Exotics:
Structure and production in Heavy Ion Collisions

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- Theory overview
- The structure of X(3872) and Tcc ($D^0D^0\pi^+$) and why it is interesting to measure Exotics in Heavy Ion Collision

Acknowledgments:

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

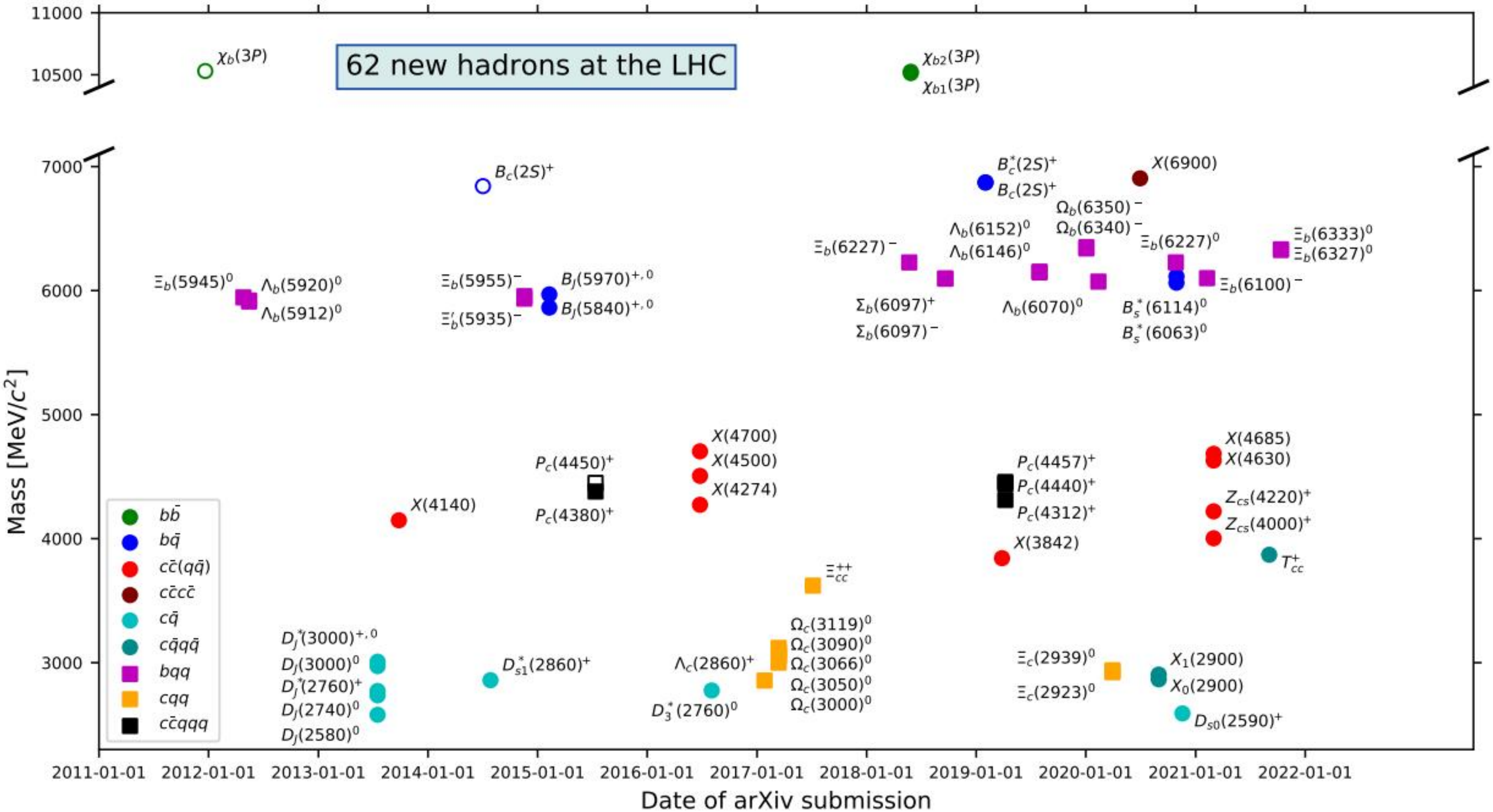
External collaborators: C. M. Ko, Sungtae Cho, Sanghoon Lim, Yongsun Kim

+ ExHIC collaboration

Exotics

1. Starting from X(3872) or χ_{c1}(3872)…..

Recent LHCb publication arXiv:2206.15233…..



Revival of an old topic: Gell-Mann (64)

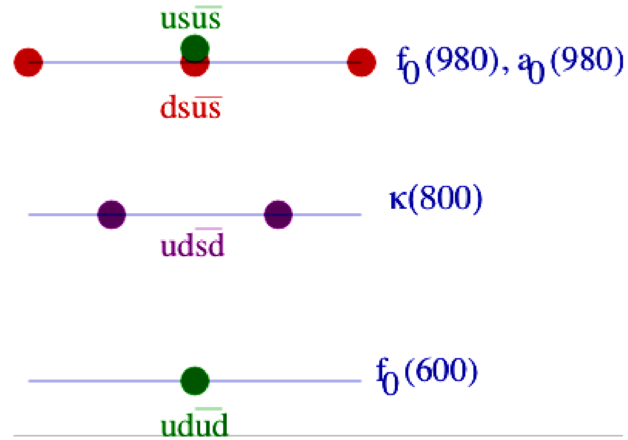
☞ Tetraquark:

- scalar tetraquark (Jaffe 76)

  → Still controversial

But ALICE(Junlee Kim) analysis suggests

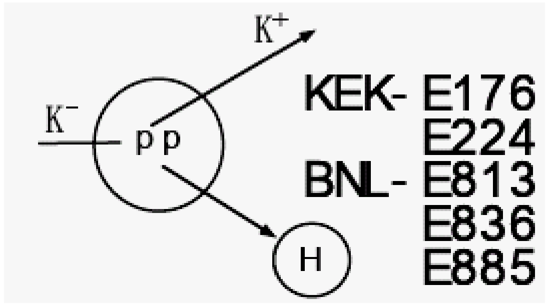
f_0 is most likely a $(\bar{q}q)$ without $(\bar{s}s)$



☞ Dibaryon

- H (ududs s) dibaryon (Jaffe 77):

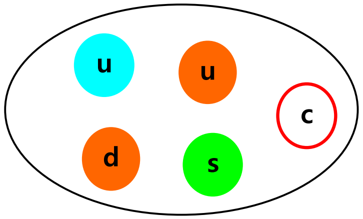
  → experimentally not found



☞ Pentaquark

- P$\bar{c}$s (Gignoux, Silvestre-Brac, Richard 87)
- P$\bar{c}$s (udus$\bar{c}$) (Lipkin 87)

  → Fermilab E791 : not found $P^0_{\bar{c}s} \to K^{*0}\, K^-\, p$



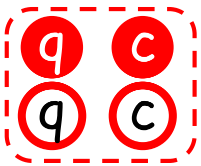
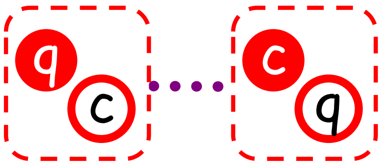
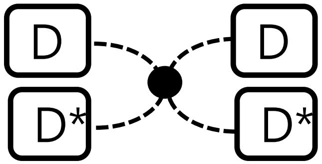
- Θ^+ (Diakonov, Petrov, Polyaov 97)

  → LEPS 2003 but not confirmed

Few examples of recent findings

	Tetraquark	Mass	Quark content	2-body Threshold	Observed mode	Exp
Bound or Near Threshold	$\chi_{c1}(3872)$ $X(3872)$	3871.65	$[c\bar{c}q\bar{q}]$	$\bar{D}^0 D^{*0}$(3871.69) $D^- D^{*+}$(3879.92)	$J/\psi\pi^-\pi^+$ …..	Belle ..
	$T_{cc}(3875)$	3875	$[c\bar{u}c\bar{d}]$	$\bar{D}^0 D^{*+}$(3875.26) $D^+ D^{*0}$(3876.51)	$\bar{D}^0 D^0 \pi^+$	LHCb
Above Threshold	$T^{\theta}_{\psi s1}$(4000) $Z_{cs}(3872)$	4003+i(131)	$[c\bar{c}u\bar{s}]$	$\bar{D}^0 D_s^{*+}$ (3977) $J/\psi K^+$(3590.58)	$J/\psi K^+$	LHCb (BES?)
	$X(5568)$	5568+i(21.9)	$[b\bar{d}u\bar{s}]$	$B^0 K^+$(5773) $B_s^0\pi^\pm$ (5506.49)	$B_s^0\pi^\pm$	D0
	$T^{a}_{c\bar{s}0}$(2900)	2908+i(136)	$[c\bar{s}u\bar{d}]$	2251.77	$D_s^+\pi^+$	LHCb

Types of Exotic particles

<table>
<tr><th></th><th>Compact multiquark</th><th>Molecule</th><th>Resonance</th></tr>
<tr><td>Picture</td><td></td><td></td><td></td></tr>
<tr><td>Size</td><td>$\langle r \rangle <$ 0.6 fm</td><td>$\langle r \rangle >$ 2 fm</td><td>$\langle r \rangle \sim$ 1 fm</td></tr>
<tr><td>Threshold</td><td>Near threshold or other</td><td>Near threshold</td><td>Above threshold or other</td></tr>
<tr><td>width</td><td>small</td><td>small</td><td>large</td></tr>
<tr><td rowspan="2">Typical model used</td><td>Quark Model: important to use full model</td><td>Meson exchange models</td><td>Unitary approach
Quark model</td></tr>
<tr><td colspan="3">Effective field theory: constants
QCD sum rules: uncertainty</td></tr>
</table>

Problem:

In many cases, two pictures seem possible. Compact and Molecular

What does quark model tell us

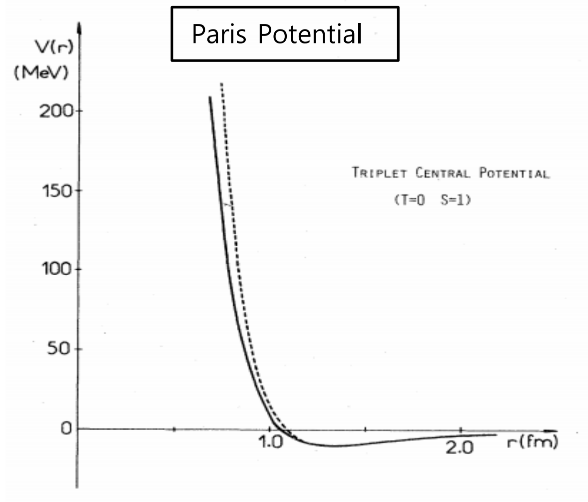
We know quark model explains the ground state meson and baryon masses well

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

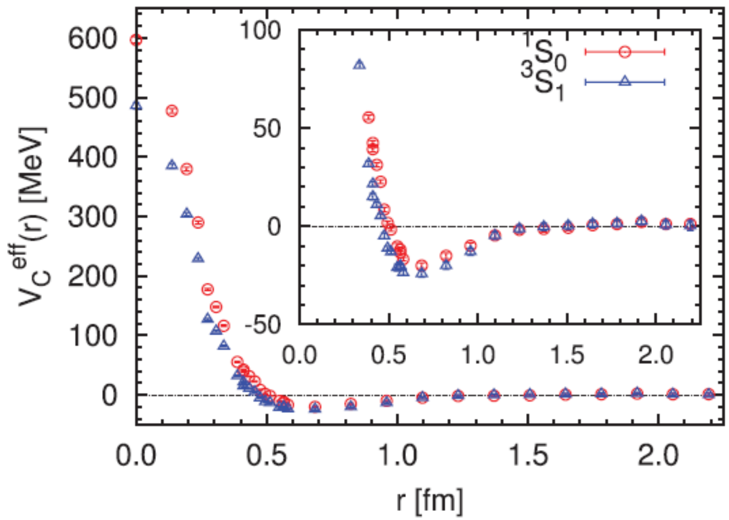
What does quark model tell us about compact (typical hadrons size) multiquark states

There are attractive channels

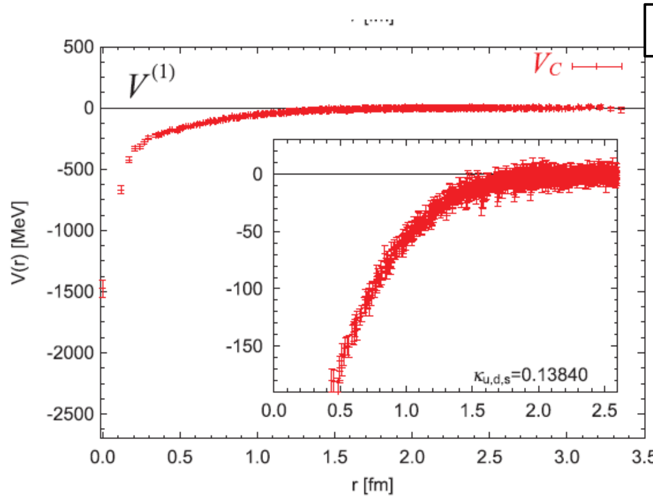
1. Nucleon-Nucleon potential at (I=0, S=1)



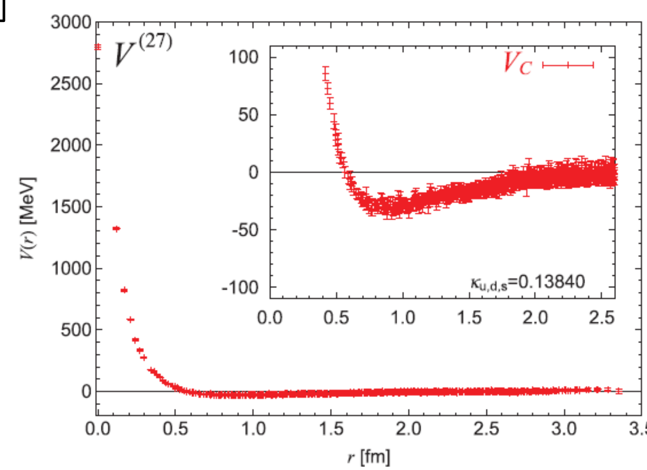
QCD HAL collaboration



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 – color-color interaction

☞ When brought together need to overcome Additional Kinetic energy >100 MeV

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

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

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

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

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

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

☞ Color-spin interaction for 2 body:

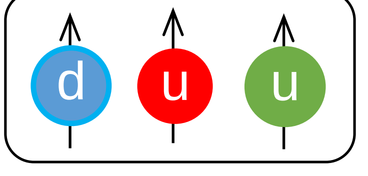
$$K=-\sum_{i<j}^{N}\left(\lambda_i^c\lambda_j^c\right)\left(\sigma_i^s\sigma_j^s\right)\longrightarrow$$

	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

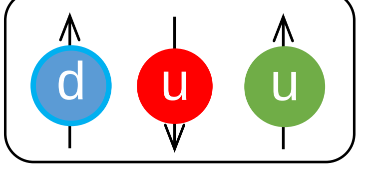
$K<0$ attraction; $K>0$ repulsion

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

Delta $S=3/2$



Proton $S=1/2$



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

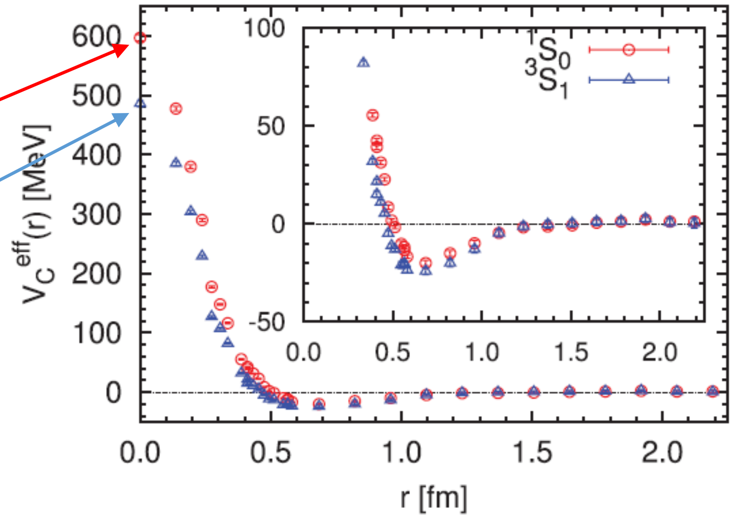
Quark Model vs Lattice comparison : A.Park, Lee, Inoue, Hatsuda, EPJA 56(2020)3,93

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

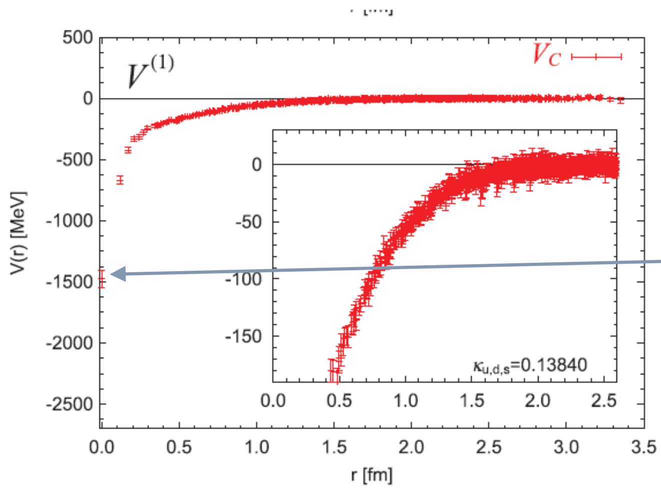
$$K_{2-N} = K_{6-quark} - \left(K_{1N} + K_{1N}\right)$$

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

QCD HAL collaboration

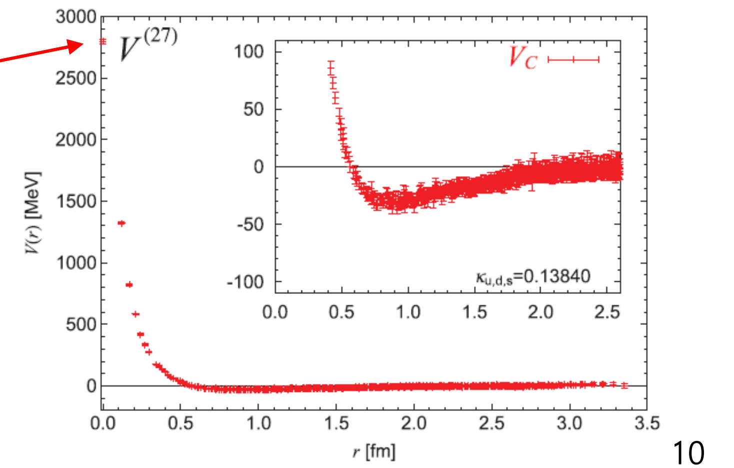


☞ H dibaryon channel: Flavor 1 vs Flavor 27



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

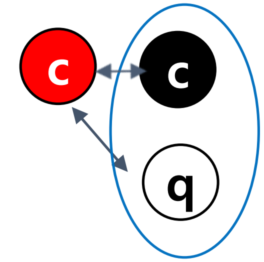
(HAL QCD Collaboration)



Why Heavy quarks are needed for multiquark configuration

☞ Coulomb interaction becomes stronger (Karliner Rosner)

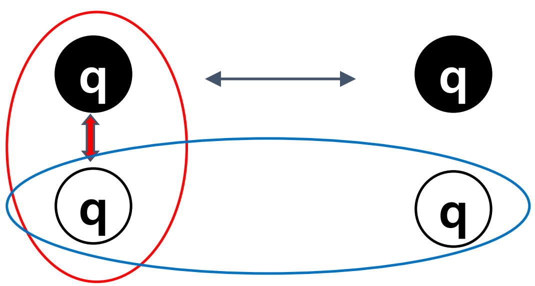
$$H_{cc} = \ldots + \lambda_i^c \lambda_j^c \left(\frac{g}{r_{ij}} \right) + \ldots . \qquad r \approx \frac{1}{mg^2}, \qquad E_C \approx -mg^4$$



☞ Color-spin interaction becomes weaker with heavy quarks

When all light quarks
Fall apart into two mesons

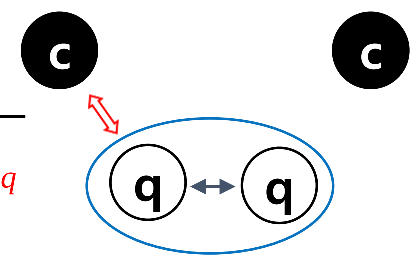
$$-16 \frac{1}{m_q m_q}$$



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

When heavy quarks,
could be compact (Tcc)

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



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

Indeed many heavy exotics were found

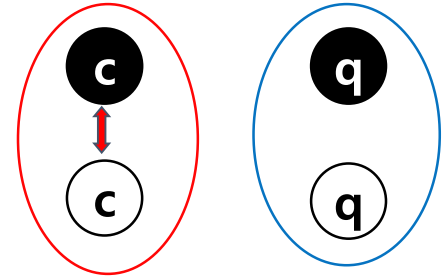
But still not clear about their structure

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?

Color-spin (X(3872)) $\quad I^G\left(J^{PC}\right) = 0^+\left(1^{++}\right) \qquad \left(c\bar{c}\right)\otimes\left(q\bar{q}\right)$

$\sim +140$ MeV

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

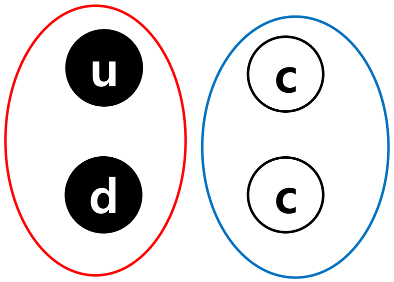
~ -20 MeV

Most attractive X(3872) $\begin{cases} \left(c\bar{c}\right) \to \left(C = 8, S = 1\right) \\ \left(q\bar{q}\right) \to \left(C = 8.S = 1\right) \end{cases}$ color-color interaction is repulsive

But -20 MeV is not strong enough to be compact (>100 MeV)

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

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



Color-spin (Tcc)

$$I^G\left(J^P\right) = 0^+\left(1^+\right)$$

$$(ud) \otimes (\overline{cc})$$

~ -100 MeV

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

$\sim +17$ MeV

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

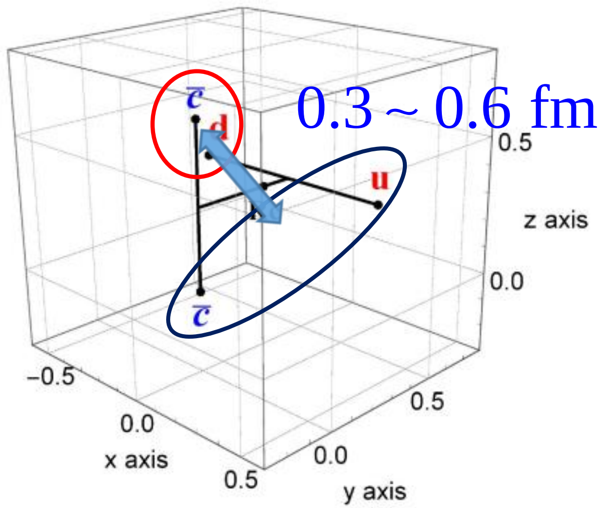
-100 MeV could be strong enough to be compact (>100 MeV)

Attraction expected from quark Model for $T_{cc}(3875)$ $I^G\left(J^P\right)=0^+\left(1^+\right)$

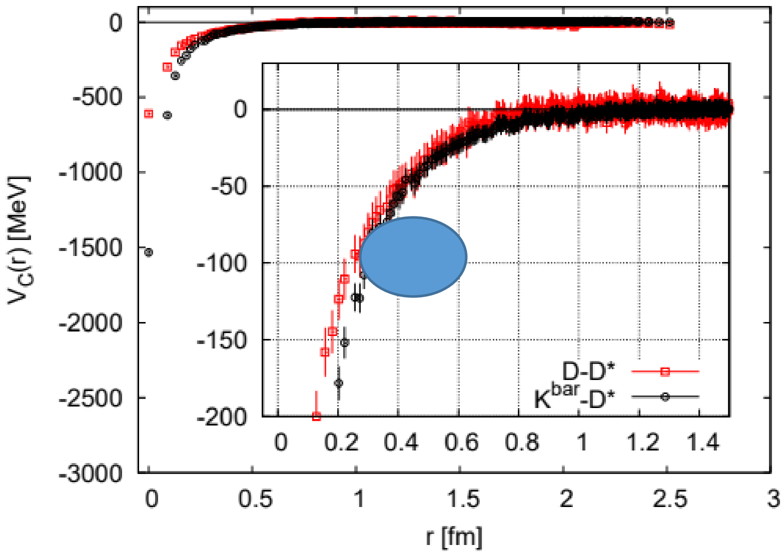
☞ Quark model estimate

(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 for Tcc: ex W. Park, S.Noh, Lee, NPA983 (2019)1

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

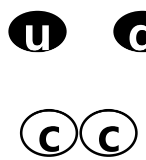
Still Tcc is marginal but Tbb is definitely a strongly bound compact multiquark-state

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 for Tcc: 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

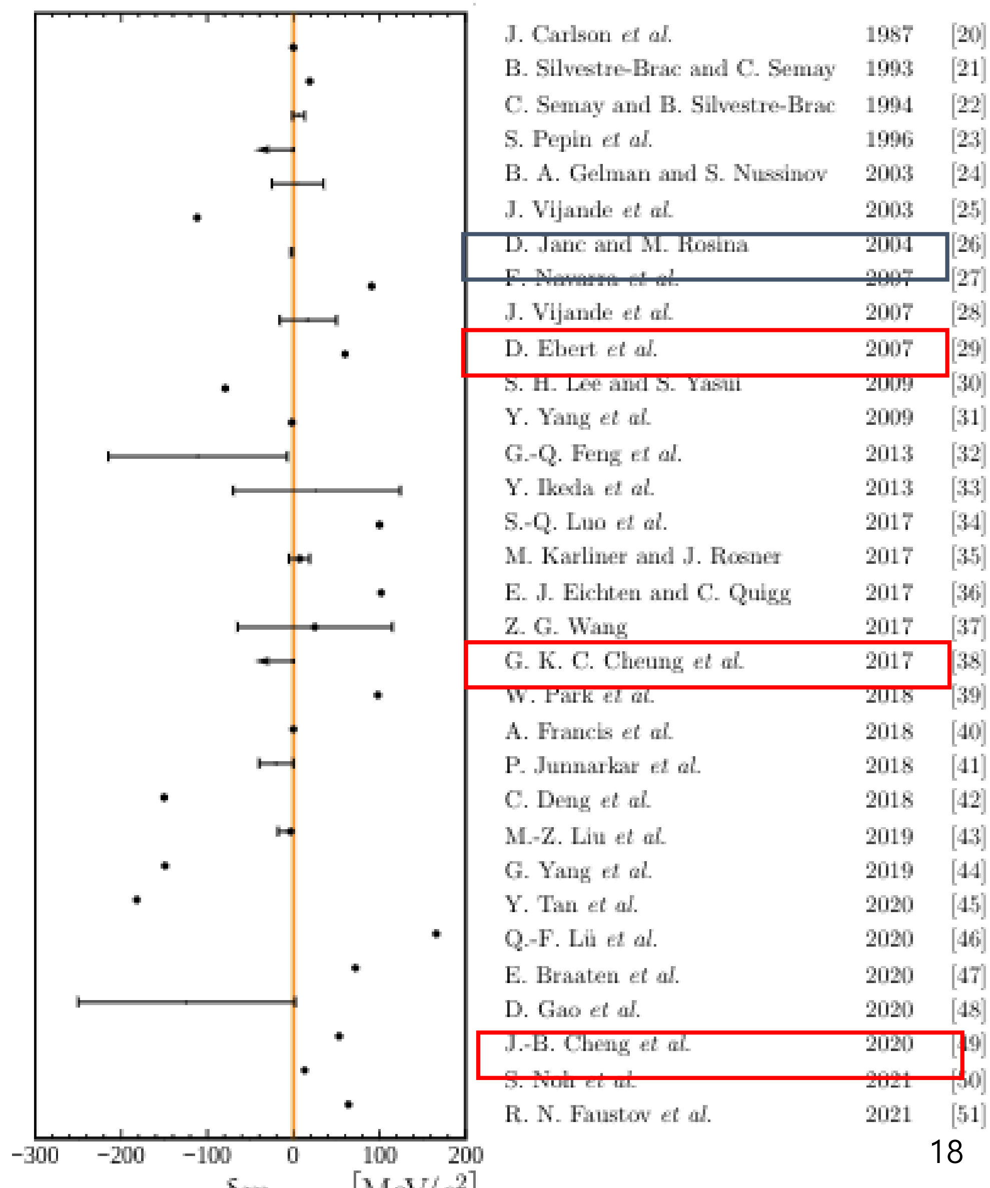
Full Quark Model calculation suggests: ex S.Noh, W.Park, Lee, PRD10(2021)114009

-2021- Tcc(3875) LHCb coll.

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

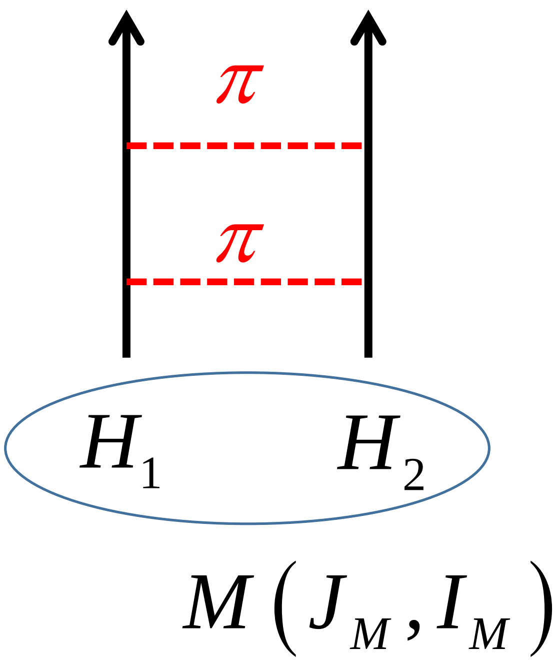
☞ The short range attraction for X(3872) is very weak

→ Can not be compact



Can X(3872) and Tcc(3875) be molecules?

Perspectives from the π-exchange



Especially important when

$J_M \neq 0$ Mixing with D-wave

and

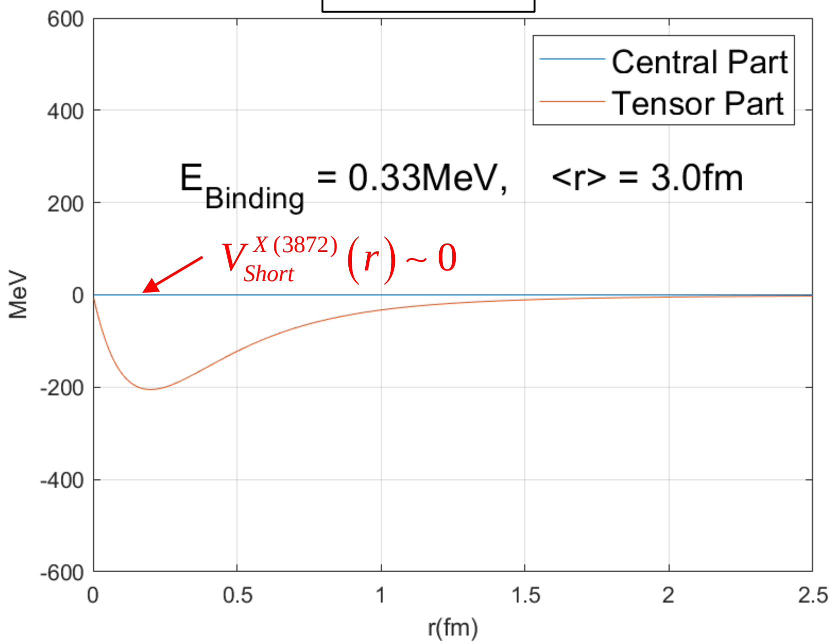
$I_M < (I_1 + I_2)$ Mixing is strong

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

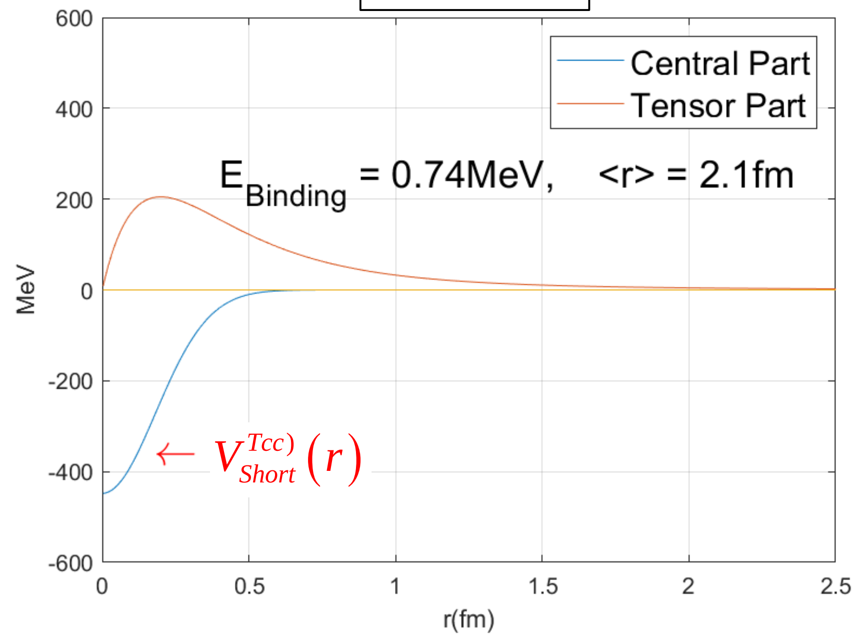
☞ $$V(r)^{-:X(3872)}_{+:Tcc} = V_{Short}(r)\begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix} \mp 3V_0\left[\begin{pmatrix}0 & -\sqrt{2}\\ -\sqrt{2} & 1\end{pmatrix}T_\pi(r)\right]$$

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

$\mathrm{X}(3872)$



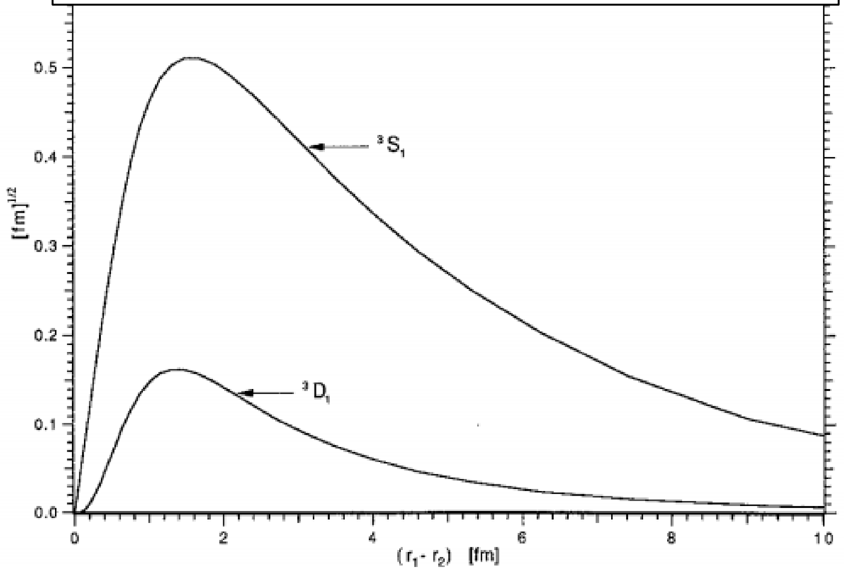
$\mathrm{T}_{cc}(3875)$



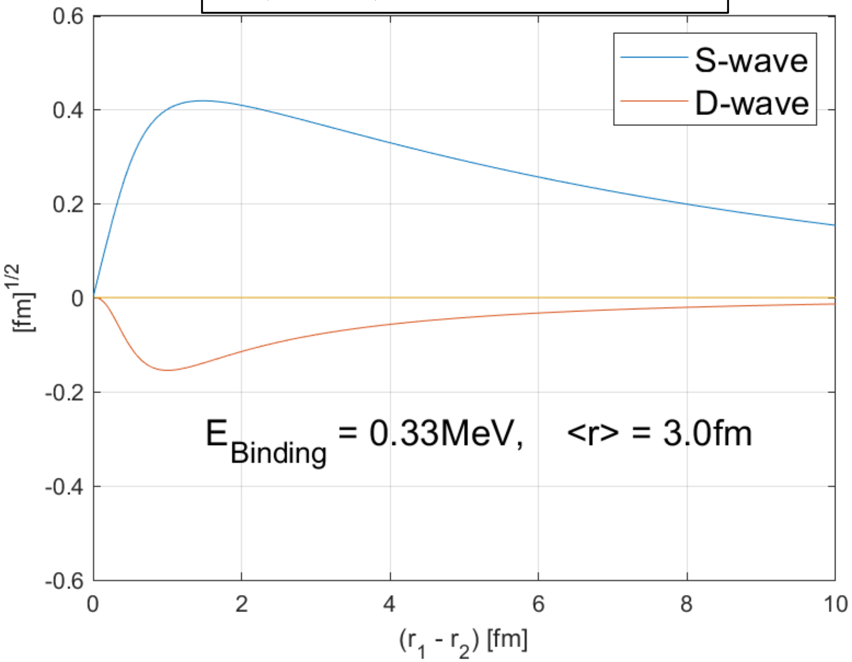
☞ Wave functions:

Similar to that of Deuteron

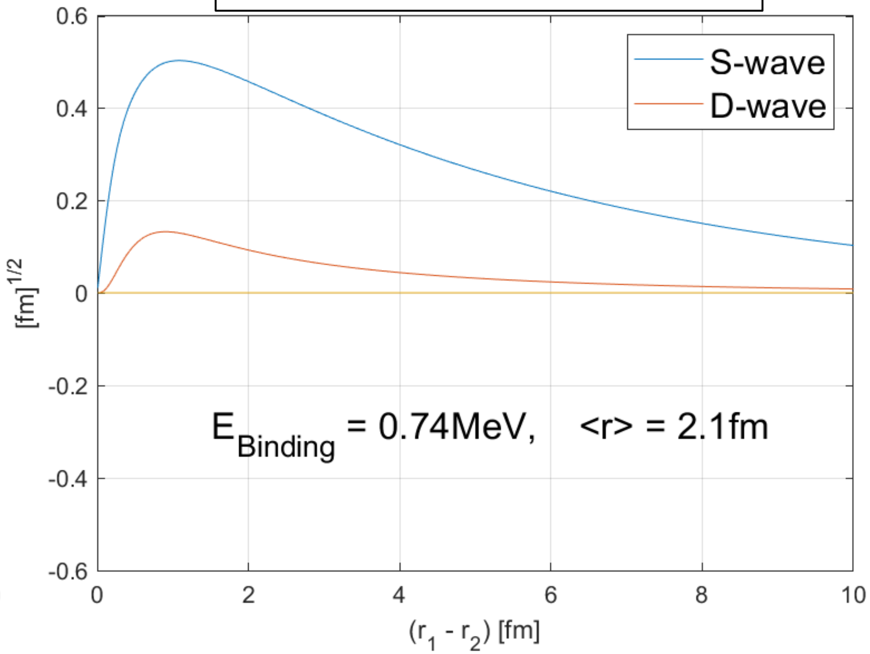
Deuteron – wave function (Törnqvist94)



$X(3872)$ – wave function



$T_{cc}(3875)$ – wave function



☞ Both X(3872) and Tcc(3875) could be a large molecular configuration

HYEONGOCK YUN *et al.* PHYSICAL REVIEW C **107**, 014906 (2023)

TABLE I. Comparison of molecular structures.

Molecule	Constituents	V_{short}	V_π (S wave)	V_π (D wave mixing)	$\langle r \rangle$ (fm)	E_b (MeV)
d	pn	repulsive	attractive	attractive	1.9	2.2
$X(3872)$	$D\bar{D}^*$	negligible	negligible	attractive	3.0	0.33
T_{cc}	DD^*	attractive	negligible	attractive	2.2	0.65

☞ X(3872) most likely not compact, butTcc(3875) could also be compact

II: Measuring Exotics in Heavy Ion Collision:

X(3872) and Tcc(3875) could be compact or molecules

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

10.3. Charmed exotics from heavy-ion collision

Our contribution to the volume

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

nature physics

Observation of an exotic narrow doubly charmed tetraquark

LHCb Collaboration*

Original prediction from ExHIC collaboration (Theory) in 2011

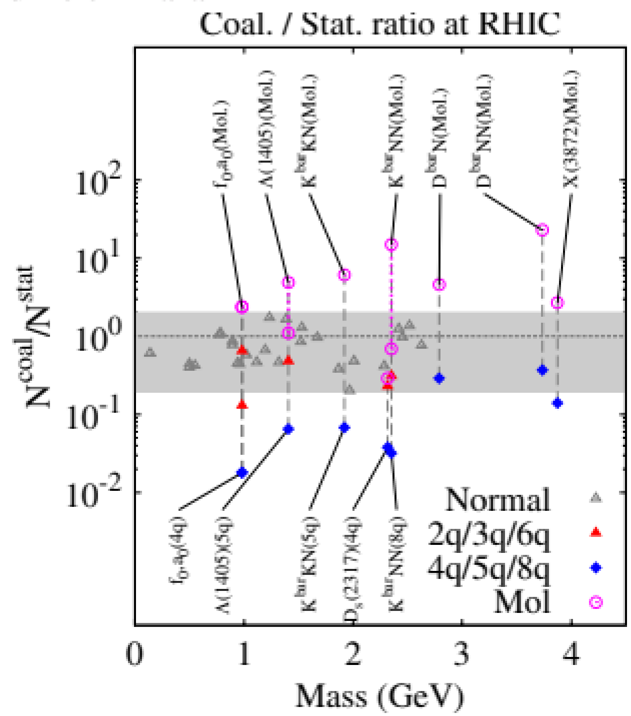
Theory prediction

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)

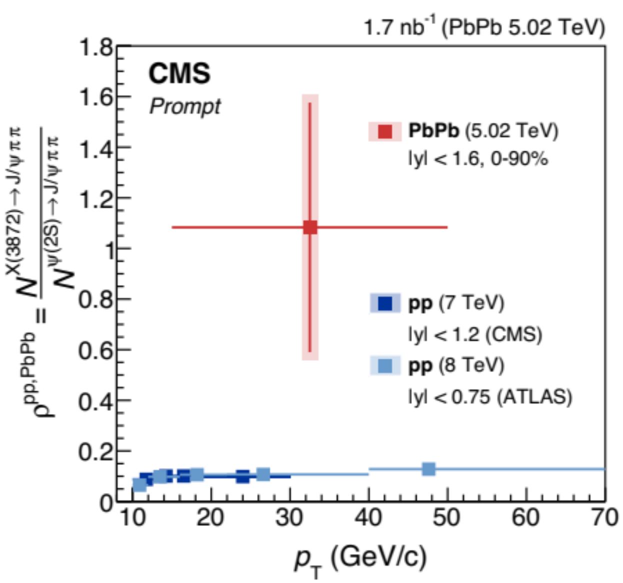


Experiment

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



Few points in Coalescence model - I

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

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

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

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

$$\frac{dN_X}{dp_X} = C\left(\frac{\gamma}{V}\right)\frac{dN_1}{dp_1}\bigg|_{p_1 = \frac{p_X}{2}} \frac{dN_2}{dp_2}\bigg|_{p_2 = \frac{p_X}{2}}$$

Few points in Coalescence model - II

- Coalescence probability is suppressed for smaller object when

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

$$\frac{dN_X}{dp_X} = \frac{1}{\left(1+\frac{1}{mT\sigma^2}\right)^{n/2}} \mathrm{C}\left(\frac{\gamma}{V}\right) \frac{dN_1}{dp_1}\bigg|_{p_1=\frac{p_X}{2}} \frac{dN_2}{dp_2}\bigg|_{p_2=\frac{p_X}{2}}$$

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

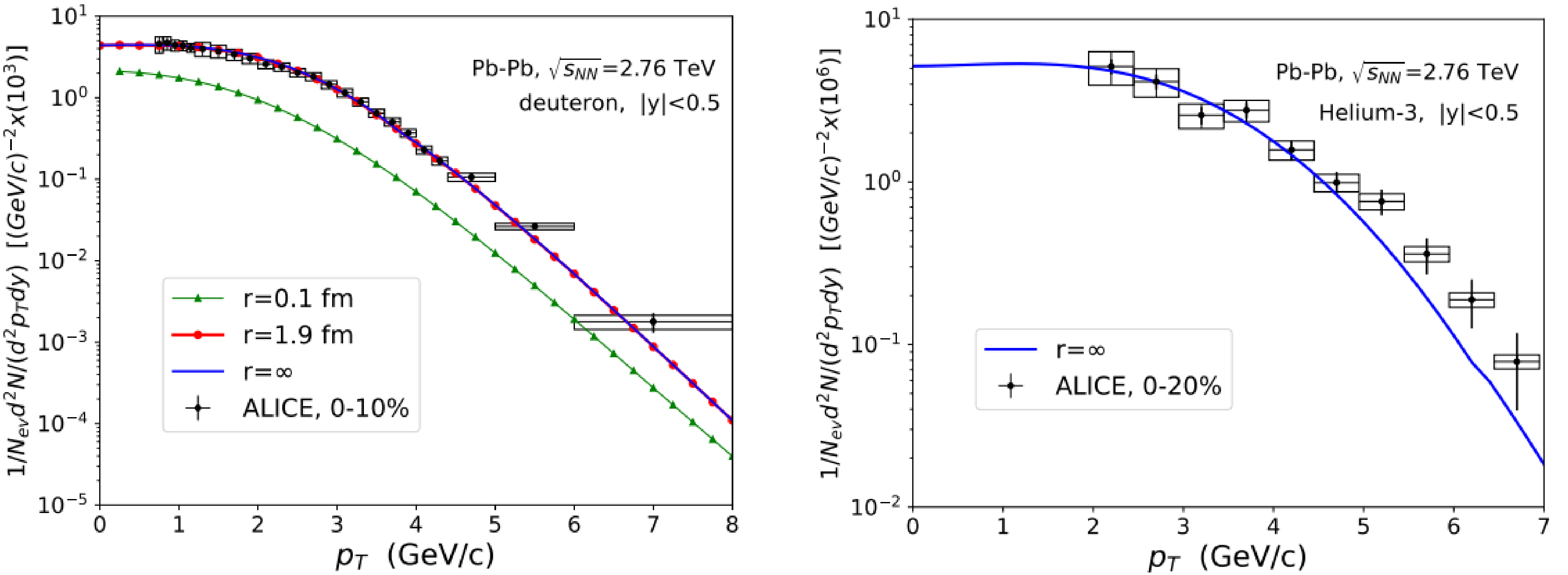
- Use $$\frac{dN_i}{dp} = R_b \left.\frac{dN_{\text{Proton}}}{dp}\right|_{\text{Measured}}$$

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

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

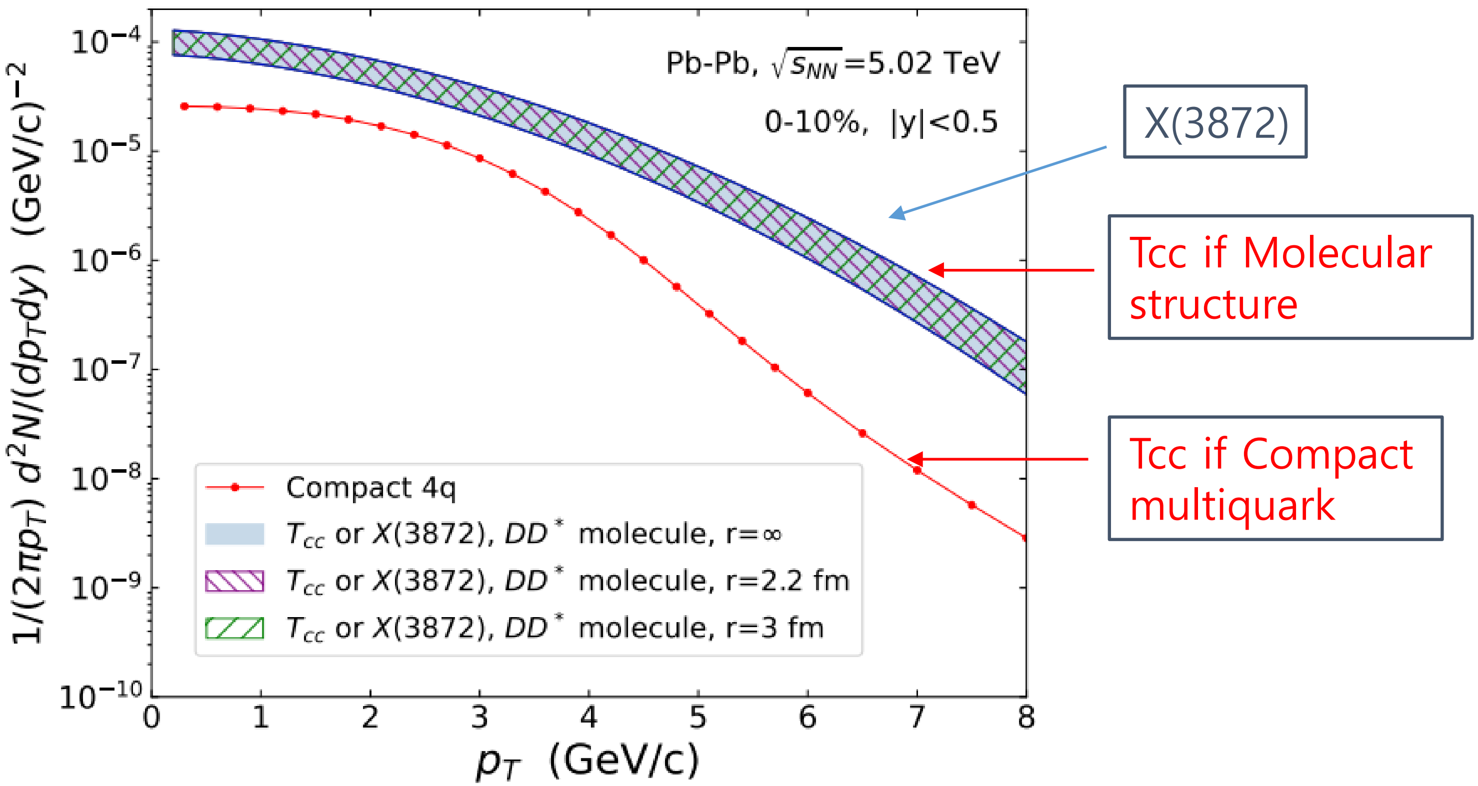
A simple fit to Deuteron and ^{3}He using (R_b ,V) - II

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 to 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
$Compact\ 4q$	6.2×10^{-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

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

- Exotics can be compact, molecules, resonances

  Discriminating the structure of Exotics provides a new venue to study QCD

  → Constrain models.

  The first step to understanding confinement in multiquark configuration

  → Deconfiment

- X(3872) can not be a compact multi-quark state. But Tcc(3875) could be either compact or molecular.

  → Measuring X(3872) and Tcc(875) or other exotics in heavy ion collision could discriminate the structure.