Production of doubly charmed tetraquarks with exotic color configurations in electron-positron collisions

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T. Hyodo, Y.R. Liu, M. Oka, K. Sudoh, S. Yasui,
arXiv:1209.6207 [hep-ph], Phys. Lett. B, in print + in preparation.

Tetraquark T_{cc}

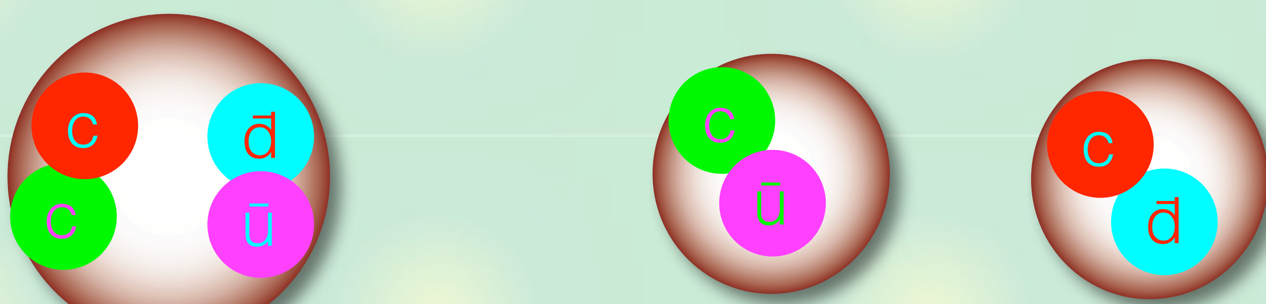
Properties of T_{cc}

- **quantum numbers (doubly charmed):** $C = \pm 2$, $I(J^P) = 0(1^+)$
- **genuine four quark state:** $T_{cc} \sim cc\bar{u}\bar{d}$ **(**$\bar{c}\bar{c}ud$**)**
- **predicted in constituent quark models**

S. Zouzou, B. Silvestre-Brac, C. Gignoux, J.M. Richard, Z. Phys. C30, 457, (1986)
H.J. Lipkin, Phys. Lett. B172, 242 (1986), ...

- **stable against strong decay if** $M(T_{cc}) < M(D)+M(D^*)$
- DD^* **molecule picture (**π **exchange)**

A.V. Manohar, M.B. Wise, Nucl. Phys. B399, 17 (1993), ...



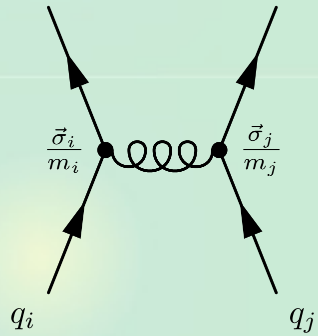
T_{cc} (1^+) D (0^-) D^* (1^-)

Classification of s-wave qq interactions

Color magnetic interaction between quarks

$$H_{\rm int} \propto \frac{1}{m_i m_j} \vec{\lambda}_i \cdot \vec{\lambda}_j \vec{\sigma}_i \cdot \vec{\sigma}_j$$

- color spin factor



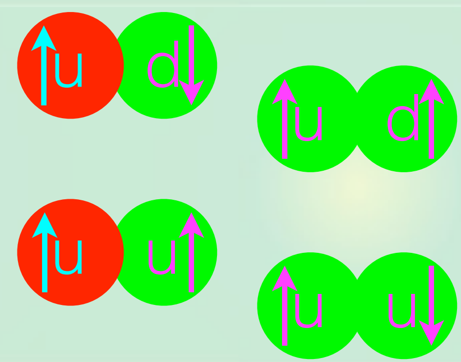
	color $\bar{3}$	**color** 6
s = 0	-6	+3
s = 1	+2	-1

Light diquarks qq

- **I=0, s=0, $\bar{3}$: -6 (good diquark)**
- **I=0, s=1, 6: -1**
- **I=1, s=1, $\bar{3}$: +2 (bad diquark)**
- **I=1, s=0, 6: +3**

attractive

repulsive

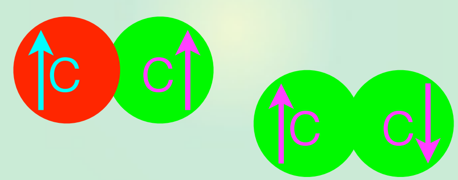


R.L. Jaffe, Phys. Rept. 409, 1 (2005)

Charm diquarks cc : flavor symmetric

- **s=1, $\bar{3}$: +2**
- **s=0, 6: +3**

repulsive

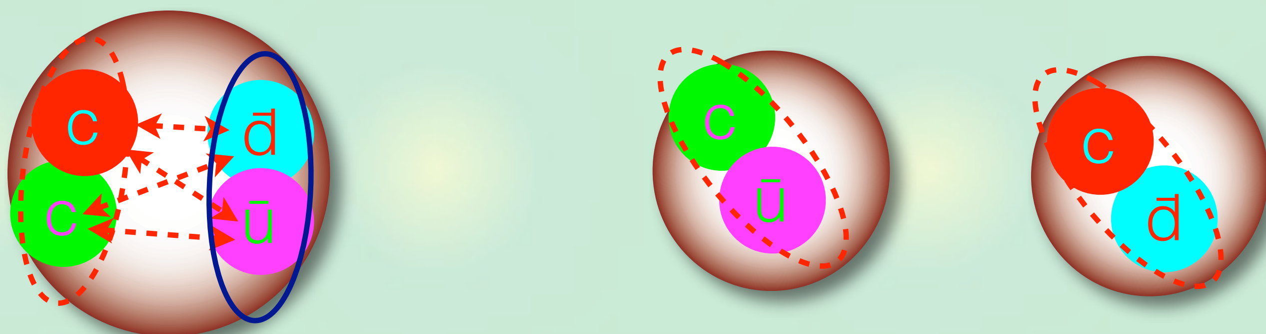


Ground state T_{cc}

Color magnetic interaction in T_{cc} and D mesons

S.H. Lee, S. Yasui, Eur. Phys. J. C64, 283 (2009)

- cc **interaction in** T_{cc}**:** $1/m_c^2$ **suppressed**
- $c\bar{q}$ **interaction in mesons:** $1/m_c$ **suppressed**
- $\bar{q}\bar{q}$ **interaction in** T_{cc}**: dominant**



T_{cc} (1^+) D (0^-) D* (1^-)

Most attractive $\bar{q}\bar{q}$ (I=0, s=0, 3) + cc (s=1, $\bar{3}$) --> T_{cc} $I(J^P) = 0(1^+)$

For $m_c \to \infty$, $M(T_{cc}) < M(D)+M(D^*)$ **: stable!**

Spectrum of T_{cc}

Baryon (cqq)	**diquark**(qq)	**Tetraquark**($\bar{c}\bar{c}$qq)
	I=1, s=0, 6: +3	$T_{cc}(0^+)$ **new**
$\Sigma_c(1/2+)$ $\Sigma_c^*(3/2+)$	I=1, s=1, $\bar{3}$: +2	$T_{cc}(0^+,1^+,2^+)$
	bad diquark	$\bar{c}$ $\bar{c}$ s=0, $\bar{6}$
c s=1/2, 3	I=0, s=1, 6: -1	$T_{cc}(1^+)$ **new**
		$\bar{c}$ $\bar{c}$ s=1, 3
$\Lambda_c(1/2+)$	**good diquark** I=0, s=0, $\bar{3}$: -6	$T_{cc}(1^+)$

Color 6 is only possible in multiquark states. Exotic!

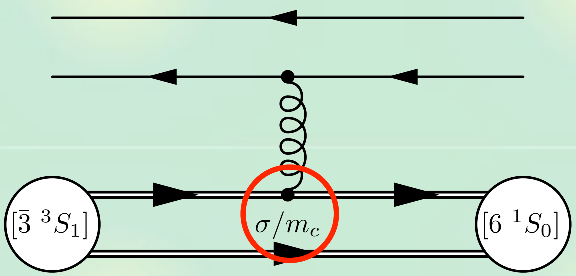
Mixing of different color configurations

Lowest energy states: $T_{cc}[\bar{3}, {}^3S_1]$ **and** $T_{cc}[6, {}^1S_0]$

color **spin**

Both have $I(J^P) = 0(1^+)$ **--> mixing ?**

- cc **spin flip amplitude ~** $1/m_c$ **suppressed**

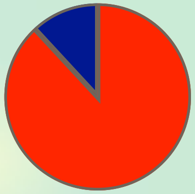


- **mixing probability ~** $1/m_c^2$

Dynamical four-quark calculation: B ~ 76 MeV below DD^*

J. Vijande, A. Valcarce, Phys. Rev. C80, 035204 (2009)

- **Fraction:** $\bar{3}$ **(0.881) v.s.** 6 **(0.119)**



$T_{cc}[\bar{3}, {}^3S_1]$ **and** $T_{cc}[6, {}^1S_0]$ **are (almost) separately realized.**

Experimental observation

How are $T_{cc}[\bar{3}, {}^3S_1]$ and $T_{cc}[6, {}^1S_0]$ produced in experiments?

- difference from color structure

- cross sections

Production of $|C|=2$ object:

- $cc\bar{c}\bar{c}$ production : $4m_c$ ~ 6 GeV

--> low energy processes (πp, γp, ...) are not feasible.

High energy experiments

- heavy ion collisions (RHIC, LHC, ...)

S. Cho, *et al*, Phys. Rev. Lett. 106, 212001 (2011); Phys. Rev. C 84, 064910 (2011)

- e^+e^- collisions (Belle)

--> double-charm production ($J/\psi+\eta_c$, ...) is observed.

K. Abe, *et al*, Belle Collaboration, Phys. Rev. Lett. 89, 142001 (2002)

Theoretical framework: NRQCD

NR(non-relativistic)QCD ~ EFT + factorization

G.T. Bodwin, E. Braaten, G.P. Lepage, Phys. Rev. D51, 1125 (1995)
A. Petrelli, *et al*, Nucl. Phys. B514, 245 (1998)

- EFT in powers of heavy quark velocity v
- Coefficients (c.f. LEC) : perturbative QCD α_s
- Matrix element of NRQCD operator : nonperturbative

$$\sigma \sim \sum_k \underbrace{f_k(\alpha_s)}_{\text{hard}} \underbrace{\left|\langle H|\mathcal{O}_k(v)|0\rangle\right|^2}_{\text{soft}}$$

- Application to charmonium decay (annihilation)
- Application to charmonium production

- Application to double-charm production ($J/\psi+\eta_c$, ...)

E. Braaten, J. Lee, Phys. Rev. D67, 054007 (2003).
K.Y. Liu, Z.G. He, K.T. Chao, Phys. Lett. B557, 45 (2003), ...

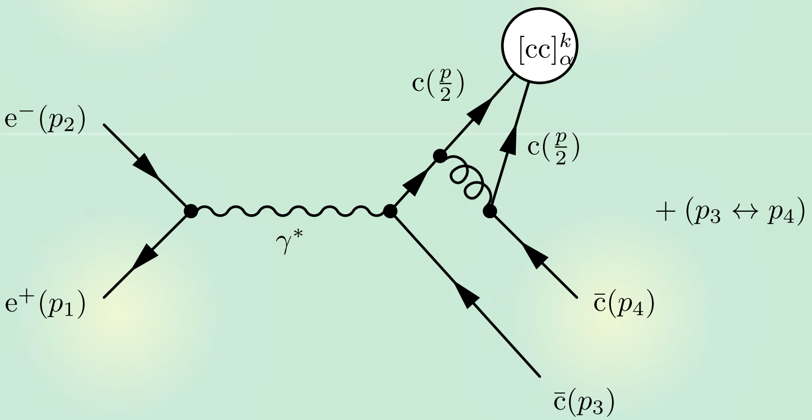
e^+e^- collisions

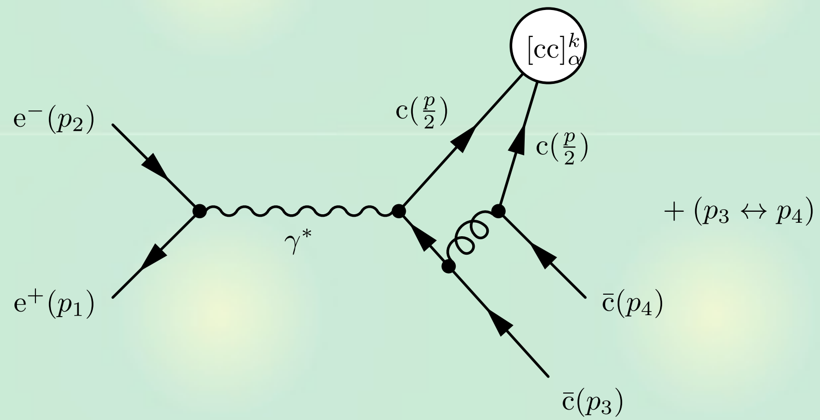
Case for T_{cc}

$$d\sigma_\alpha(e^+e^- \to T_{cc}[\alpha] + X) = \sum_k d\hat{\sigma}(e^+e^- \to \underline{[cc]^k_\alpha} + \bar{c} + \bar{c}) \left|\langle T_{cc} + X|[cc]^k_\alpha|0\rangle\right|^2$$

cc **with color-spin projection**

Hard part? leading order in α_s by pQCD calculation





Soft part? leading order both in v : a number.

$$\left|\langle T_{cc} + X|[cc]^k_\alpha|0\rangle\right|^2\Big|_{k=\mathrm{LO}} = \begin{cases} h_3 & \text{for } \alpha = [\bar{\mathbf{3}}, {}^3\mathrm{S}_1] \\ h_6 & \text{for } \alpha = [\mathbf{6}, {}^1\mathrm{S}_0] \end{cases}$$

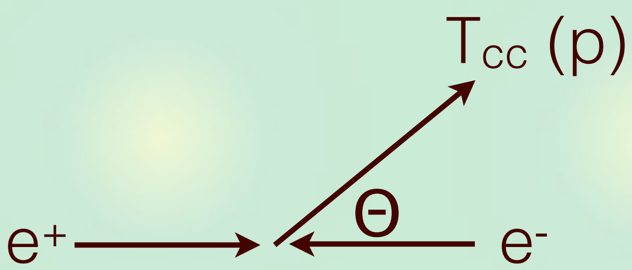
--> cancel when normalized by the total cross section $d\sigma/\sigma$

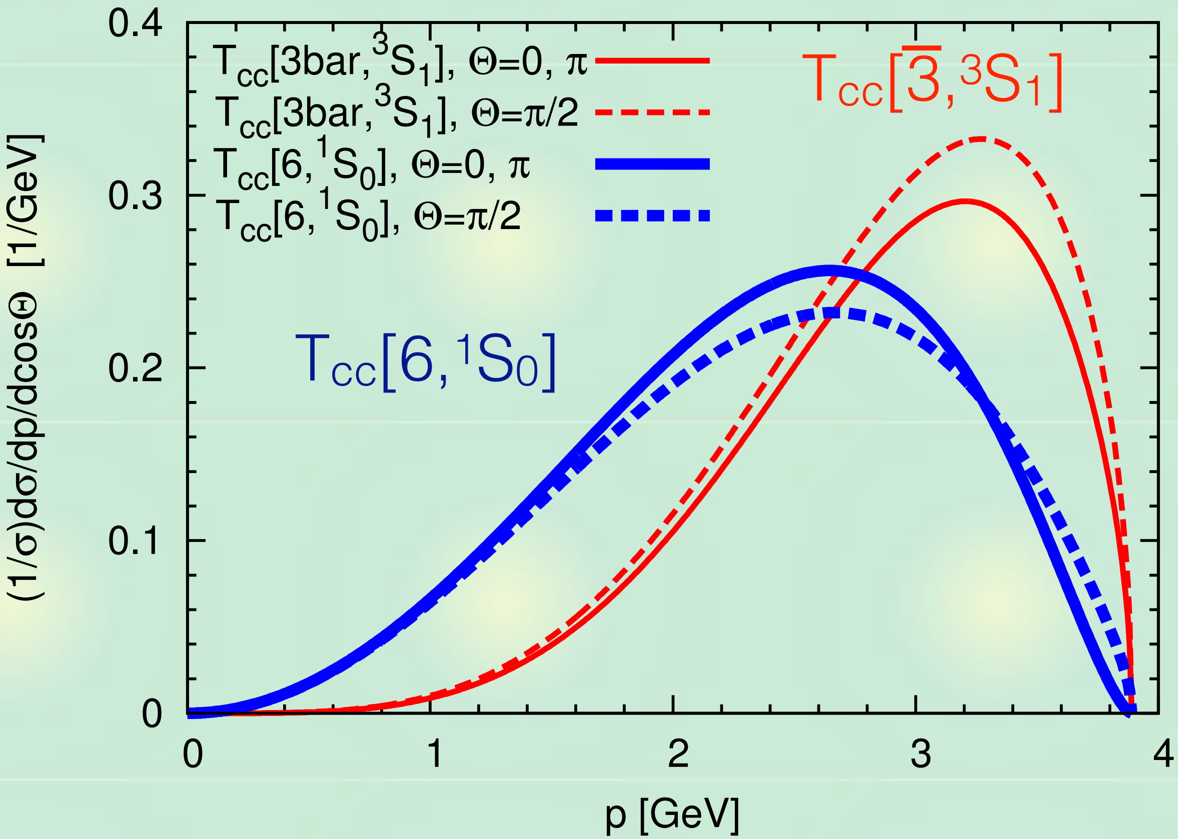
Differential cross sections

Normalized differential cross section

$$\frac{1}{\sigma}\frac{d\sigma_\alpha}{dp\, d\cos\Theta}$$

- m_c = **1.8 GeV**
- α_s = **0.212**
- $s^{1/2}$ = **10.6 GeV**





Different color configuration
--> different momentum distribution

Exotic color 6 configuration can be separated.

Total cross sections

For absolute value, we need nonperturbative matrix element.

Charmonium case: $c\bar{c}$ **wavefunction at origin**

G.T. Bodwin, E. Braaten, G.P. Lepage, Phys. Rev. D51, 1125 (1995)
A. Petrelli, *et al*, Nucl. Phys. B514, 245 (1998)

$$\left|\langle J/\psi|\bar{c}c|0\rangle\right|^2 \sim \frac{1}{4\pi}|R_{cc}(x=0)|^2$$

Previous studies for Ξ_{cc} = ccu, ccd

J.P. Ma, Z. G. Si, Phys. Lett. B568, 135 (2003)

- Casimir factor from $\bar{c}c$

Present study: adopt constituent quark model for $R_{cc}(0)$

- h_3 **~ 0.089 GeV³,** h_6 **~ 0.054 GeV³**

$$\sigma = \begin{cases} 13.8\ \mathrm{fb} & [\bar{\mathbf{3}}, {}^3\mathrm{S}_1] \\ 4.1\ \mathrm{fb} & [\mathbf{6}, {}^1\mathrm{S}_0] \end{cases}$$

with caution...

Experimental searches

Belle group analysis

T. Iijima, private communications

Exclusive search : e^+e^- --> $D^-\bar{D}^0 T_{cc}$

- **look for the missing mass of** $D^-\bar{D}^0$
- **any mass of** T_{cc} **(bound and resonance)**
- **Cross section is small (exclusive).**

Inclusive search : e^+e^- --> T_{cc} X --> $D^{*0}D^+$X

- **look for the invariant mass of** $D^{*0}D^+$
- T_{cc} **above** DD^* **threshold (only resonance)**
- **Cross section is large (inclusive).**

Summary

We study the color structures of T_{cc} and its production in e^+e^- collisions.

- **Tetraquark $T_{cc}(cc\bar{u}\bar{d})$ with $I(J^P)=0(1^+)$ can be stable against strong decay.**
- T_{cc} **with color 6 cc pair (exotic) can be separately realized from color $\bar{3}$.**
- **Momentum distribution in e^+e^- collisions: Experimental method to discriminate the color structures.**

T. Hyodo, Y.R. Liu, M. Oka, K. Sudoh, S. Yasui,
arXiv:1209.6207 [hep-ph], Phys. Lett. B in print + in preparation.