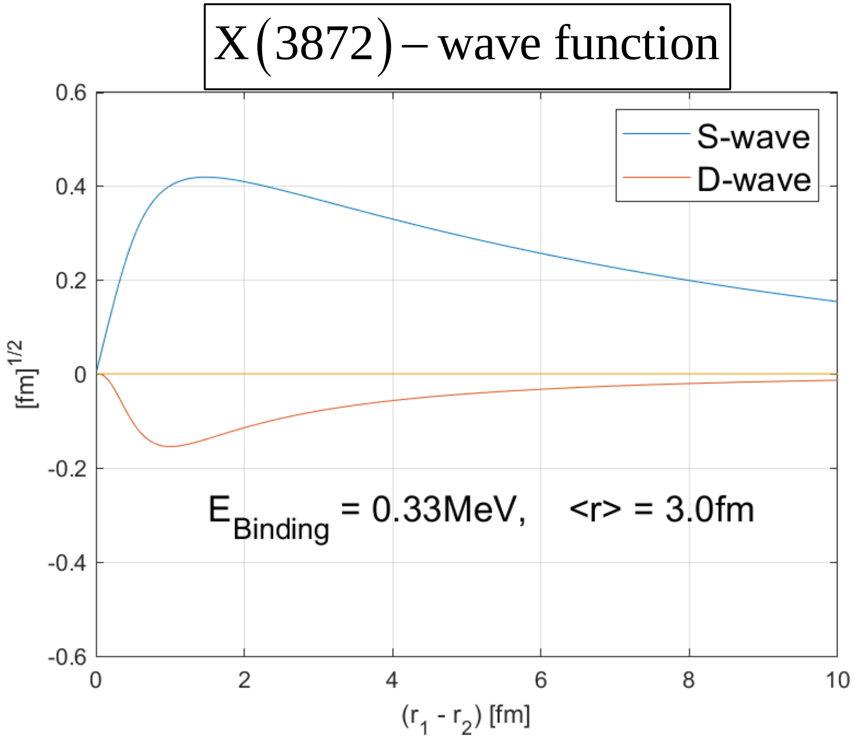


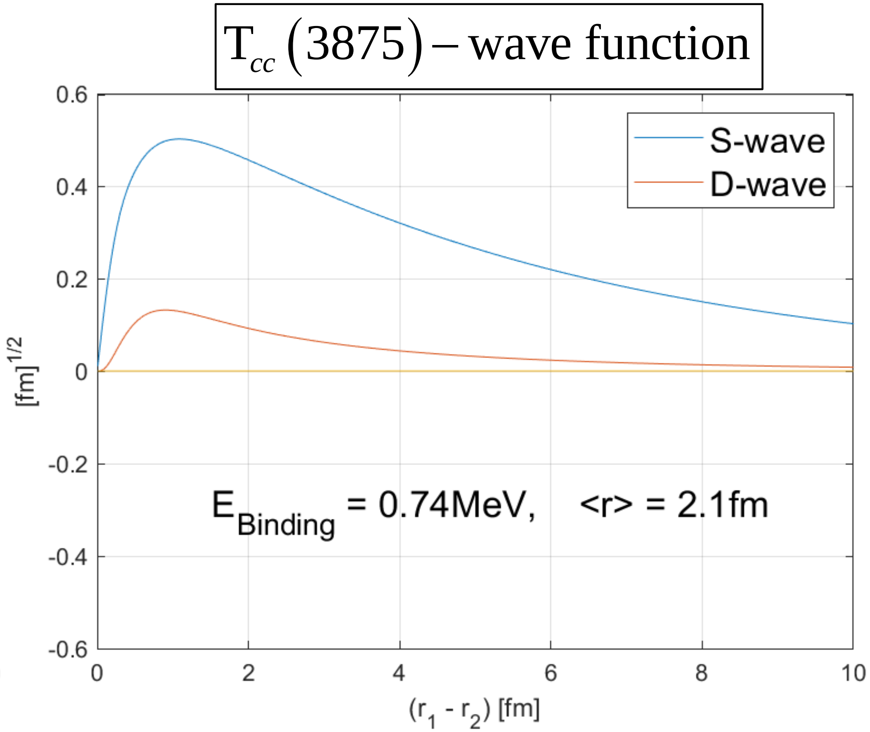


☞ Wave functions:

Similar to that of Deuteron







II: Measuring Exotics in Heavy Ion Collision:

Some remarks: in 2008,

IOPscience

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.

Our contribution to the volume

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

Original prediction from ExHIC collaboration (Theory) in 2011

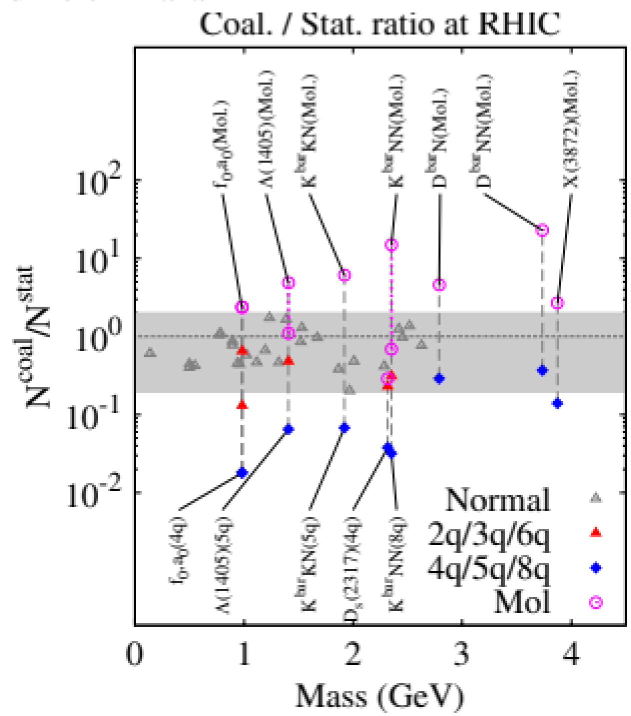
Theory prediction

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)



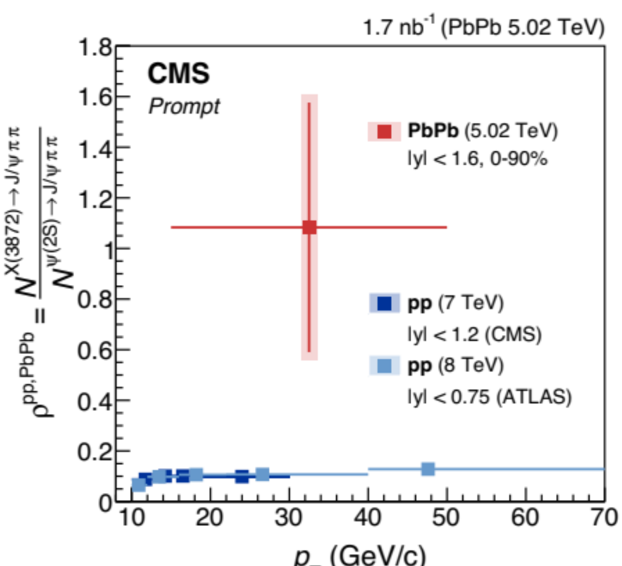
Experiment

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

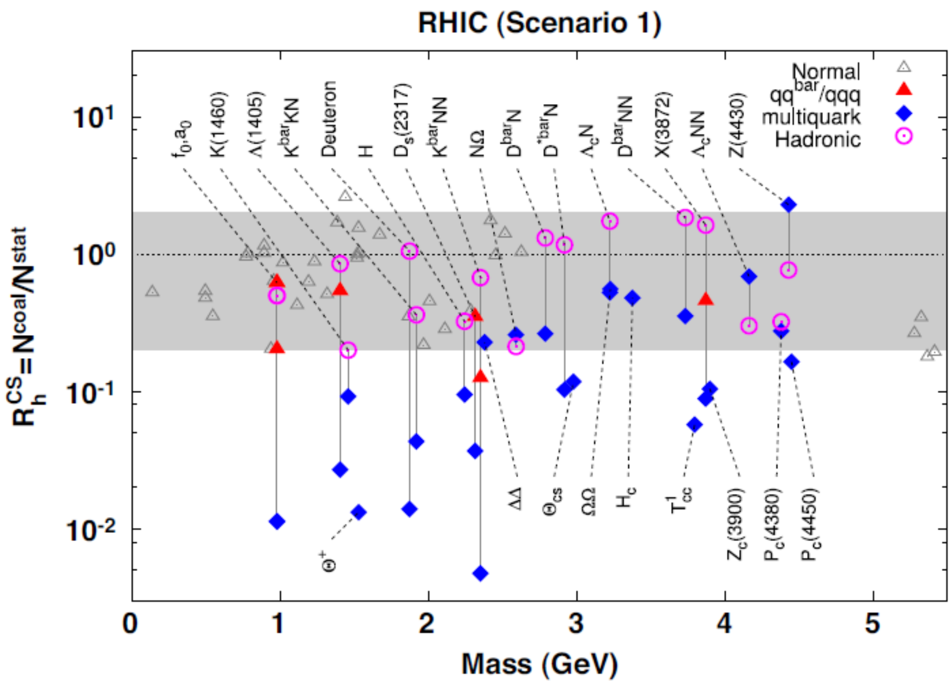
A. M. Sirunyan *et al.*[*]

CMS Collaboration



Production of compact multiquark state in 2017

Production rate normalized to statistical model



△ Normal Hadron

▲

○ Molecule

◆ Compact multiquark

Progress in Particle and Nuclear Physics 95 (2017) 279–322

Exotic hadrons from heavy ion collisions☆

Sungtae Cho[a], Tetsuo Hyodo[b], Daisuke Jido[c], Che Ming Ko[d], Su Houng Lee[e,*], Saori Maeda[f], Kenta Miyahara[g], Kenji Morita[b], Marina Nielsen[h], Akira Ohnishi[b], Takayasu Sekihara[i], Taesoo Song[j], Shigehiro Yasui[f], Koichi Yazaki[k] (ExHIC Collaboration)

Few points in Coalescence model - I

$$\frac{dN_X}{dp_X} = C\int dx_1 dx_2 dp_1 dp_2 \frac{dN_1}{Vdp_1}\frac{dN_2}{Vdp_2} W\left(x_1, x_2, p_1, p_2\right)\delta\left(p_X - p_1 - p_2\right)$$

- Normalization conditions $\int dx_i dp_i \frac{dN_i}{Vdp_{i1}} = N_i \qquad \int dxdpW\left(x, p\right) = \left(2\pi\right)^n$

- Wigner function $W\left(x, p\right) = \left(2\right)^n \exp\left[-\frac{x^2}{\sigma^2} - \sigma^2 p^2\right]$

Should use x, p in CM frame S. Cho, K.J. Sun, C.M. Ko, SH Lee, Y. Oh, PRC101(20)024909

- σ → infinity limit

$$\frac{dN_X}{dp_X} = C\left(\frac{\gamma}{V}\right)\frac{dN_1}{dp_1}\bigg|_{p_1=\frac{p_X}{2}} \frac{dN_2}{Vdp_2}\bigg|_{p_2=\frac{p_X}{2}}$$

Few points in Coalescence model - II

- Coalescence probability is suppressed for smaller object when

$$\frac{dN_i}{Vdp_i} \propto \exp\left[-\frac{p_i^2}{2mT}\right] \qquad W(x,p) = (2)^n \exp\left[-\frac{x^2}{\sigma^2} - \sigma^2 p^2\right]$$

$$\frac{dN_X}{dp_X} = \frac{1}{\left(1+\frac{1}{mT\sigma^2}\right)^{n/2}} C\left(\frac{\gamma}{V}\right) \left.\frac{dN_1}{dp_1}\right|_{p_1=\frac{p_X}{2}} \left.\frac{dN_2}{Vdp_2}\right|_{p_2=\frac{p_X}{2}}$$

correction becomes visible when σ<0.5 fm

A simple fit to Deuteron and ^{3}He using (R_b, V) - I

- Deuteron Pt distribution should be determined by that of proton

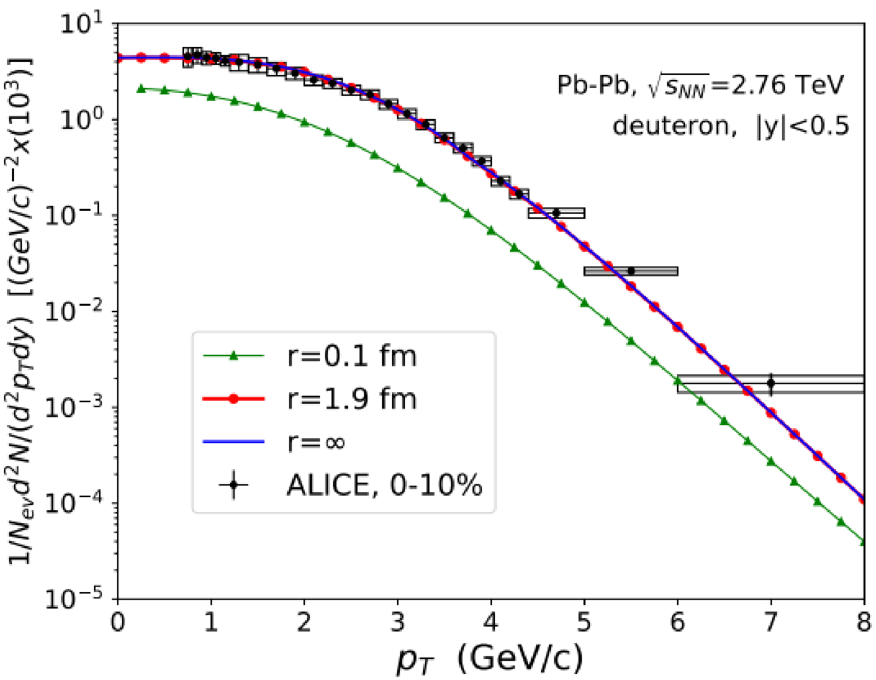
- Use $$\frac{dN_i}{dp} = R_b \left.\frac{dN_{\text{Proton}}}{dp}\right|_{\text{Measured}}$$

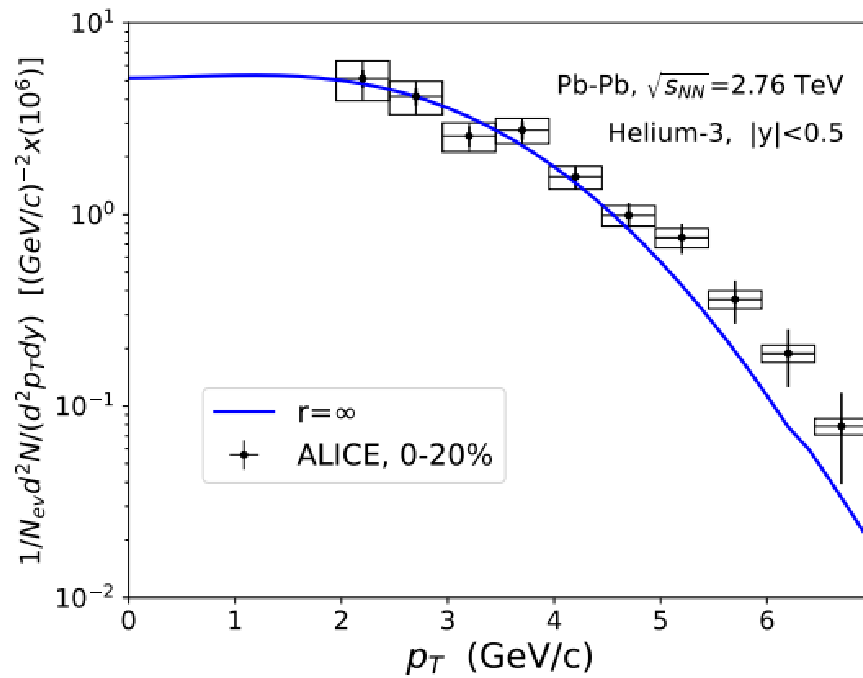
$$\frac{d^2N_{\text{deuteron}}}{d^2p_T} = \frac{g_d}{g_1 g_2}(2\pi)^2\gamma\frac{R_b^2}{V}\left.\frac{d^2N_{\text{Proton}}}{d^2p_1}\right|_{p_1=\frac{p_T}{2}}\left.\frac{d^2N_{\text{Proton}}}{d^2p_2}\right|_{p_2=\frac{p_T}{2}}$$

$$\frac{d^2N_{^3\text{He}}}{d^2p_T} = \frac{g_h}{g_1 g_2 g_3}(2\pi)^4\gamma^2\frac{R_b^3}{V^2}\left.\frac{d^2N_{\text{Proton}}}{d^2p_1}\right|_{p_1=\frac{p_T}{3}}\left.\frac{d^2N_{\text{Proton}}}{d^2p_2}\right|_{p_2=\frac{p_T}{3}}\left.\frac{d^2N_{\text{Proton}}}{d^2p_3}\right|_{p_3=\frac{p_T}{3}}$$

A simple fit to Deuteron and ^{3}He using (R_b ,V) - II

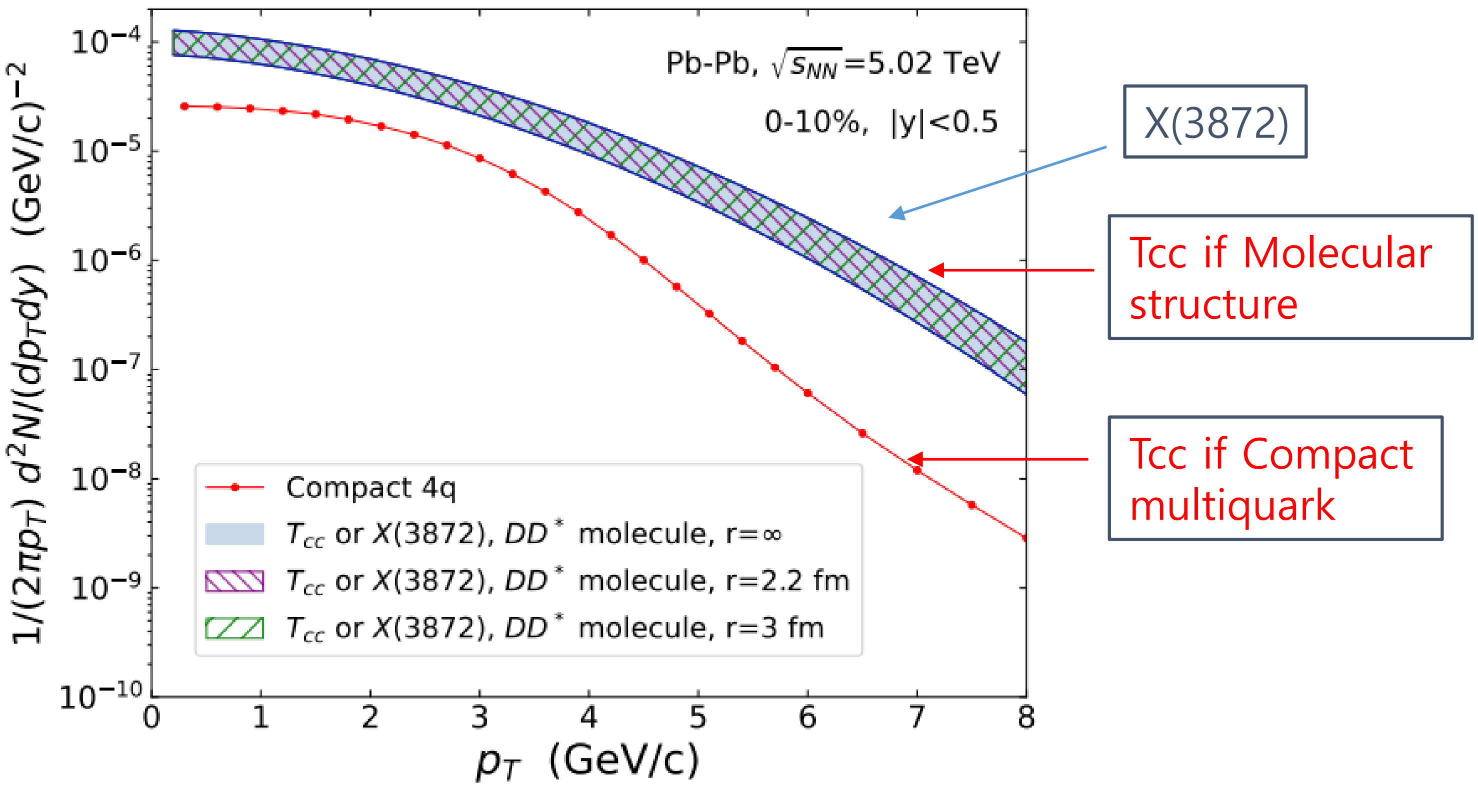
1. For r>1.9 fm result are similar to $\sigma \rightarrow$ infinity result
2. Both can be fit by choosing R_b=0.36 → similar to feed-down effects SHM
3. V(2-dim)=608 fm^2





Expectation for Molecular configuration of X(3872) and Tcc

1. Use measured D and D* Pt distribution
2. Use R_b=0.31 from feed-down effects SHM
3. Use same V(2-dim)=608 fm^2



Integrated yields for loosely bound molecules

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

Nucleus	$N^{Nucleus}_{SHM}/N^p_{SHM}$	$N^{Nucleus}_{coal}/N^p_{SHM}$
d	9.07×10^{-3}	8.84×10^{-3}
^{3}He	2.68×10^{-5}	2.03×10^{-5}

TABLE II. The yield ratio of light nucleus with proton in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. 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	$N_{coal}/N^{X(3872)}_{SHMc}$	$N_{coal}/N^{\psi(2S)}_{SHMc}$
DD^* molecule	$(2.45 \pm 0.71) \times 10^{-3}$	2.47 ± 0.716	0.806 ± 0.234
$Compact\ 4q$	$6.2\ \times 10^{-4}$	6.25×10^{-1}	0.204

no feed down for D*

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

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 $dN_{\psi(2S)}/dy = 3.04 \times 10^{-3}$ and $N_{X(3872)}/N_{\psi(2S)} = 0.326$ obtained in SHMc.

Summary

- Can probe possible compact configuration from quark model

- Most exotics have multiple heavy quark: RHIC is an excellent factory

- X(3872) can not be a compact multi-quark state: quark model

- Tcc(3875) can either be a compact or molecular configuration

- Measuring the Pt dependence can discriminate the structure of X(3872) and Tcc(3875): Analogy with deuteron

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.

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

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

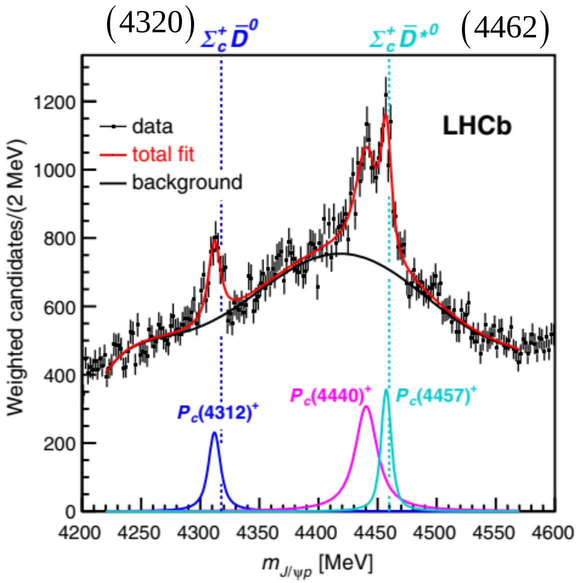
Tetraquark LHCb,BES?	Mass +i(width)	Quark content	$\bar{D}^0 D_s^{*+}$	$\bar{D}^{0*} D_s^+$	Observed mode
Zcs(4000)	4003+i(131)	$(u\bar{d})(c\bar{c})$	3977	3978	$J/\psi K^+$

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	→

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



2. Pc states could also be molecular configurations.

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

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

Additions – New pentaquarks

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

ΔE : Expected binding with negative K factor

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

$P_{sc\bar{c}}(udsc\bar{c})[4458]$

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

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

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

could be $\Xi_{cc}K$ molecule

Note $\Xi^{++}_{cc}(3621.40) \rightarrow \Lambda_c K^- \pi^+ \pi^+$ (LHCb 1707.01621)