

# Exotic configurations and particle production in heavy ion Heavy Ion Collisions

**Su Houg Lee**



- Introduction
- Why is exotics interesting: quark model perspective
- $\chi_{c1}(3872)$  and  $T_{cc}$  () 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

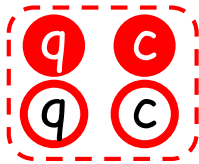
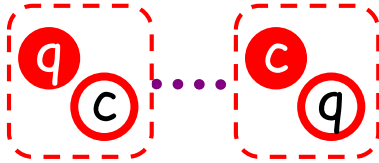
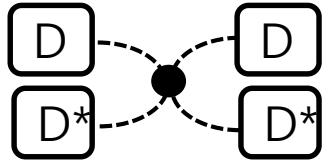
# Few examples of recent findings that could be probed in HIC

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
$T_{\psi s1}^\theta(4000)$ $Z_{cs}(3872)$	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
$T_{c\bar{s}0}^a(2900)$	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	$\langle r \rangle < 0.6 \text{ fm}$ Near threshold or other small	$\langle r \rangle > 2 \text{ fm}$ Near threshold small	$\langle r \rangle \sim 1 \text{ fm}$ Above threshold or other large
Typical mode l 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

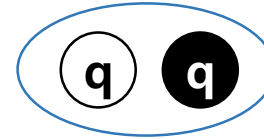
# Why are compact exotics interesting

- A New color configuration

A new color configuration of SU(3)

☞ Meson only color 1

$$\begin{array}{|c|} \hline \square \\ \hline \square \\ \hline \end{array} \times \square = \begin{array}{|c|} \hline \square \\ \hline \square \\ \hline \square \\ \hline \end{array} + \begin{array}{|c|c|} \hline \square & \square \\ \hline \square & \square \\ \hline \end{array}$$



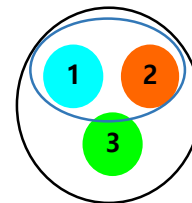
$$(q\bar{q})_{C=1}$$

$$\bar{3} \times 3 = 1 + 8$$

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

$$\square \times \square \times \square = \left[ \begin{array}{|c|} \hline \square \\ \hline \square \\ \hline \end{array} + \begin{array}{|c|c|} \hline \square & \square \\ \hline \square & \square \\ \hline \end{array} \right] \times \square = \begin{array}{|c|} \hline \square \\ \hline \square \\ \hline \square \\ \hline \end{array} + 2 \begin{array}{|c|c|} \hline \square & \square \\ \hline \square & \square \\ \hline \end{array} + \begin{array}{|c|c|c|} \hline \square & \square & \square \\ \hline \end{array}$$

$$3 \times 3 \times 3 = (\bar{3} + 6) \times 3 = 1 + 2 \cdot 8 + 10$$

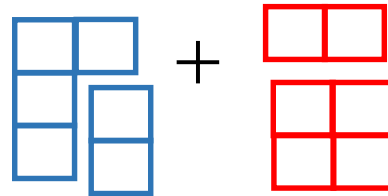


$$(qq)_{C=\bar{3}}$$

☞ But Exotics contain additional configurations with higher degeneracy

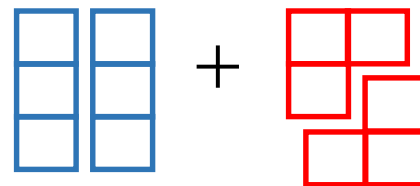
– Tetraquark basis 1:  $(qq)_{C=3} \otimes (\bar{q}\bar{q})_{C=3}$  and  $(qq)_{C=6} \otimes (\bar{q}\bar{q})_{C=\bar{6}}$

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



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

$$3 \times \bar{3} \times 3 \times \bar{3} = (1 + 8) \times (1 + 8) = 1 [1 \times 1 + 8 \times 8] + \dots$$



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

Color-spin interaction for 2 body:

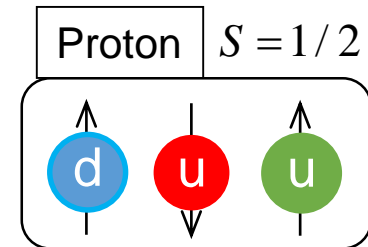
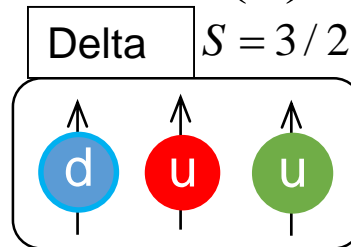
	Q-Q				Q-Q̄			
Color	A	S	A	S	1	8	1	8
Flavor	A	A	S	S				
Spin	A(0)	S(1)	S(1)	A(0)	0	0	1	1
<i>K</i>	-8	-4/3	8/3	4	-16	2	16/3	-2/3

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

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

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

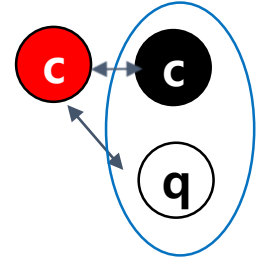
$K$  factor of 1  $\rightarrow$  18 MeV



# Why Heavy quarks are needed for multiquark configuration

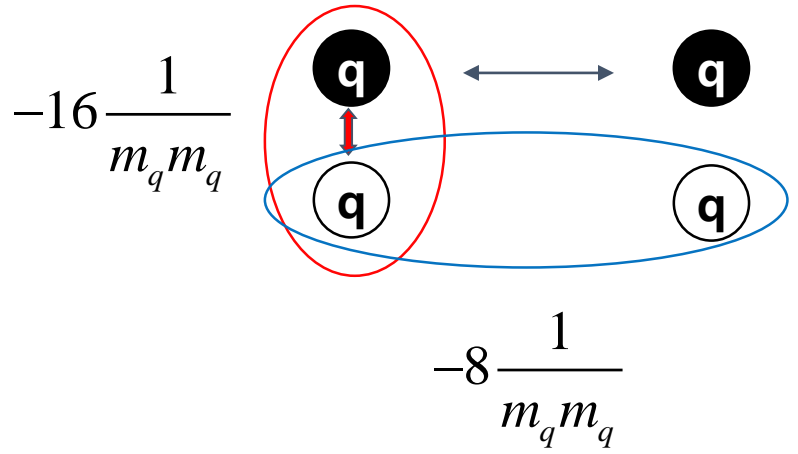
➡ Coulomb interaction becomes stronger (Karlner Rosner)

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

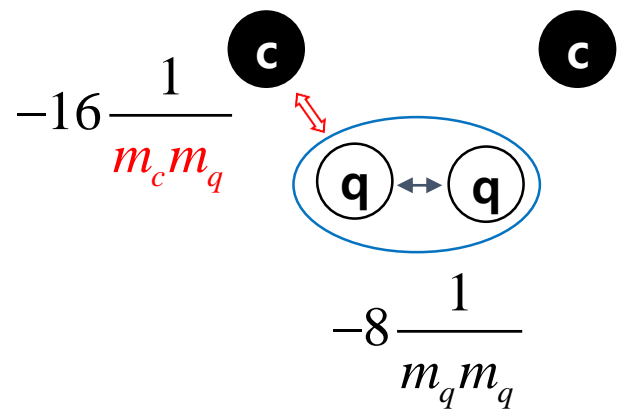


➡ Color-spin interaction becomes weaker with heavy quarks

When all light quarks  
Fall apart into two mesons



When heavy quarks,  
could be compact (Tcc)

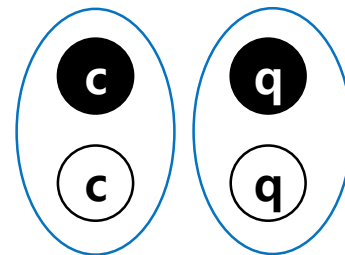




X(3872)

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

W.Park, SHL NPA925(2014)161



Color-spin (C=color, S=spin)

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

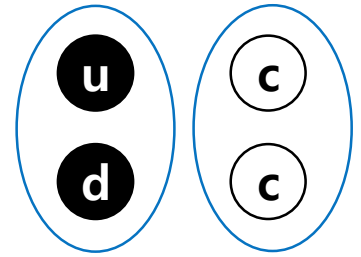
$(c\bar{c})_{S=1}^{C=1} \otimes (q\bar{q})_{S=1}^{C=1}$   
 $(c\bar{c})_{S=1}^{C=8} \otimes (q\bar{q})_{S=1}^{C=8}$

$\sim +140 \text{ MeV}$   
 $\sim -20 \text{ MeV}$

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

Probably not compact (attraction has to be  $>100 \text{ MeV}$ )

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



☞ Color-spin

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

↖  $\sim -100 \text{ MeV}$

↘  $\sim +17 \text{ MeV}$

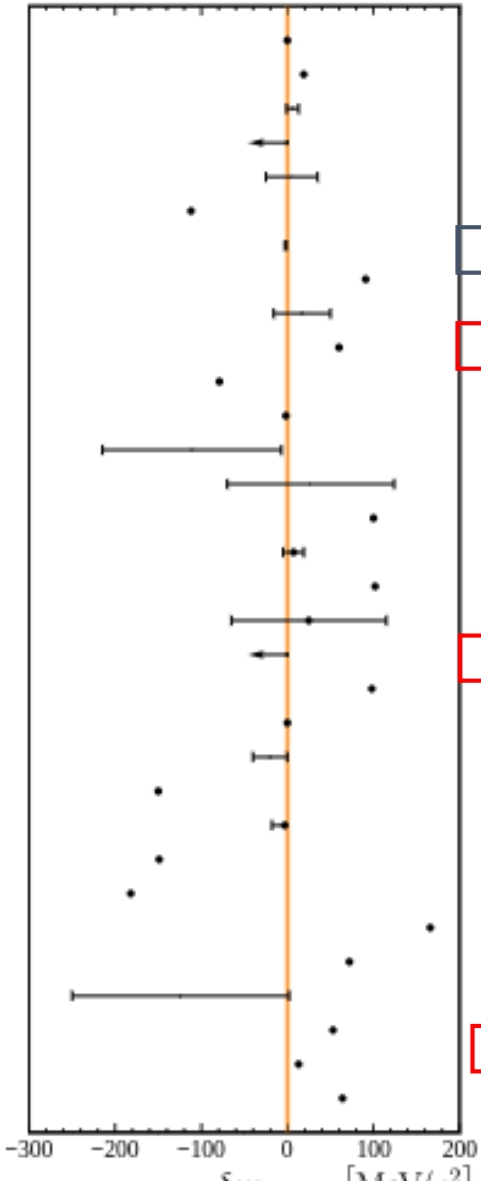
☞ Color-color interaction of  $(ud)_{S=0}^{C=\bar{3}} \otimes (\bar{c}c)_{S=1}^{C=3}$  is attractive

Could be compact (attraction has to be  $>100 \text{ MeV}$ )

-2021-  $T_{cc}(3875)$  LHCb coll.

There is a strong short range attraction for  $T_{cc} \rightarrow$  Could be compact, but depends sensitively on parameters:

The short range attraction for  $X(3872)$  is very weak  $\rightarrow$  Can not be compact

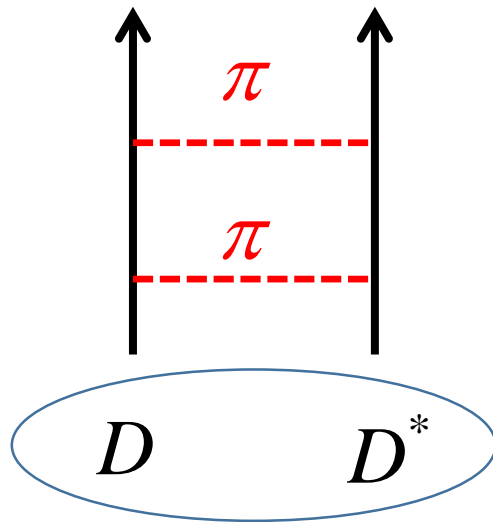


J. Carlson <i>et al.</i>	1987	[20]
B. Silvestre-Brac and C. Semay	1993	[21]
C. Semay and B. Silvestre-Brac	1994	[22]
S. Pepin <i>et al.</i>	1996	[23]
B. A. Gelman and S. Nussinov	2003	[24]
J. Vijande <i>et al.</i>	2003	[25]
D. Janc and M. Rosina	2004	[26]
F. Navarra <i>et al.</i>	2007	[27]
J. Vijande <i>et al.</i>	2007	[28]
D. Ebert <i>et al.</i>	2007	[29]
S. H. Lee and S. Yasui	2009	[30]
Y. Yang <i>et al.</i>	2009	[31]
G.-Q. Feng <i>et al.</i>	2013	[32]
Y. Ikeda <i>et al.</i>	2013	[33]
S.-Q. Luo <i>et al.</i>	2017	[34]
M. Karliner and J. Rosner	2017	[35]
E. J. Eichten and C. Quigg	2017	[36]
Z. G. Wang	2017	[37]
G. K. C. Cheung <i>et al.</i>	2017	[38]
W. Park <i>et al.</i>	2018	[39]
A. Francis <i>et al.</i>	2018	[40]
P. Junnarkar <i>et al.</i>	2018	[41]
C. Deng <i>et al.</i>	2018	[42]
M.-Z. Liu <i>et al.</i>	2019	[43]
G. Yang <i>et al.</i>	2019	[44]
Y. Tan <i>et al.</i>	2020	[45]
Q.-F. Lü <i>et al.</i>	2020	[46]
E. Braaten <i>et al.</i>	2020	[47]
D. Gao <i>et al.</i>	2020	[48]
J.-B. Cheng <i>et al.</i>	2020	[49]
S. Noh <i>et al.</i>	2021	[50]
R. N. Faustov <i>et al.</i>	2021	[51]

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

D-wave mixing through  $\pi$ -exchange (Tornqvist 94+ ..)

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



$$M(J_M, I_M)$$

Especially important when

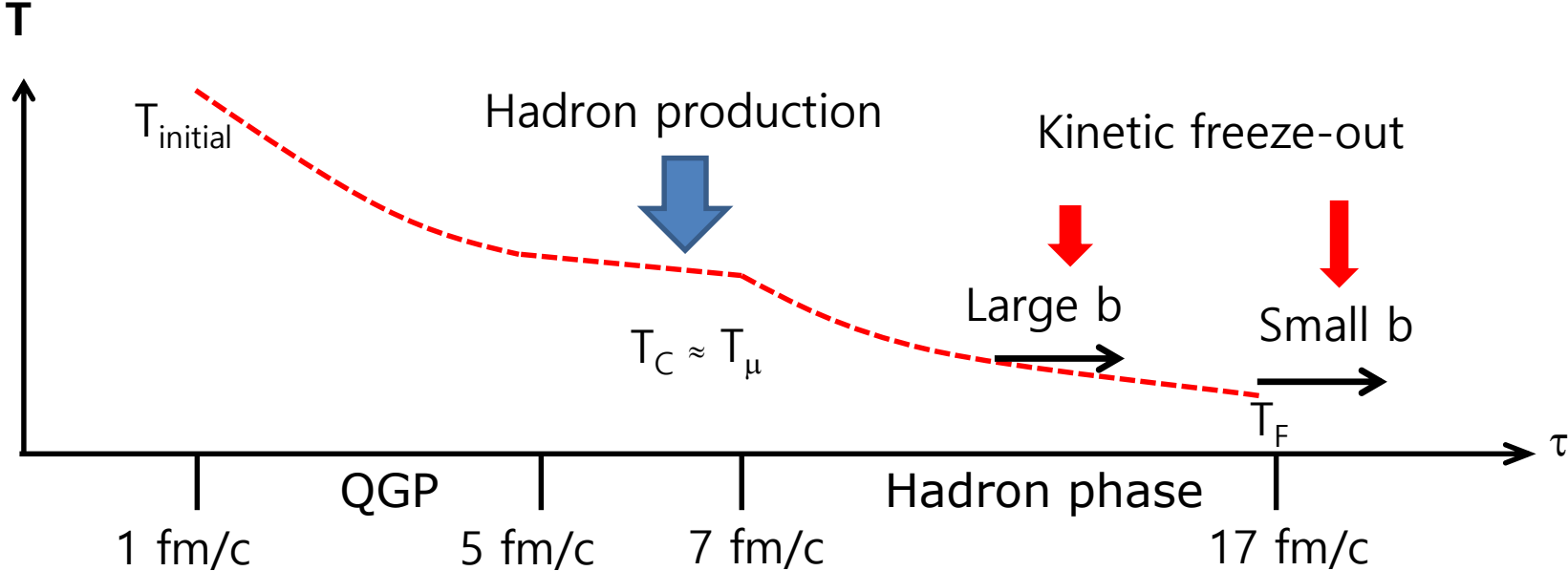
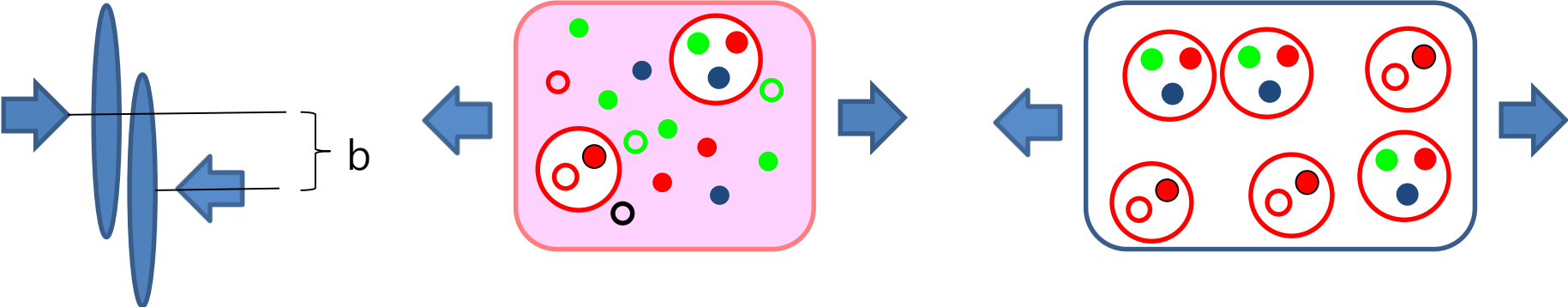
$J_M \neq 0$       Mixing with D-wave  
and

$I_M < (I_D + I_{D^*})$       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



Theory prediction

### Identifying Multiquark Hadrons from Heavy Ion Collisions

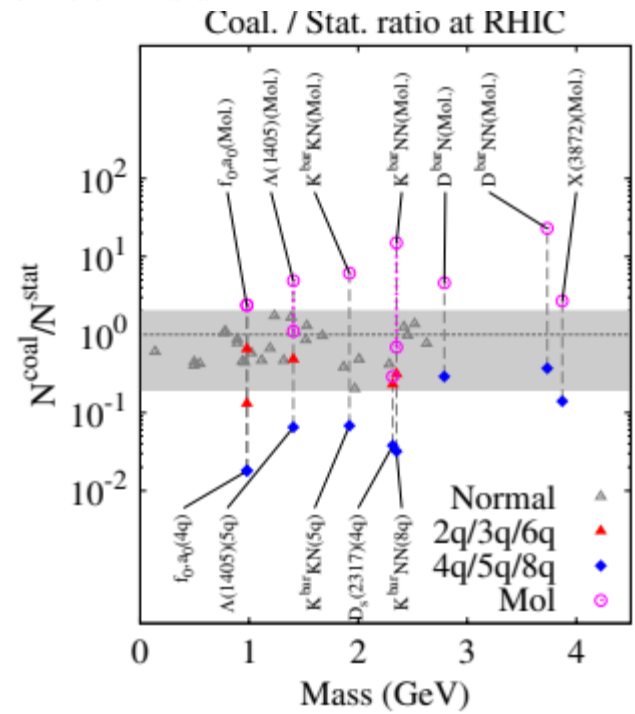
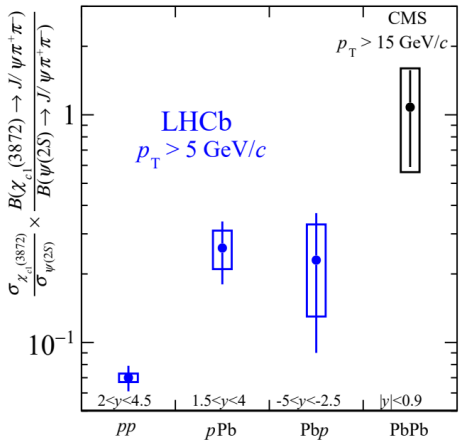
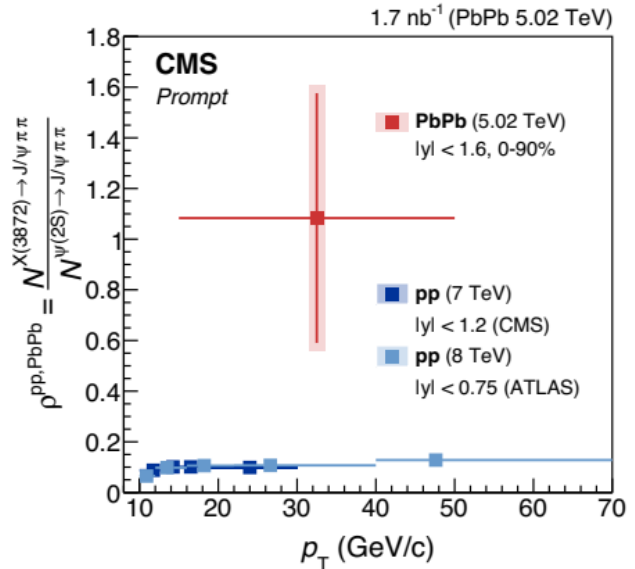
Sungtae Cho,<sup>1</sup> Takenori Furumoto,<sup>2,3</sup> Tetsuo Hyodo,<sup>4</sup> Daisuke Jido,<sup>2</sup> Che Ming Ko,<sup>5</sup> Su Houng Lee,<sup>1,2</sup>  
Marina Nielsen,<sup>6</sup> Akira Ohnishi,<sup>2</sup> Takayasu Sekihara,<sup>2,7</sup> Shigehiro Yasui,<sup>8</sup> and Koichi Yazaki<sup>2,3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

(ExHIC Collaboration)

Experiment

#### 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



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

Normalization conditions  $\int dx_i dp_i \frac{dN_i}{V dp_i} = N_i$        $\int dx dp W(x, p) = (2\pi)^n$

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

$\sigma \rightarrow$  infinity limit

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



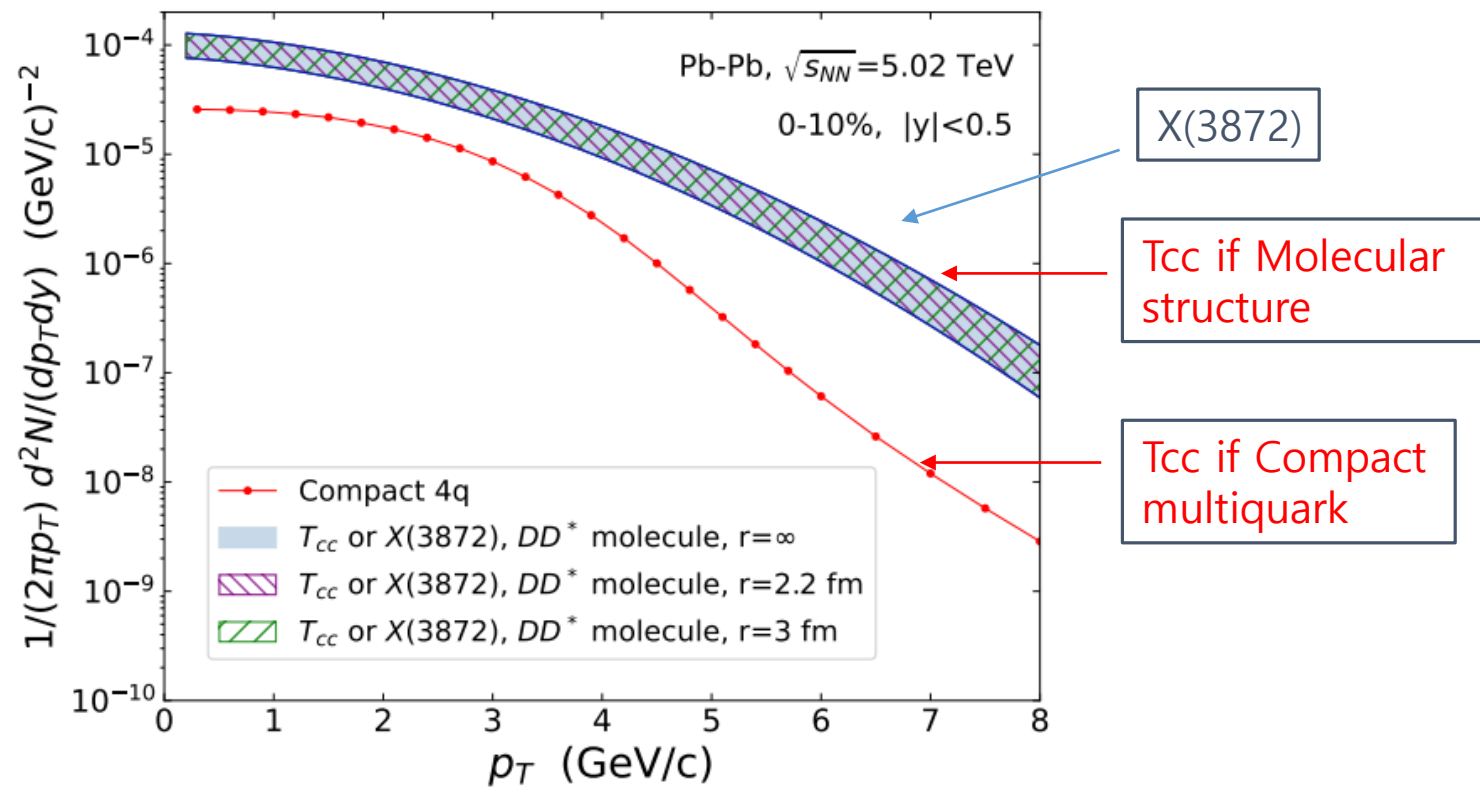
- Coalescence probability is suppressed for smaller object when

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

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

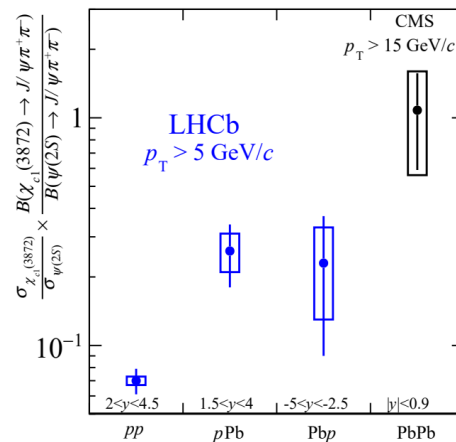
correction becomes visible when  $\sigma < 0.5$  fm

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

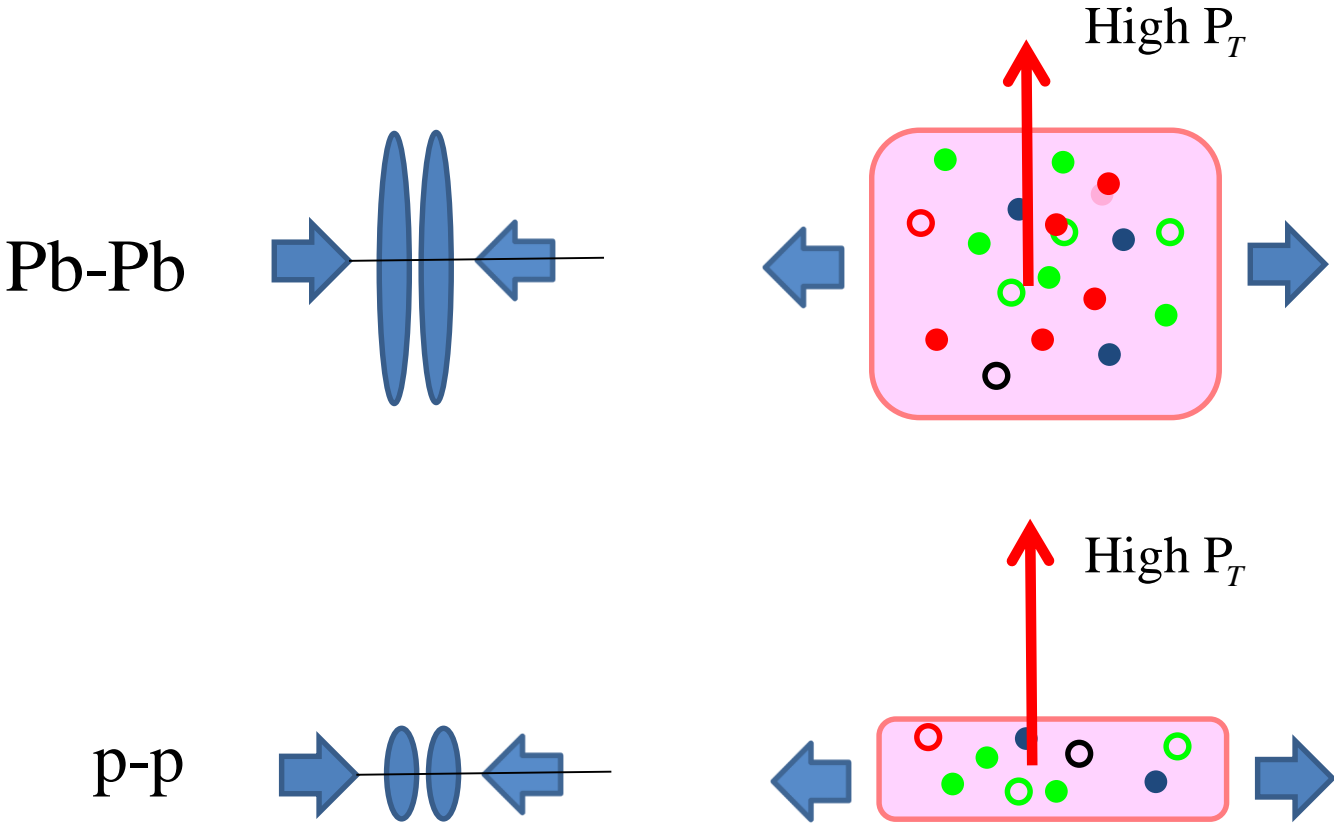


## Final Thoughts:

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



# *PbPb vs pp : large vs small coalescence contribution*

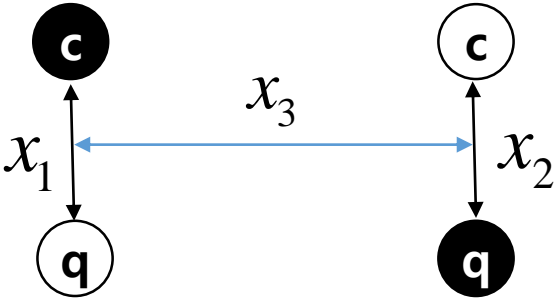


Quark Spatial wave function of  $X(3872) : D\bar{D}^*$  molecule

☞ S-wave in  $D - \bar{D}^*$  basis

$$\psi_1^{Spatial} \propto \exp[-a_1 x_1^2 - a_2 x_2^2 - a_3 x_3^2]$$

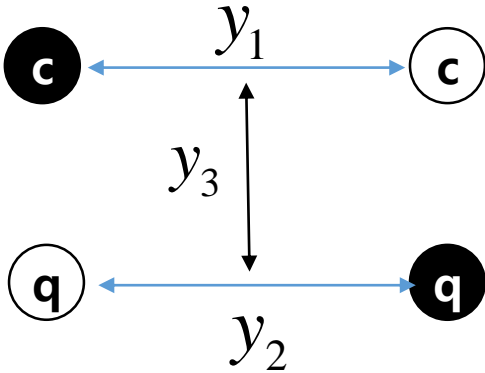
$$R_{D \text{ or } D^*} \sim 0.55 \text{ fm}, \quad R_{D-\bar{D}^*} \sim 4 \text{ fm}$$



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

$$\psi_1^{Spatial} \propto \exp[-b_1 y_1^2 - b_{12} y_1 \cdot y_2 - b_2 y_2^2 - b_3 y_3^2]$$

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

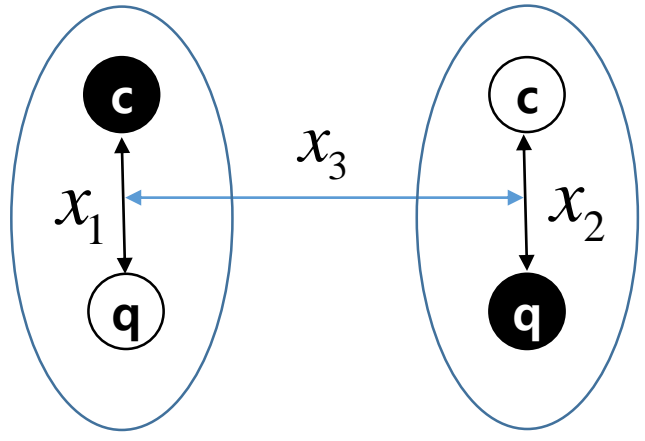


# Quark Color-spin wave function of X(3872): $D\bar{D}^*$ molecule

☞ In  $D - \bar{D}^*$  basis

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

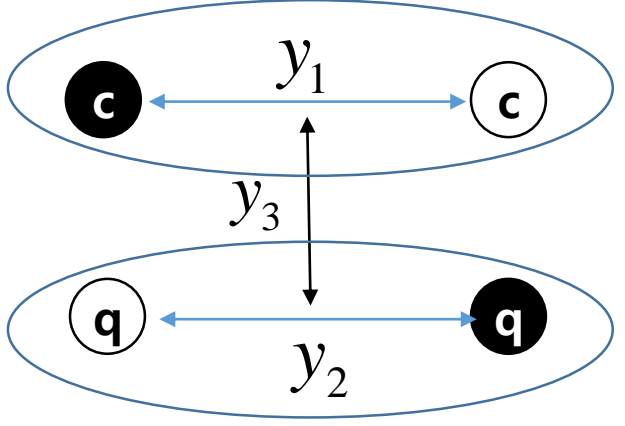
$$|2'\rangle = (q\bar{c})_{S=0}^{C=8} \otimes (c\bar{q})_{S=1}^{C=8}$$



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

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

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



➔

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

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

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

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

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

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

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

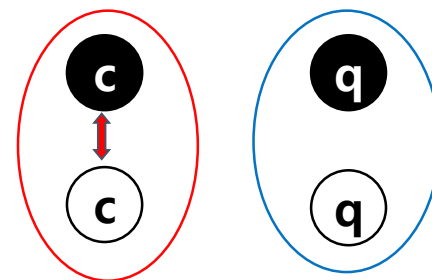
# Summary

- ⊙ Most exotics have multiple heavy quark: HIC is an excellent factory
- ⊙ Exotics contain unexplored color configuration
  
- ⊙ Some color configurations are predominately produced : A new realm of QCD
  - Measuring  $X(3872)$  and  $T_{cc}(875)$  or other exotics in heavy ion collision could discriminate the structure and exotic color configuration.



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

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



### Color-Color (X(3872))

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

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

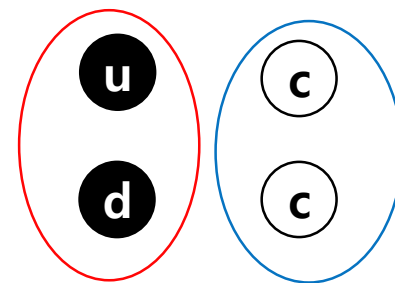
If  $cc$  is in  $(C=8, S=1)$

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

No additional attraction from color-color interaction

→ X(3872) can not be compact multiquark state

$$T_{cc}(3875) \begin{cases} (ud) \rightarrow (C = \bar{3}, S = 0) \\ (\bar{c}\bar{c}) \rightarrow (C = 3, S = 1) \end{cases} \quad H_{cc} = \lambda_c^a \left( \lambda_c^a \frac{g}{r_{cc}} \right) ?$$



### Color-Color ( $T_{cc}$ )

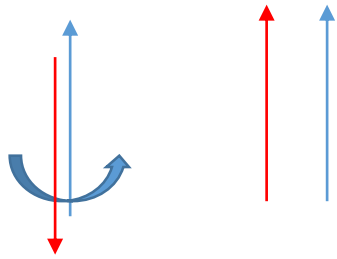
$$\lambda_c^a(\lambda_c^a) = \frac{1}{2} \left[ (\lambda_c^a + \lambda_c^a)^2 - \lambda_c^2 - (\lambda_c^a)^2 \right]$$

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

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

Hence there is additional attraction

→ Tcc(3875) could be a compact multiquark state



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:

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

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

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