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T_{cc}'s and their production in electron-positron collisions

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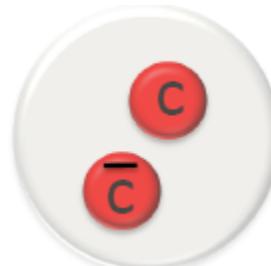
arXiv: 1209.6207 [hep-ph]

Content

- Exotic tetraquarks: T_{cc}
- T_{cc} production in e^+e^- collisions
- Summary and perspectives

What is T_{cc} ?

- Conventional and exotic hadrons



- Charmonium



- Λ_c

Σ_c



- E_{cc}



T_{cc}

Flavor exotic

no annihilation!!



Existent?
Stable?

Diquarks in conventional baryons

- Color-spin interaction from gluon exchange

$$H_{\text{int}} = \sum_{i < j} \frac{C_H}{m_i m_j} \left(-\frac{3}{8} \right) \vec{\lambda}_i \cdot \vec{\lambda}_j \vec{s}_i \cdot \vec{s}_j$$

$$C_H = v_0 \langle \delta(r_{ij}) \rangle$$

TABLE I. The expectation values of $(-3/8)\vec{\lambda}_i \cdot \vec{\lambda}_j \vec{s}_i \cdot \vec{s}_j$ for quarks i and j with spin $s = 0, 1$ and color $\bar{3}, 6$.

	$\bar{3}$	6
$s = 0$	$-\frac{3}{4}$	$\frac{3}{8}$
$s = 1$	$\frac{1}{4}$	$-\frac{1}{8}$

- “Good” light diquark in Λ_c
color= $\bar{3}$, $s=0$, $|l|=0$
- “Bad” light diquark in Σ_c & Σ_c^*
color= $\bar{3}$, $s=1$, $|l|=1$



Diquarks in conventional baryons

- Heavy diquark in Ξ_{cc}

cc: color=3, $s=1, l=0$

cc: color=6, $s=0, l=0$



$$|H_{QQ}\rangle = c_1 |QQq\rangle + c_2 |QQqg\rangle + c_3 |QQqgg\rangle + \dots$$

- NRQCD $c_1 \sim c_2 \sim c_3 \dots$

TABLE I. The expectation values of $(-3/8)\vec{\lambda}_i \cdot \vec{\lambda}_j \vec{s}_i \cdot \vec{s}_j$ for quarks i and j with spin $s = 0, 1$ and color 3, 6.

	3	6
$s = 0$	$-\frac{3}{4}$	$\frac{3}{8}$
$s = 1$	$\frac{1}{4}$	$-\frac{1}{8}$

J.P. Ma , Z.G. Si,
Phys. Lett. B 568, 135 (2003).

Diquarks in T_{cc}

- T_{cc} with “Good” light diquark

$\bar{u}\bar{d}$: color=3, s=0, l=0

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

cc: color=3, s=1, l=0

$$H_{\text{int}} = \sum_{i < j} \frac{C_H}{m_i m_j} \left(-\frac{3}{8} \right) \vec{\lambda}_i \cdot \vec{\lambda}_j \vec{s}_i \cdot \vec{s}_j$$

- Interactions

$\bar{u}\bar{d}$: $1/m_c^0$ dominant attraction

$c\bar{q}$: $1/m_c^1$ suppressed

cc: $1/m_c^2$ suppressed



Stable?

	3	6
$s = 0$	$-\frac{3}{4}$	$\frac{3}{8}$
$s = 1$	$\frac{1}{4}$	$-\frac{1}{8}$

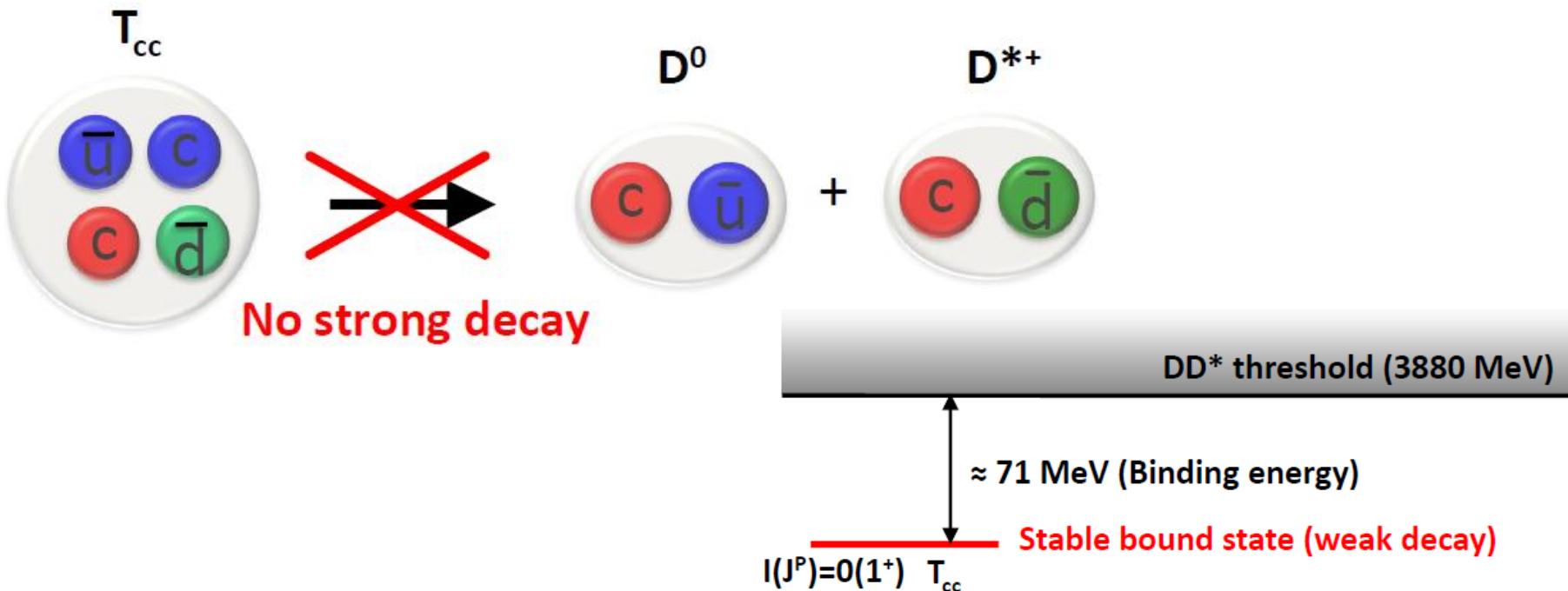
Stability of T_{cc}

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

- Lowest two-meson threshold: DD^*
- Binding energy from this threshold

$$\text{B.E.} \approx 71 \text{ MeV} \quad \Leftarrow$$

$$H_{\text{int}} = \sum_{i < j} \frac{C_H}{m_i m_j} \left(-\frac{3}{8} \right) \vec{\lambda}_i \cdot \vec{\lambda}_j \vec{s}_i \cdot \vec{s}_j$$



- T_{cc} studied in many Refs.

Support its existence

Doubly charmed compact tetraquark $I(J^P)=0(1^+)$

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$$T_{cc}[\bar{\mathbf{3}}, {}^3S_1] \& T_{cc}[\mathbf{6}, {}^1S_0]$$

- Notation for the ground T_{cc} : $T_{cc}[\bar{\mathbf{3}}, {}^3S_1]$
- Another configuration: $T_{cc}[\mathbf{6}, {}^1S_0]$

$\bar{u}\bar{d}$: color=6, $s=1$, $|l|=0$

cc: color=6, $s=0$, $|l|=0$

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



TABLE I. The expectation values of $(-3/8)\vec{\lambda}_i \cdot \vec{\lambda}_j \vec{s}_i \cdot \vec{s}_j$ for quarks i and j with spin $s = 0, 1$ and color $\bar{\mathbf{3}}, \mathbf{6}$.

	$\bar{\mathbf{3}}$	$\mathbf{6}$
$s = 0$	$-\frac{3}{4}$	$\frac{3}{8}$
$s = 1$	$\frac{1}{4}$	$-\frac{1}{8}$

Weaker attraction

Decay of $T_{cc}[6, {}^1S_0]$

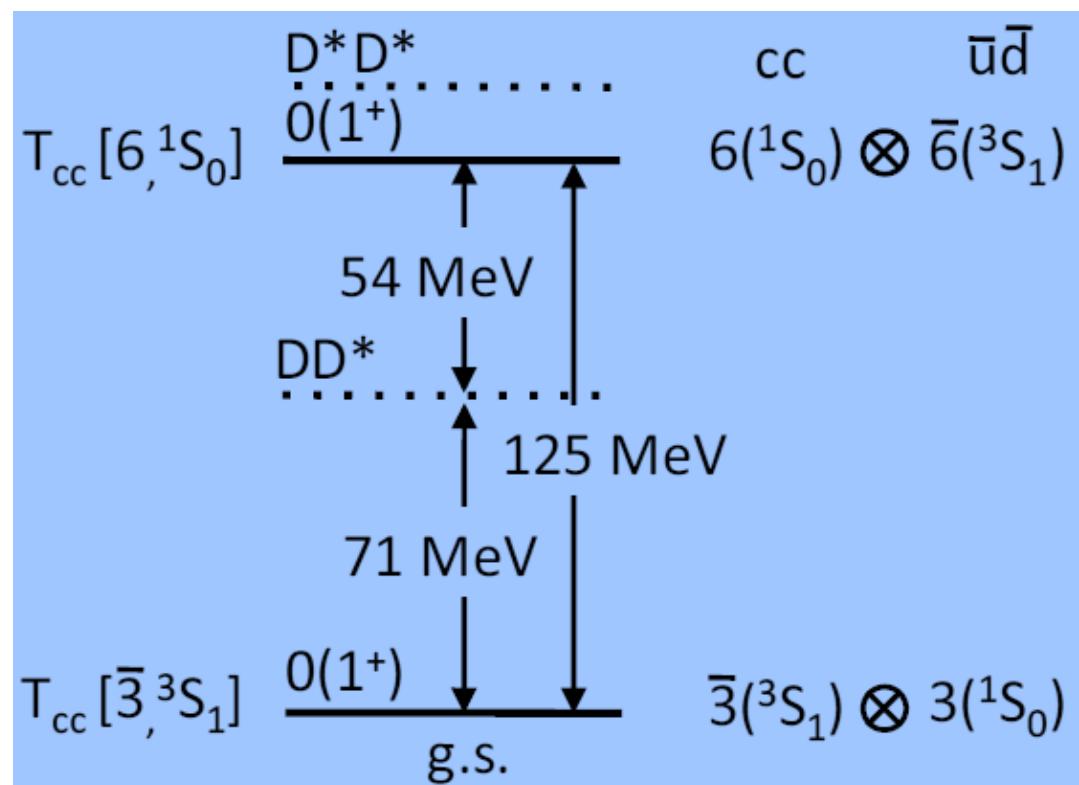
- Mass splitting between $T_{cc}[\bar{3}, {}^3S_1]$ and $T_{cc}[6, {}^1S_0]$

M.S. ≈ 125 MeV

$$H_{\text{int}} = \sum_{i < j} \frac{C_H}{m_i m_j} \left(-\frac{3}{8} \right) \vec{\lambda}_i \cdot \vec{\lambda}_j \vec{s}_i \cdot \vec{s}_j$$

- Energy levels

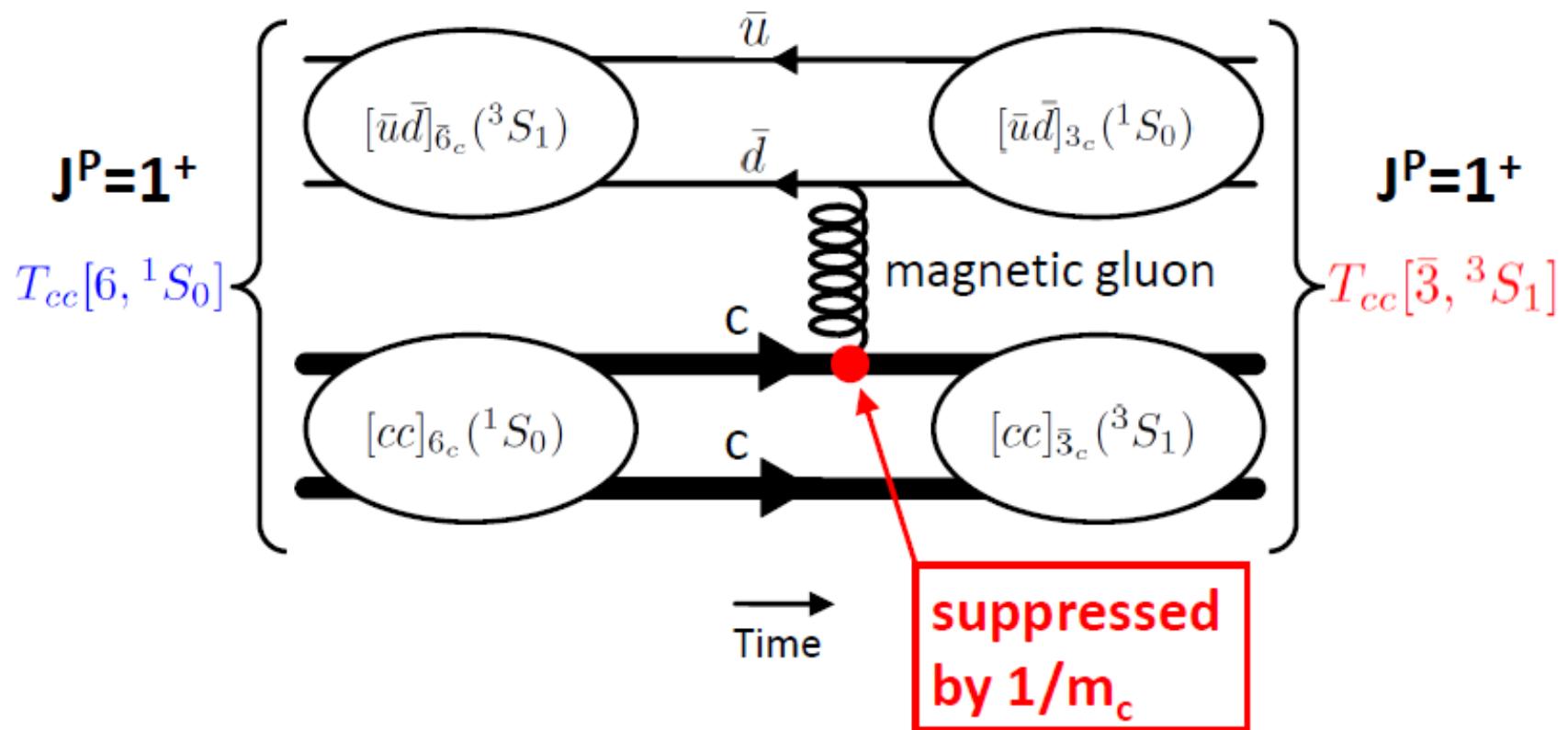
$$I(J^P) = 0(1^+)$$



Decay of $T_{cc}[6, {}^1S_0]$

- To $\pi\pi$ and $T_{cc}[\bar{3}, {}^3S_1]$: kinematically forbidden
- To DD*: dominant decay, color recombination and size of $cc \rightarrow$ may be narrow
- Two “narrow” T_{cc} states:
 $T_{cc}[\bar{3}, {}^3S_1]$ $T_{cc}[6, {}^1S_0]$
- Mixing?

Mixing between $T_{cc}[\bar{3}, {}^3S_1]$ and $T_{cc}[6, {}^1S_0]$



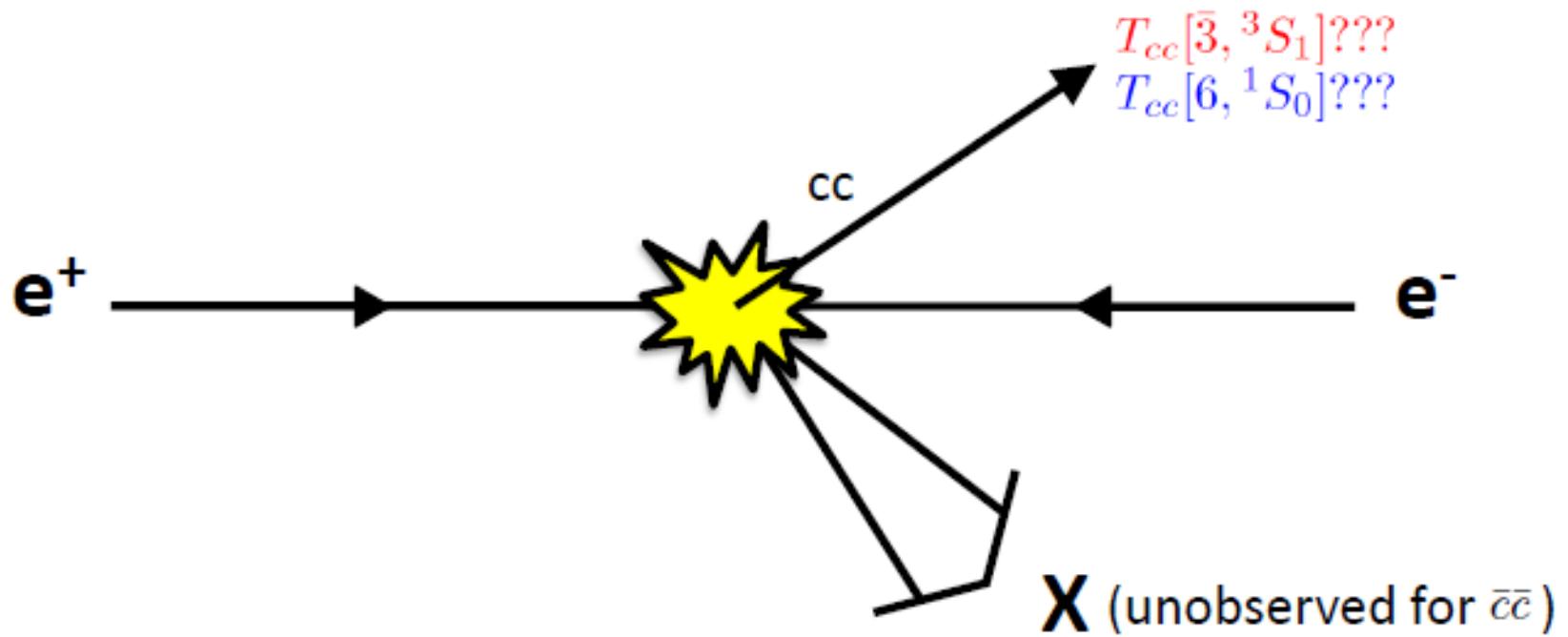
Production of T_{cc}

TABLE I. Estimations for the T_{cc} tetraquark production at various facilities. At RHIC experiment, the results are for scattering of the nucleon on gold. Production rate for the gold-gold scattering is due to the small luminosity significantly smaller. Estimate for production at SELEX and in Belle B factory are obtained from experimental data on double charm production.

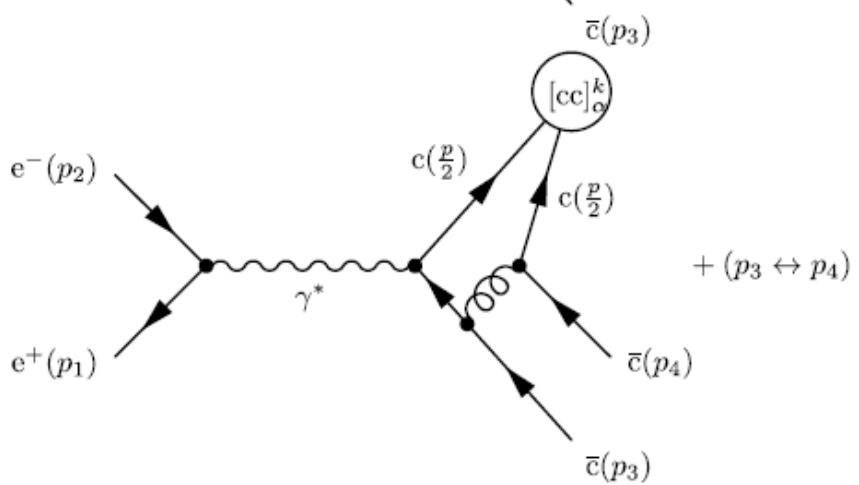
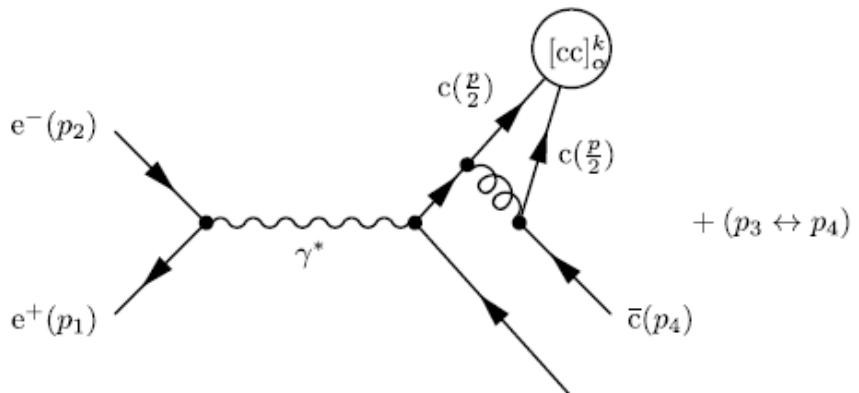
	LHC LHCb	ALICE	Tevatron	RHIC	SELEX	Belle
Luminosity ($cm^{-2}s^{-1}$)	10^{33}	10^{33}	8×10^{31}	2×10^{27}		
Cross section (nb)	27	58	21	755		
No. of events	9700/hour	20900/hour	600/hour	12/hour	5	1000/year

A. Del Fabbro, D. Janc, M. Rosina, D. Treleani, PRD71, 014008 (2005)

T_{cc} production in $e^+e^- \rightarrow T_{cc} + X$



T_{cc} production in $e^+e^- \rightarrow T_{cc} + X$



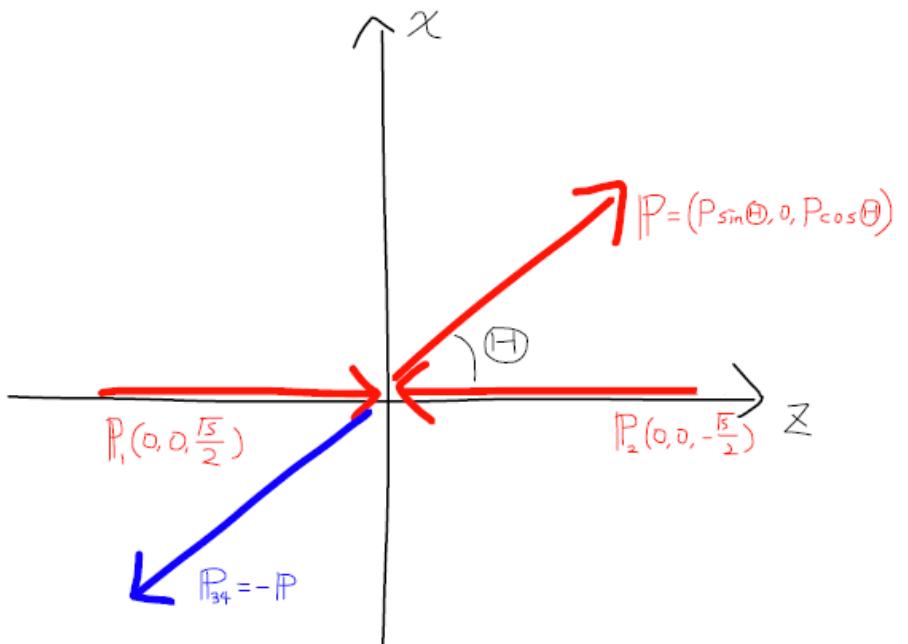
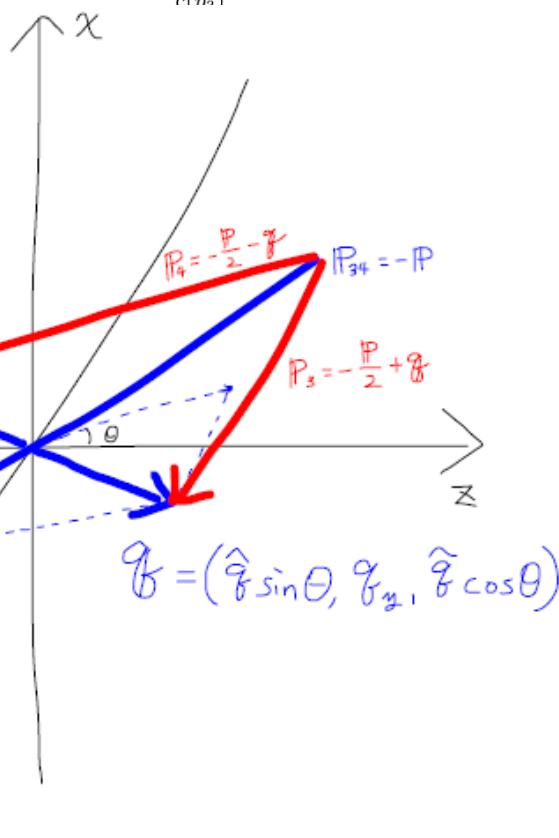
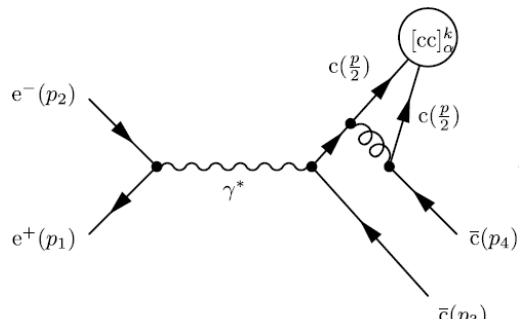
Framework: NRQCD

Inclusive Ξ_{cc} production:
J.P. Ma , Z.G. Si,
Phys. Lett. B 568, 135 (2003).

$$\langle \mathcal{O}^k(T_{cc}[\alpha]) \rangle \Big|_{k=\text{LO}} = \begin{cases} h_{[\bar{3}, {}^3S_1]} & \text{for } \alpha = [\bar{3}, {}^3S_1] \\ h_{[6, {}^1S_0]} & \text{for } \alpha = [6, {}^1S_0] \end{cases}$$

$$d\sigma_\alpha(e^+e^- \rightarrow T_{cc}[\alpha] + X) = \underbrace{\sum_k d\hat{\sigma}(e^+e^- \rightarrow [cc]_\alpha^k + \bar{c} + \bar{c})}_{\text{short distance}} \underbrace{\langle \mathcal{O}^k(T_{cc}[\alpha]) \rangle}_{\text{long distance}}$$

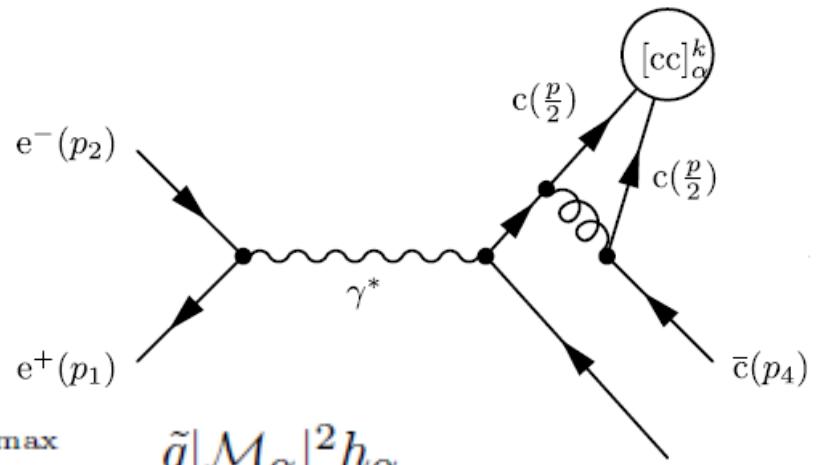
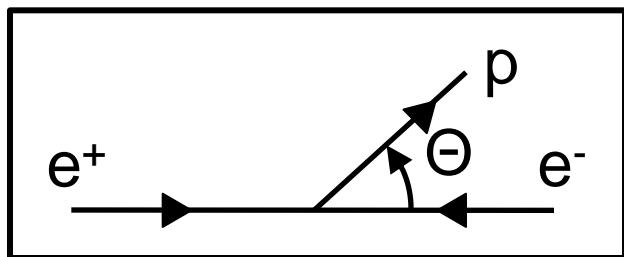
T_{cc} production in $e^+e^- \rightarrow T_{cc} + X$



$$p^\mu = (E_p, p \sin \Theta, 0, p \cos \Theta)$$

$$E_p = \sqrt{4m_c^2 + p^2}, p = |\mathbf{p}|$$

T_{cc} production in $e^+e^- \rightarrow T_{cc} + X$

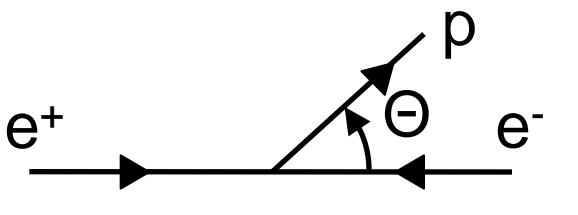


$$\frac{d\sigma_\alpha}{dp d\cos\Theta} = \frac{1}{(2\pi)^4} \frac{p^2}{16m_c s E_p} \int_0^{2\pi} d\theta \int_0^{\tilde{q}_{\max}} d\tilde{q} \frac{\tilde{q} |\mathcal{M}_\alpha|^2 h_\alpha}{q_y(E_3 + E_4)}$$

$$q_y = \frac{\sqrt{A - B\tilde{q}^2 + C\tilde{q}^2 \cos^2 \theta'}}{2(\sqrt{s} - E_p)},$$

$$\tilde{q}_{\max} = \sqrt{\frac{A}{B - C \cos^2 \theta'}},$$

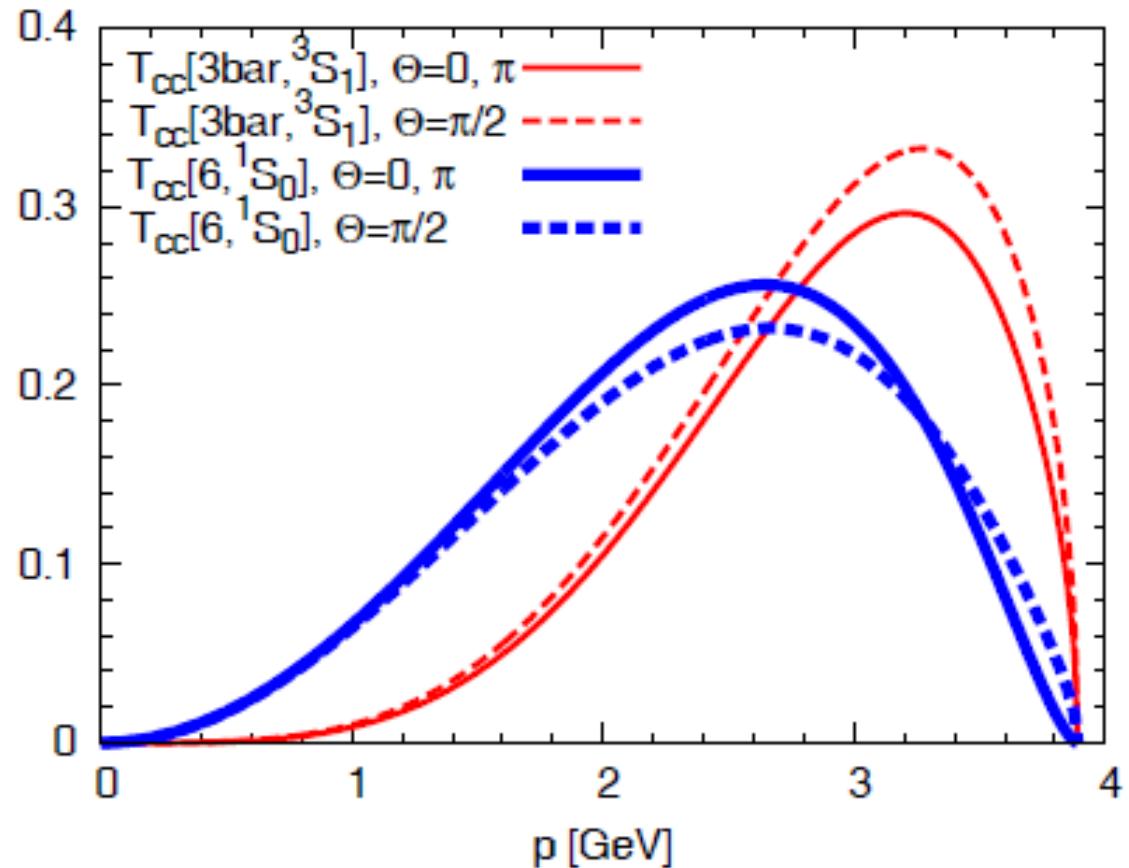
where s is the total energy squared, $E_{3,4} = \sqrt{m_c^2 + |\mathbf{p}_{3,4}|^2}$, $\theta' = \theta - \Theta$, $A = \sqrt{s}(\sqrt{s} - 2E_p)(\sqrt{s} - E_p)^2$, $B = 4(\sqrt{s} - E_p)^2$, and $C = 4p^2$.



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

[1/GeV]

Independent of h_α



Different behavior for $T_{cc}[\bar{3}, {}^3S_1]$ and $T_{cc}[6, {}^1S_0]$

- Peak position and height
- Θ -dependence
- ...

$$\sqrt{s} = 10.6 \text{ GeV}$$

$$m_c = 1.8 \text{ GeV}$$

$$\alpha_s = 0.212$$

$$M_{T_{cc}} = 2m_c$$

Total cross section

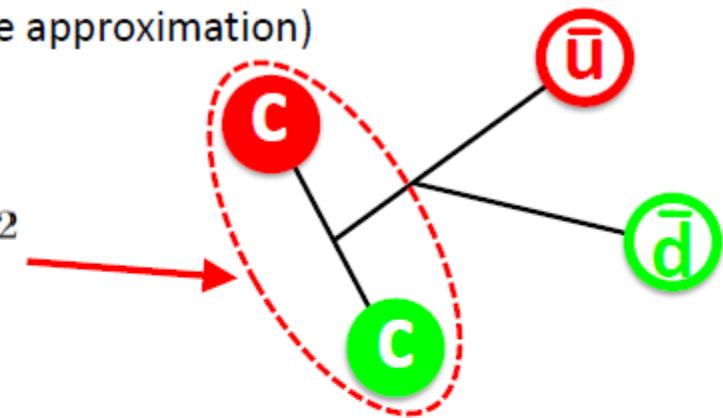
Estimate by quark model (crude approximation)

$$T_{cc}[\bar{3}, {}^3S_1]$$

$$\begin{aligned} h_3 &= \frac{1}{4\pi} |R_{cc}^{\bar{3}_c({}^3S_1)}(0)|^2 \\ &\approx 0.089 \text{ GeV}^3 \end{aligned}$$

$$T_{cc}[6, {}^1S_0]$$

$$h_6 = \frac{1}{4\pi} |R_{cc}^{6_c({}^1S_0)}(0)|^2$$



H.O. potential

Cf. Ξcc production based on NRQCD formalism

- Ma, Si, Physics Letters B568, 135 (2003)
- Jian, Wu, Liao, Zheng, Fang, arXiv:1208.3051 [hep-ph]

$$\sum_{i < j} \left(-\frac{3}{16}\right) \vec{\lambda}_i \cdot \vec{\lambda}_j \frac{k}{2} |\vec{r}_i - \vec{r}_j|^2$$

Total cross section

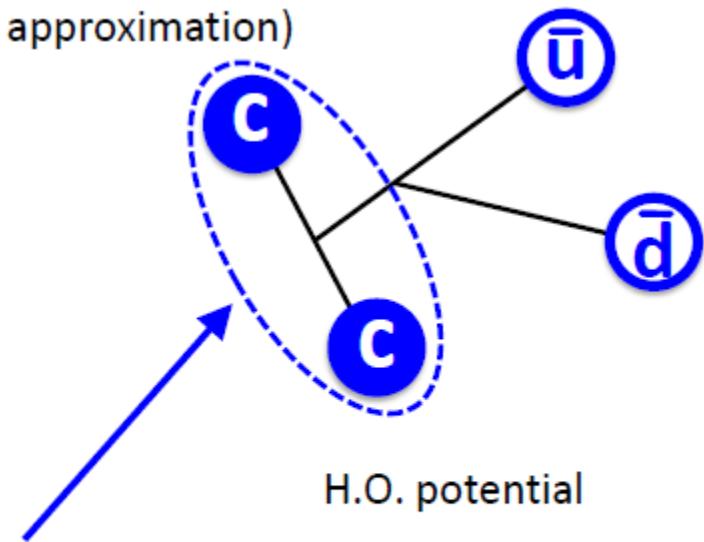
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$$T_{cc}[6, {}^1S_0]$$

$$\begin{aligned} h_6 &= \frac{1}{4\pi} |R_{cc}^{6_c({}^1S_0)}(0)|^2 \\ &\approx 0.054 \text{ GeV}^3 \end{aligned}$$



Cf. Ξcc production based on NRQCD formalism

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$$\sum_{i < j} \left(-\frac{3}{16}\right) \vec{\lambda}_i \cdot \vec{\lambda}_j \frac{k}{2} |\vec{r}_i - \vec{r}_j|^2$$

Total cross section

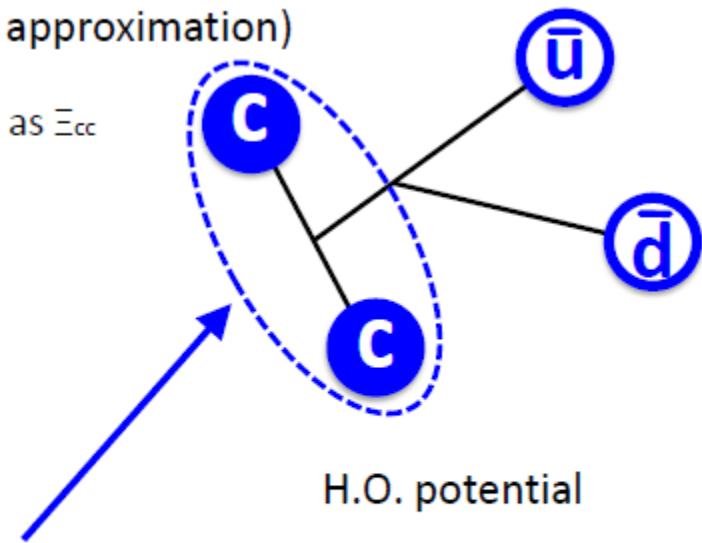
Estimate by quark model (crude approximation)

$T_{cc}[\bar{3}, {}^3S_1]$ $\sigma = 18.8 \text{ fb}$ almost same as Ξ_{cc}

$$h_3 = \frac{1}{4\pi} |R_{cc}^{\bar{3}_c({}^3S_1)}(0)|^2 \\ \approx 0.089 \text{ GeV}^3$$

$T_{cc}[6, {}^1S_0]$ $\sigma = 4.1 \text{ fb}$

$$h_6 = \frac{1}{4\pi} |R_{cc}^{6_c({}^1S_0)}(0)|^2 \\ \approx 0.054 \text{ GeV}^3$$



Cf. Ξ_{cc} production based on NRQCD formalism

- Ma, Si, Physics Letters B568, 135 (2003)
- Jian, Wu, Liao, Zheng, Fang, arXiv:1208.3051 [hep-ph]

$$\sum_{i < j} \left(-\frac{3}{16}\right) \vec{\lambda}_i \cdot \vec{\lambda}_j \frac{k}{2} |\vec{r}_i - \vec{r}_j|^2$$

Summary and perspectives

- Color configurations in doubly charmed T_{cc}
- Estimate the cross sections of $T_{cc}[\bar{3}, {}^3S_1]$ and $T_{cc}[6, {}^1S_0]$ produced in e^+e^- collisions: different momentum- and angle-dependence
- More rigorous studies should be required:
mixing, h_α , ...

Thank you!