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

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Tetraquark T_{cc}

Properties of T_{cc}

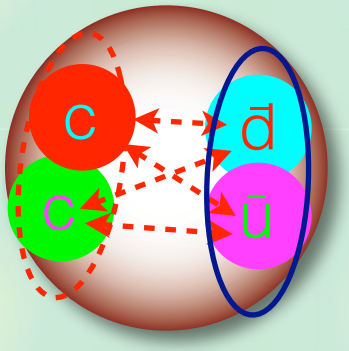
- **quantum numbers (doubly charmed):** $C = \pm 2$, $I(J^P) = 0(1^+)$
- **genuine four quark state:** $T_{cc} \sim cc\bar{u}\bar{d}$ **(**$\bar{c}\bar{c}ud$**)**
- **color magnetic interaction:**

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

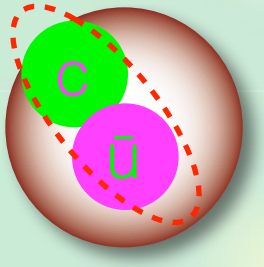
--> attraction in $\bar{u}\bar{d}$ **(good diquark)**

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

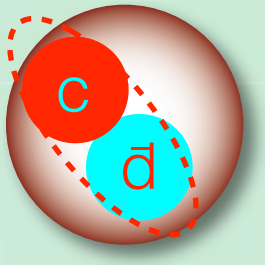
- **stable against strong decay if** $M(T_{cc}) < M(D)+M(D^*)$



T_{cc} (1^+)



D (0^-)



D* (1^-)

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	$\bar{c}$ $\bar{c}$
	q q	s=0, $\bar{6}$
c	—— I=0, s=1, 6: -1	$\overline{T_{cc}(1^+)}$ new
s=1/2, 3		$\bar{c}$ $\bar{c}$
	q q	s=1, 3
	good diquark	
$\Lambda_c(1/2+)$	—— I=0, s=0, $\bar{3}$: -6	$T_{cc}(1^+)$

Color 6 is only possible in multiquark states. Exotic!

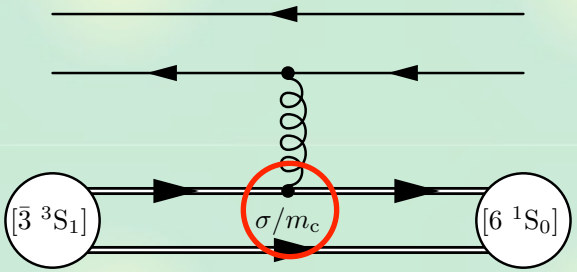
Mixing of different color configurations

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 ?**

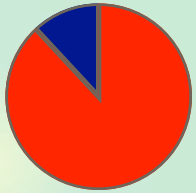
- cc **spin flip amplitude ~** $1/m_c$ **suppressed**



- **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.**

Theoretical framework: NRQCD

Producion in experiments?

- 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)

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

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

- 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), ...

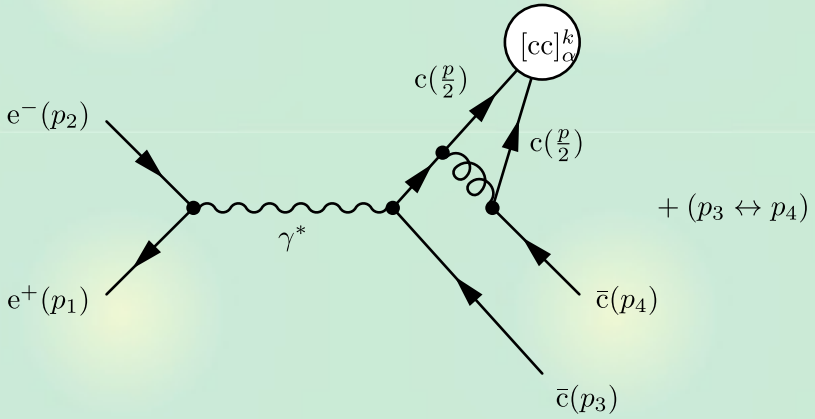
T_{cc} production in e^+e^- collisions

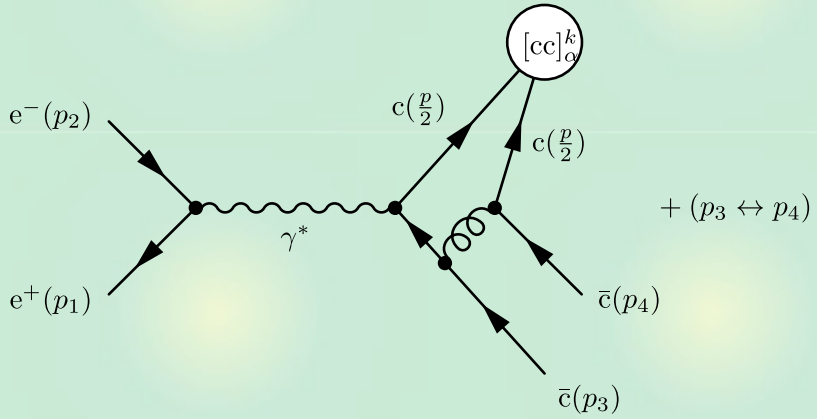
Case for inclusive production of T_{cc}

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

Hard part: leading order in α_s by pQCD calculation

cc with color-spin projection





Soft part: leading order in v --> a number.

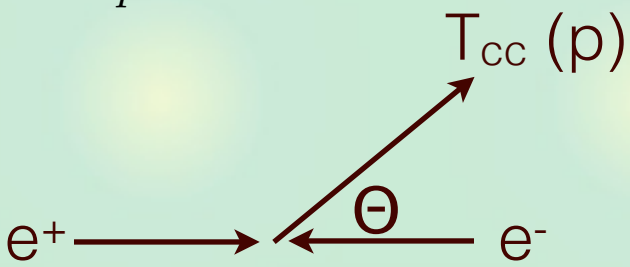
$$\left| \langle T_{cc} + X | [cc]^k_\alpha | 0 \rangle \right|^2 \Big|_{k=\mathrm{LO}} = \begin{cases} h_3 & \text{for } \alpha = [\bar{\mathbf{3}}, {}^3S_1] \\ h_6 & \text{for } \alpha = [\mathbf{6}, {}^1S_0] \end{cases}$$

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

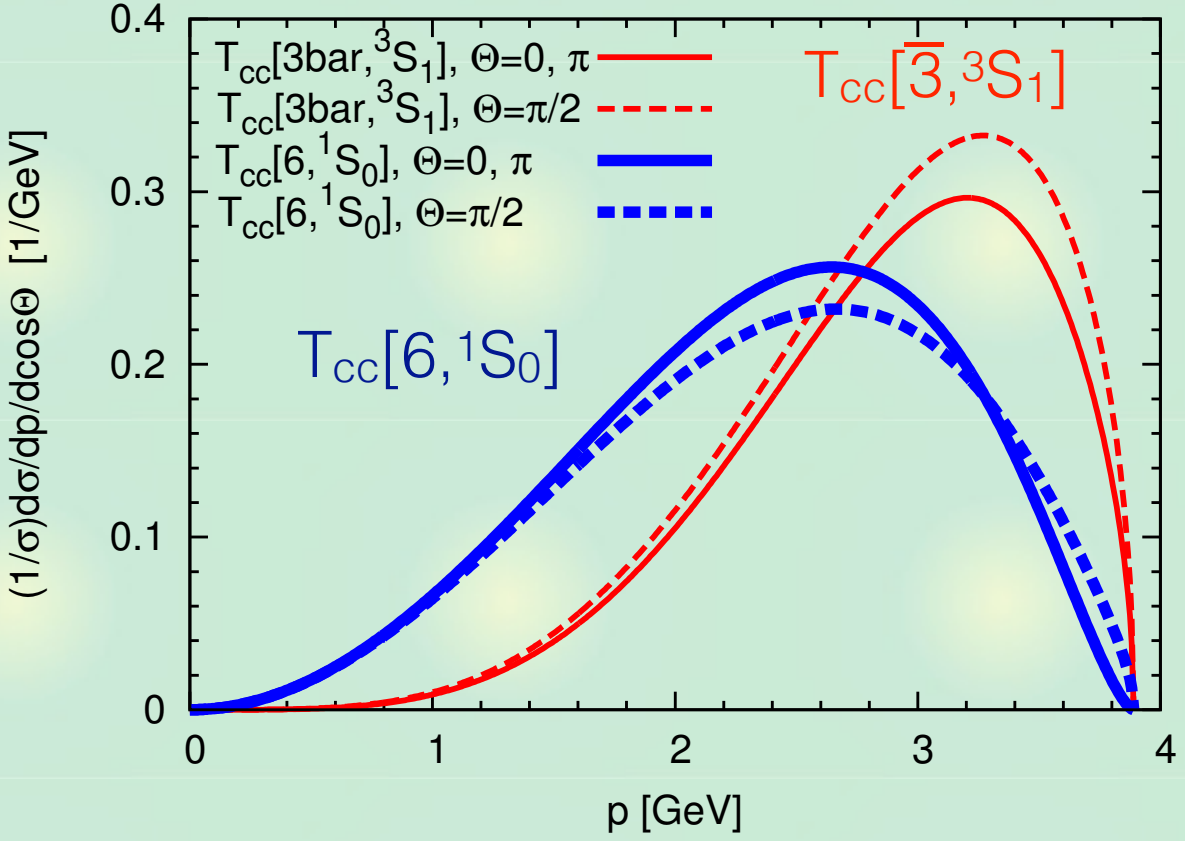
Differential cross sections

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)

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

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

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

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

Caution!

- **Leading order both in v and α_s**
- **Light quark dynamics (fragmentation) is not considered.**
  --> production of T_{cc} = production of Ξ_{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 $\overline{3}$.**
- **Momentum distribution in e^+e^- collisions: experimental method to clarify the color structures.**

T. Hyodo, Y.R. Liu, M. Oka, K. Sudoh, S. Yasui, Phys. Lett. B 721, 56 (2013)
+ in preparation.