4th workshop on the XYZ particles@buaa

Ξ_{cc} and T_{cc} states

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2016.11.24

Recent works about multiquark states

- “X(5568) and its partner states”, 1603.01131
- “Heavy-flavored tetraquark states with the $QQ\underline{QQ}$ configuration ”, 1605.01134
- “X(4140), X(4270), X(4500), and X(4700) and their $cs\underline{cs}$ tetraquark partners”, 1608.07900
- “Triply heavy tetraquark states with the $QQ\underline{Qq}$ configuration”, 1609.06117
- “*Hidden-charm pentaquarks and their partner states*”, to be submitted

In collaboration with X. Liu, S.L. Zhu

Today's talk

- Xicc and Tcc: masses

- Xicc and Tcc: production

- Summary

Based on:

(1) Production of doubly charmed tetraquarks with exotic color configurations in electron–positron collisions, PLB 721, 56 (2013)

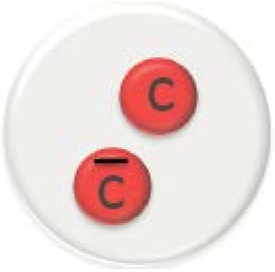
(2) Search for a doubly charmed hadron at *B factories, PRD 89, 094006 (2014)*

Collaborators: Y. Jin, S.Y. Li, Z.G. Li, T. Yao, T. Hyodo, M. Oka, K. Sudoh, S. Yasui

Introduction

- Quark model

  Quark-antiquark meson:



  3-quark baryon:

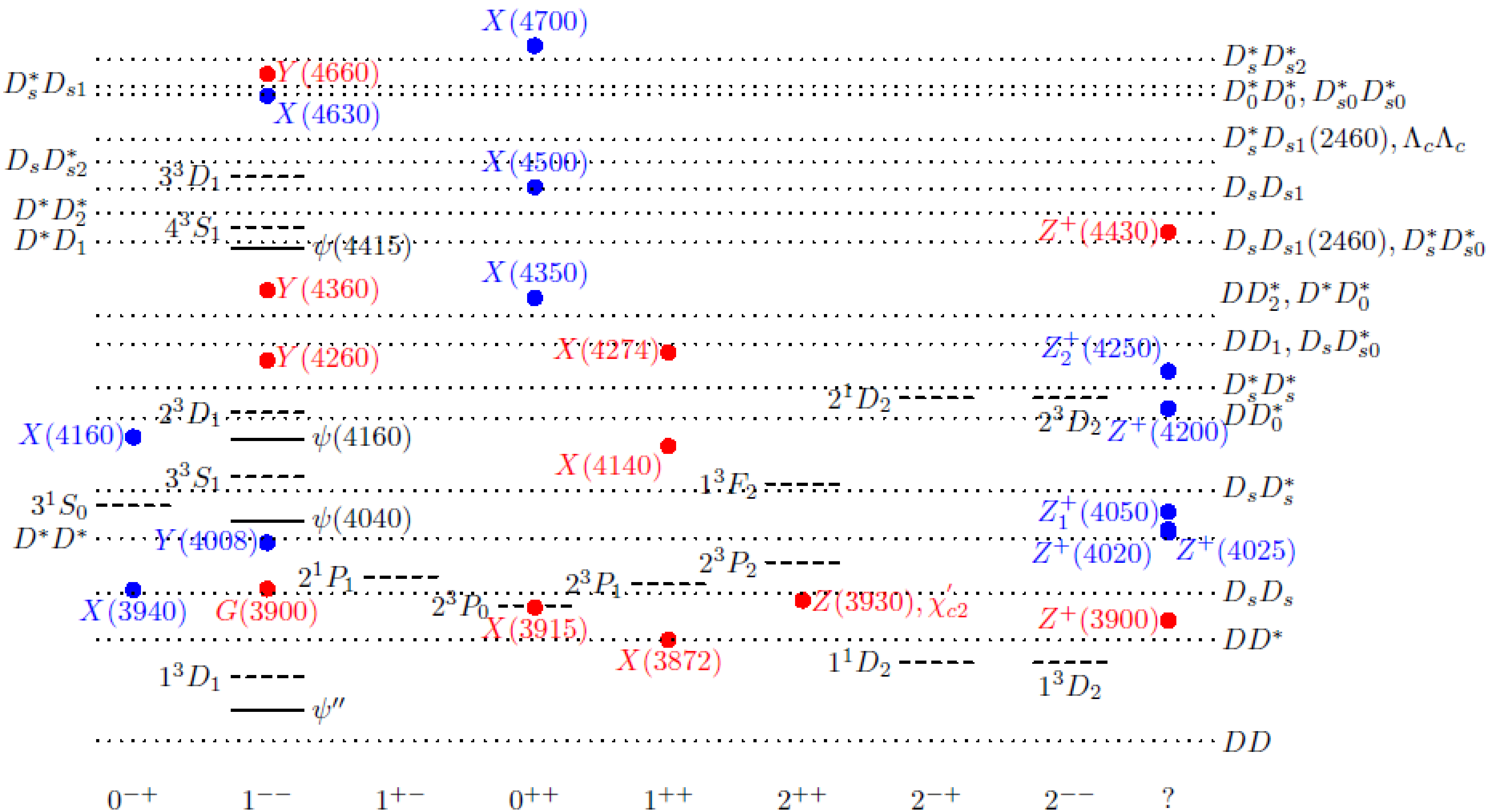
- Exotic states

  Tetraquark, pentaquark,

  hybrid, ...

- XYZ: four-quark states exist!

XYZ mesons

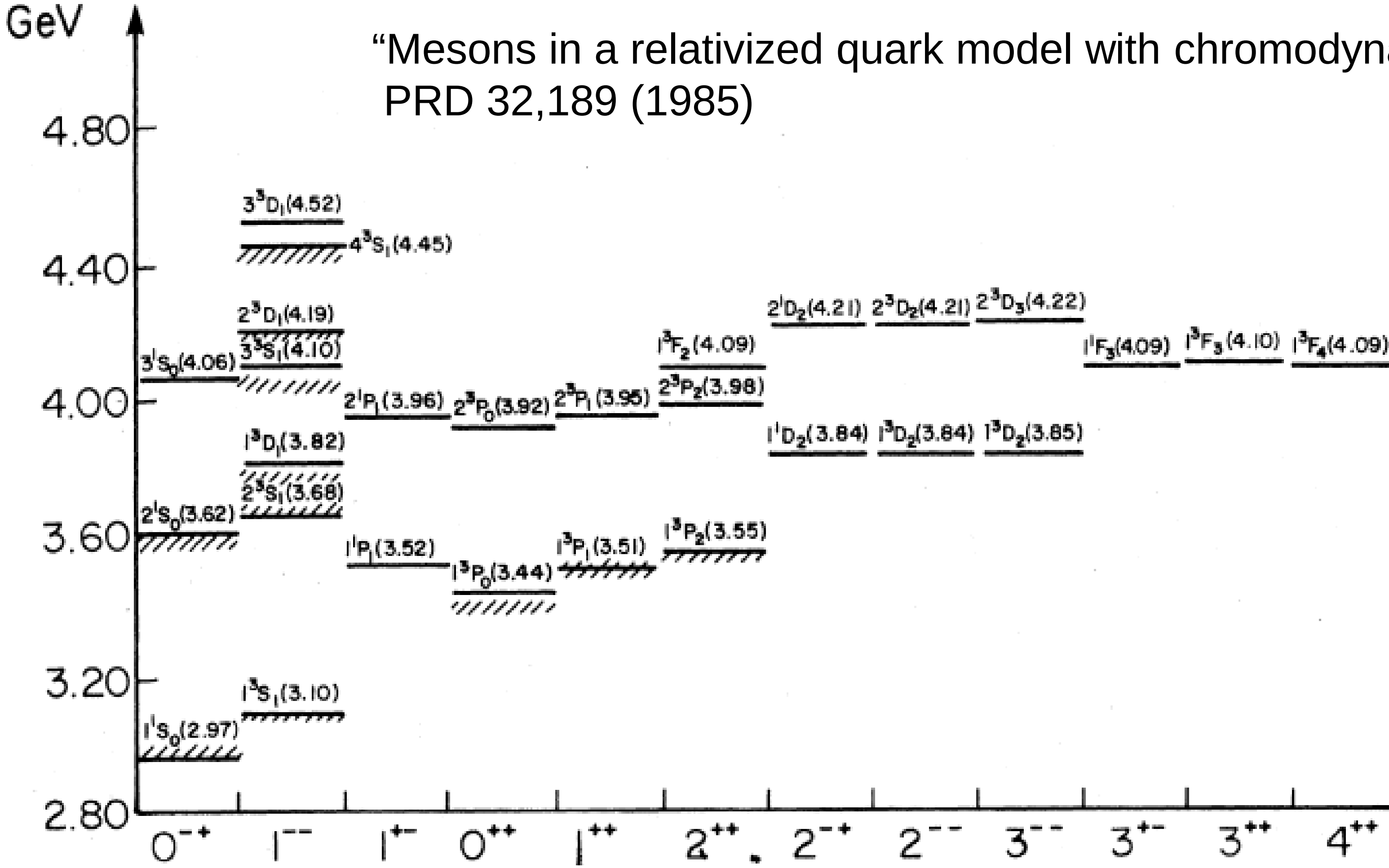


$X(4700)$
$D_s^* D_{s2}^*$
$D_s^* D_{s1}$
$Y(4660)$
$D_0^* D_0^*, D_{s0}^* D_{s0}^*$
$X(4630)$
$D_s^* D_{s1}(2460), \Lambda_c \Lambda_c$
$D_s D_{s2}^*$
$X(4500)$
$3^3 D_1$
$D_s D_{s1}$
$D^* D_2^*$
$4^3 S_1$
$Z^+(4430)$
$D^* D_1$
$\psi(4415)$
$D_s D_{s1}(2460), D_s^* D_{s0}^*$
$X(4350)$
$Y(4360)$
$D D_2^*, D^* D_0^*$
$X(4274)$
$Y(4260)$
$Z_2^+(4250)$
$D D_1, D_s D_{s0}^*$
$2^1 D_2$
$D_s^* D_s^*$
$2^3 D_1$
$2^3 D_2$
$Z^+(4200)$
$D D_0^*$
$X(4160)$
$\psi(4160)$
$X(4140)$
$3^3 S_1$
$1^3 F_2$
$D_s D_s^*$
$3^1 S_0$
$\psi(4040)$
$Z_1^+(4050)$
$D^* D^*$
$Y(4008)$
$Z^+(4020)$
$Z^+(4025)$
$2^1 P_1$
$2^3 P_2$
$2^3 P_1$
$D_s D_s$
$2^3 P_0$
$X(3940)$
$G(3900)$
$X(3915)$
$Z(3930), \chi_{c2}'$
$Z^+(3900)$
$D D^*$
$X(3872)$
$1^3 D_1$
$1^1 D_2$
$1^3 D_2$
ψ''
DD
0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++} 2^{-+} 2^{--} ?

Quark model spectra

- Charmonia and other mesons in GI model

“Mesons in a relativized quark model with chromodynamics”,
PRD 32,189 (1985)



Quark model spectra

- Charmed baryons in GI model

“Baryons in a relativized quark model with chromodynamics”, PRD 34,2809 (1986)

No results for csu, ccq, ccc types

TABLE X. The Λ_c and Σ_c baryons.

State, J^P	Predicted masses (MeV)							
$\Lambda_c\ \frac{1}{2}^+$	2265							
$\Lambda_c^*\ \frac{1}{2}^-$	2630	2780	2830	3030	3200	3240	3255	
$\Lambda_c^*\ \frac{3}{2}^-$	2640	2840	2885	3035	3240	3255	3290	
$\Lambda_c^*\ \frac{5}{2}^-$	2900	3130	3275					
$\Lambda_c^*\ \frac{7}{2}^-$	3125							
$\Lambda_c^*\ \frac{1}{2}^+$	2775	2970	3015	3075	3170	3185	3200	
$\Lambda_c^*\ \frac{3}{2}^+$	2910	3035	3080	3145	3190	3200	3220	
$\Lambda_c^*\ \frac{5}{2}^+$	2910	3140	3165	3225	3230			
$\Lambda_c^*\ \frac{7}{2}^+$	3175							
$\Sigma_c\ \frac{1}{2}^+$	2440							
$\Sigma_c\ \frac{3}{2}^+$	2495							
$\Sigma_c^*\ \frac{1}{2}^-$	2765	2770	2840	3185	3195	3250	3290	
$\Sigma_c^*\ \frac{3}{2}^-$	2770	2805	2865	3195	3210	3260	3285	
$\Sigma_c^*\ \frac{5}{2}^-$	2815	3220	3280	3295				
$\Sigma_c^*\ \frac{7}{2}^-$	3290							
$\Sigma_c^*\ \frac{1}{2}^+$	2890	3005	3035	3080	3175	3185		
$\Sigma_c^*\ \frac{3}{2}^+$	2985	3060	3065	3130	3140	3200	3200	3220
$\Sigma_c^*\ \frac{5}{2}^+$	3065	3080	3155	3185	3240			
$\Sigma_c^*\ \frac{7}{2}^+$	3090	3230						

Quark model and hadrons

Quarks: $u,\ d,\ s,\ c,\ b\ [\ell\!:\ u,\ d]$

$\ell\bar{\ell}$	$c\bar{\ell},\ \bar{c}\ell\quad \ell\bar{b},\ \bar{\ell}b$	$c\bar{c}$
$\ell\bar{s},\ \bar{\ell}s$	$c\bar{s},\ \bar{c}s\quad s\bar{b},\ \bar{s}b$	$c\bar{b},\ \bar{c}b$
$s\bar{s}$		$b\bar{b}$

TABLE I: Quark-antiquark mesons.

Heavy quark hadrons

Not confirmed

$\ell\ell\ell$						ccc
$\ell\ell s$	$\ell\ell c$	$\ell\ell b$				ccb
ℓss	ℓsc	ℓsb	ℓcc	ℓcb	ℓbb	cbb
sss	ssc	ssb	scc	scb	sbb	bbb

TABLE II: 3-quark baryons.

Red color:
not observed

DOUBLY CHARMED BARYONS $(C = +2)$

$\Xi_{cc}^{++} = ucc$, $\Xi_{cc}^{+} = dcc$, $\Omega_{cc}^{+} = scc$

Ξ_{cc}^{+}

$I(J^P) = ?(?^?)$ Status: *

OMITTED FROM SUMMARY TABLE

This would presumably be an isospin-1/2 particle, a ccu Ξ_{cc}^{++} and a ccd Ξ_{cc}^{+}. However, opposed to the evidence cited below, the BABAR experiment has found no evidence for a Ξ_{cc}^{+} in a search in $\Lambda_c^+ K^- \pi^+$ and $\Xi_c^0 \pi^+$ modes, and no evidence of a Ξ_{cc}^{++} in $\Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^0 \pi^+ \pi^+$ modes (AUBERT,B 06D). Nor have the BELLE (CHISTOV 06, KATO 14) or LHCb (AAIJ 13CD) experiments found any evidence for this state.

Ξ_{cc}^{+} MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3518.9±0.9 OUR AVERAGE					
3518 ±3	6	[1] OCHERASHVI...05		SELX	Σ^- nucleus ≈ 600 GeV
3519 ±1	16	[2] MATTSON	02	SELX	Σ^- nucleus ≈ 600 GeV

[1] OCHERASHVILI 05 claims "an excess of 5.62 events over ... 1.38 ± 0.13 events" for a significance of 4.8 σ in pD^+K^- events.

[2] MATTSON 02 claims "an excess of 15.9 events over an expected background of 6.1 ±0.5 events, a statistical significance of 6.3 σ" in the $\Lambda_c^+ K^- \pi^+$ invariant-mass spectrum. The probability that the peak is a fluctuation increases from 1.0×10^{-6} to 1.1×10^{-4} when the number of bins searched is considered.

Ξ_{cc}^{+} MEAN LIFE

VALUE (10^{-15} s)	CL%	DOCUMENT ID		TECN	COMMENT
<33	90	MATTSON	02	SELX	Σ^- nucleus, ≈600 GeV

Ξ_{cc}^{+} DECAY MODES

	Mode
Γ_1	$\Lambda_c^+ K^- \pi^+$
Γ_2	$pD^+ K^-$

$\Gamma(pD^+K^-)/\Gamma(\Lambda_c^+ K^- \pi^+)$ — Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.36±0.21	6	OCHERASHVI...05	SELX	Σ^- ≈ 600 GeV

Ξ_{cc}^{+} REFERENCES

KATO	14	PR D89 052003	Y. Kato *et al.*	(BELLE Collab.)
AAIJ	13CD	JHEP 1312 090	R. Aaij *et al.*	(LHCb Collab.)
AUBERT,B	06D	PR D74 011103	B. Aubert *et al.*	(BABAR Collab.)
CHISTOV	06	PRL 97 162001	R. Chistov *et al.*	(BELLE Collab.)
OCHERASHVI...05		PL B628 18	A. Ocherashvili *et al.*	(FNAL SELEX Collab.)
MATTSON	02	PRL 89 112001	M. Mattson *et al.*	(FNAL SELEX Collab.)

Quark model and hadrons

- Why four-quark states easier to find than heavier baryons?

Baryon or flavor number,   Pauli principle

- Xicc and Tcc:

Similarity: [<u>ud</u>] ~ q in color 3

Quark model spectra

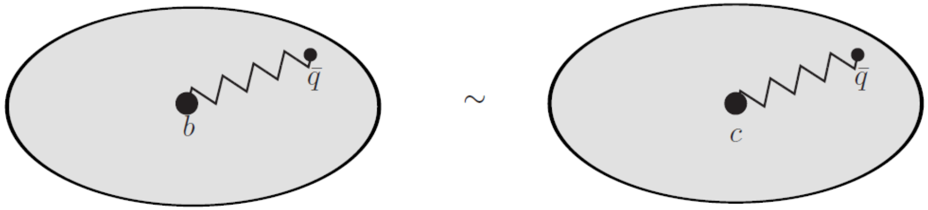
- Simplified model to explore mass splittings (S-wave)

$$
\begin{aligned}
H &= \sum_i m_i + \sum_i T_i + V_{eff}, \\
V_{eff} &= \sum_{i<j} \left[A(r_{ij}) \lambda_i \cdot \lambda_j + B \frac{\delta^3(r_{ij})}{m_i m_j} \lambda_i \cdot \lambda_j \sigma_i \cdot \sigma_j \right].
\end{aligned}
$$

$$
\Rightarrow \quad
\begin{aligned}
H &= \sum_i m_i^{eff} + H_{eff}, \\
H_{eff} &= -\sum_{i<j} \frac{C_{ij}}{m_i m_j} \lambda_i \cdot \lambda_j \sigma_i \cdot \sigma_j.
\end{aligned}
$$

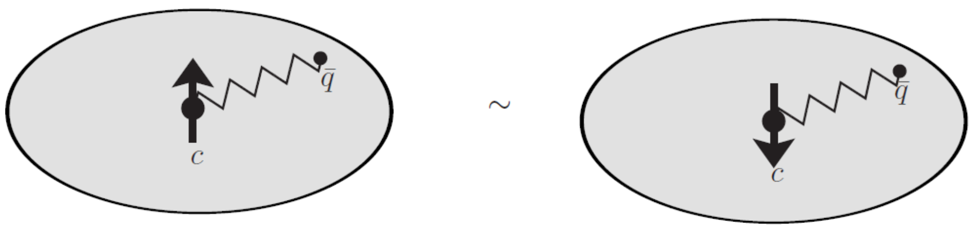
Heavy quark symmetry

- HQFS



Symmetry breaking $\propto 1/m_b - 1/m_c$

- HQSS



Symmetry breaking $\propto 1/m_Q$

$$J = j_\ell \pm j_Q \qquad \vec{j}_\ell \equiv \vec{L} + \vec{S}_{\bar{q}}$$

both conserved

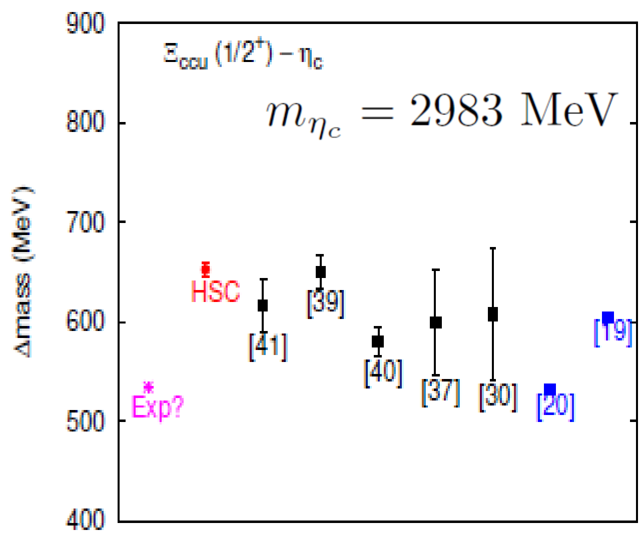
Masses

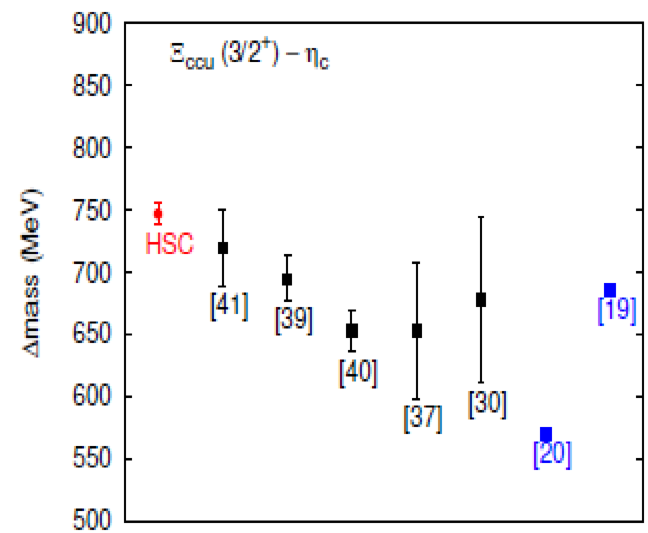
- Xicc: CMI model not applicable

hep-ph/0212358, Narodetskii et al ⇒

Baryon	This Work	Ref.[12]	Ref.[15]	Ref.[16]	Ref.[17]
Ξ_{cc}	3.66	3.69	3.57	3.69	3.70
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

hep-lat/1502.01845, Padmanath et al ⇒





- Tcc: CMI

no annihilation!!

Flavor exotic

Existent?
Stable?

Meaning?

Diquarks in conventional baryons

- Color-spin interaction from gluon exchange

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

$$C_{\rm H} = v_0 \langle \delta(r_{ij}) \rangle$$

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 $\bar{\mathbf{3}}$, $\mathbf{6}$.

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

- "Good" light diquark in Λ_c

  color=$\bar{3}$, s=0, I=0

- "Bad" light diquark in Σ_c & Σ_c*

  color=$\bar{3}$, s=1, I=1

Diquarks in conventional baryons

- Heavy diquark in Ξ_{cc}

  cc: color=$\bar{3}$, s=1, I=0

  cc: color=6, s=0, I=0

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

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

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

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 $\bar{\mathbf{3}}$, $\mathbf{6}$.

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

Diquarks in T_{cc}

- T_{cc} with "Good" light diquark

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

  cc: color=$\bar{3}$, s=1, I=0

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

- Interactions

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

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

  $c\bar{q}$: $\mathbf{1/m_c^1}$ suppressed (0 in this case)

  cc: $\mathbf{1/m_c^2}$ suppressed

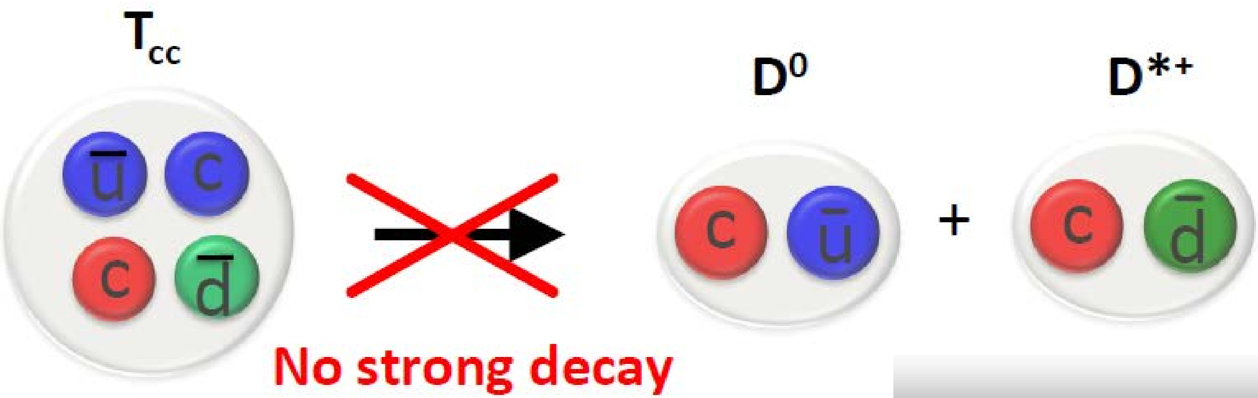
Stable?

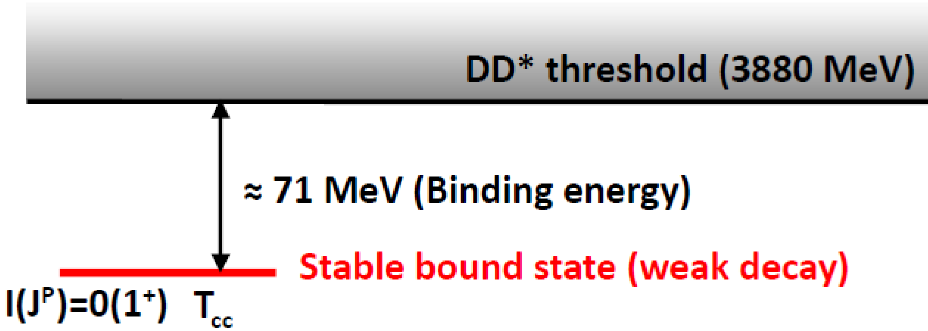
	$\bar{\mathbf{3}}$	$\mathbf{6}$
$s=0$	$-\frac{3}{4}$	$\frac{3}{8}$
$s=1$	$\frac{1}{4}$	$-\frac{1}{8}$

Stability of T_{cc} $I(J^P) = 0(1^+)$

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

B.E. ≈ 71 MeV $\Leftarrow$ $$H_{\rm int} = \sum_{i<j} \frac{C_{\rm H}}{m_i m_j} \left(-\frac{3}{8}\right) \vec{\lambda}_i \cdot \vec{\lambda}_j \, \vec{s}_i \cdot \vec{s}_j$$





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

- 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=$\bar{6}$, s=1, I=0

cc: color=6, s=0, I=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 $\mathrm{T_{cc}}[\mathbf{6}, {}^1\mathrm{S}_0]$

- Mass splitting between $\mathrm{T_{cc}}[\bar{\mathbf{3}}, {}^3\mathrm{S}_1]$ and $\mathrm{T_{cc}}[\mathbf{6}, {}^1\mathrm{S}_0]$

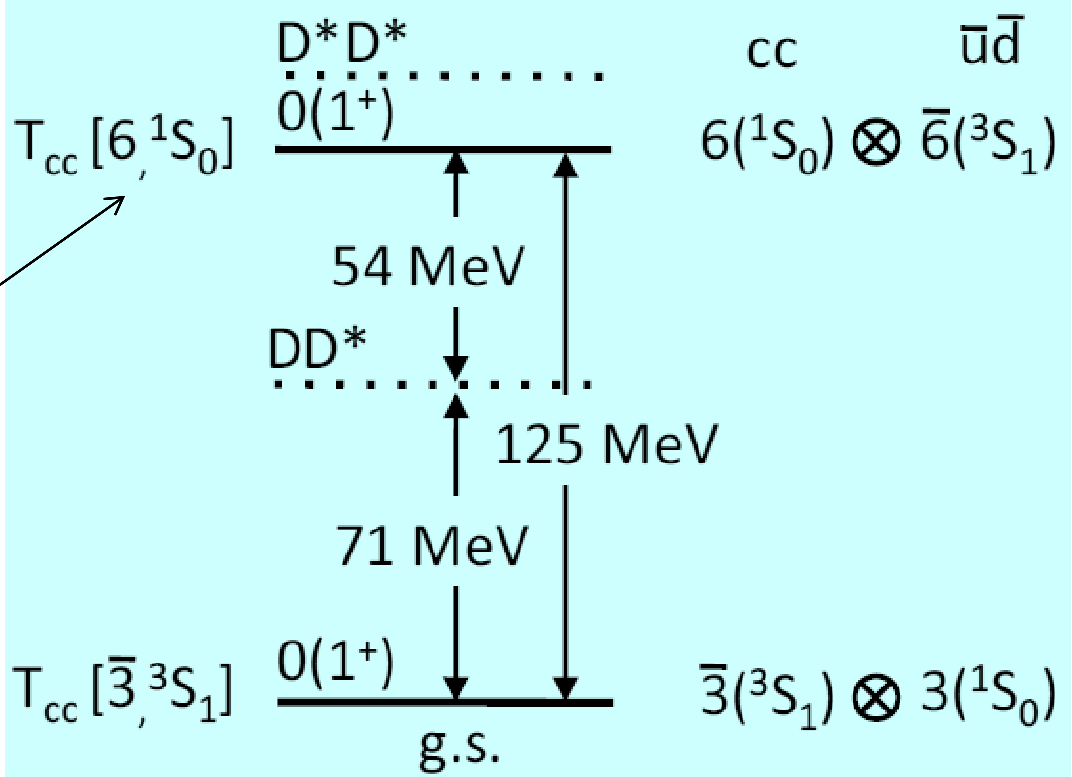
  M.S. ≈ 125 MeV $\Longleftarrow$ $H_{\rm int} = \sum_{i<j} \frac{C_{\rm H}}{m_i m_j}\left(-\frac{3}{8}\right)\vec{\lambda}_i\cdot\vec{\lambda}_j\,\vec{s}_i\cdot\vec{s}_j$

- Energy levels

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

~3925

~3800



Decay of $\mathrm{T_{cc}}[\mathbf{6}, {}^1\mathrm{S}_0]$

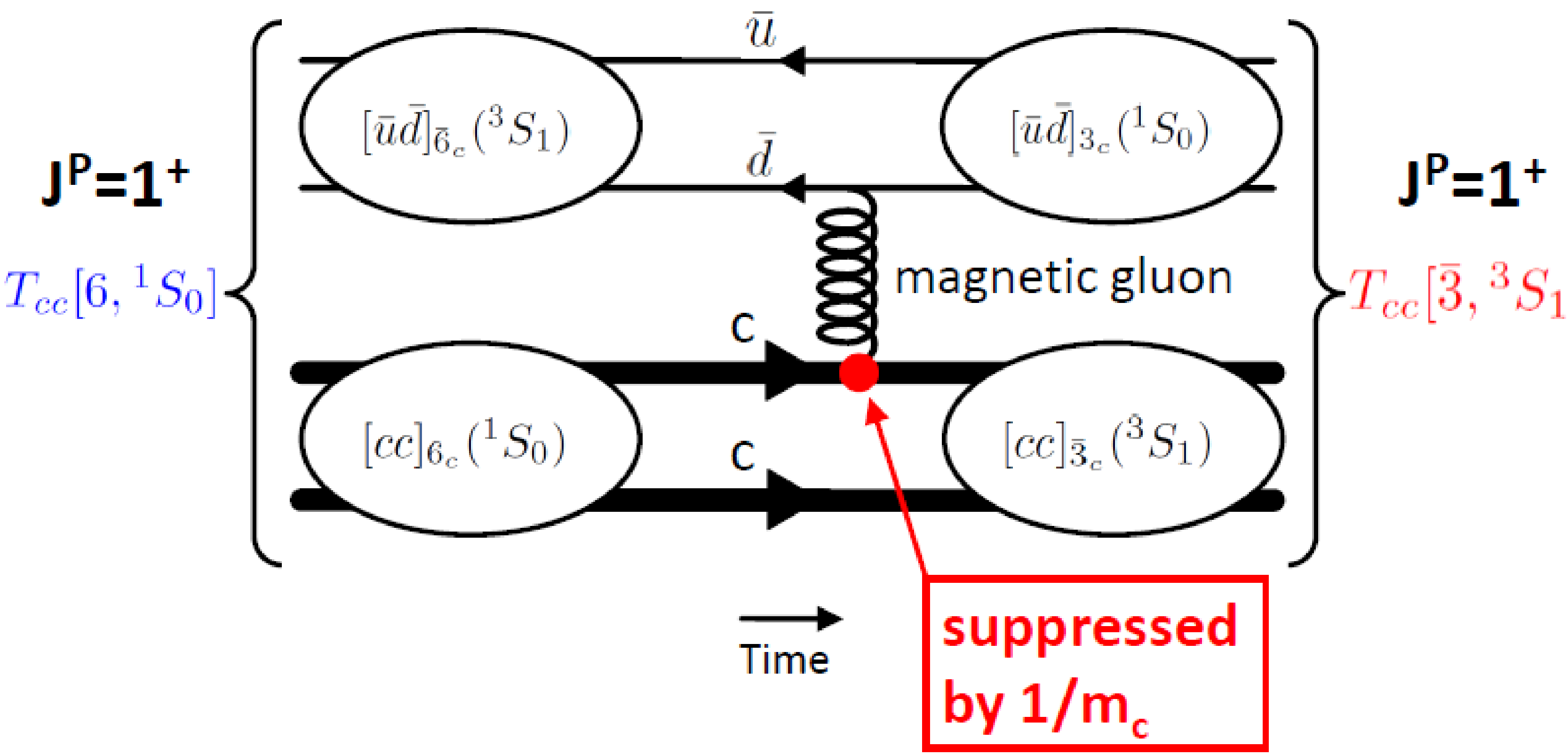
- To $\pi\pi$ and $\mathrm{T_{cc}}[\bar{\mathbf{3}}, {}^3\mathrm{S}_1]$: kinematically forbidden
- To DD*: dominant decay, color recombination $\to$ may be narrow

- Two "narrow" $\mathrm{T_{cc}}$ states:

$$\mathrm{T_{cc}}[\bar{\mathbf{3}}, {}^3\mathrm{S}_1] \qquad \mathrm{T_{cc}}[\mathbf{6}, {}^1\mathrm{S}_0]$$

- Mixing?

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



- T_{cc} studied in many Refs.

Support its existence

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

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- F. S. Navarra, M. Nielsen and S. H. Lee, Phys. Lett. B 649, 166 (2007).
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- J. Vijande, A. Valcarce and T. F. Carames, Few Body Syst. 50, 195 (2011).

Tcc mass

- “Masses of tetraquarks with two heavy quarks in the relativistic quark model”,

  D. Ebert et al, PRD 76, 114015 (2007)

TABLE V. Comparison of different theoretical predictions for the masses of heavy $(QQ')(\bar{q}\bar{q}')$ tetraquarks (in MeV).

System	$I(J^P)$	this work	[21]	[22]	[23]	[24]	[25]	[26]	[27]
$(cc)(\bar{u}\,\bar{d})$									
	$0(1^+)$	3935	3931	3876		3764	3927	3905	4000 ± 200
	$1(0^+)$	4056				4150			
	$1(1^+)$	4079				4186			
	$1(2^+)$	4118				4211			
$(bb)(\bar{u}\,\bar{d})$									

Xicc: production in e^+e^-

- Belle: $\sqrt{s} = 10.6\ \mathrm{GeV}$
- N=σ×Lint (Lint>1000 fb^{-1}, Babar: ~550)
- σ≈150 fb (hep-ph/0303145,Berezhnoy, Likhoded)
- σ≈230 fb (PLB 568, 135 (2003), J.P. Ma, Z.G. Si)
- σ≈(10-100) fb (PLB 721, 56 (2013), Hyodo et al)
- Z: $\sqrt{s} = m_Z$

"Doubly heavy baryon production at a high luminosity ete collider", J.Jiang et al, PRD 86, 054021(2012)

TABLE I. Total cross section (in pb) for the production of $\Xi_{QQ'}(n)$ baryons (where n stands for the intermediate diquark state) through e^+e^- annihilation at the Z^0 peak ($\sqrt{S} = m_Z$).

Production channel	Cross section (pb)
$e^+e^- \to \gamma \to \Xi_{cc}([^3S_1]_{\bar{3}})$	8.90×10^{-4}
$e^+e^- \to \gamma \to \Xi_{cc}([^1S_0]_6)$	4.29×10^{-4}
$e^+e^- \to Z^0 \to \Xi_{cc}([^3S_1]_{\bar{3}})$	0.727
$e^+e^- \to Z^0 \to \Xi_{cc}([^1S_0]_6)$	0.353

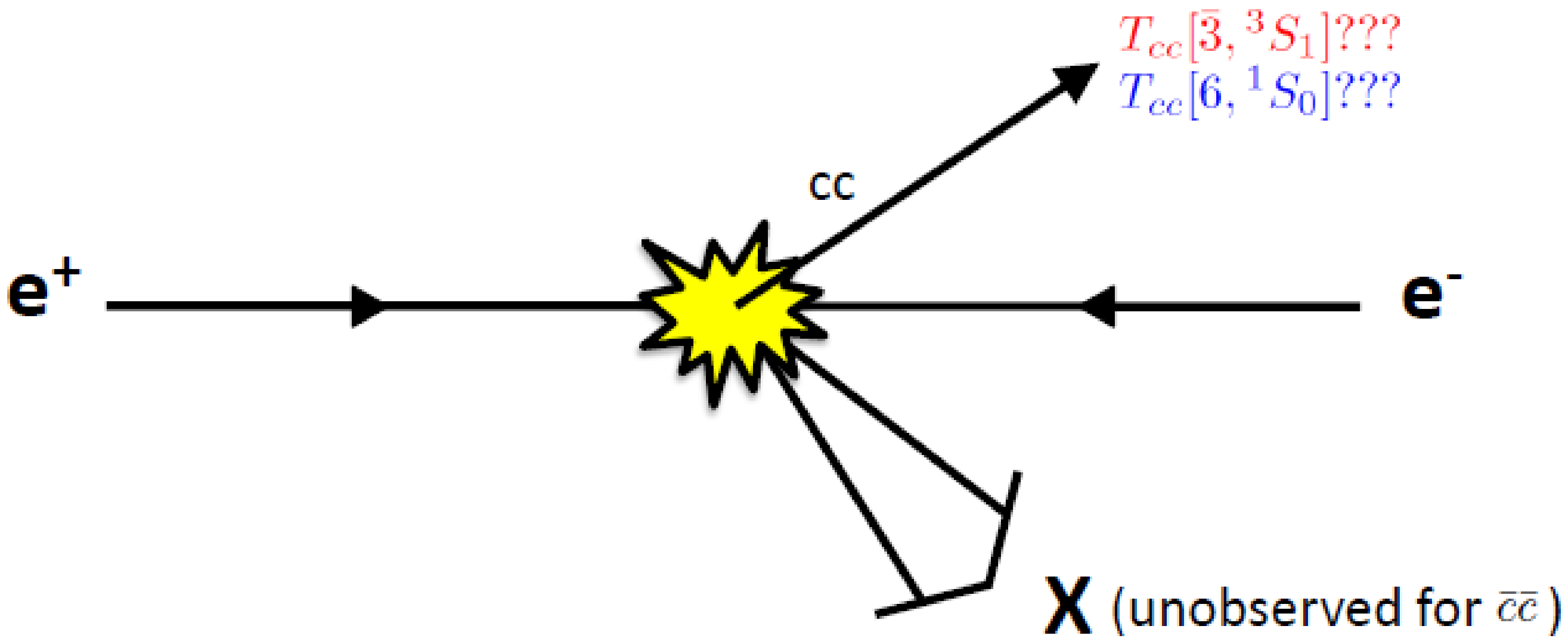
Tcc: production

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

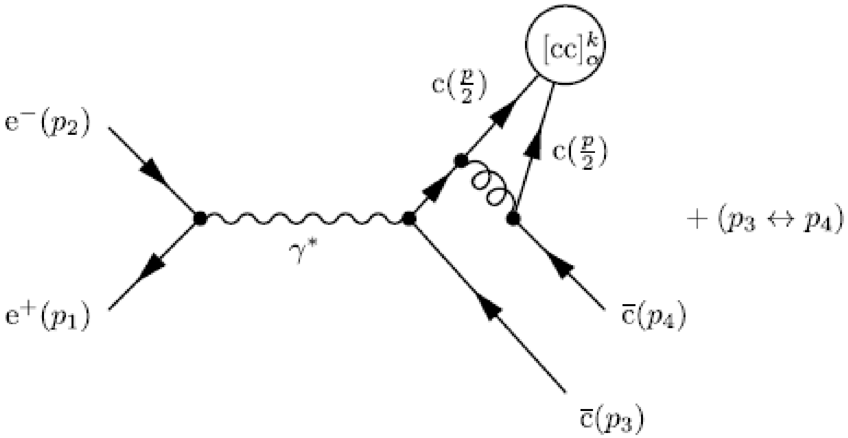
A. Del Fabbro, D. Janc, M. Rosina, D. Treleani, PRD71, 014008 (2005)

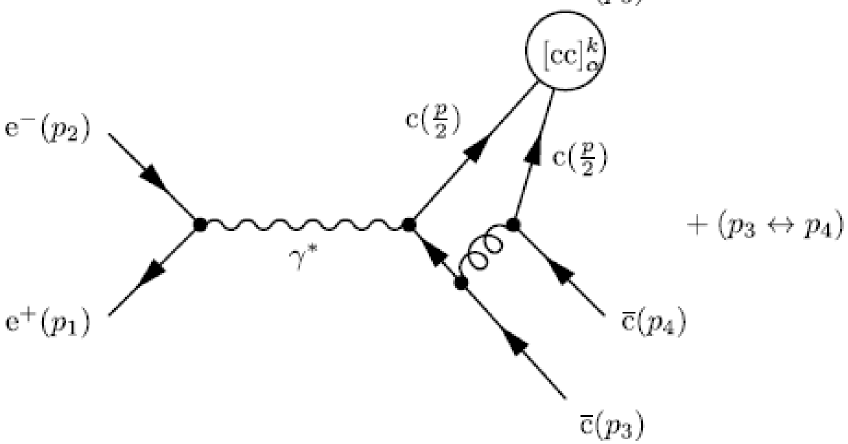
T_{cc} production in $e^+e^- \to T_{cc} + X$



Same framework in discussing Xicc production in
PLB 568, 135 (2003), J.P. Ma, Z.G. Si

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





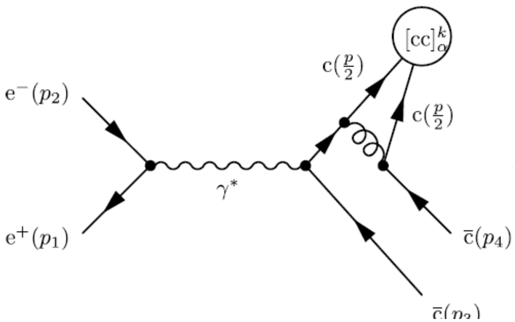
Framework: NRQCD

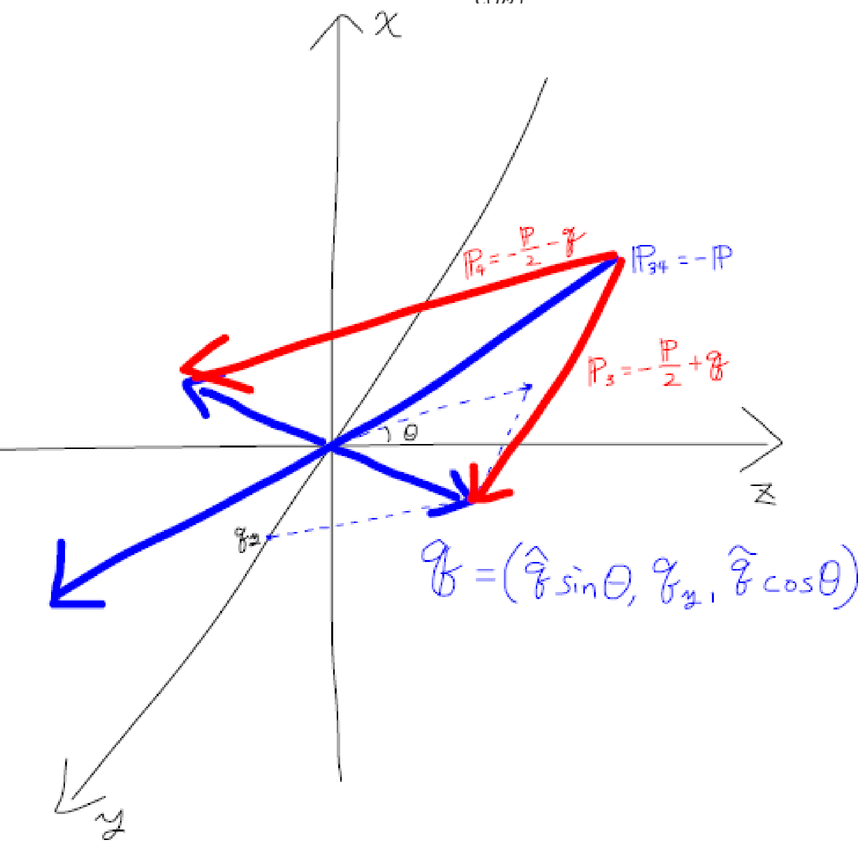
Inclusive Ξ_{cc} production:
J.P. Ma , Z.G. Si,
Phys. Lett. B 568, 135 (2003).

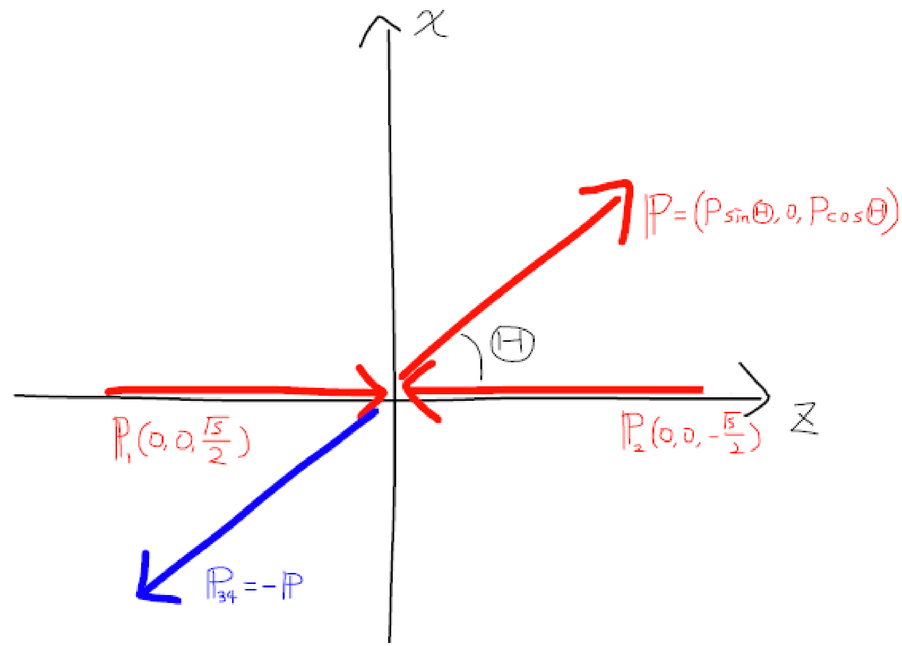
$$\langle \mathcal{O}^k(\mathrm{T_{cc}}[\alpha])\rangle\Big|_{k=\mathrm{LO}} = \begin{cases} h_{[\bar{\mathbf{3}},{}^3\mathrm{S}_1]} & \text{for } \alpha = [\bar{\mathbf{3}}, {}^3\mathrm{S}_1] \\ h_{[\mathbf{6},{}^1\mathrm{S}_0]} & \text{for } \alpha = [\mathbf{6}, {}^1\mathrm{S}_0] \end{cases}$$

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

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



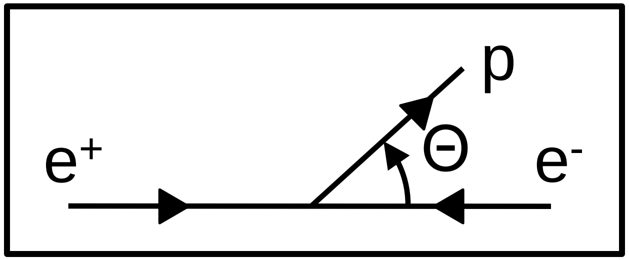


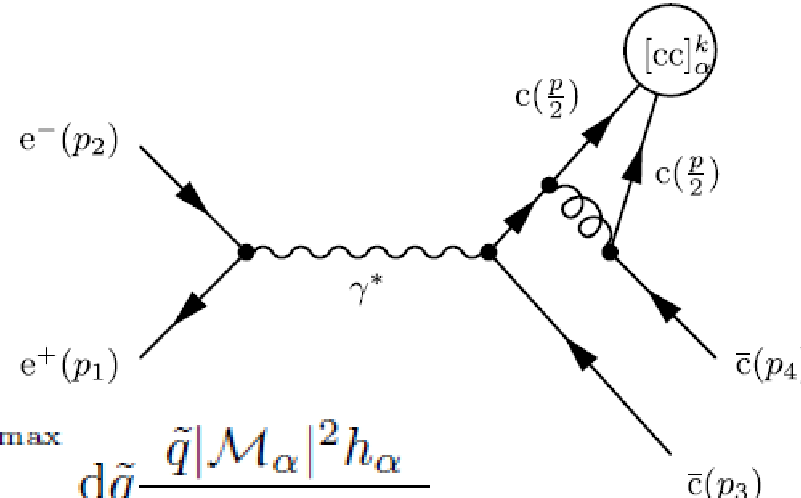


$$p^\mu = (E_p, p\sin\Theta, 0, p\cos\Theta)$$

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

$\mathrm{T_{cc}}$ production i$\mathrm{e^+e^-} \to \mathrm{T_{cc}} + \mathrm{X}$



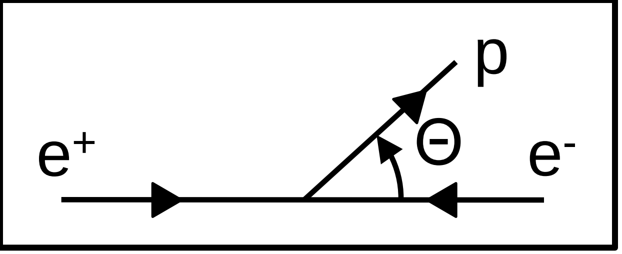


$$\frac{d\sigma_\alpha}{dp\, d\cos\Theta} = \frac{1}{(2\pi)^4}\frac{p^2}{16 m_c s E_p}\int_0^{2\pi} d\theta \int_0^{\tilde{q}_{\max}} d\tilde{q}\frac{\tilde{q}|\mathcal{M}_\alpha|^2 h_\alpha}{q_y(E_3+E_4)}$$

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

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

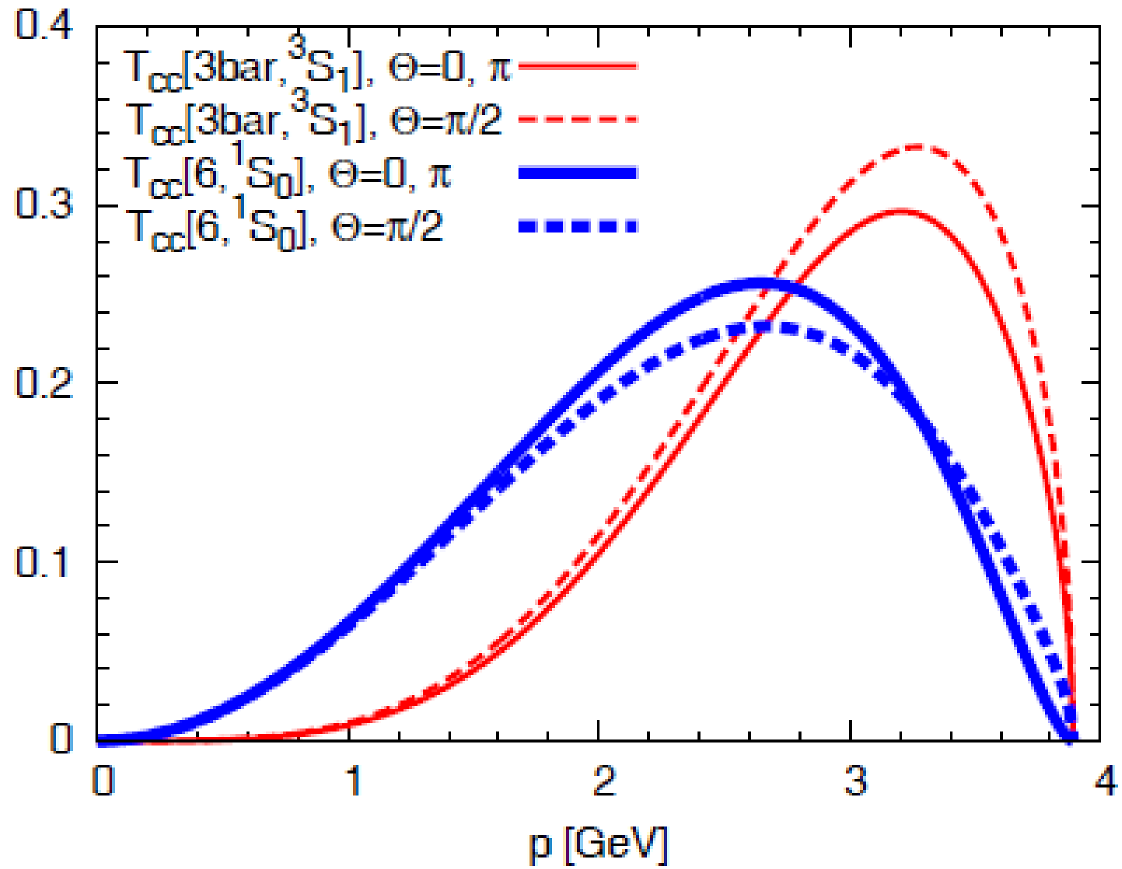
where s is the total energy squared, $E_{3,4} = \sqrt{m_c^2 + |p_{3,4}|^2}$, $\theta' = \theta - \Theta$, $A = \sqrt{s}(\sqrt{s}-2E_p)(\sqrt{s}-E_p)^2$, $B = 4(\sqrt{s}-E_p)^2$, and $C = 4p^2$.



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

[1/GeV]

Independent of h_α



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

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

$$\alpha_s = 0.212$$

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

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

- Peak position and height
- Θ-dependence
- …

Jiang, Wu, Liao, Zheng, Fang, PRD 86, 054021(2012)

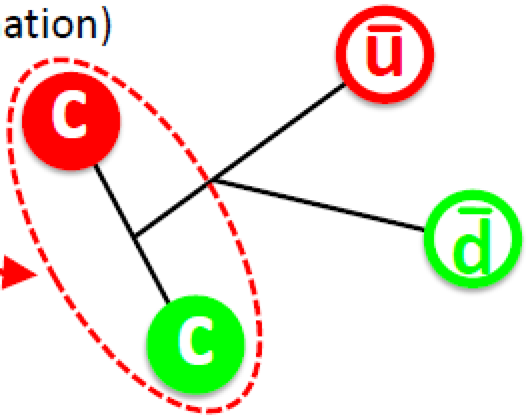
Total cross section

Estimate by quark model (crude approximation)

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

$$h_3 = \frac{1}{4\pi}|R_{\rm cc}^{\bar{\bf 3}_{\rm c}({}^3{\rm S}_1)}(0)|^2$$

$\approx 0.089\ \mathrm{GeV}^3$



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

$$h_6 = \frac{1}{4\pi}|R_{\rm cc}^{{\bf 6}_{\rm c}({}^1{\rm S}_0)}(0)|^2$$

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

Estimate by quark model (crude approximation)

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

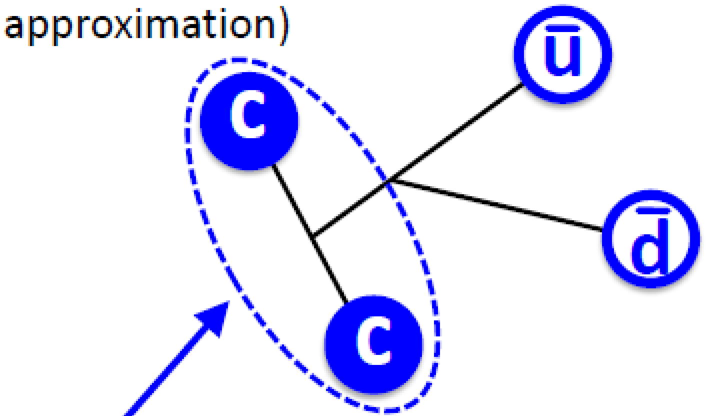
$$h_3 = \frac{1}{4\pi} |R_{\rm cc}^{\bar{\mathbf{3}}_{\rm c}({}^3{\rm S}_1)}(0)|^2$$

≈ 0.089 GeV^3

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

$$h_6 = \frac{1}{4\pi} |R_{\rm cc}^{\mathbf{6}_{\rm c}({}^1{\rm S}_0)}(0)|^2$$

≈ 0.054 GeV^3



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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

- Xicc (Belle)

  $\sigma \approx 150$ fb (hep-ph/0303145,Berezhnoy, Likhoded)

  $\sigma \approx 230$ fb (PLB 568, 135 (2003), J.P. Ma, Z.G. Si)

  $\sigma \approx (10\text{-}100)$ fb (PLB 721, 56 (2013), Hyodo et al)

- Tcc (Belle)

  $\sigma \approx 13.8$ fb, 4.1 fb for $T_{cc}[\bar{3}, {}^3S_1]$ and $T_{cc}[6, {}^1S_0]$,resp.

  (another parameter set: 65 fb, 21 fb)

Why are they not observed by Belle

where L_{int}=1000 fb^{-1} ?

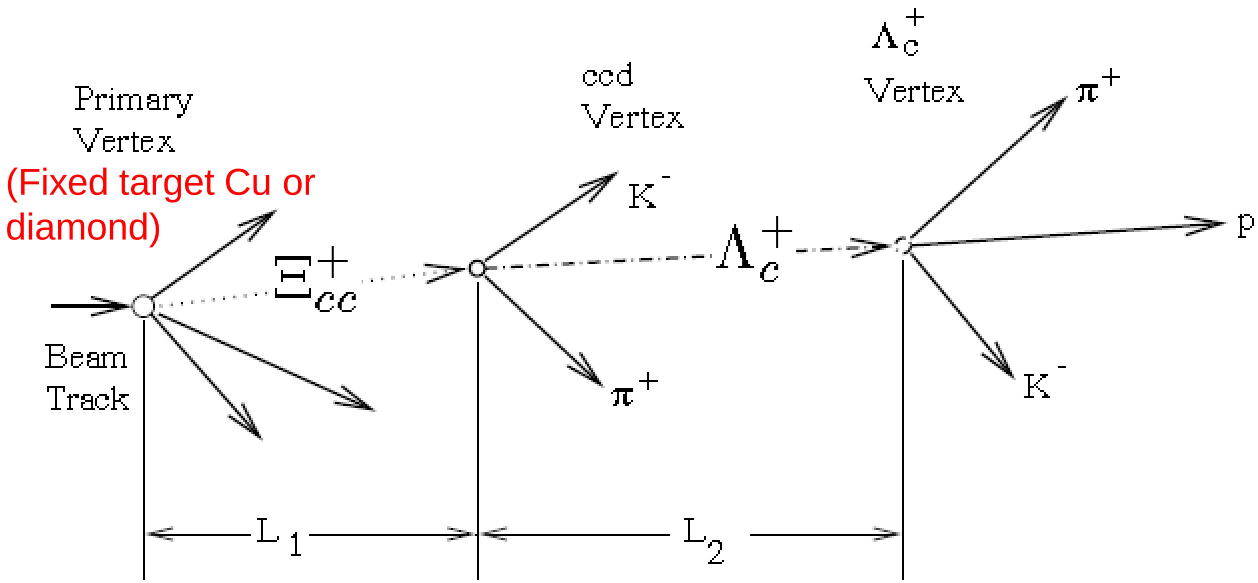
Maybe backgroud affects

Search for Ξcc

- SELEX in

$\Lambda_c^+ K^- \pi^+$

$\& \ pD^+ K^-$



Schematic of $\Xi_{cc}^+ \rightarrow \mathrm{K}^- \pi^+ \Lambda_\mathrm{c}^+$

The SELEX experiment at Fermilab is a 3-stage magnetic spectrometer [3]. The negative 600 GeV/c Fermilab Hyperon Beam had about equal fluxes of π^- and Σ^-. The positive beam was 92% protons. For charm momenta in a range

(Taken from hep-ex/0209075)

BELLE, LHCb, BABAR, & FOCUS give negative results!

SELEX: much smaller number of Λc(~1650) than BABAR (~600,000) and Focus(~19,500)

Search for Ξcc & Tcc

- Exist? Why? How?
- Only produced in Σp collision?

  Special production mechanism:

  (dds)(uud)→dcc+... ? ⇐ Vcs=0.97,Vcd=0.23
- BELLE&BABAR: 4π records more reactions
- Theories: observation at Belle is possible
- Maybe it could be observed

  if backgrounds are suppressed

Search for Ξcc & Tcc

- Signal: $$e^+e^- \rightarrow c\bar{c}c\bar{c} + ... \rightarrow \Xi_{cc}^+ + X \rightarrow (\underbrace{\Lambda_c^+}_{\rightarrow K^-\pi^+p} K^-\pi^+) + X$$

  background: $$e^+e^- \rightarrow c\bar{c} + ... \rightarrow \underbrace{\Lambda_c^+}_{\rightarrow K^-\pi^+p} + X$$

  (1) background >> signal;

  (2) used Kπ in reconstructing Ξcc may also be from X

- Suggestion: 3-jet event shape

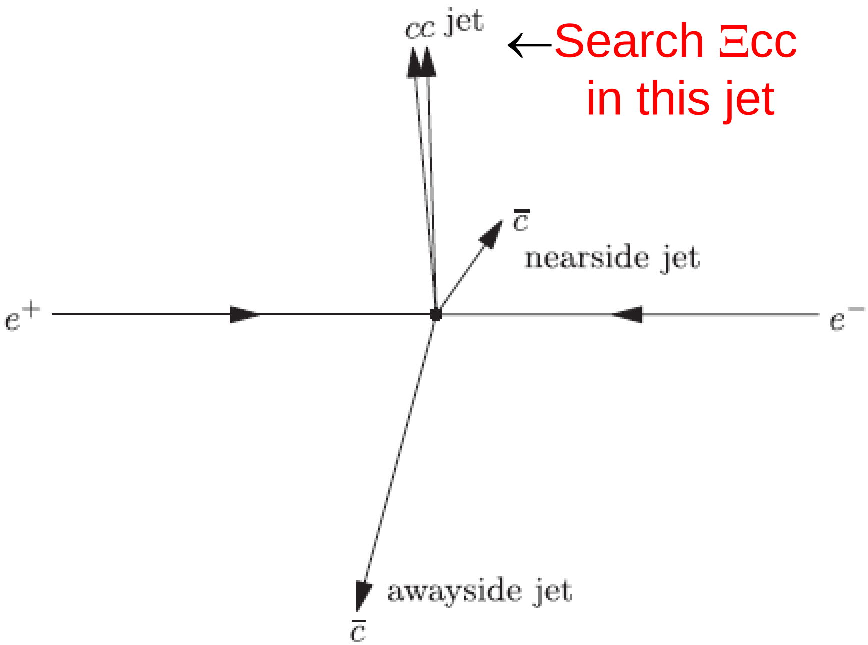
  [Jin et al., PRD 89, 094006 (2014)]

Jade algorithm: $$y_{ij} = \frac{(p_i + p_j)^2}{E_{cm}^2}$$

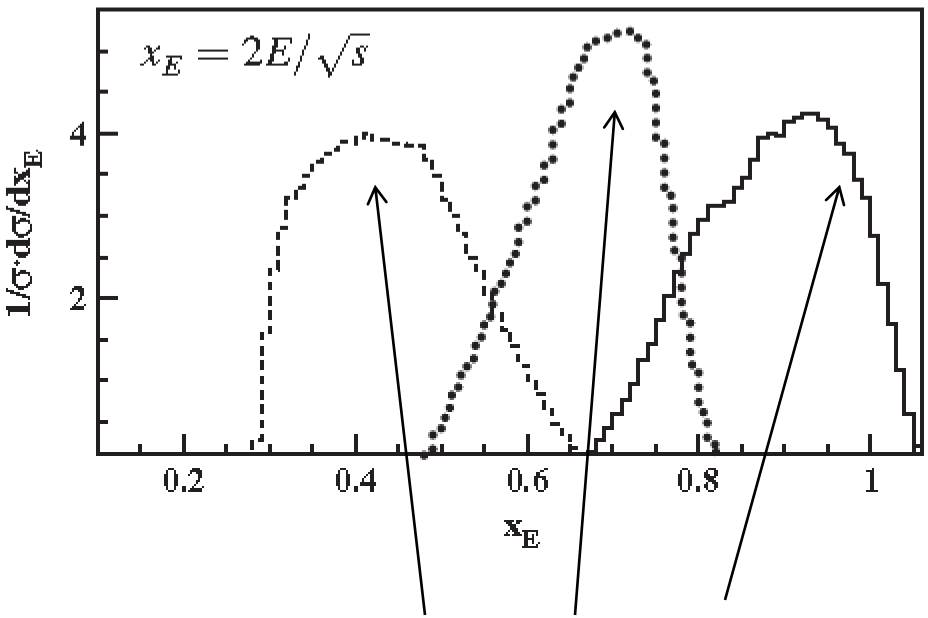
2 partons/particles in one jet when: $y_{ij} < y_{cut}$

Search for Ξcc & Tcc

- 3-jet event in Ξcc production



←Search Ξcc
in this jet



Jet-3, Jet-2, Jet-1(cc jet)

From angular distribution analysis:
Jet-2=awayside jet

Most/second/least energetic jet
=cc/awayside/nearside jet

Search for Ξ_{cc} & Tcc

- The 3 jets may be identified from energy ordering and jet direction;
- Once identified, backgrounds can be significantly suppressed while signals are not affected;
- Look for them in Λ_c^+K^-π^+, D^-K^-π^+ in Jet-1;
- Average of Ξcc & Ξcc* (Tcc & Tcc*): further study to distinguish them.

Summary

- Model calculations favor the existence of both Xicc and Tcc.
- Searching for them in e^+e^- process is possible

  ($\sigma \approx 10 \sim 230$ fb, L_{int}=1000 fb^{-1} at Belle)
- Suppression of background is helpful
- More studies: on going ...

Thank you very much!