Exotic configurations and particle production in heavy ion Heavy Ion Collisions

Su Houng Lee

YONSEI UNIVERSITY

- Introduction
- Why is exotics interesting: quark model perspective
- χ_{c1}(3872) and Tcc () production in Heavy Ion Collision: molecule, compact, high PT
- Final remarks

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

+ other ExHIC collaboration

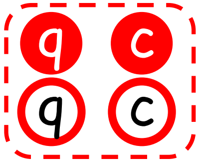
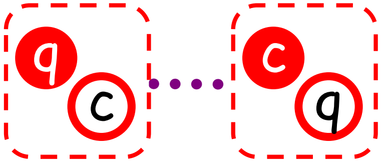
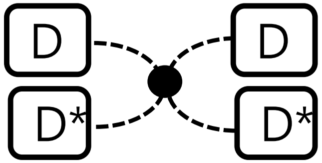
Few examples of recent findings that could be probed in HIC

Bound
Near Threshold

Above
Threshold

Tetraquark	Mass	Quark content	2-body Threshold	Observed mode	Exp
$\chi_{c1}(3872)$ $X(3872)$	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
$T^{\theta}_{\psi s1}$(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
X(6600) X(6900)		$[c\bar{c}c\bar{c}]$	6193.8 MeV	$J/\psi J/\psi$	CMS LHCb

Types of Exotic particles

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

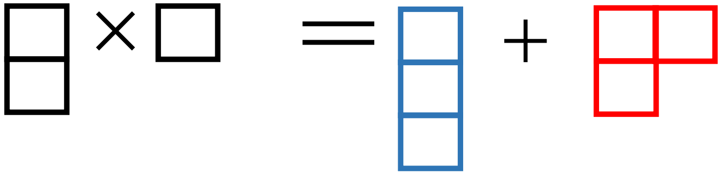
- In many cases, two pictures seem possible. Compact and Molecular
- Yet, there are common features to exotics not seen in usual hadrons

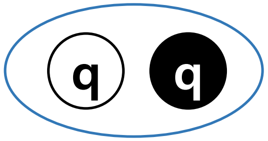
Why are compact exotics interesting

- A New color configuration

A new color configuration of SU(3)

☞ Meson only color 1

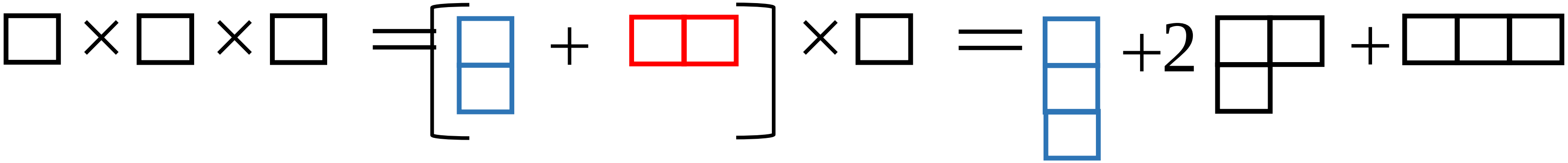




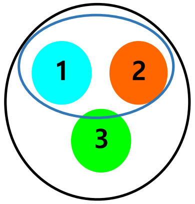
$$\left(q\bar{q}\right)_{C=1}$$

$$\bar{3}\times 3=\color{blue}{1}\color{black}{+}\color{red}{8}$$

☞ Baryon: 2-quarks are only color $\bar{3}$



$$3\times 3\times 3=\left(\color{blue}{\bar{3}}\color{black}{+}\color{red}{6}\color{black}{}\right)\times 3=\color{blue}{1}\color{black}{+2\cdot 8+10}$$



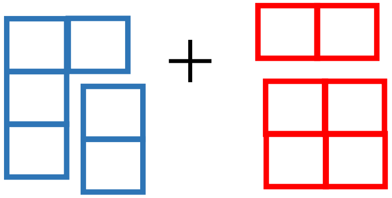
$$\left(qq\right)_{C=\bar{3}}$$

A new color configuration of SU(3)

☞ But Exotics contain additional configurations with higher degeneracy

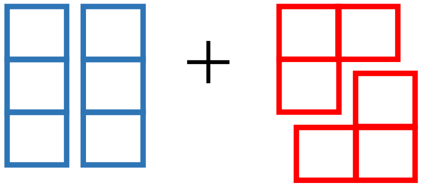
– Tetraquark basis 1: $(qq)_{C=\bar{3}} \otimes (\overline{qq})_{C=3}$ and $(qq)_{C=6} \otimes (\overline{qq})_{C=\bar{6}}$

$$3\times3\times\bar{3}\times\bar{3}=(\bar{3}+6)\times(3+\bar{6})=1\left[3\times\bar{3}+6\times\bar{6}\right]+\dots$$



– Tetraquark basis 2: $(q\bar{q})_{C=1} \otimes (q\bar{q})_{C=1}$ and $(q\bar{q})_{C=8} \otimes (q\bar{q})_{C=8}$

$$3\times\bar{3}\times3\times\bar{3}=(1+8)\times(1+8)=1\left[1\times1+8\times8\right]+\dots$$



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

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

☞ Color-spin interaction for 2 body:

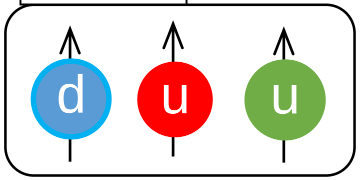
$$K=-\sum_{i<j}^{N}\left(\lambda_i^c\lambda_j^c\right)\left(\sigma_i^s\sigma_j^s\right)\longrightarrow$$

	Q–Q				*Q–$\bar{Q}$*			
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	$\boxed{-8}$	$\boxed{-4/3}$	8/3	4	$\boxed{-16}$	2	16/3	$\boxed{-2/3}$

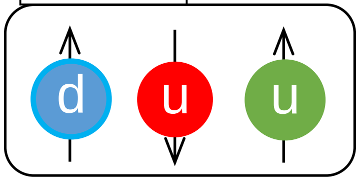
$K<0$ attraction; $K>0$ repulsion

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

Delta $S=3/2$



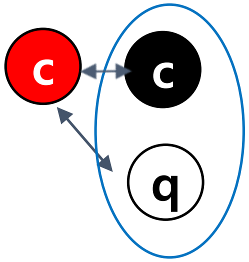
Proton $S=1/2$



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

Why Heavy quarks are needed for multiquark configuration

- ☞ Coulomb interaction becomes stronger (Karliner Rosner)



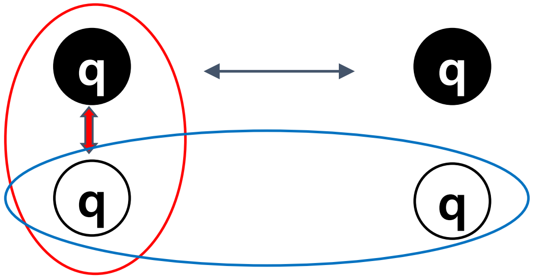
$$H_{cc} = \ldots + \lambda_i^c \lambda_j^c \left(\frac{g}{r_{ij}} \right) + \ldots. \qquad r \approx \frac{1}{mg^2}, \qquad E_C \approx -mg^4$$

- ☞ Color-spin interaction becomes weaker with heavy quarks

When all light quarks

Fall apart into two mesons

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

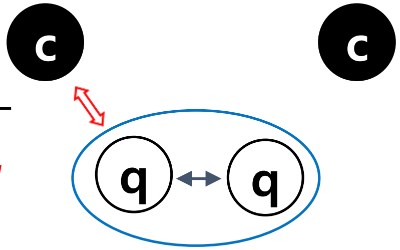


$$-8 \frac{1}{m_q m_q}$$

When heavy quarks,

could be compact (Tcc)

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

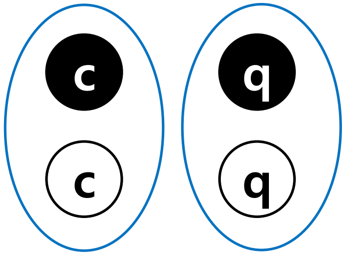


$$-8 \frac{1}{m_q m_q}$$

X(3872)

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

W.Park, SHL NPA925(2014)161



☞ Color-spin $\left(\text{C=color, S=spin}\right)$

~ +140 MeV

$$K_{X(3872)} - K_D - K_{D^*} = \begin{array}{c} \\ \end{array}\left(\begin{array}{cc} \boxed{\frac{16}{3}\frac{1}{m_c^2}+\frac{16}{3}\frac{1}{m_q^2}+\frac{32}{3}\frac{1}{m_c m_q}} & 0 \\ 0 & \boxed{-\frac{2}{3}\frac{1}{m_c^2}-\frac{2}{3}\frac{1}{m_q^2}-\frac{4}{3}\frac{1}{m_c m_q}} \end{array}\right)\begin{array}{l} \left(c\bar{c}\right)^{C=1}_{S=1}\otimes\left(q\bar{q}\right)^{C=1}_{S=1} \\ \left(c\bar{c}\right)^{C=8}_{S=1}\otimes\left(q\bar{q}\right)^{C=8}_{S=1} \end{array}$$

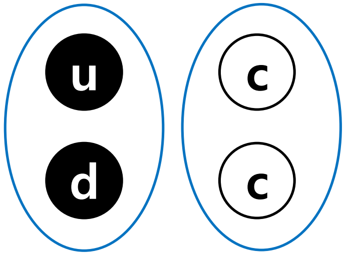
~ −20 MeV

☞ Color-color interaction of $\left(c\bar{c}\right)^{C=8}_{S=1}\otimes\left(q\bar{q}\right)^{C=8}_{S=1}$ is repulsive

Probably not compact (attraction has to be >100 MeV)

Tcc(3875) $I^G(J^P)=0^+(1^+)$

W.Park, SHL NPA925(2014)161



☞ Color-spin

$$K_{T_{cc}(3875)} - K_D - K_{D^*} = \left(\begin{array}{cc} \overset{\sim -100\text{ MeV}}{\boxed{-8\frac{1}{m_q^2}+\frac{8}{3}\frac{1}{m_c^2}+\frac{32}{3}\frac{1}{m_c m_q}}} & -8\sqrt{2}\frac{1}{m_c m_q} \\ -8\sqrt{2}\frac{1}{m_c m_q} & \underset{\sim +17\text{ MeV}}{\boxed{-\frac{4}{3}\frac{1}{m_q^2}+4\frac{1}{m_c^2}+\frac{32}{3}\frac{1}{m_c m_q}}} \end{array}\right) \begin{array}{l} (ud)^{C=\bar{3}}_{S=0}\otimes(\overline{cc})^{C=3}_{S=1} \\ (ud)^{C=6}_{S=1}\otimes(\overline{cc})^{C=\bar{6}}_{S=0} \end{array}$$

☞ Color-color interaction of $(ud)^{C=\bar{3}}_{S=0}\otimes(\overline{cc})^{C=3}_{S=1}$ is attractive

Could be compact (attraction has to be >100 MeV)

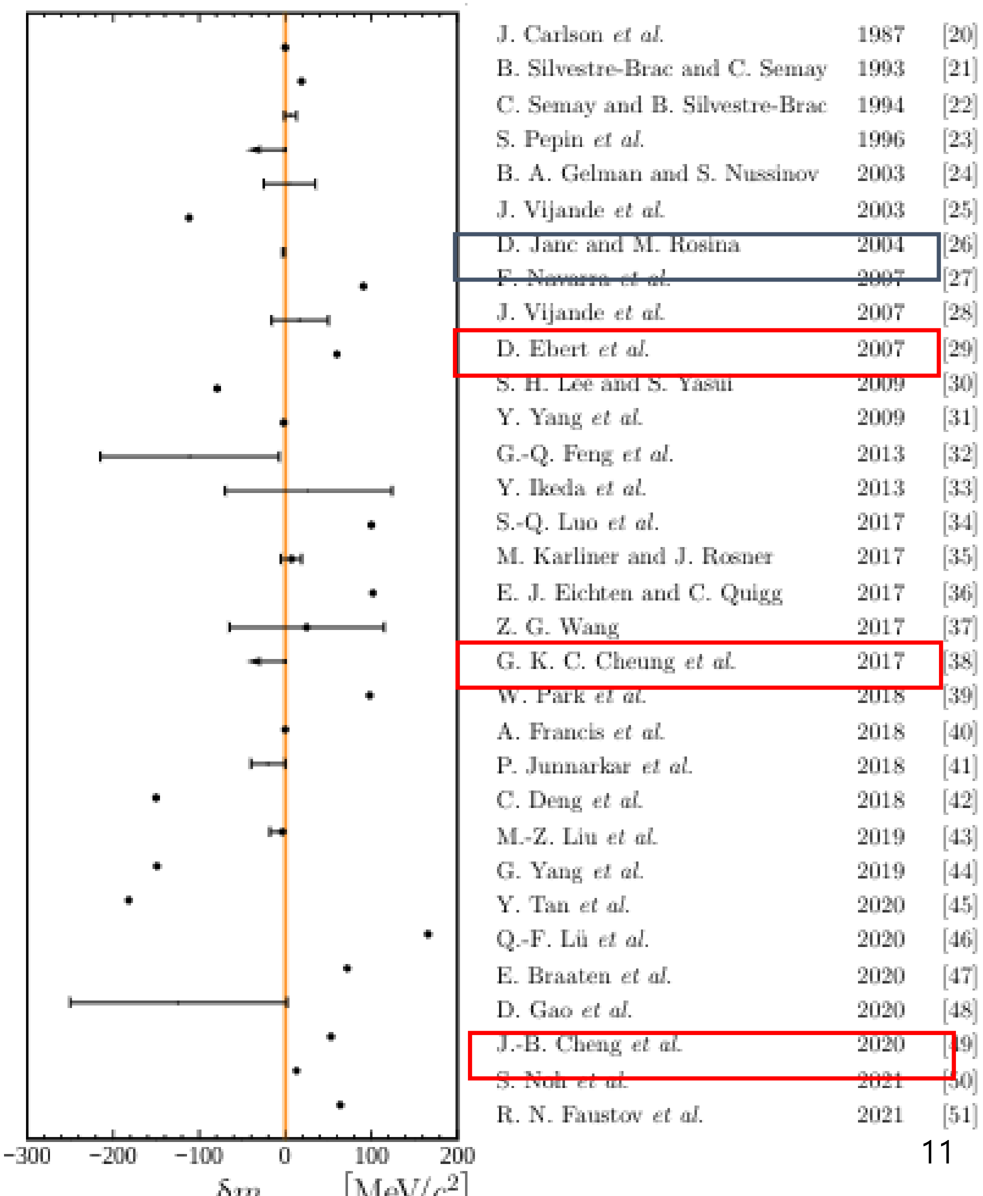
Full Quark Model calculation suggests: ex S.Noh, W.Park, Lee, PRD10(2021)114009

-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

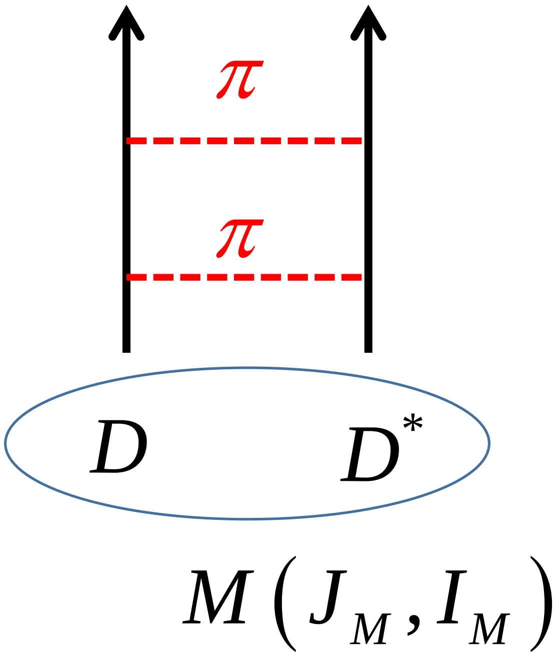
→ Can not be compact



Both X(3872) be D-$\bar{D}^*$ and Tcc be D-D^* could be Molecules

D-wave mixing through π-exchange (Tornqvist 94+ ..)

H. Yun, SHL et al. PRC107(2023)014906



Especially important when

$J_M \neq 0$ Mixing with D-wave

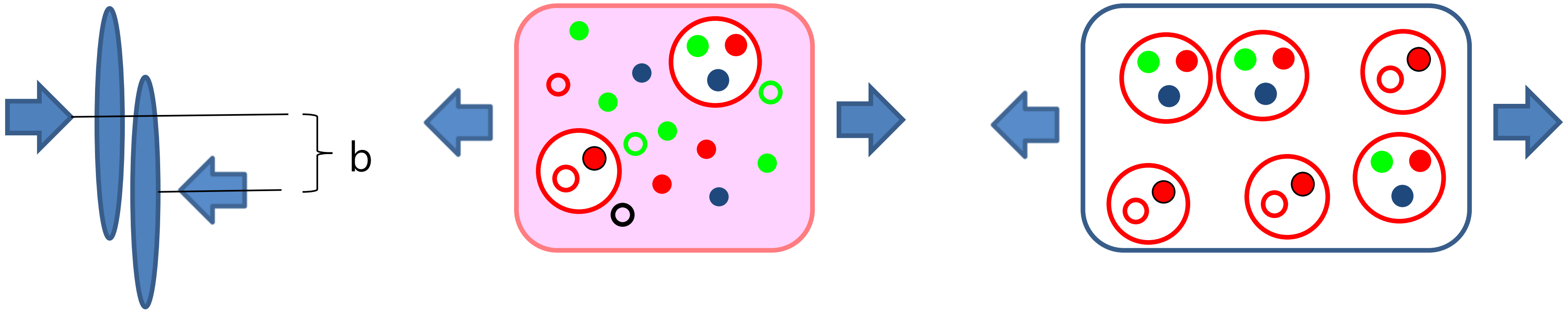
and

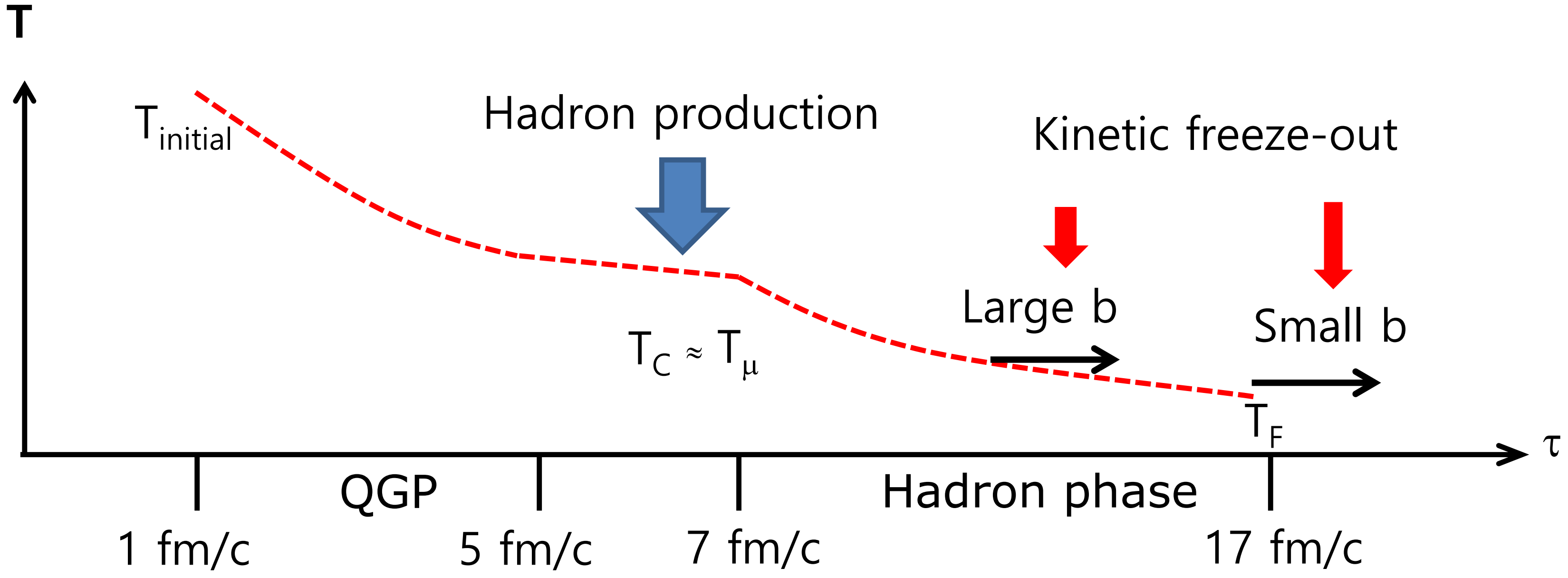
$I_M < (I_D + I_{D^*})$ Mixing is strong

II: Measuring Exotics in Heavy Ion Collision:

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

Particle production in heavy ion collision





Original prediction from ExHIC collaboration (Theory) in 2011

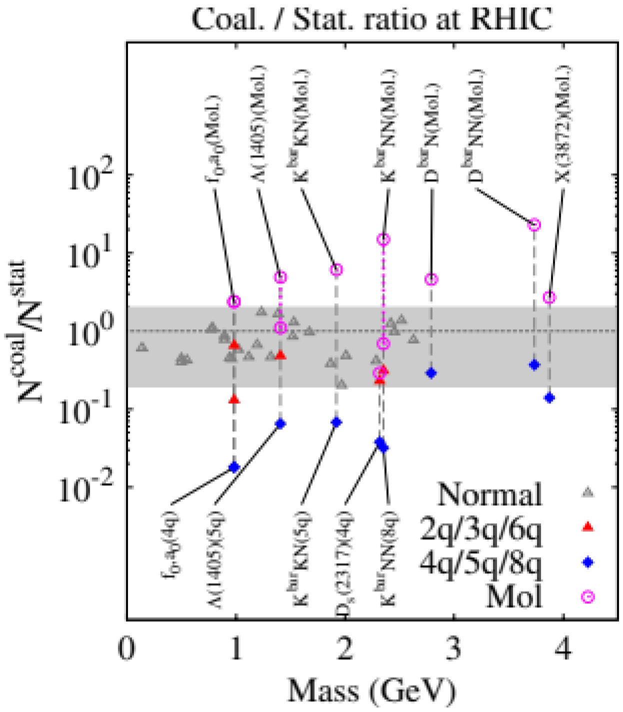
Theory prediction

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)

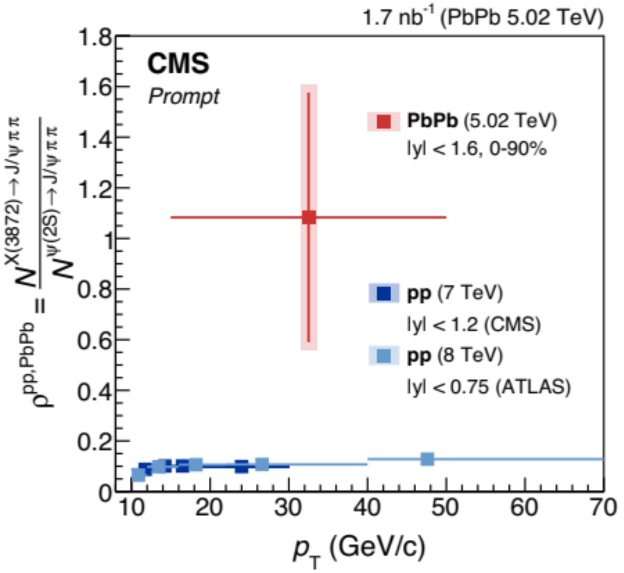


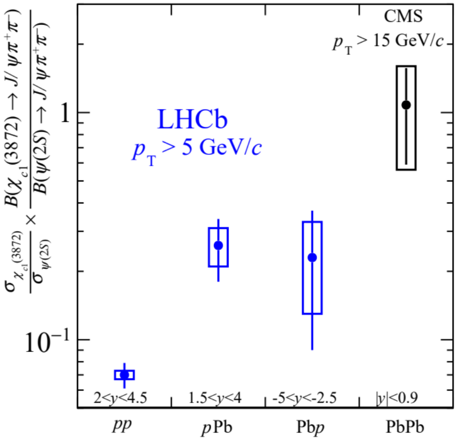
Experiment

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

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

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

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

Few points in Coalescence model - II

- Coalescence probability is suppressed for smaller object when

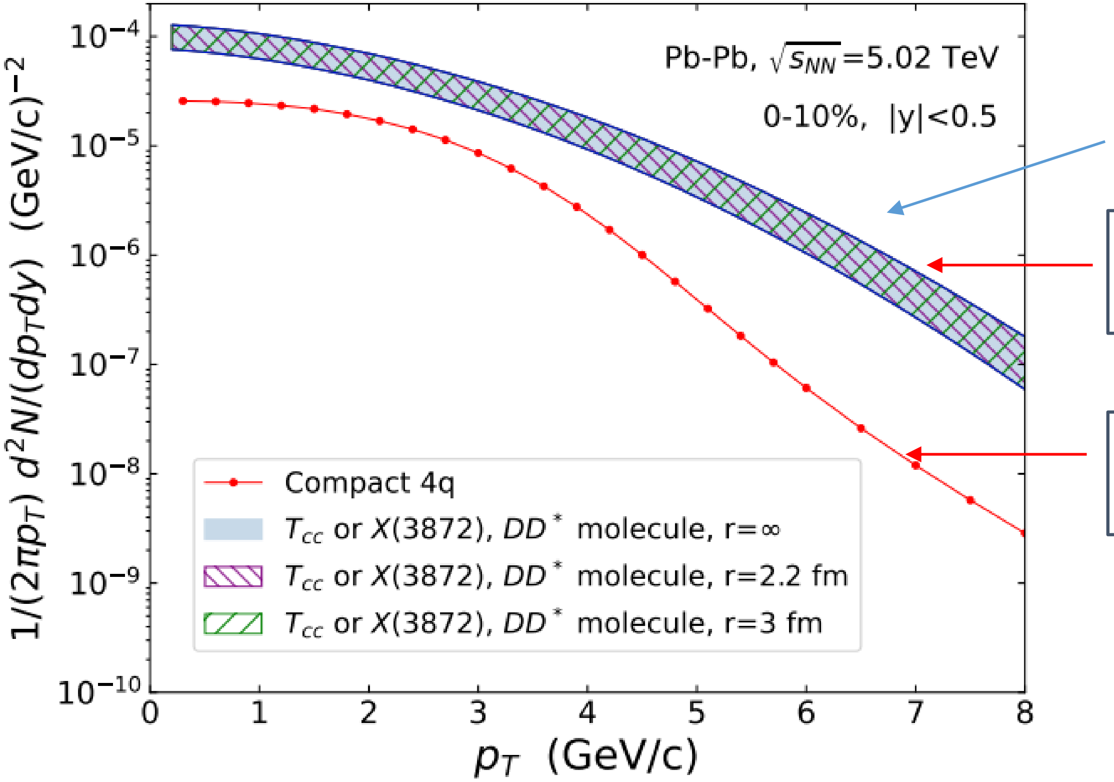
$$\frac{dN_i}{Vdp_i} \propto \exp\left[-\frac{p_i^2}{2mT}\right] \qquad W(x,p) = (2)^n \exp\left[-\frac{x^2}{\sigma^2} - \sigma^2 p^2\right]$$

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

correction becomes visible when σ<0.5 fm

Expectation for Molecular configuration of X(3872) and Tcc: Yun, Lee et al, PRC107 (2023) 014906

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



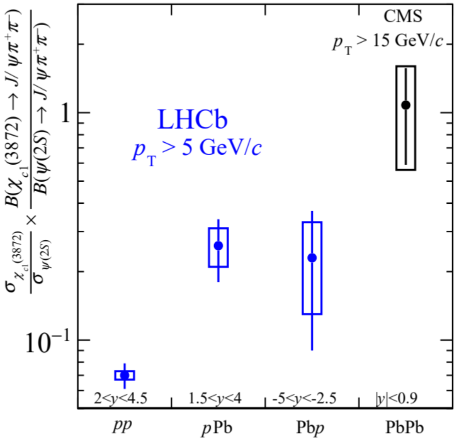
X(3872)

Tcc if Molecular structure

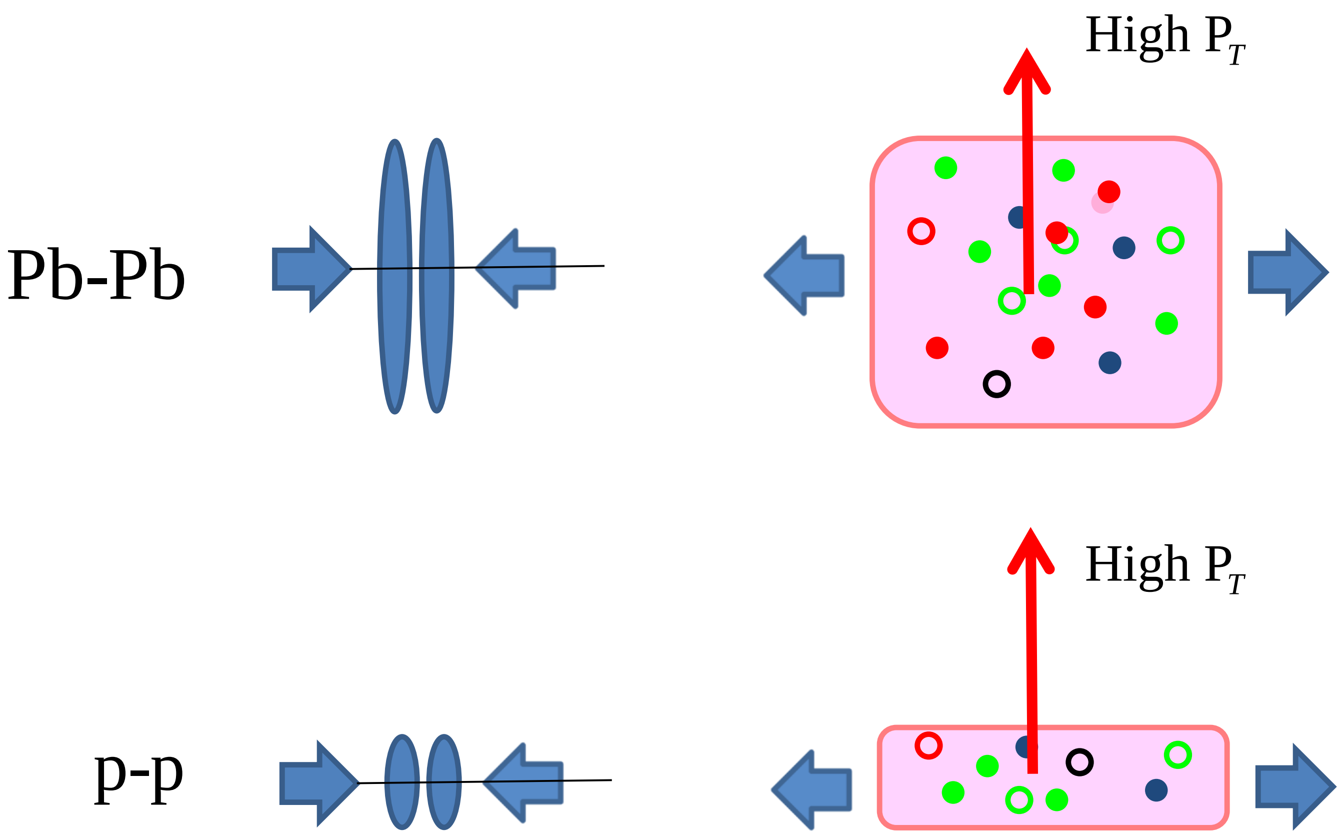
Tcc if Compact multiquark

Final Thoughts:

If X(3872) is a $\bar{\mathrm{D}}\,\mathrm{D}^*$ S-wave molecule (with S. Noh, A. Park)

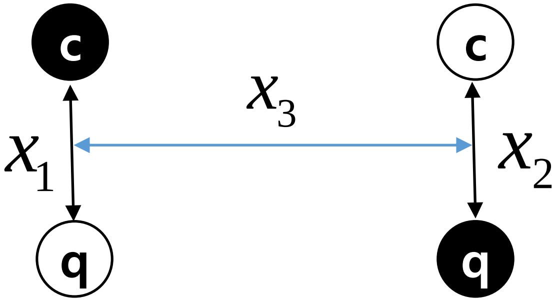


PbPb vs pp : large vs small coalescence contribution



Quark Spatial wave function of X(3872) : $D\bar{D}^*$ molecule

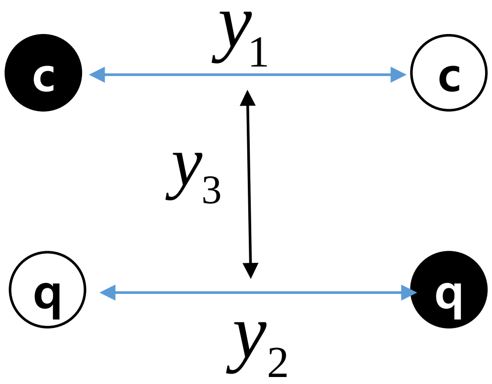
- ☞ S-wave in $D-\bar{D}^*$ basis



$$\psi_1^{Spatial} \propto \exp\left[-a_1x_1^2 - a_2x_2^2 - a_3x_3^2\right]$$

$$R_{D \text{ or } D^*} \sim 0.55 \text{ fm}, \quad R_{D-D^*} \sim 4 \text{ fm}$$

- ☞ Transformation into $J/\psi-\omega$ basis



$$\psi_1^{Spatial} \propto \exp\left[-b_1y_1^2 - b_{12}y_1\cdot y_2 - b_2y_2^2 - b_3y_3^2\right]$$

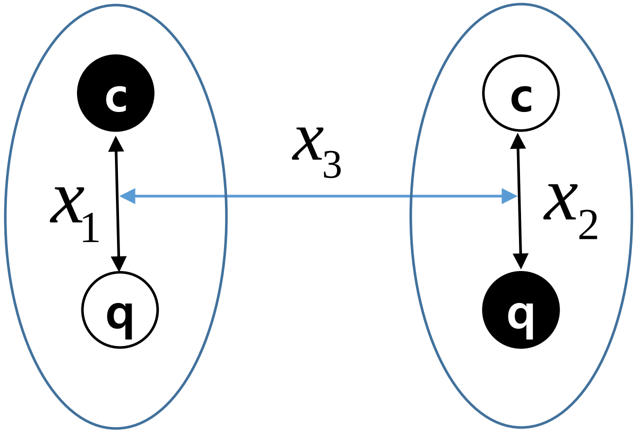
$$R_{J/\psi} \sim 4.01 \text{ fm}, \quad R_{\omega} \sim 4.06 \text{ fm}, \quad R_{J/\psi-\omega} \sim 0.394 \text{ fm}$$

Quark Color-spin wave function of X(3872): $D\bar{D}^*$ molecule

☞ In $D-\bar{D}^*$ basis

$$|1'\rangle = (q\bar{c})^{C=1}_{S=0} \otimes (c\bar{q})^{C=1}_{S=1}$$

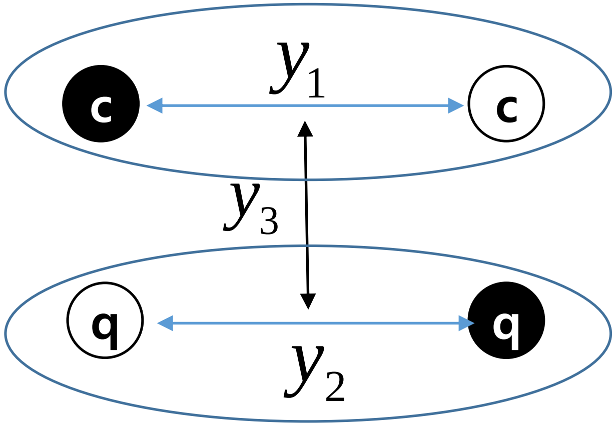
$$|2'\rangle = (q\bar{c})^{C=8}_{S=0} \otimes (c\bar{q})^{C=8}_{S=1}$$



☞ Transformation into $J/\psi-\omega$ basis

$$|1\rangle = (c\bar{c})^{C=8}_{S=1} \otimes (q\bar{q})^{C=8}_{S=1}$$

$$|2\rangle = (c\bar{c})^{C=1}_{S=1} \otimes (q\bar{q})^{C=1}_{S=1}$$



$$\Rightarrow \quad |1'\rangle = \frac{2\sqrt{2}}{3}|1\rangle + \frac{1}{3}|2\rangle$$

$$|2'\rangle = -\frac{1}{3}|1\rangle + \frac{2\sqrt{2}}{3}|2\rangle$$

$\Rightarrow$ $D\bar{D}^*$ is mostly composed of $(c\bar{c})^{C=8}_{S=1} \otimes (q\bar{q})^{C=8}_{S=1}$

Possible explanation of abundant production of X(3872)

☞ Dominant production of J/ψ at high PT is $\left(c\bar{c}\right)_{S=1}^{C=8}$ pair

☞ $D\bar{D}^*$ is mostly composed of $\left(c\bar{c}\right)_{S=1}^{C=8} \otimes \left(q\bar{q}\right)_{S=1}^{C=8}$

☞ $R_{J/\psi} \sim 4.01\ \mathrm{fm}$, $R_{\omega} \sim 4.06\ \mathrm{fm}$, $R_{J/\psi-\omega} \sim 0.394\ \mathrm{fm}$

☞ There are coalescence Production of $\left(c\bar{c}\right)_{S=1}^{C=8}$ with $\left(q\bar{q}\right)_{S=1}^{C=8}$ from QGP in PbPb collision

Summary

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

- Exotics contain unexplored color configuration

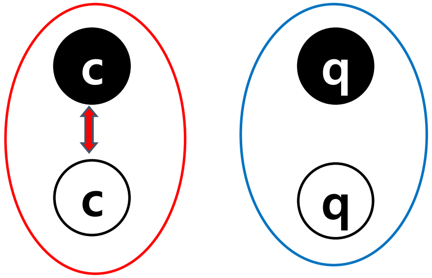
- Some color configurations are predominatly produced : A new realm of QCD

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

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

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

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



Color-Color (X(3872)

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

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

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

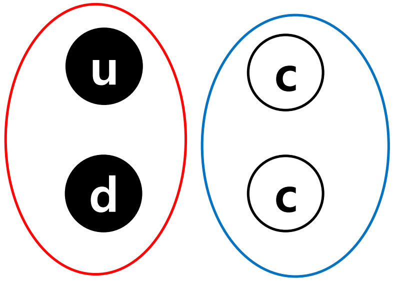
$$\lambda_c^a\left(\lambda_c^a\right) = \frac{4}{2}\left[3-2\frac{4}{3}\right] = \frac{2}{3} > 0$$

No additional attraction from color-color interaction

→ X(3872) can not be compact multiquark state

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

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



Color-Color (Tcc)

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

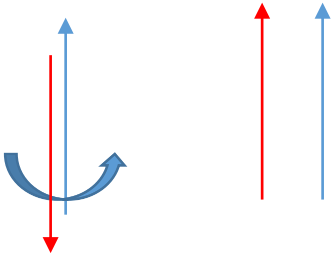
$$\frac{1}{4}\lambda^2=C=\frac{1}{3}\left(p^2+q^2+pq+3(p+q)\right)\qquad C(p=0,q=1)=\frac{4}{3},\quad C(p=1,q=0)=\frac{4}{3}$$

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

Hence there is additional attraction

→ Tcc(3875) could be a compact multiquark state

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



when two spin is pointing in the same direction

outside $H = -\mu_2 \cdot B_1 = s_2 \cdot B_1 \approx s_2 \cdot s_1 > 0$ Hence repulsive

inside $H = -\mu_2 \cdot B_1 = s_2 \cdot B_1 \approx -s_2 \cdot s_1 < 0$ Hence attractive

☞ 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	$\boxed{-8}$	$\boxed{-4/3}$	8/3	4	$\boxed{-16}$	2	16/3	$\boxed{-2/3}$

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

when two spin is pointing in opposite direction

outside $H = -\mu_2 \cdot B_1 = s_2 \cdot B_1 \approx s_2 \cdot s_1 < 0$ Hence attractive

inside $H = -\mu_2 \cdot B_1 = s_2 \cdot B_1 \approx -s_2 \cdot s_1 > 0$ Hence repulsive