Structure and Production of Exotic Particles in HIC

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Why it is interesting to measure Exotics in Heavy Ion Collision

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

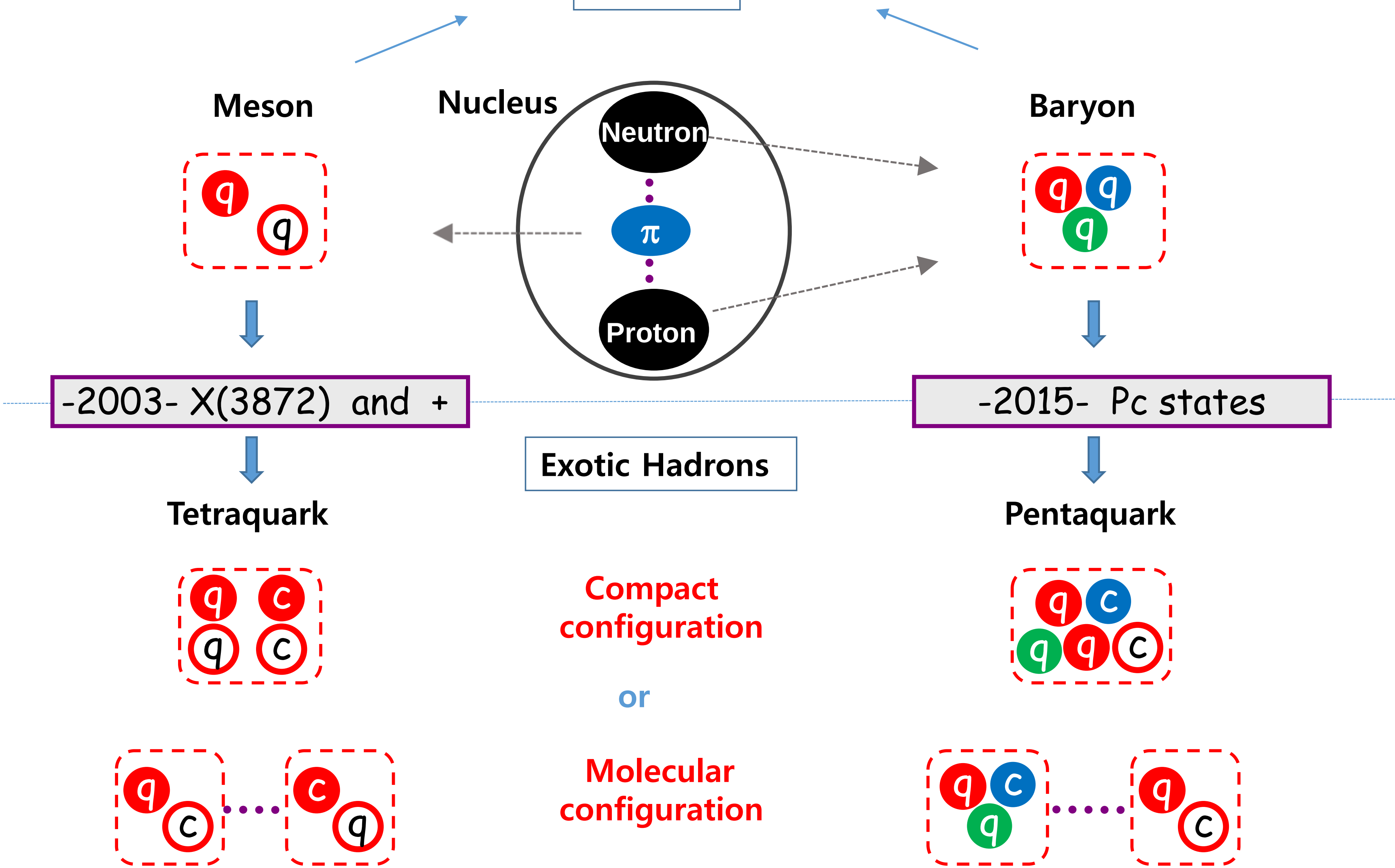
Acknowledgements:

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

Some perspectives



Which structure? → short distance vs long distance interaction

I: Short distance:

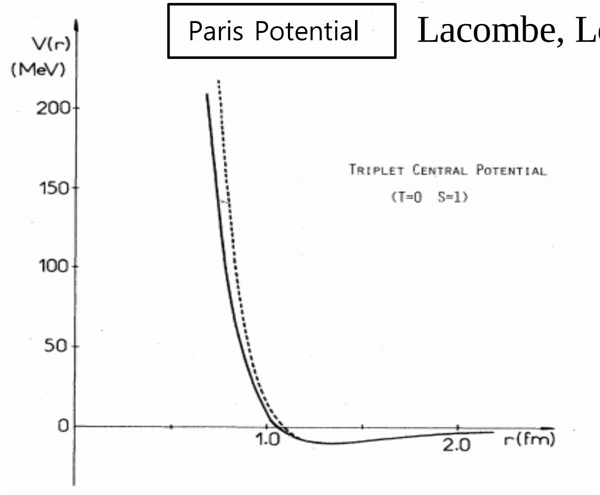
Perspectives from a quark model

There are attractive channels

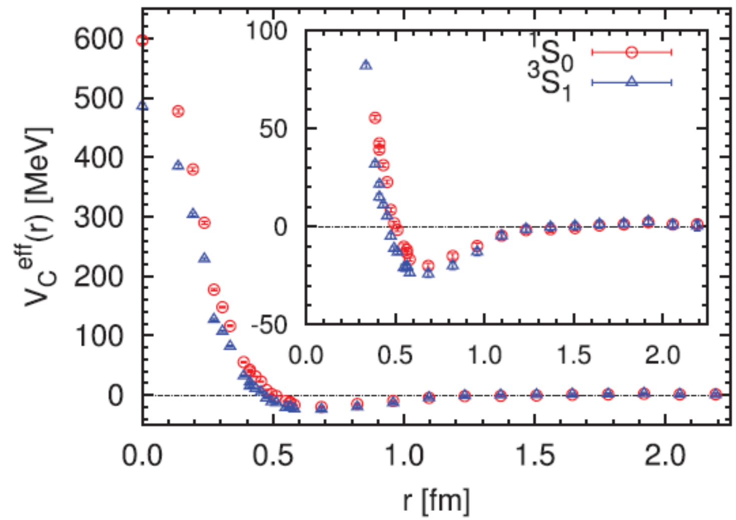
1. Nucleon-Nucleon potential at $(I=0, S=1)$

Paris Potential

Lacombe, Loiseau, Richard, ...

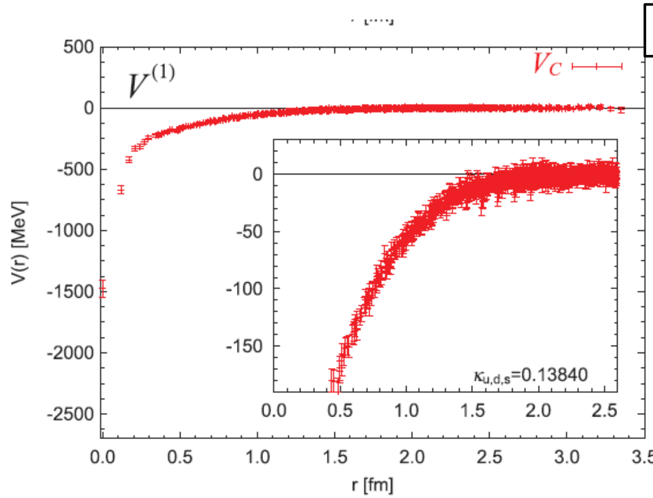


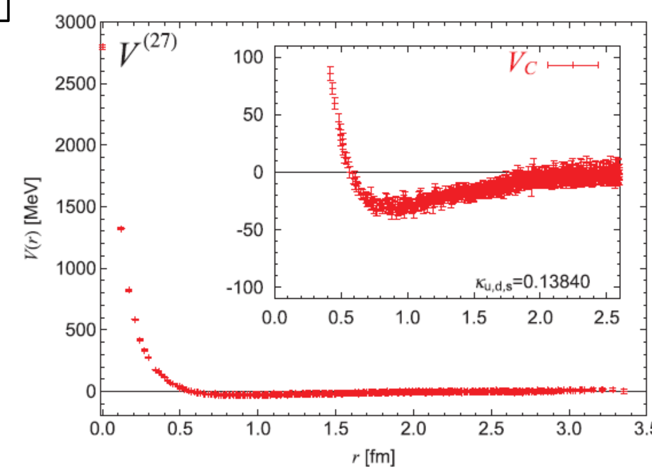
QCD HAL collaboration



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

QCD HAL collaboration





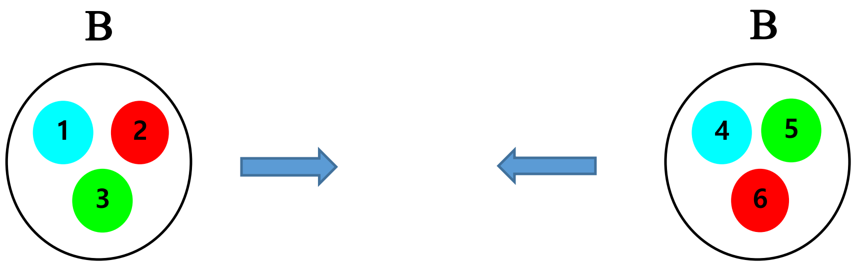
Quark Model perspectives on Interaction at short distance – Kinetic term

Quark model : interaction between quarks

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

☞ When brought together need to overcome Additional Kinetic energy

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



→ 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

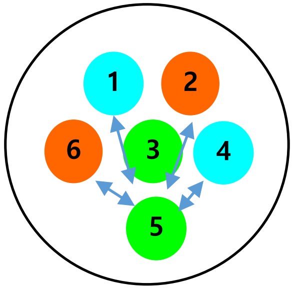
$$H=\sum_{i=1}^{n}\left(m_i+\frac{p_i^2}{2m_i}\right)-\sum_{i<j}^{n}\underline{\left(\lambda_i^c\lambda_j^c\right)V_{ij}^C\left(r_{ij}\right)}-\sum_{i<j}^{n}\frac{\left(\lambda_i^c\lambda_j^c\right)\left(\sigma_i\sigma_j\right)}{m_im_j}V_{ij}^{SS}\left(r_{ij}\right)$$

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

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

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

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



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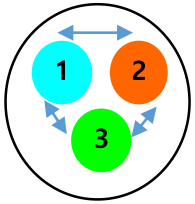

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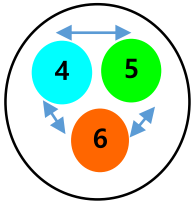


Quark Model perspectives on Interaction at short distance – color-spin interaction

Quark model

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

☞ Color-spin interaction for 2 body:

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

	$Q-Q$				$Q-\overline{Q}$			
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

$$K<0\quad \text{attraction;}\qquad K>0\quad \text{repulsion}$$

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

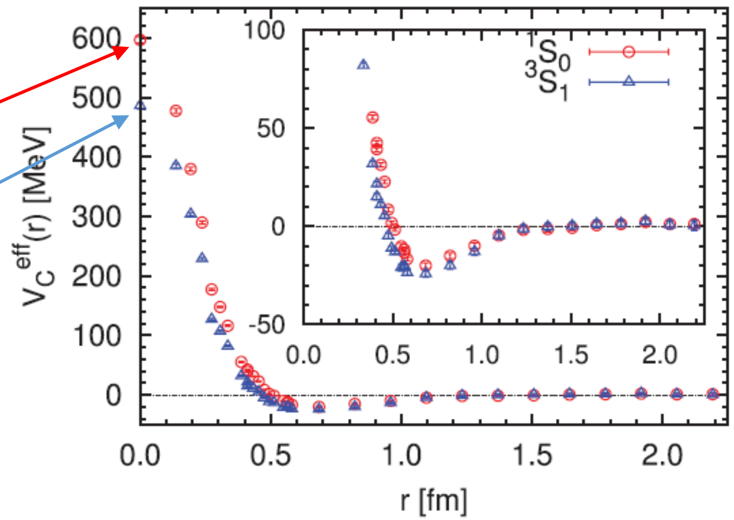
$$K\ \text{factor of}\ 1\ \rightarrow\ 18\ \text{MeV}$$

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

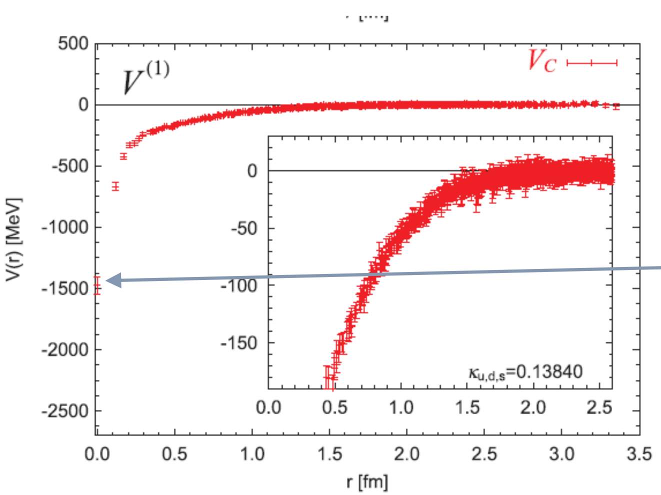
QCD HAL collaboration

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

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

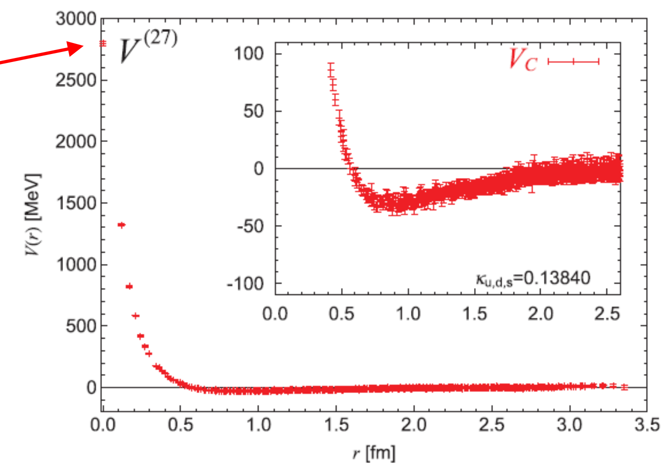


☞ H dibaryon channel: Flavor 1 vs Flavor 27



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

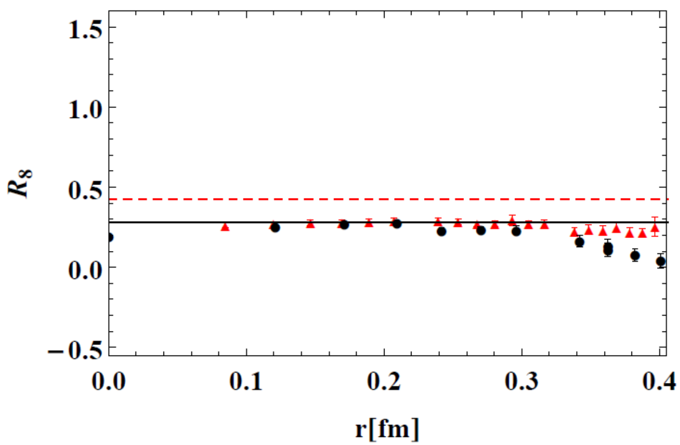
(HAL QCD Collaboration)

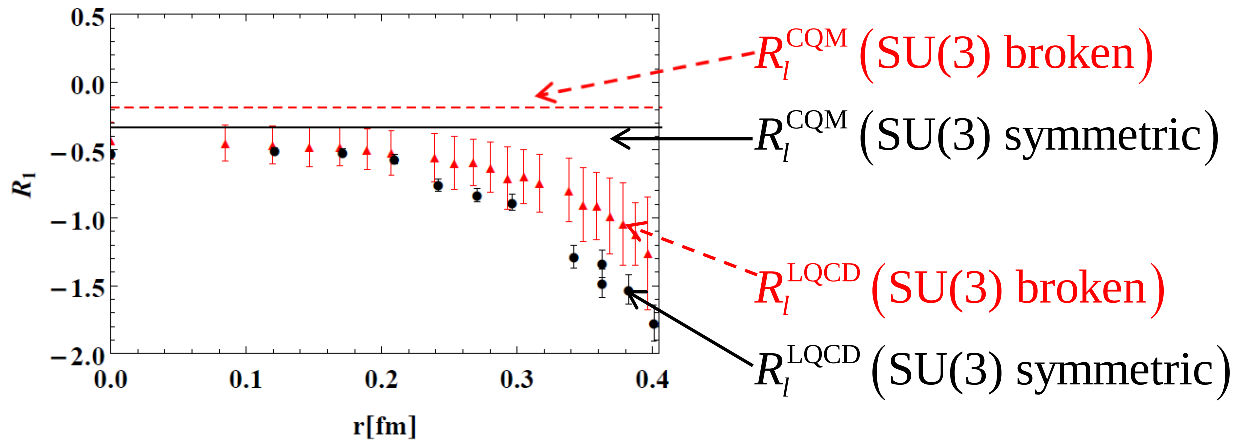


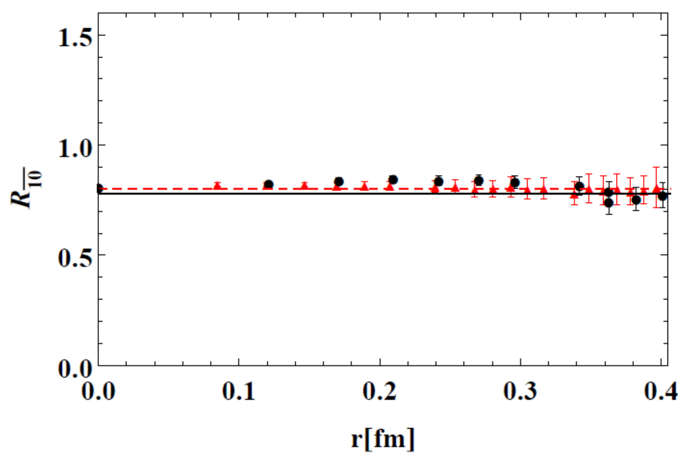
Full quark model calculation vs Lattice – A.Park, Lee, Inoue, Hatsuda, EPJA 56(20203,93

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

In fact, the K factors are good enough

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

X(3872): Belle 2003

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

$$K_{X(3872)}-K_D-K_{D^*}=\begin{pmatrix} \frac{16}{3}\frac{1}{m_c^2}+\frac{16}{3}\frac{1}{m_q^2}+\frac{32}{3}\frac{1}{m_c m_q} & 0 \\ 0 & \boxed{-\frac{2}{3}\frac{1}{m_c^2}-\frac{2}{3}\frac{1}{m_q^2}-\frac{4}{3}\frac{1}{m_c m_q}} \end{pmatrix} \begin{array}{l} (1\otimes 1)_c(V\otimes V)_{S=1} \\ (8\otimes 8)_c(V\otimes V)_{S=1} \end{array}$$

Assuming typical hadron size → ~ -20 MeV Too small to be compact

T_{cc}(3875): LHCb 2021

Z. Zouzou, B. Silverstre-Brac, C. Gilgnooux, J M Richard (86)

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

$$K_{T_{cc}(3875)}-K_D-K_{D^*}=\begin{pmatrix} \boxed{-8\frac{1}{m_q^2}+\frac{8}{3}\frac{1}{m_c^2}+\frac{32}{3}\frac{1}{m_c m_q}} & -8\sqrt{2}\frac{1}{m_c m_q} \\ -8\sqrt{2}\frac{1}{m_c m_q} & -\frac{4}{3}\frac{1}{m_q^2}+4\frac{1}{m_c^2}+\frac{32}{3}\frac{1}{m_c m_q} \end{pmatrix} \begin{array}{l} (\bar{3}\otimes 3)_c(S\otimes V)_{S=1} \\ (6\otimes \bar{6})_c(V\otimes S)_{S=1} \end{array}$$

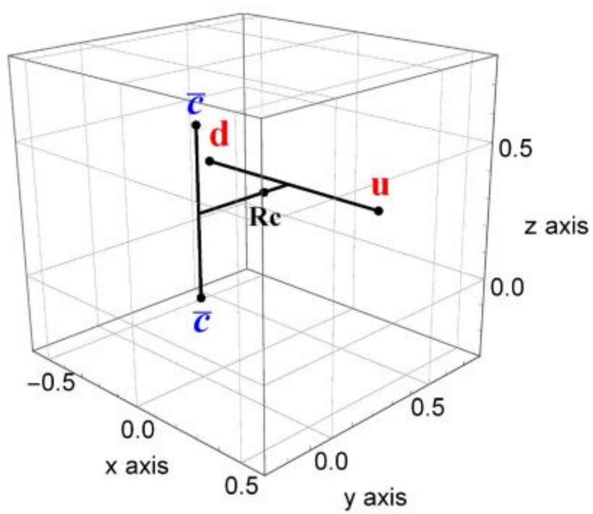
Lowest Eigenvalues ~ -100 MeV Note: addition Kinetic Energy -> +100 MeV

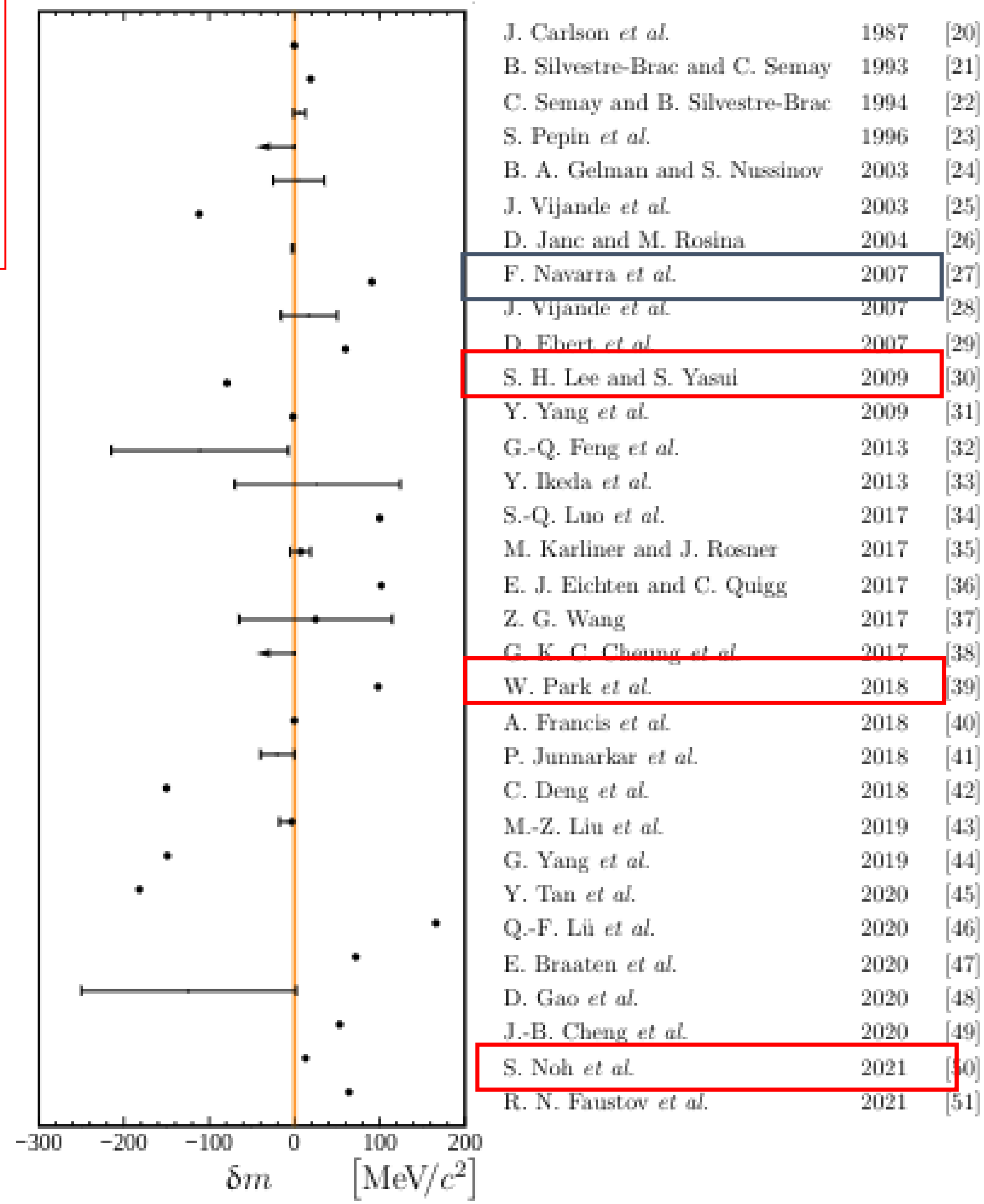
Many calculations on Tcc pioneered by Z. Zouzou, B. Silverstre-Brac, C. Gilgnooux, J Richard (86)

-2021- Tcc(3875) LHCb coll.

- Tcc is an attractive channel, could be a compact 4-quark state
- X(3872) unlikely to be compact !!

S.Noh, W.Park, Lee, PRD10(2021)114009





II: Long distance:

Perspectives from the π-exchange

π -exchange potential for Deuteron, X(38722) and Tcc: N.A. Tornqvist (94)

☞ $$V_{\text{deuteron}}(r) = -\frac{25}{3}V_0\left[\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}C_\pi(r) + \begin{pmatrix}0 & \sqrt{8}\\ \sqrt{8} & -2\end{pmatrix}T_\pi(r)\right]$$

Deuteron Binding from attractive Tensor force : $C_\pi(r) = \dfrac{e^{-m_\pi r}}{m_\pi r} \ll T_\pi(r)$

☞ $$V^{I=0,S=1,C=+}_{D-\bar{D}^*}(r) = -3V_0\left[\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}C_\pi(r) + \begin{pmatrix}0 & -\sqrt{2}\\ -\sqrt{2} & 1\end{pmatrix}T_\pi(r)\right]$$

Same for $\mathrm{X}(3872)$ and bound with $\langle r\rangle \sim 3$ to 4 fm

☞ $$V^{I=0,S=1}_{D-D^*}(r) = +3V_0\left[\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}C_\pi(r) + \begin{pmatrix}0 & -\sqrt{2}\\ -\sqrt{2} & 1\end{pmatrix}T_\pi(r)\right]$$

Not strong enough and $\mathrm{T}_{cc}(3875)$ is not bound

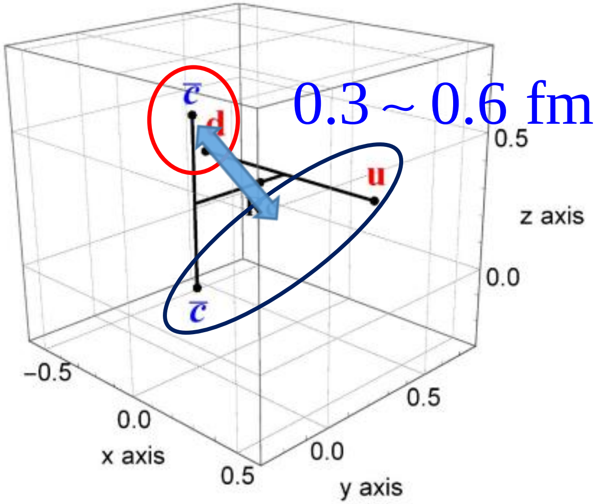
But quark model $\rightarrow$ short range attraction should be added

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

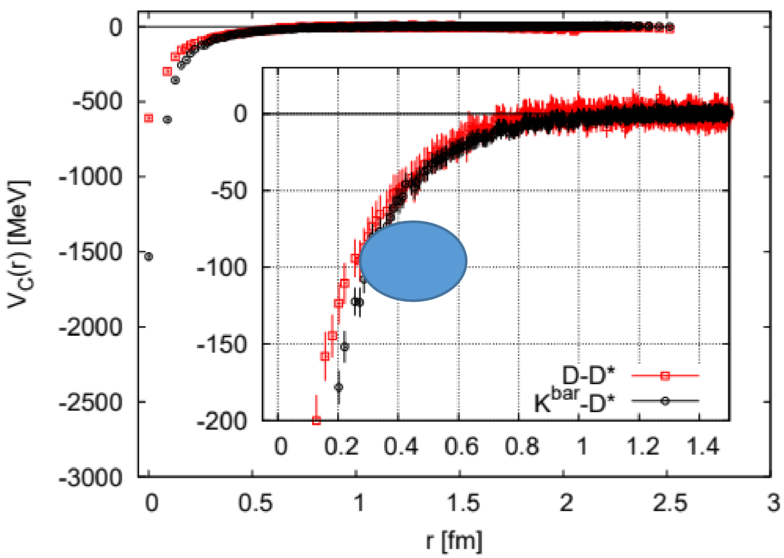
$\boxed{T_{cc}(3875)}$ $I^G\left(J^P\right) = 0^+\left(1^+\right)$

(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



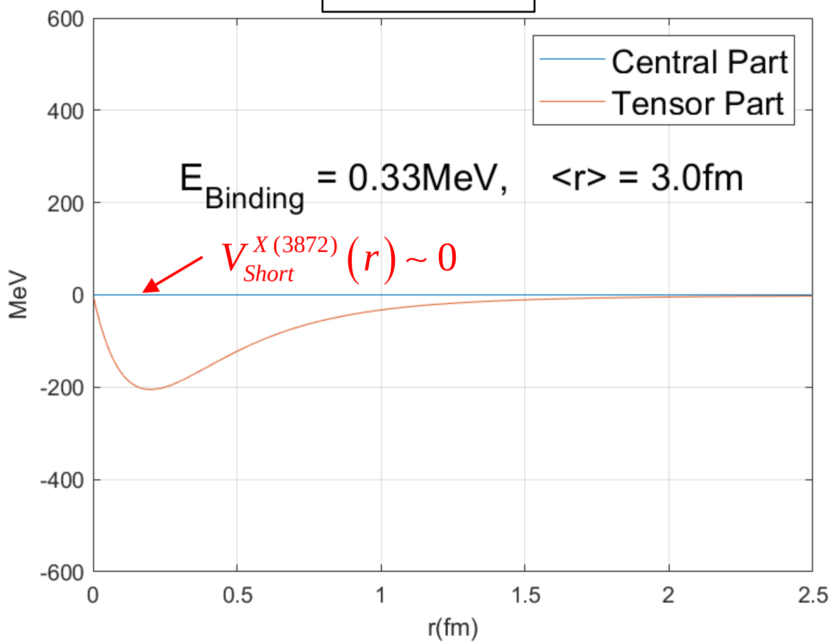
$m_\pi \simeq 410$ MeV

π -exchange potential with short range attraction: D. Park et al. (in preparation)

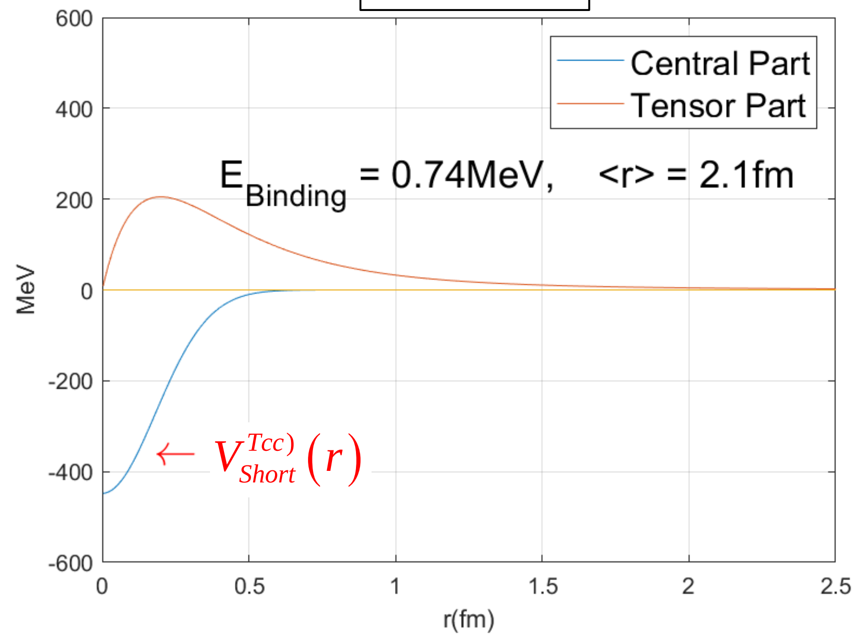
$$V(r)^{-:X(3872)}_{+:Tcc} = V_{Short}(r)\begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix} \mp 3V_0\left[\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}C_\pi(r) + \begin{pmatrix}0 & -\sqrt{2}\\ -\sqrt{2} & 1\end{pmatrix}T_\pi(r)\right]$$

Central Part$=V_{Short}(r) \mp 3V_0 C_\pi(r)$; Tensor Part$=\pm T_\pi(r)$

$X(3872)$



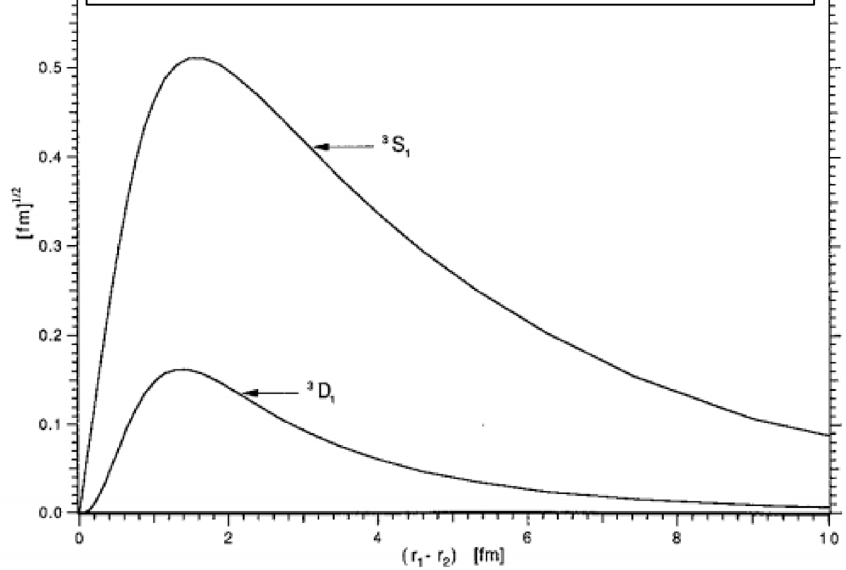
$T_{cc}(3875)$



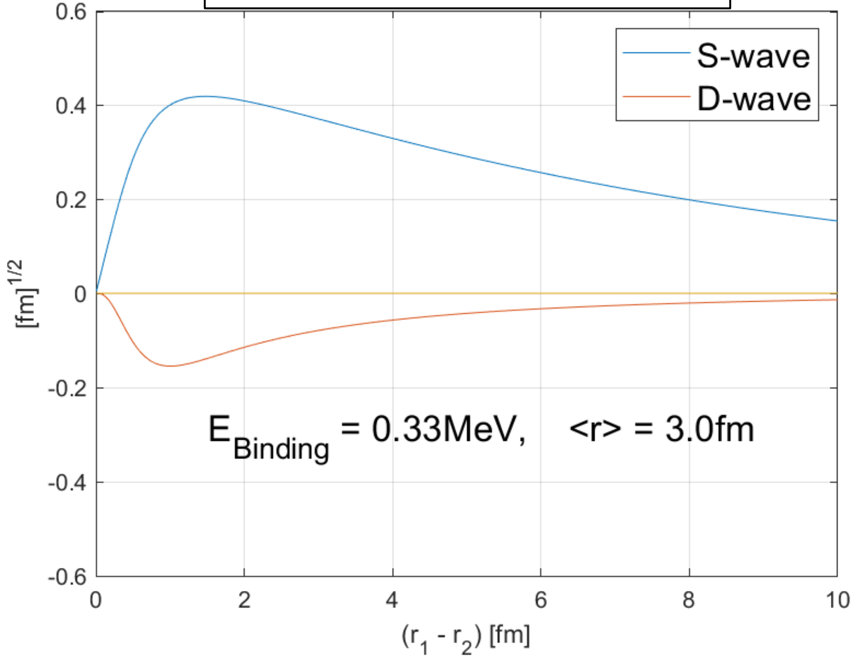
☞ Wave functions:

Similar to that of Deuteron

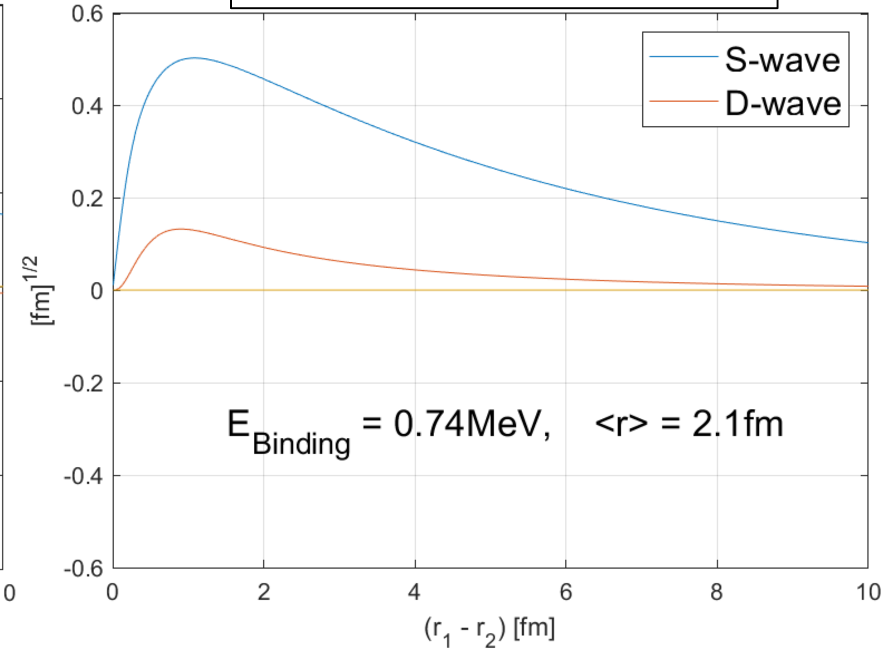
Deuteron – wave function (Peskin94)



$X(3872)$ – wave function



$T_{cc}(3875)$ – wave function



Why measure X(3872) and Tcc in Heavy Ion Collision

1. Expectation for structure of X(3872) and Tcc

	quark content /meson content	V_{Short} (Lee et al.)	V_{π} (Tornqvist 1994)	S/D mixing	Structure
X(3872)	$(uc)(\overline{uc})/\bar{D}D^*$	Small Can not be compact	Attractive	Attractive	Molecule
T_{cc}(3875)	$(ud)(\overline{cc})/DD^*$	Attractive But exact strength?	Repulsive	Attractive	Compact or Molecule

2. X should be a molecular configuration
3. But depending on the exact strength of the short range attraction, Tcc can either be compact multiquark or molecular configuration

→ Identifying the structure will be important

→ Can be done by measuring them in Heavy Ion collision

III: Measuring Exotics in Heavy Ion Collision:

Original prediction from ExHIC collaboration (Theory)

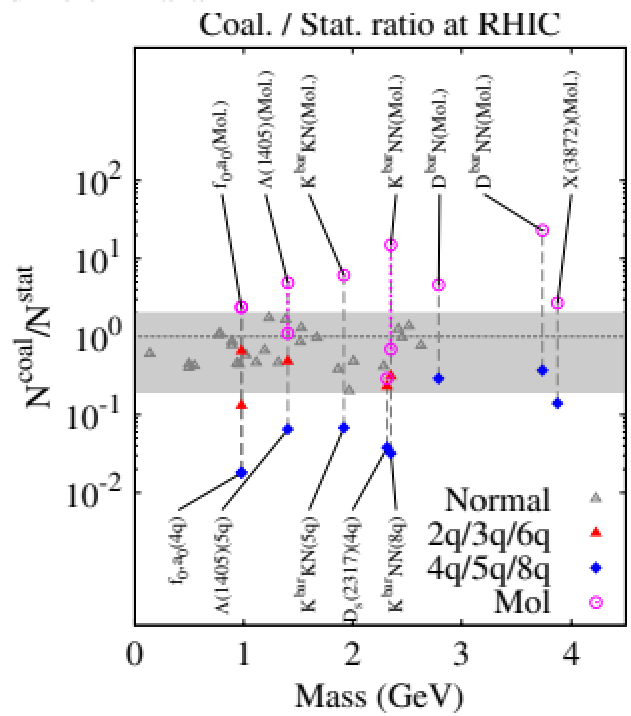
Theory prediction

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)

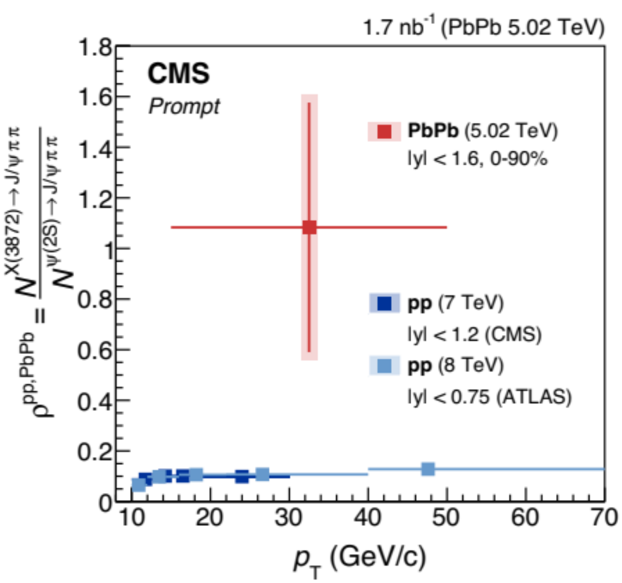


Experiment

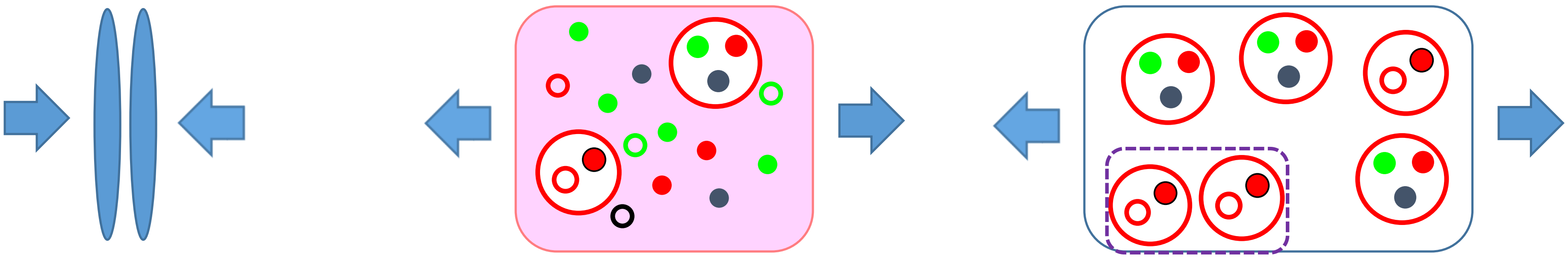
PHYSICAL REVIEW LETTERS **128,** 032001 (2022)

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

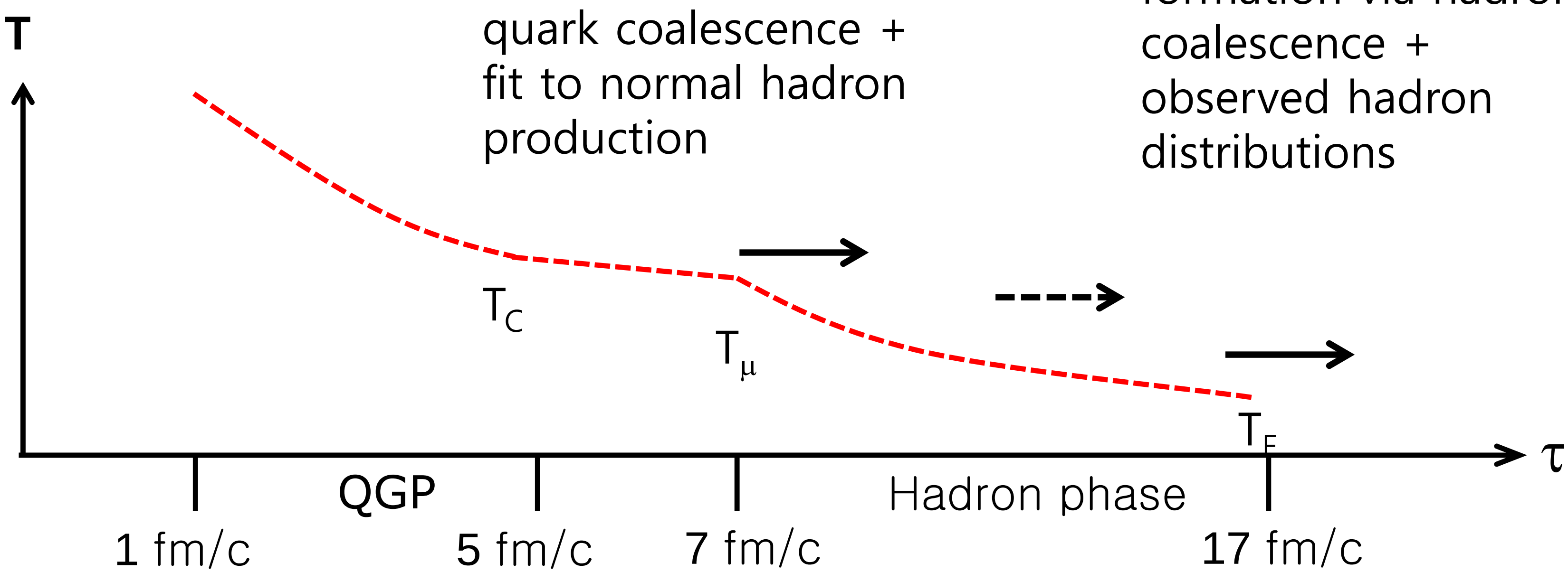


Hadron Production in Heavy Ion Collision



Compact Multiquark formation via quark coalescence + fit to normal hadron production

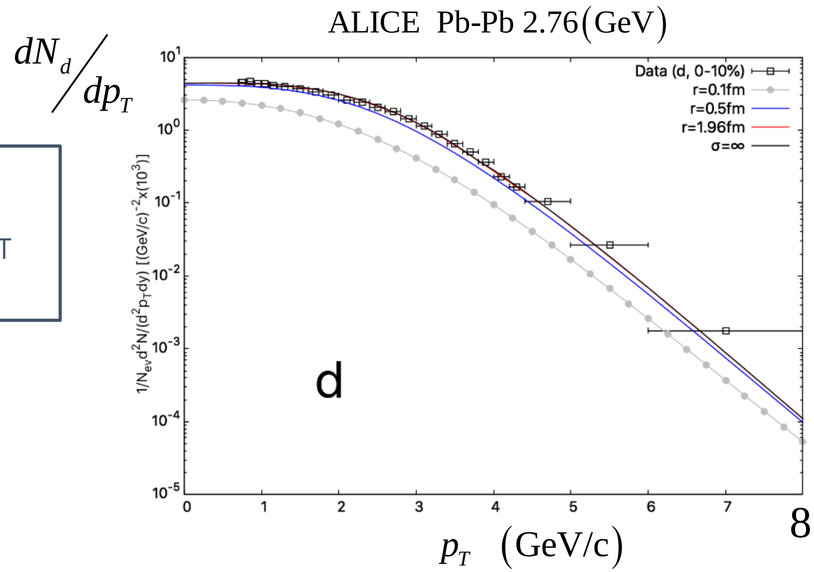
Hadronic Molecule formation via hadron coalescence + observed hadron distributions



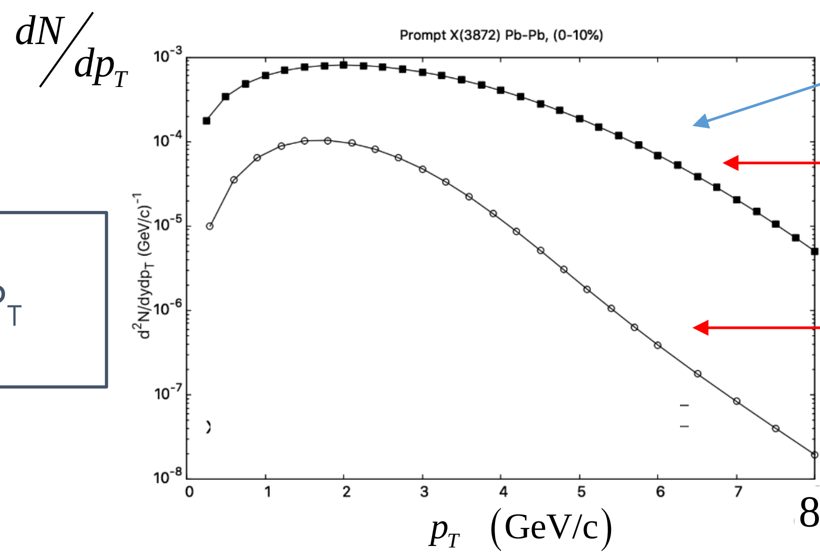
Predictions for Pt distribution: H Yoon Parallel Talk Wed 12:10 Resonances and Hypernuclei

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

Input:
Observed proton P_T distribution



Output:
Deuteron Pt distribution



X(3872)

Tcc if Molecular structure

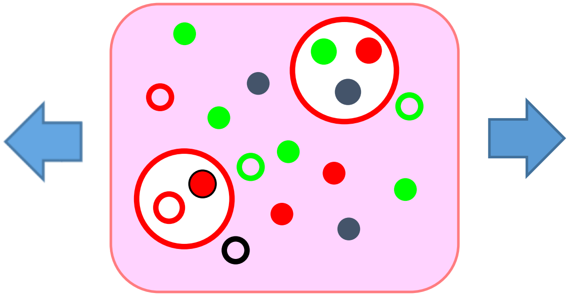
Tcc if Compact multiquark

S. Cho, Lee PRC101(2020)024902

Input:
Observed D D* P_T distribution

Summary

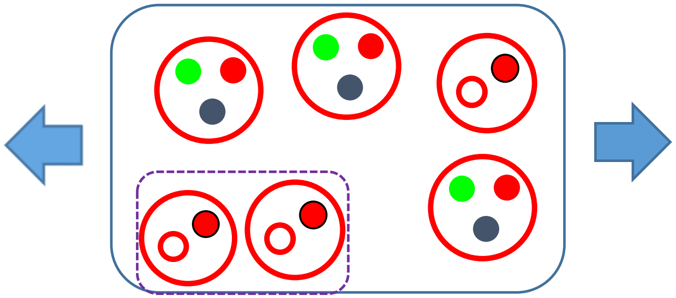
☞ Heavy collision: When strong short attraction exists (K factor) compact multiquarks are formed at hadronization point



If no short attraction but strong pion attraction exist,

molecular configurations will form

at kinetic freeze-out point



→ Will have different production rates and Pt distribution

☞ Discriminating configuration will constraint short distance physics

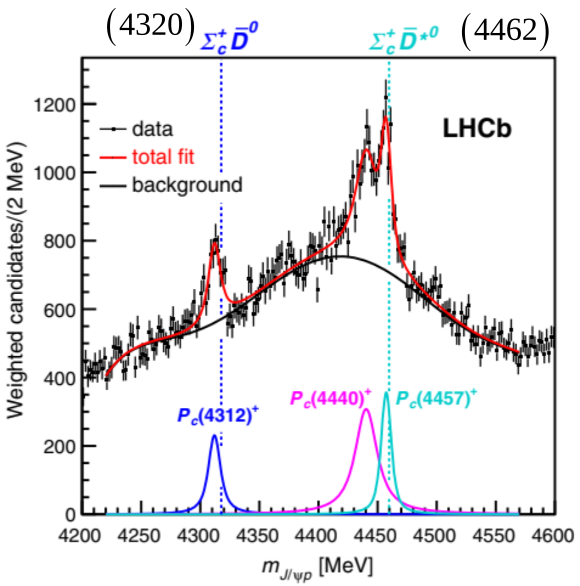
→ Important step towards understanding confinement and dense matter

Additions - 1

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	→

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



2. Pc states could also be molecular configurations.

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

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

Additions - 2

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	$\Xi_{cc}K(4)$

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

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

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

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

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

PHYSICAL REVIEW D **104,** 094024 (2021)

Case for quarkyoniclike matter from a constituent quark model

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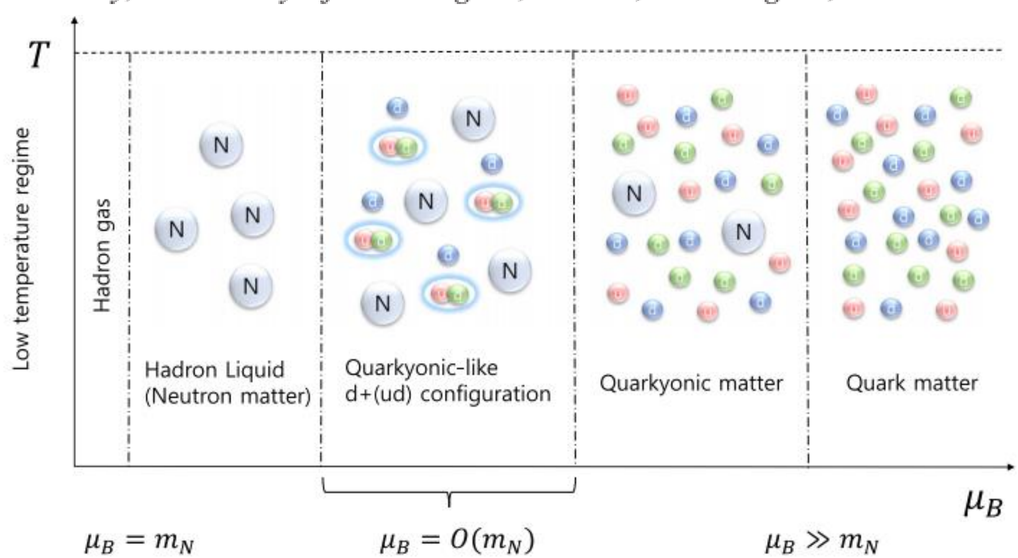


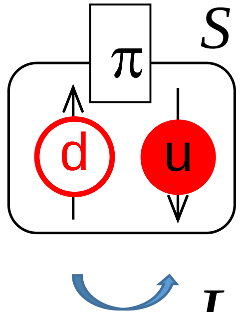
Ground state Mesons

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

$J^P = 0^-$

$m_\pi^0 = 135$ MeV

$S = 0$

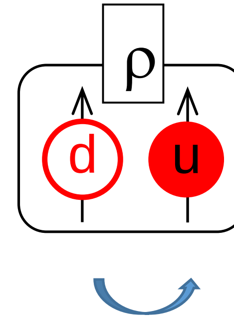


$L = 0$

$J^P = 1^-$

$m_\rho^0 = 775$ MeV

$S = 1$



$L = 0$

P-wave Mesons

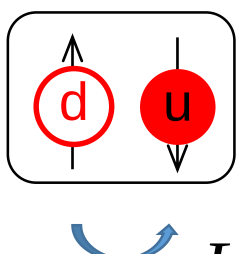
$$P = (-1)^{L+1}, \quad C = (-1)^{L+S}$$

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

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

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

$S = 0$



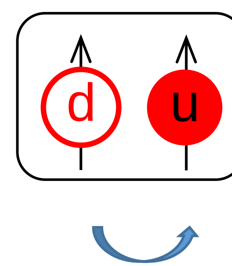
$L = 1$

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

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

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

$S = 1$



$L = 1$

P-wave Mesons

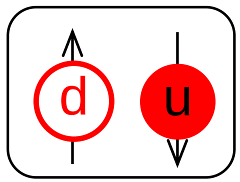
$$P = (-1)^{L+1}, \quad C = (-1)^{L+S}$$

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

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

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

$S = 0$



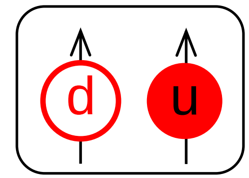
$L = 1$

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

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

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

$S = 1$



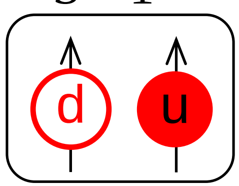
$L = 1$

which one ?

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

$m_{a_1}^{I=1} = 1260\ \text{MeV}$

$S = 1$



$L = 1$

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

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

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

Mass of 2 diquarks

$S = L = 0$