

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



Tetsuo Hyodo

Tokyo Institute of Technology

with Y.R. Liu, M. Oka, K. Sudoh, S. Yasui

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Tetraquark T_{cc}

Properties of T_{cc}

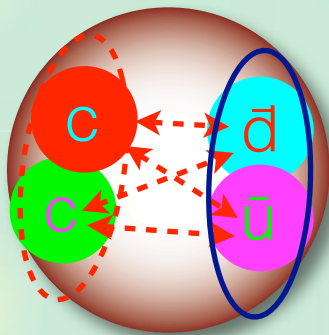
- quantum numbers (**doubly charmed**): $C = \pm 2$, $I(J^P) = 0(1^+)$
- genuine four quark state: $T_{cc} \sim cc\bar{u}\bar{d}$ ($\bar{c}\bar{c}ud$)
- attraction in $\bar{u}\bar{d}$ (**good diquark**)

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

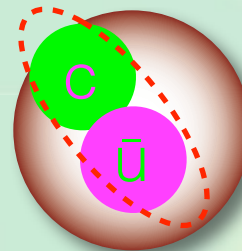
H.J. Lipkin, Phys. Lett. B172, 242 (1986), ...

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

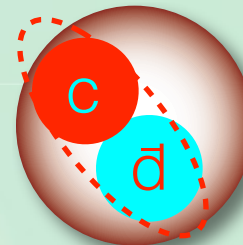
A.V. Manohar, M.B. Wise, Nucl. Phys. B399, 17 (1993), ...



$T_{cc} (1^+)$



$D (0^-)$



$D^* (1^-)$

Spectrum of T_{cc}

Baryon (cqq)

$\Sigma_c(1/2^+)$ $\Sigma_c^*(3/2^+)$



$s=1/2, 3$

$\Lambda_c(1/2^+)$

diquark(qq)

— $l=1, s=0, 6: +3$

— $l=1, s=1, \bar{3}: +2$

bad diquark



— $l=0, s=1, 6: -1$



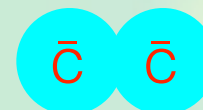
good diquark

— $l=0, s=0, \bar{3}: -6$

Tetraquark($\bar{c}\bar{c}qq$)

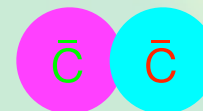
$T_{cc}(0^+)$ **new**

$T_{cc}(0^+, 1^+, 2^+)$



$s=0, \bar{6}$

$T_{cc}(1^+)$ **new**



$s=1, 3$

$T_{cc}(1^+)$

Color 6 is only possible in multiquark states. Exotic!

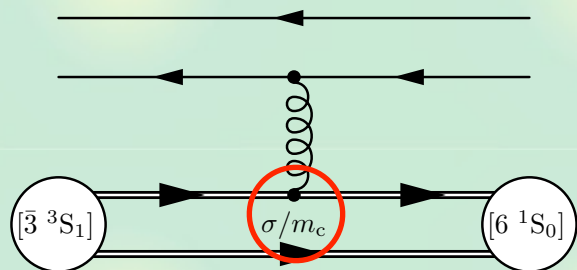
Mixing of different color configurations

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

↑ ↑
color spin

Both have $I(J^P) = 0(1^+) \rightarrow$ mixing ?

- cc spin flip amplitude $\sim 1/m_c$ **suppressed**

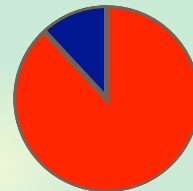


- mixing probability $\sim 1/m_c^2$

Dynamical four-quark calculation: $B \sim 76$ 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.

Theoretical framework: NRQCD

Production in experiments?

- e^+e^- collisions (Belle)
- > double-charm production ($J/\psi+\eta_c, \dots$) is **observed**.

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

NR(non-relativistic)QCD \sim 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 $v=p/m_c$
- Coefficients (c.f. LEC) : **perturbative** QCD α_s
- Matrix element of NRQCD operator : **nonperturbative**

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

- applied to double-charm productions

E. Braaten, J. Lee, Phys. Rev. D67, 054007 (2003).

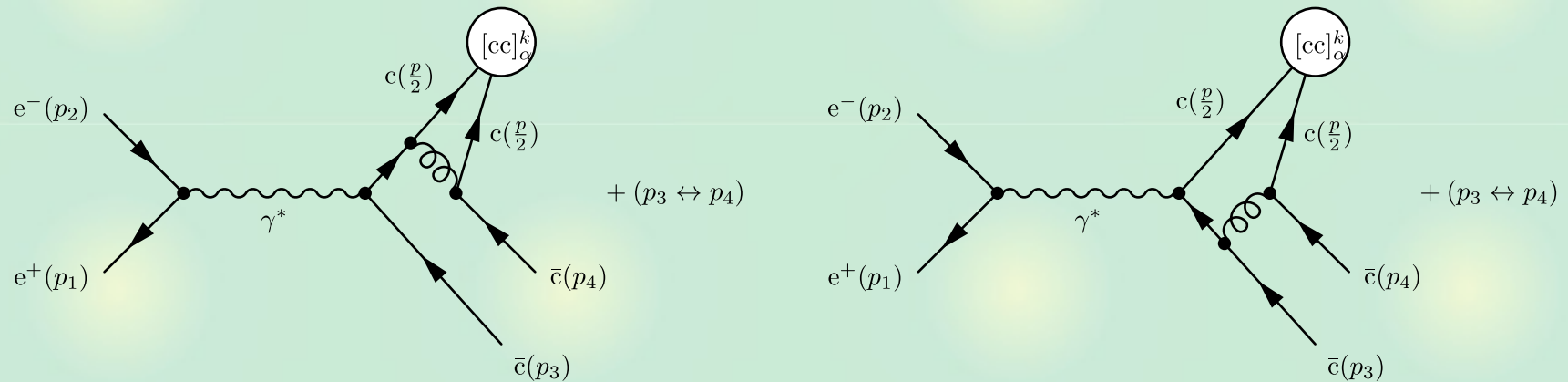
K.Y. Liu, Z.G. He, K.T. Chao, Phys. Lett. B557, 45 (2003), ...

T_{cc} production in e^+e^- collisions

Case for inclusive production of T_{cc}

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

Hard part: leading order in α_s by pQCD calculation
 CC with color-spin projection



Soft part: leading order in $v \rightarrow$ a number.

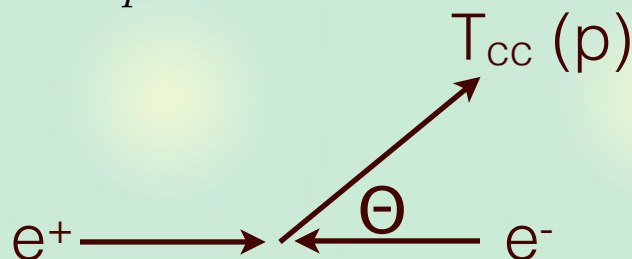
$$\left. |\langle T_{cc} + X | [cc]_\alpha^k | 0 \rangle|^2 \right|_{k=LO} = \begin{cases} h_3 & \text{for } \alpha = [\bar{\mathbf{3}}, {}^3S_1] \\ h_6 & \text{for } \alpha = [\mathbf{6}, {}^1S_0] \end{cases}$$

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

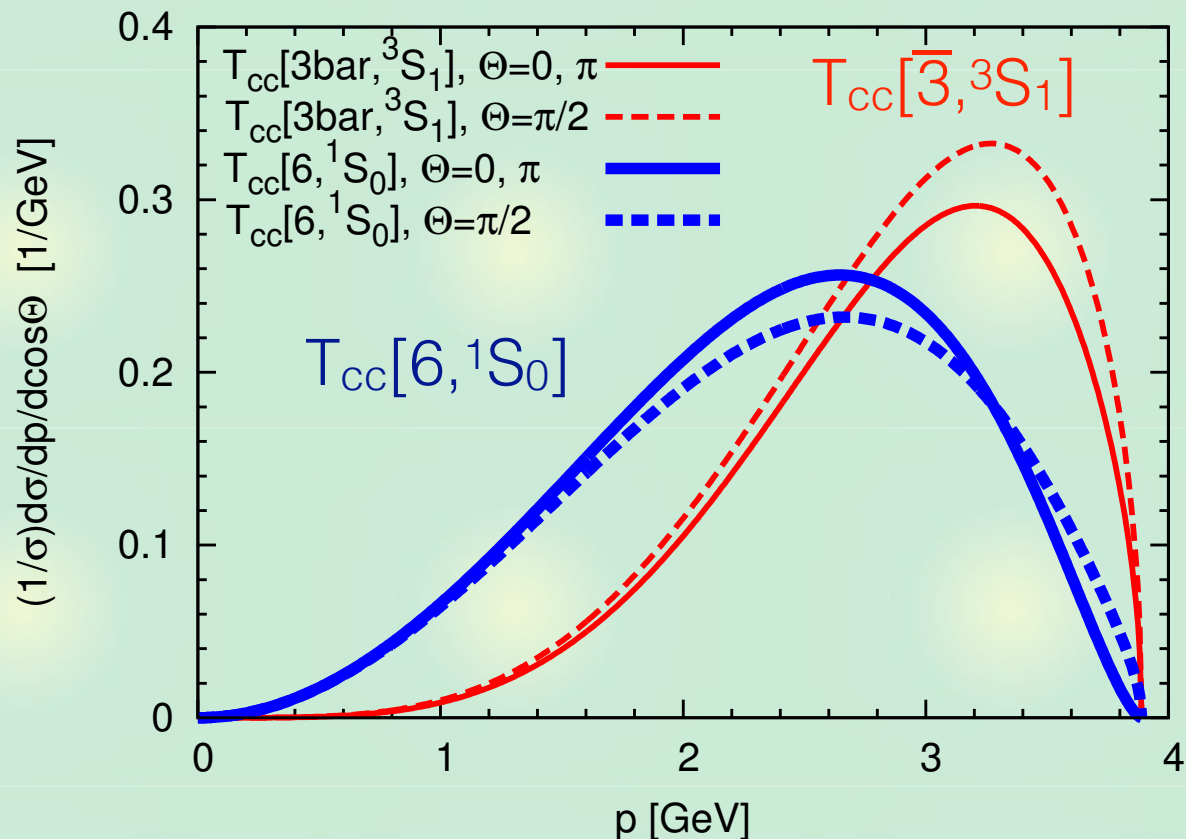
Differential cross sections

Normalized differential cross section

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



- $m_c = 1.8 \text{ GeV}$
- $\alpha_s = 0.212$
- $s^{1/2} = 10.6 \text{ GeV}$



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. D* **51**, 1125 (1995)

A. Petrelli, *et al*, *Nucl. Phys. B* **514**, 245 (1998)

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

Constituent quark model for $R_{cc}(0)$ of T_{cc}

- $h_3 \sim 0.089 \text{ GeV}^3$, $h_6 \sim 0.054 \text{ GeV}^3$




$$\sigma = \begin{cases} 13.8 \text{ fb} & [\bar{\mathbf{3}}, {}^3S_1] \\ 4.1 \text{ fb} & [\mathbf{6}, {}^1S_0] \end{cases}$$

Caution!

- Leading order both in v and α_s
- **Light quark dynamics** (fragmentation) is not considered.
- > production of $T_{cc} =$ production of $\bar{\Xi}_{cc}$

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