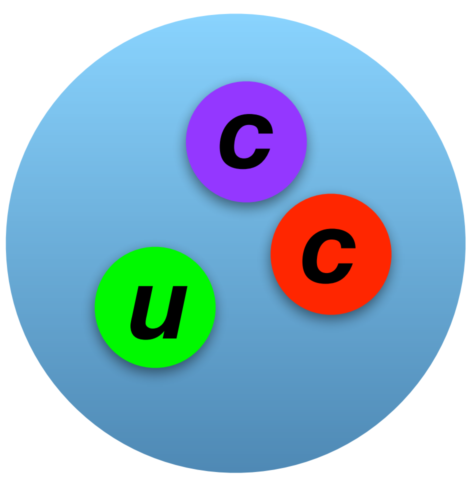
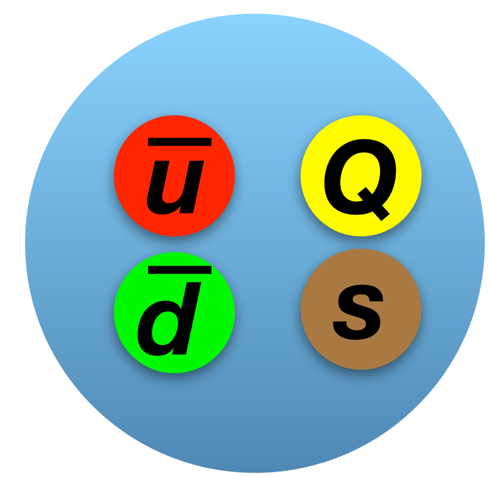
Discovery Potentials

— Ξ_{cc} and tetraquarks



Fu-Sheng Yu

Lanzhou University



5th workshop on the XYZ particles

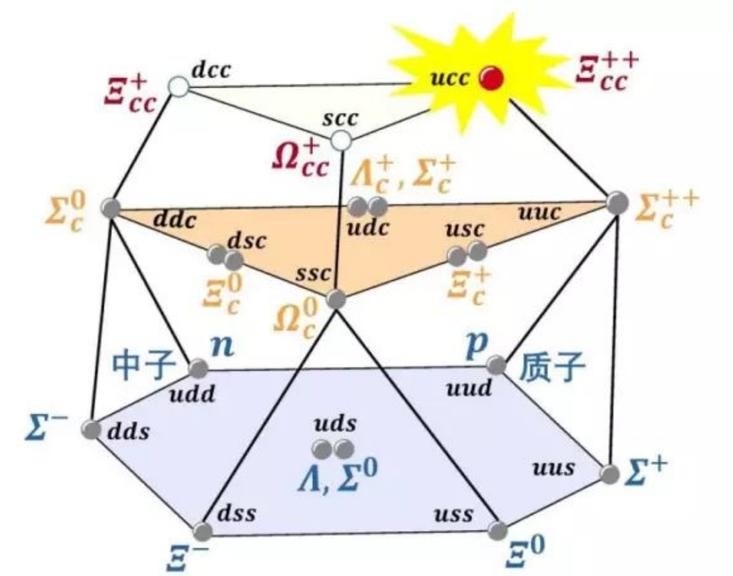
Zhengzhou, 2018.10.23

Outline

1. Discovery potentials of doubly charmed baryons
   — Weak decays
2. Discovery potentials of open-flavor heavy tetraquarks
   — Prompt production

Double-charm-baryon Searches

- **History** See Jibo’s talk



Doubly charmed baryons exists in the quark model: SU(3)

- **Evidence**

$\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ SELEX, ’02 $\Xi_{cc}^{+} \to p D^{+} K^{-}$ SELEX, ’04

- **But not confirmed**

$\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ FOCUS, ‘02

$\Xi_{cc}^{+(+)} \to \Xi_c^{0} \pi^{+}(\pi^{+})$ and $\Lambda_c^{+} K^{-} \pi^{+}(\pi^{+})$ Babar,’06; Belle, ’06,’13

$\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ LHCb, ‘13

Double-charm-baryon Searches

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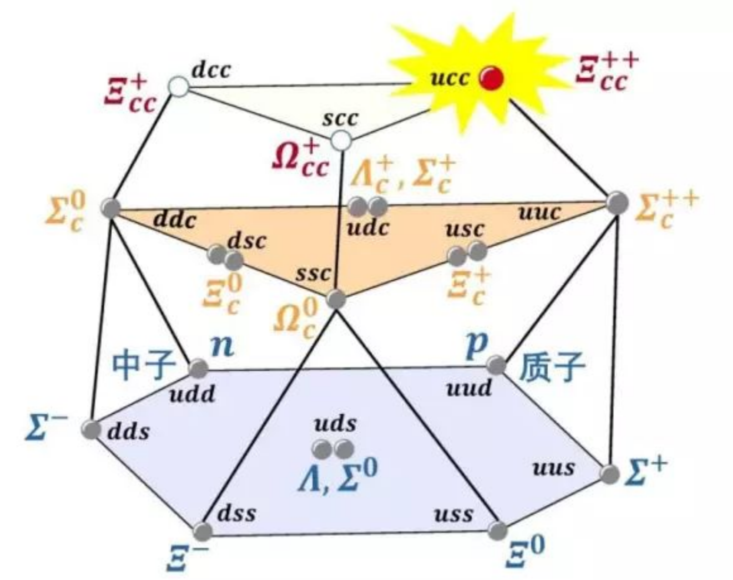

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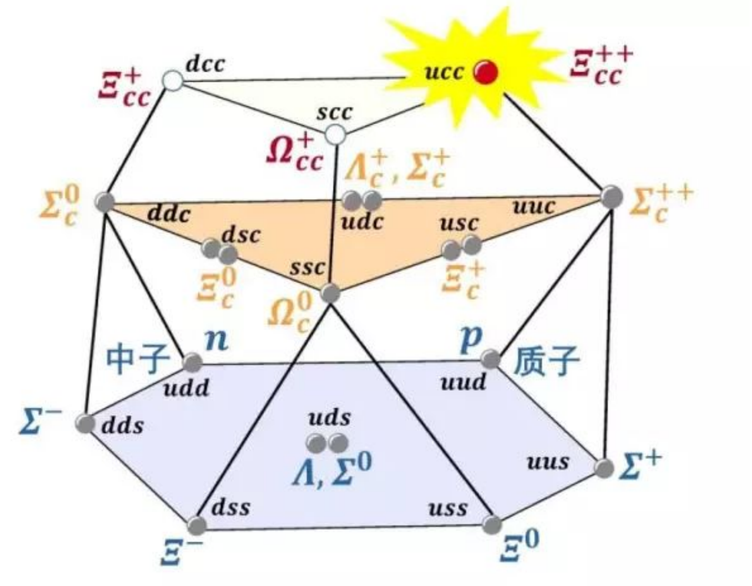
Misleading !!

Double-charm-baryon Searches

- **History** See Jibo's talk



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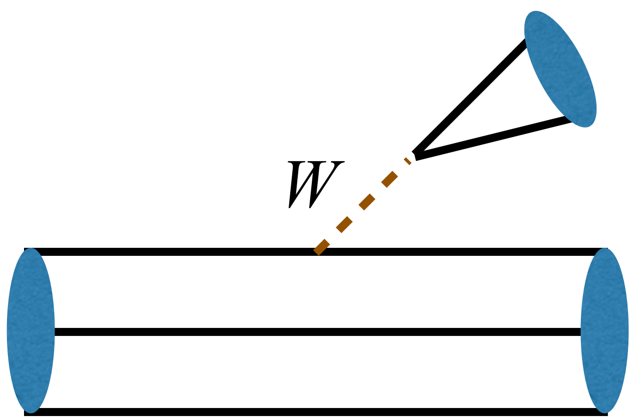
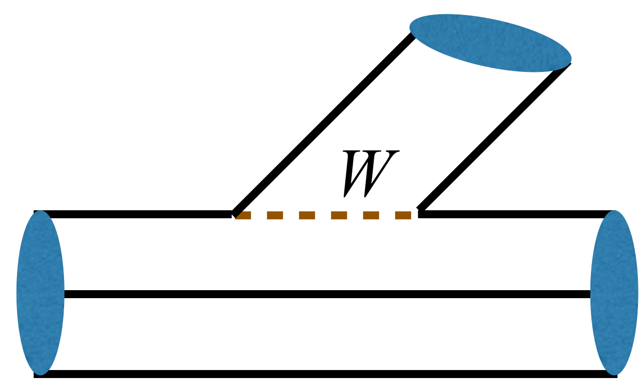
Misleading !!

2016, LHCb Run II, Jibo: What discovery channel?

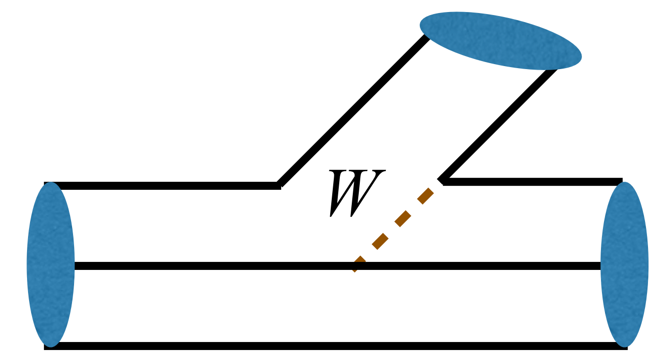
Topologies of two-body non-leptonic charmed baryon decays



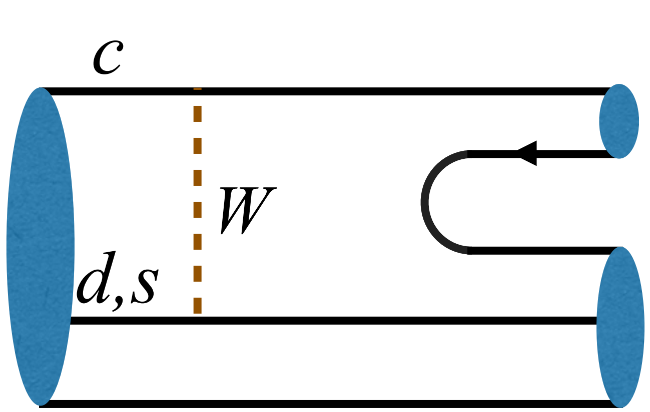
(T)
color-favored tree emitted



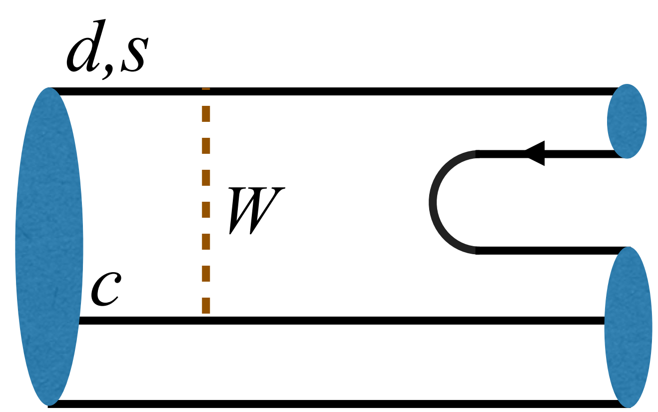
(C)
color-suppressed emitted



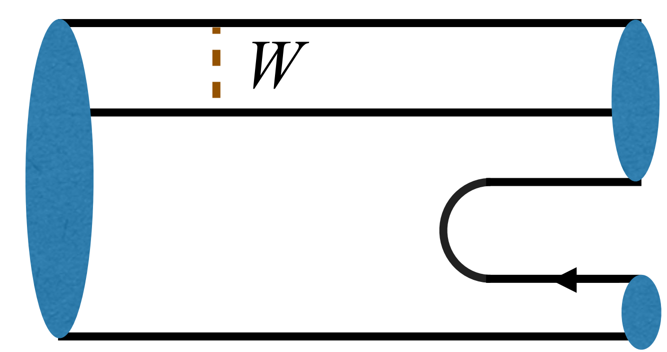
(C′)
color-commensurate



(E_1)
W-exchange 1



(E_2)
W-exchange 2



(B)
Bow tie

Hierarchy in heavy quark expansion

SCET: $|C/T| \sim |C'/T| \sim |E/T| \sim O(\Lambda_{QCD}/m_Q)$, $|B/E| \sim O(\Lambda_{QCD}/m_Q)$,

Leibovich, Ligeti, Stewart, Wise, '04

b decay: $|C/T| \sim |C'/T| \sim |E/T| \sim |P/T| \sim O(\Lambda_{QCD}/m_Q) \sim 0.2$

$|B/E| \sim O(\Lambda_{QCD}/m_Q) \sim 0.2$

c decay: $|C/T| \sim |C'/T| \sim |E/T| \sim O(\Lambda_{QCD}/m_Q) \sim 1$

$|B/E| \sim O(\Lambda_{QCD}/m_Q) \sim 1$

$|P| \sim 0$

Hierarchy in heavy quark expansion

SCET: |C/T|~|C'/T|~|E/T|~$O(\Lambda_{QCD}/m_Q)$, |B/E|~$O(\Lambda_{QCD}/m_Q)$,

[Leibovich, Ligeti, Stewart, Wise, '04]

c decay: |C/T|~|C'/T|~|E/T|~$O(\Lambda_{QCD}/m_Q)\sim 1$

|B/E|~$O(\Lambda_{QCD}/m_Q)\sim 1$

|P|~0

$$\lambda_{sd} \equiv V_{cs}^* V_{ud}$$

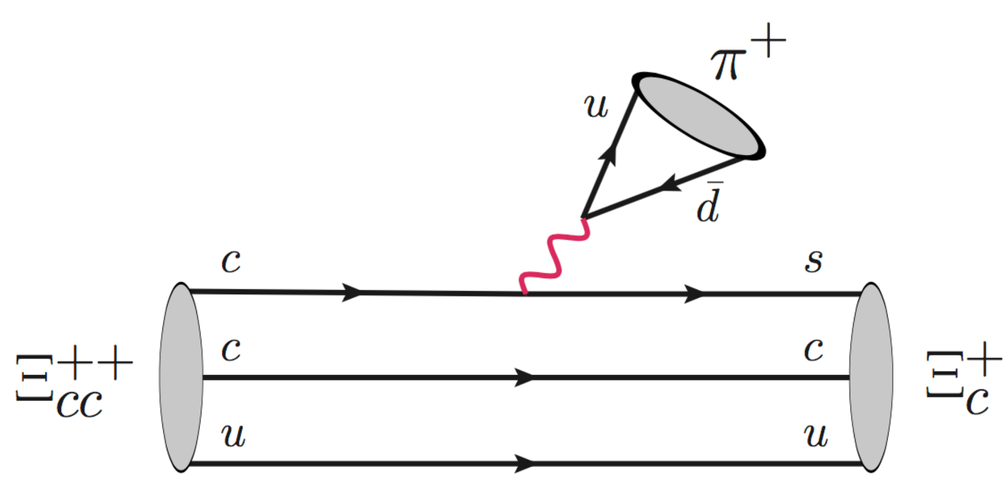
	Modes	Representation	$\mathcal{B}_{\rm exp}$
Λ_c^+	$p\overline{K}^0$	$\lambda_{sd}(C+E)$	$(3.04 \pm 0.17)\%$
	$\Lambda^0\pi^+$	$\lambda_{sd}(T-C'+B-E)/\sqrt{2}$	$(1.24 \pm 0.08)\%$
	$\Delta^{++}K^-$	$\lambda_{sd}E$	$(1.18 \pm 0.27)\%$

Λ_c decay would help to understand dynamics

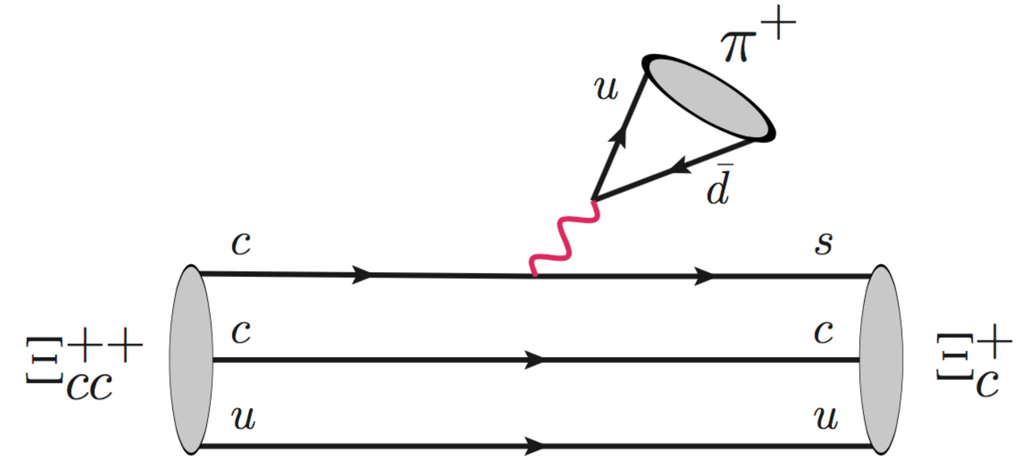
Short-distance contributions

— external W-emission diagrams

- Calculate form factors in light-front quark model
- Calculate amplitudes using factorization approach



Short-Distance Contributions



- External W-emission processes using factorization approach

$$A(\Xi_{cc} \to \mathcal{B}_c M)_{\rm SD}$$
$$= \frac{G_F}{\sqrt{2}} V^*_{cq'} V_{uq} a_1(a_2) \langle M | \bar{u}\gamma^\mu (1-\gamma_5) q | 0 \rangle \langle \mathcal{B}_c | \bar{q}' \gamma_\mu (1-\gamma_5) | \Xi_{cc} \rangle$$

- Relative branching fractions are reliable

$$\mathcal{B}(\Xi_{cc}^+ \to \Xi_c^0 \pi^+)/\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) = \mathcal{R}_\tau = 0.25 \sim 0.37,$$
$$\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ \pi^+)/\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) = 0.056,$$
$$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \ell^+ \nu)/\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) = 0.71,$$

Uncertainties of form factors are mostly cancelled

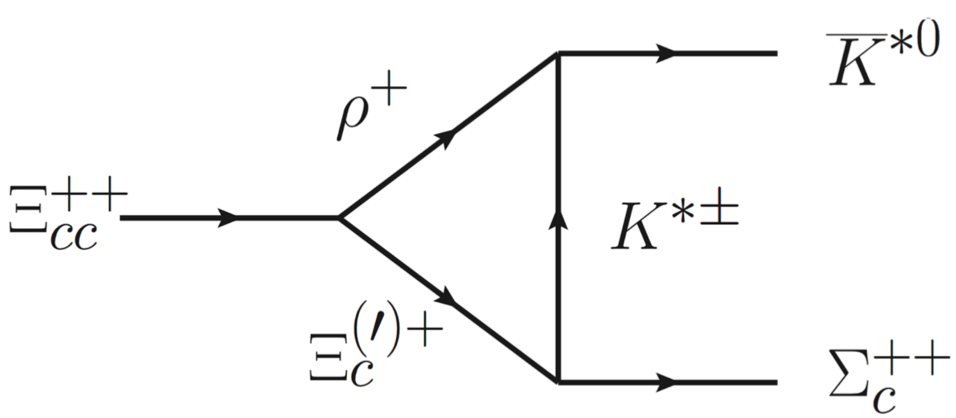
$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+)$ **is the largest one**

Long-distance contributions

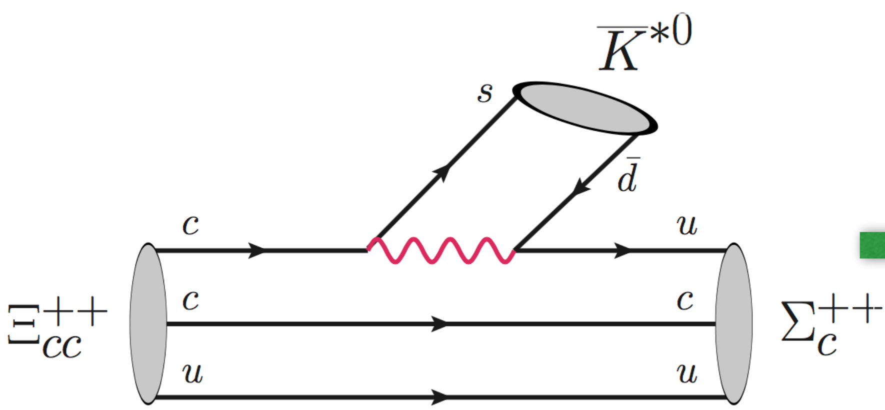
— final-state interacting (FSI) effects

  — significantly large in charm decays

- Calculate rescattering effects

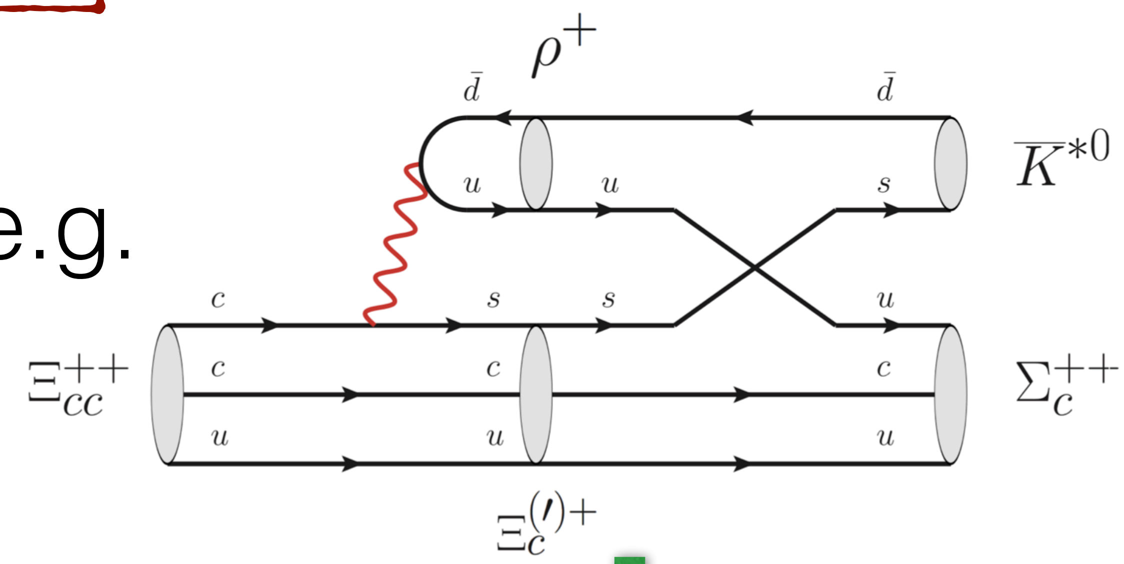


$$\boxed{\Xi_{cc}^{++} \to \Sigma_c^{++} \overline{K}^{*0}}$$

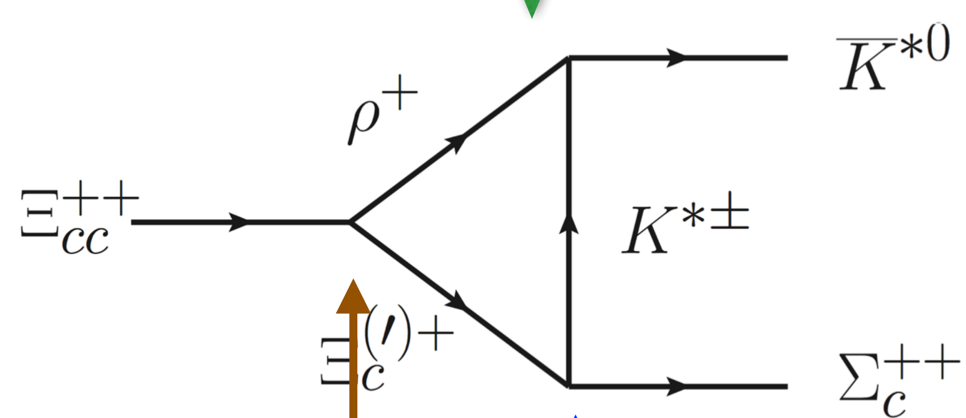


FSI

e.g.



Rescattering mechanism of the final-state interacting effects



Absorptive part:

weak vertex

rescattering

$$\mathrm{Abs}\mathcal{M}(p_i \to p_f q) =$$

$$\frac{1}{2}\sum_j \left(\prod_{k=1}^{j} \int \frac{d^3 p_k}{(2\pi)^3 2E_k}\right)(2\pi)^4 \quad \times \delta^4\Big(p_f + q - \sum_{k=1}^{j} p_k\Big) \boxed{M(p \to \{p_k\})} \boxed{T^*(p_f q \to \{p_k\})}$$

Relative Branching Fractions with long-distance contributions

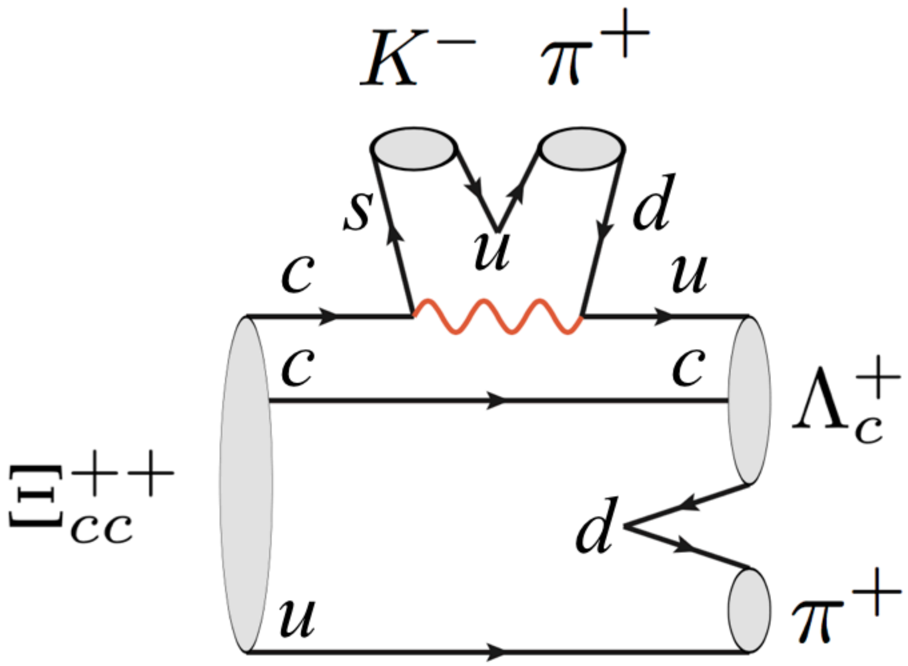
Baryons	Modes	$\mathcal{B}_{\rm LD}$
$\Xi_{cc}^{++}(ccu)$	$\Sigma_c^{++}(2455)\overline{K}^{*0}$	defined as 1
	pD^{*+}	0.04
	pD^{+}	0.0008
$\Xi_{cc}^{+}(ccd)$	$\Lambda_c^{+}\overline{K}^{*0}$	$(\mathcal{R}_\tau/0.3)\times 0.22$
	$\Sigma_c^{++}(2455)K^{-}$	$(\mathcal{R}_\tau/0.3)\times 0.008$
	$\Xi_c^{+}\rho^{0}$	$(\mathcal{R}_\tau/0.3)\times 0.04$
	ΛD^{+}	$(\mathcal{R}_\tau/0.3)\times 0.004$
	pD^{0}	$(\mathcal{R}_\tau/0.3)\times 0.002$

Largest

Theoretical uncertainties are still very large, but reduced in the relative branching fractions

$$\boxed{\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+}$$

$\overline{K}^{*0}$ or $(K\pi)_{\text{S-wave}}$



$$\Xi_{cc}^{++} \to \Sigma_c^{++}(2455)\overline{K}^{*0}$$

is actually a four-body decay

$\Sigma_c^{++}(2455)$ or $\Sigma_c^{++}(2520)$

In charmed hadron decays,
final-state particles are not energetic,
and easily located in the momentum range of resonances

$$\mathcal{B}(\Xi_{cc}^{++} \to \Sigma_c^{++}(2455)\overline{K}^{*0}) = \left(\frac{\tau_{\Xi_{cc}^{++}}}{300\,\text{fs}}\right) \times (3.8 \sim 24.6)\%$$

It would be expected to be as large as $\mathcal{O}(10\%)$

$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$$ **v.s.** $$\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$$

SELEX's discovery channel,
LHCb measured

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	$\Xi_c^+\rho^0$	$(\mathcal{R}_\tau/0.3)\times 0.04$
	ΛD^+	$(\mathcal{R}_\tau/0.3)\times 0.004$
	pD^0	$(\mathcal{R}_\tau/0.3)\times 0.002$

$\tau \times (\sim 3)$

Br × 5

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

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

$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ has more signal yields around one more order than $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$

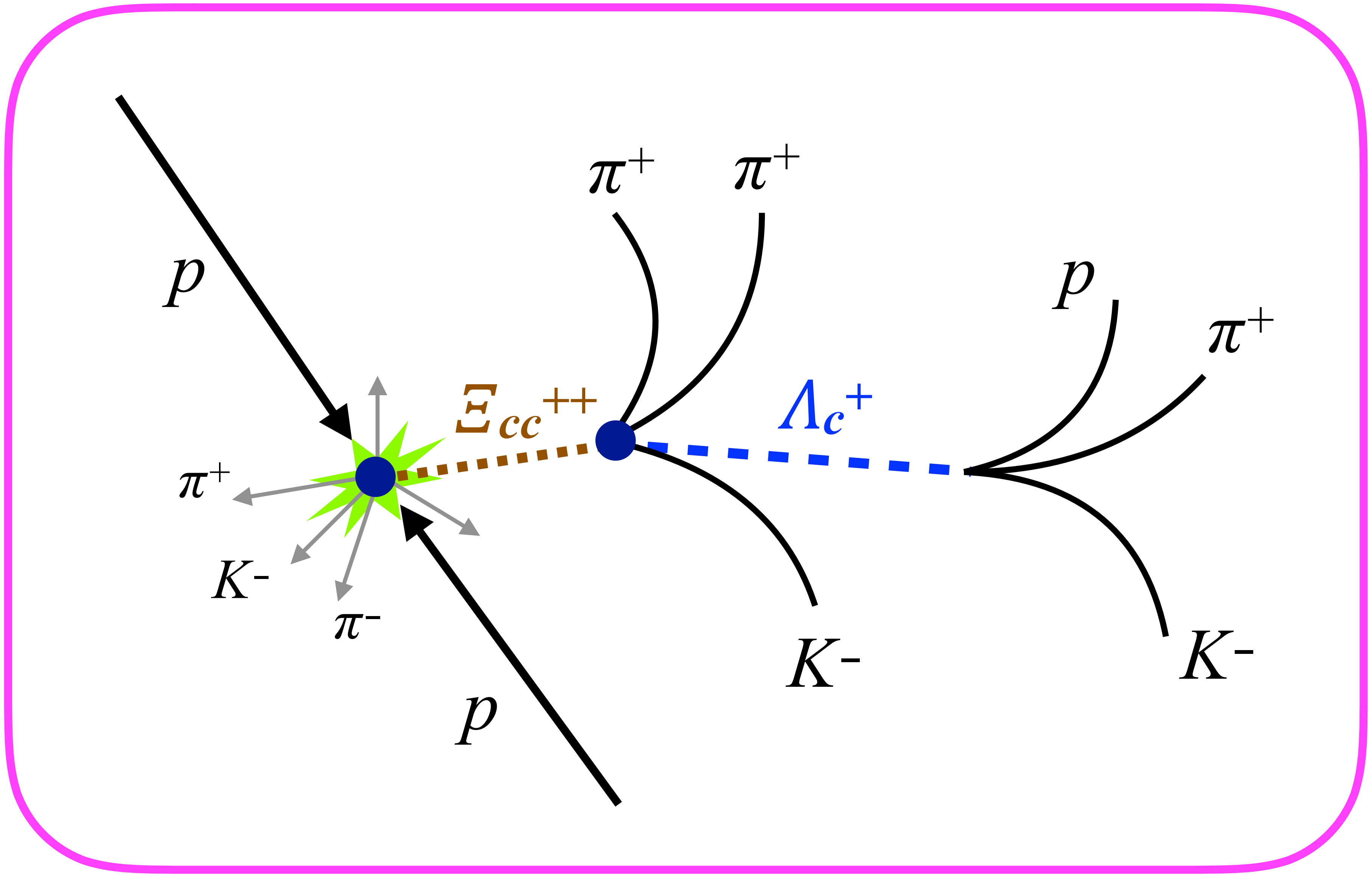
Lifetimes

Literatures	Ξ_{cc}^{++} (fs)	Ξ_{cc}^{+} (fs)
Karliner, Rosner, 2014	185	53
Kiselev, Likhoded, Onishchenko, 1998	430±100	110±10
Kiselev, Likhoded, 2002	460±50	160±50
Chang, Li, Li, Wang, 2007	670	250
Cheng, Shi, 2018	300	45

But much less ambiguity of ratio of lifetimes

$$\boxed{\mathcal{R}_\tau \equiv \frac{\tau_{\Xi_{cc}^{+}}}{\tau_{\Xi_{cc}^{++}}} = 0.25 \sim 0.37}$$

$$\boxed{\tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^{+})}$$



Longer Lifetime is important in exp

colliders [41–43], the longer lifetime of the Ξ_{cc}^{++} baryon should make it significantly easier to observe than the Ξ_{cc}^{+} baryon in such experiments, due to the use of real-time (online) event-selection requirements designed to reject backgrounds originating from the primary interaction point.

[LHCb, PRL119,112001(2017)]

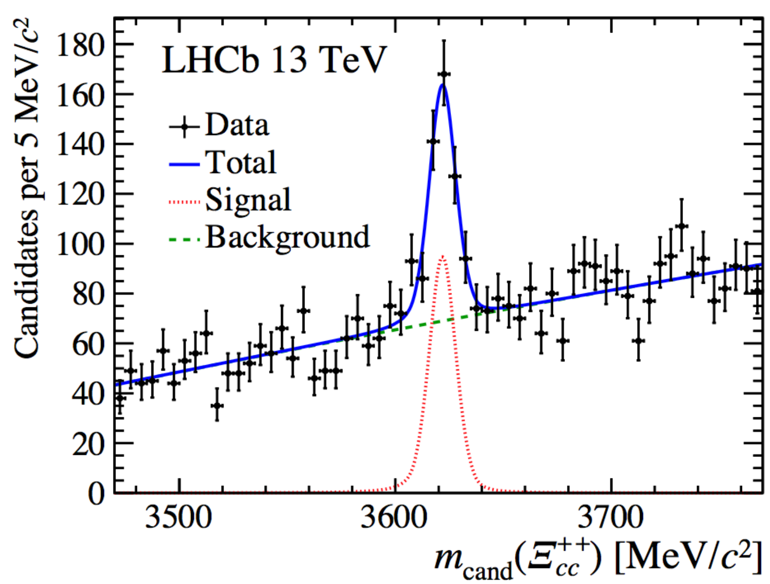
Discovery Potentials of Doubly Charmed Baryons

Abstract

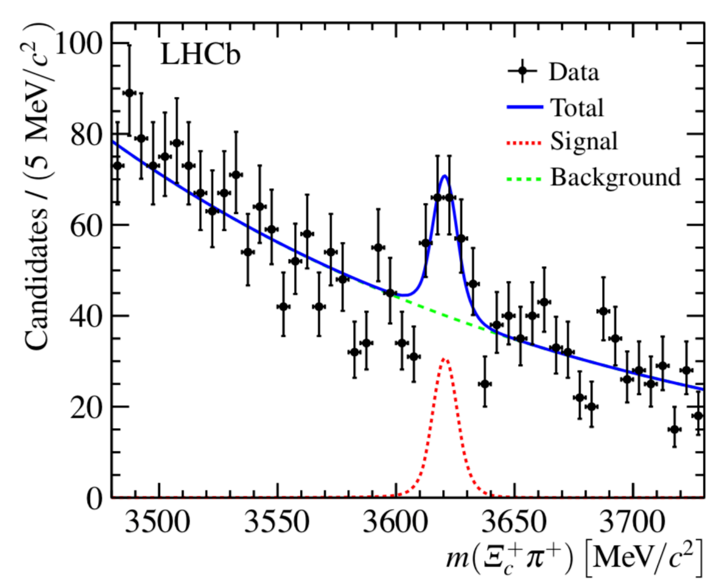
The existence of doubly heavy flavor baryons has not been well established experimentally so far. In this Letter we systematically investigate the weak decays of the doubly charmed baryons, Ξ_{cc}^{++} and Ξ_{cc}^{+}, which should be helpful for experimental searches for these particles. The long-distance contributions are first studied in the doubly heavy baryon decays, and found to be significantly enhanced. Comparing all the processes, $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ are the most favorable decay modes for experiments to search for doubly heavy baryons.

FSY, Jiang, Li, Lü, Wang, Zhao, 1703.09086

July 2017



$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$$

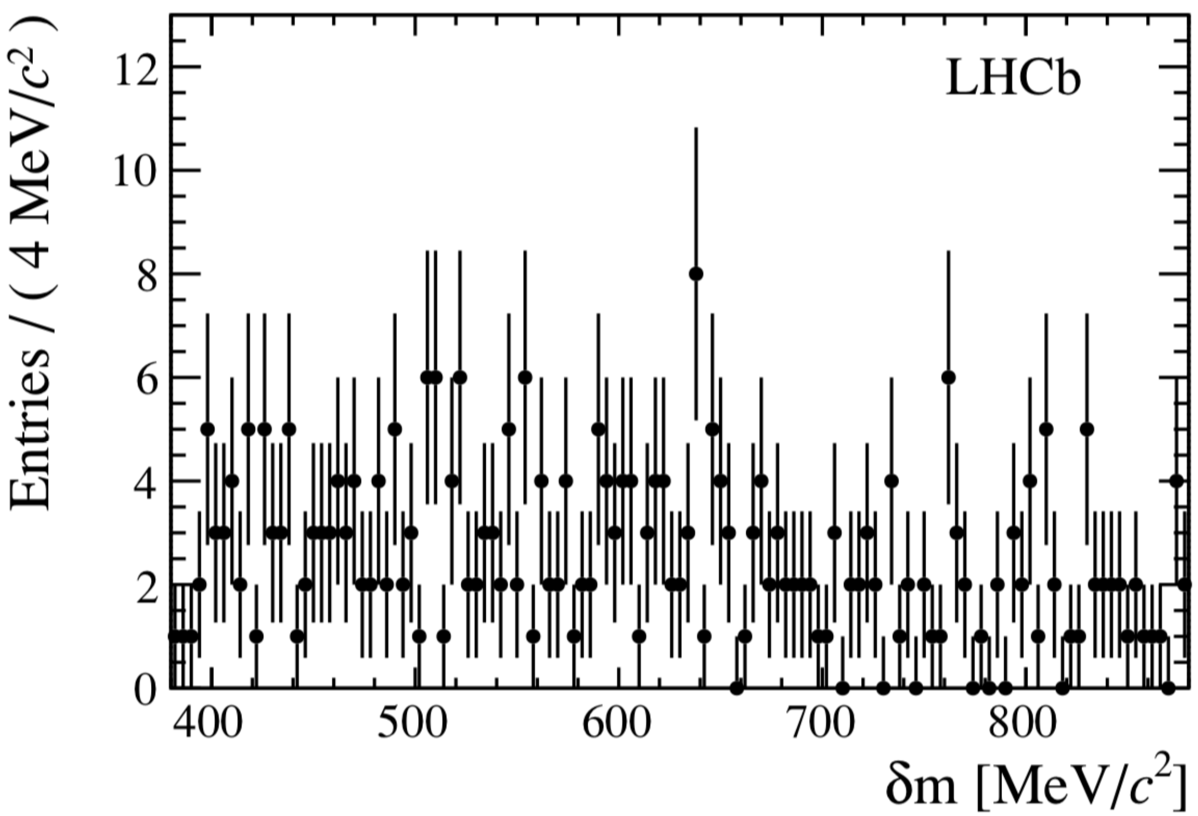


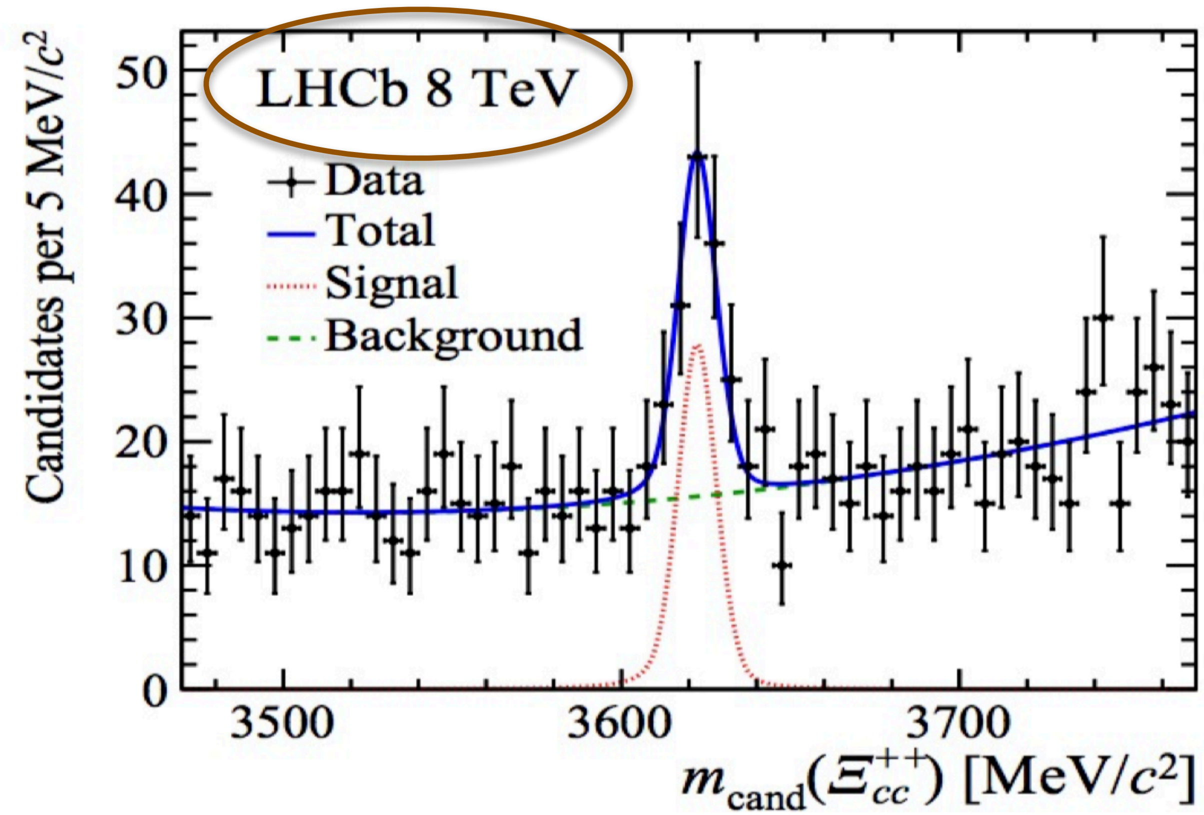
July 2018

$$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$$

LHCb observed Ξ_{cc}^{++}

LHCb Run-I Data Analysis





$$\boxed{\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}}$$

$$\boxed{\Xi_{cc}^{++} \to \Lambda_c^{+} K^{-} \pi^{+} \pi^{+}}$$

No signal

[LHCb, JHEP 12 (2013)090]

Observation

See Jibo's talk

It could be observed in 2013 if using the correct mode !!!

List of studies on weak decays

1. Doubly heavy baryon weak decays: $\Xi_{bc}^0 \to pK^-$, $\Xi_{cc}^+ \to \Sigma_c^{++}K^-$ 1701.03284

2. Discovery potentials of doubly charmed baryons 1703.09086

$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+, \quad \Xi_c^+ \pi^+$$

3. Weak decays of doubly heavy baryons: the 1/2 → 1/2 case 1707.02834

4. Weak decays of doubly heavy baryons : SU(3) analysis 1707.06570

5. Weak decays of doubly heavy baryons : decay constant 1711.10289

6. Weak decays of doubly heavy baryons : Multi-body decays 1712.03830

7. Weak decays of doubly heavy baryons: the 1/2 → 3/2 case 1805.10878

8. Weak decays of doubly heavy baryons: $\mathscr{B}_{cc} \to \mathscr{B}_c V$ 1810.00541

9. Weak decays of triply heavy baryons 1803.01476

……

WG：兰州大学、高能所、上海交大、内蒙古大学、烟台大学、南京师大

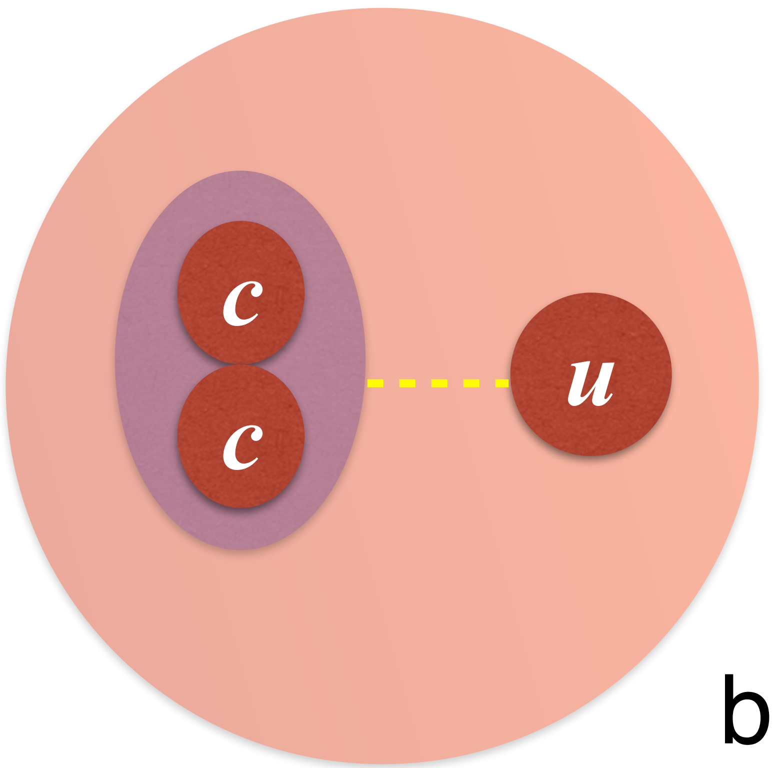
Prospect of theoretical studies

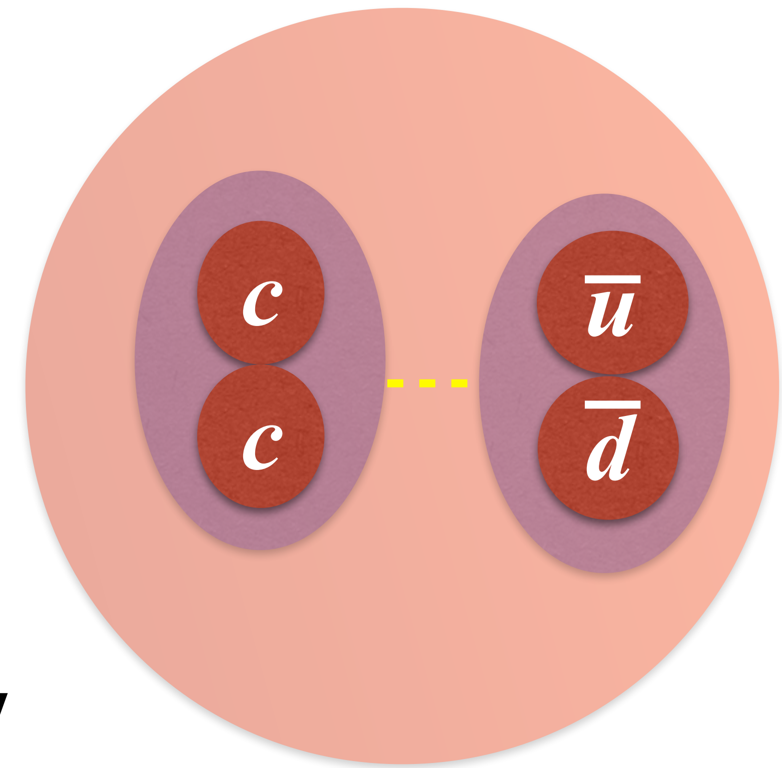
1. Discovery potentials of Xi_cc^+, Omega_cc^+
2. Discovery potentials of Xi_bc
3. Semileptonic decays
4. Effective theory of doubly heavy baryons
5. Lifetimes?
6. New physics and CPV?
7. Omega_ccc?

……

WG：兰州大学、高能所、上海交大、内蒙古大学、烟台大学、南京师大

What can we do further?





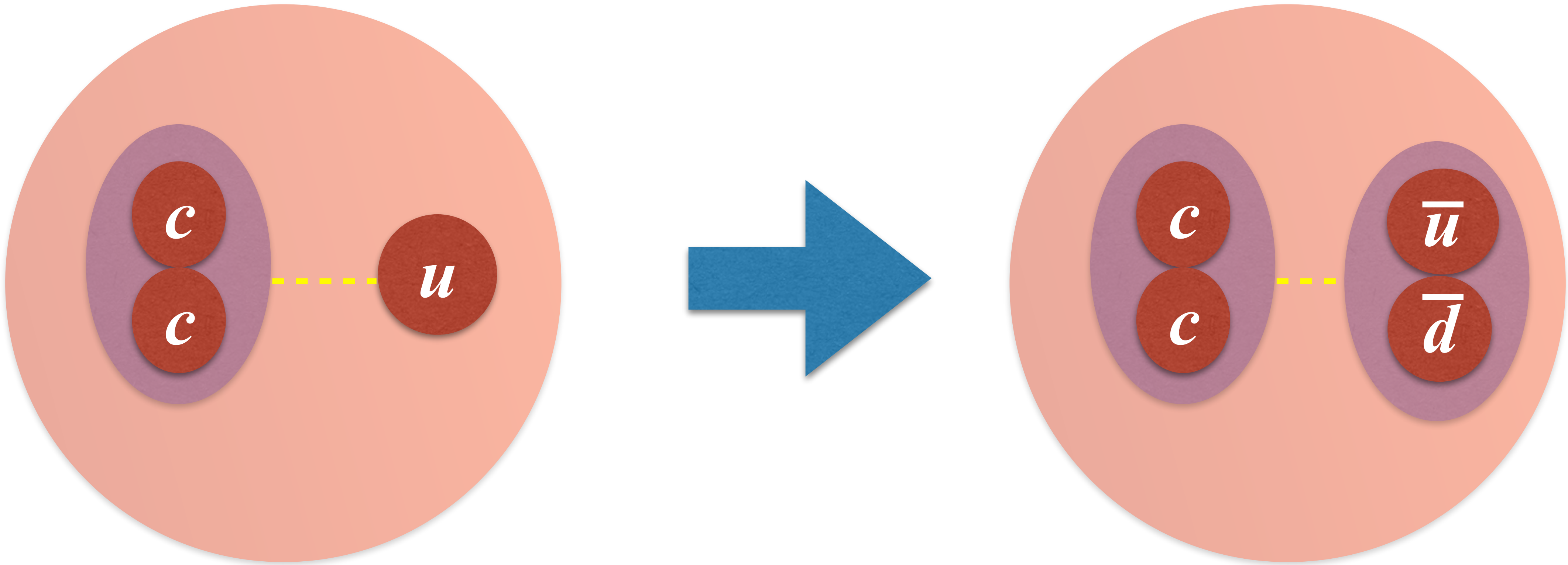
binding energy of cc-diquark

Ξ_{cc}^{++}

cc-Tetraquark

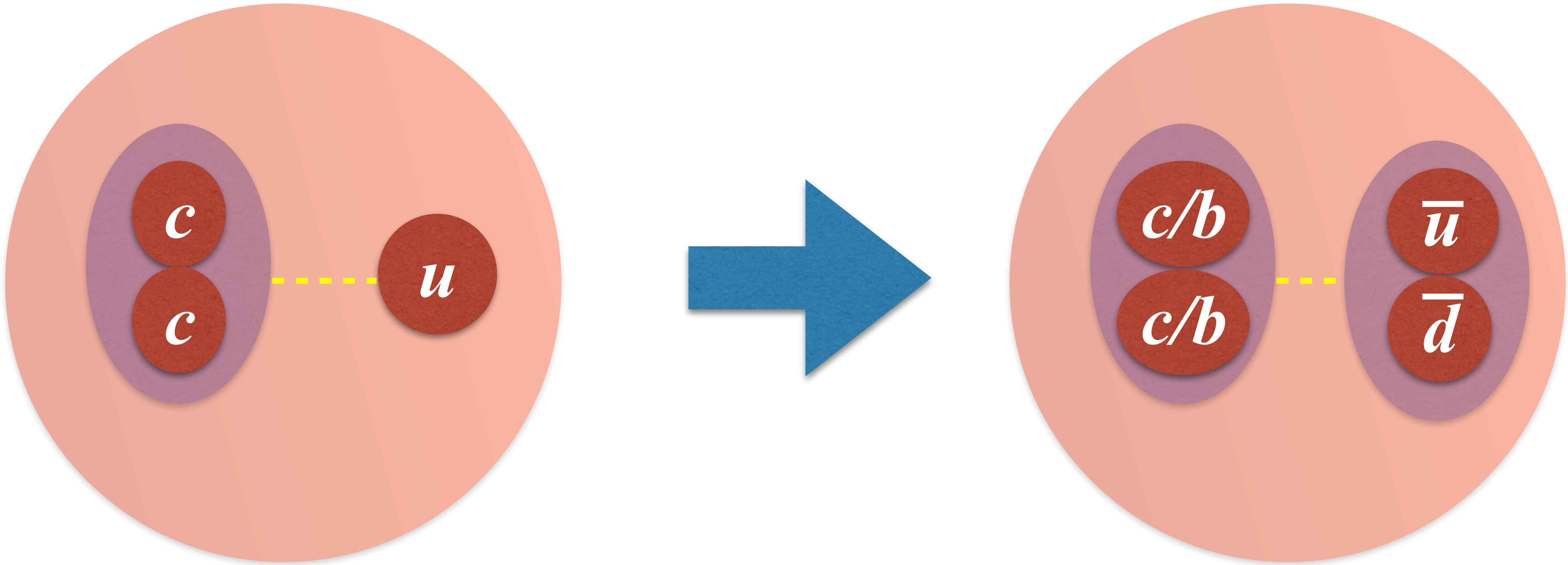
QCD: q: color triplet
$\bar{q}\bar{q}$: color triplet

Searching for tetraquarks?



Ξ_{cc}^{++} cc-Tetraquark

1. If observed by directly **produced at pp collision**, it must be a resonance, but **not kinematic effect**
2. If observed via weak decays with the mass **deeply** below threshold, it is signal of **tetraquark**

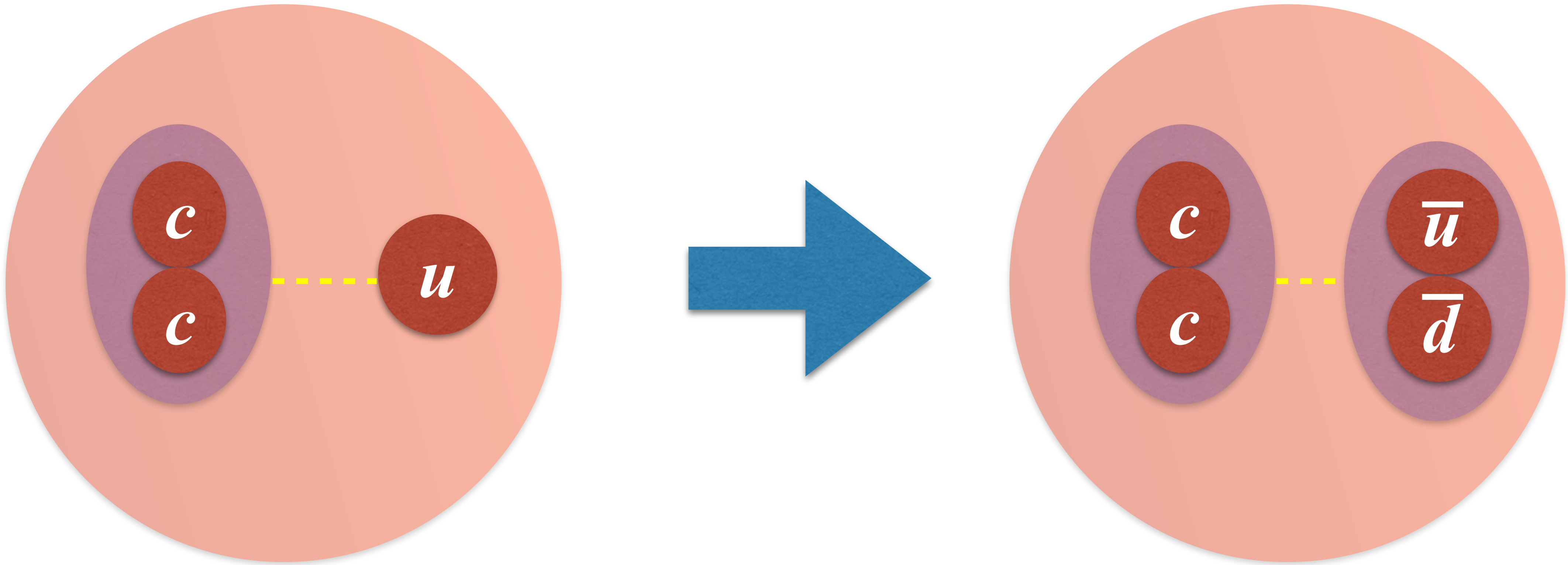


Ξ_{cc}^{++}

T_{cc}, T_{cb}, T_{bb}

Ader, Richard, Taxil, PRD'82
Du,Chen,Chen,Zhu,PRD'13
Karliner, Nussinov, JHEP'13
Francis,Hudspith,Lewis,Maltman,PRL'17
Bicudo,Scheunert,Wagner,PRD'17
Luo,Chen,Liu,Liu,Zhu,EPJC'17

Karliner, Rosner, PRL'17
Eichten, Quigg, PRL'17
Z.G.Wang, Yan, EPJC'17
Mehen, PRD'17
Yan, Zhong, Zhu, '18
Ali, Qin, Wang, '18
Xing, Zhu, '18



$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$$

strong → $D^0 D^+$

or weak → $D^+ K^- \pi^+$

yield ~ 300 @ LHCb2016

[LHCb, PRL119,112001(2017)]

Production suppressed by one order

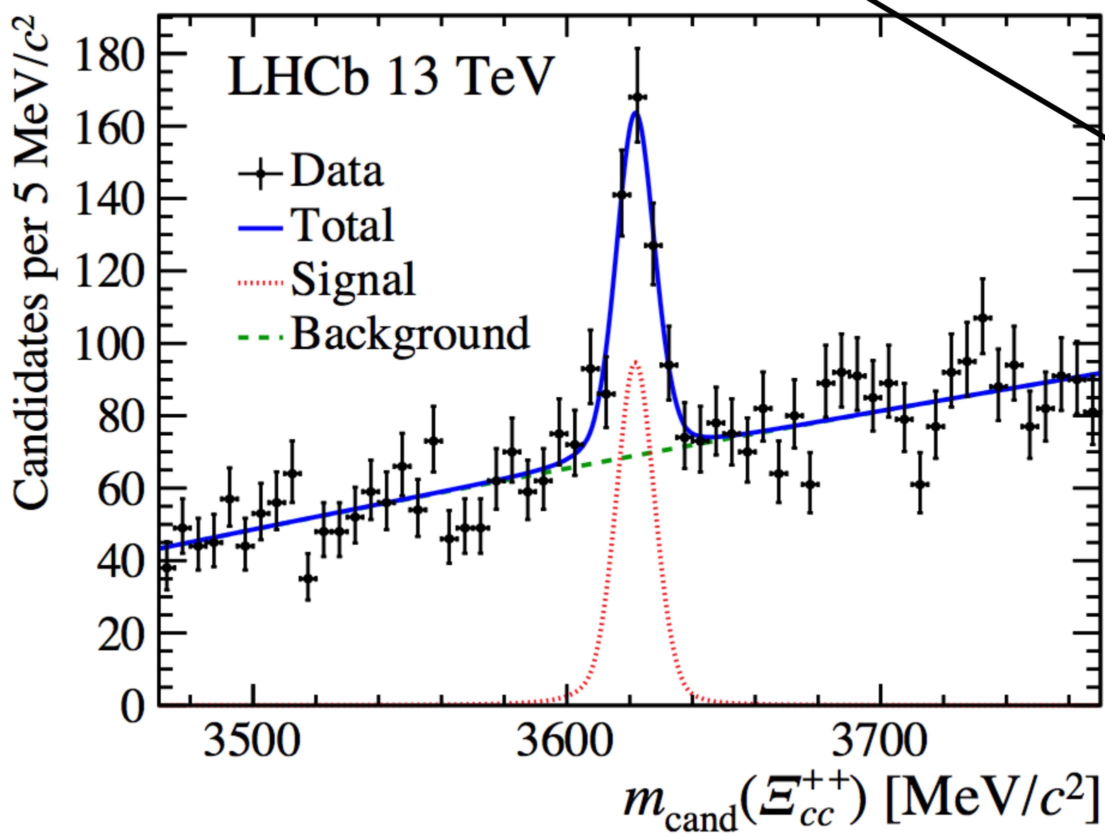
$$f_{B_u} : f_{\Lambda_b} \sim 1 : 0.1$$

Waiting for more data @ LHCb RUN-II

$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$$

yield ~ 300 @ LHCb2016

[LHCb, PRL119,112001(2017)]



strong decay of $T_{cc} \to D^0 D^+$
or weak decay of $T_{cc} \to D^+ K^- \pi^+$

- Production suppressed by one order

$$f_{B_u} : f_{\Lambda_b} \sim 1 : 0.1$$

- Expected O(10) events
- Waiting more data @ LHCb RUN-II for *cc*-tetraquark

$$\frac{\sigma(b)\times Br(b\to J/\Psi)}{\sigma(c)\times Br(c\to s)} \sim 10^{-3}$$

$\Rightarrow$ **Impossible** to observe T_{bc} & T_{bb} @ LHCb Run2

What are detectable?

More thinkings

1. What tetraquarks can be produced with enough data to be observed?

2. What potential state has larger threshold for more possibility with mass below threshold and hence decays weakly?

More thinkings

1. What tetraquarks can be produced with enough data to be observed?

doubly heavy → singly heavy

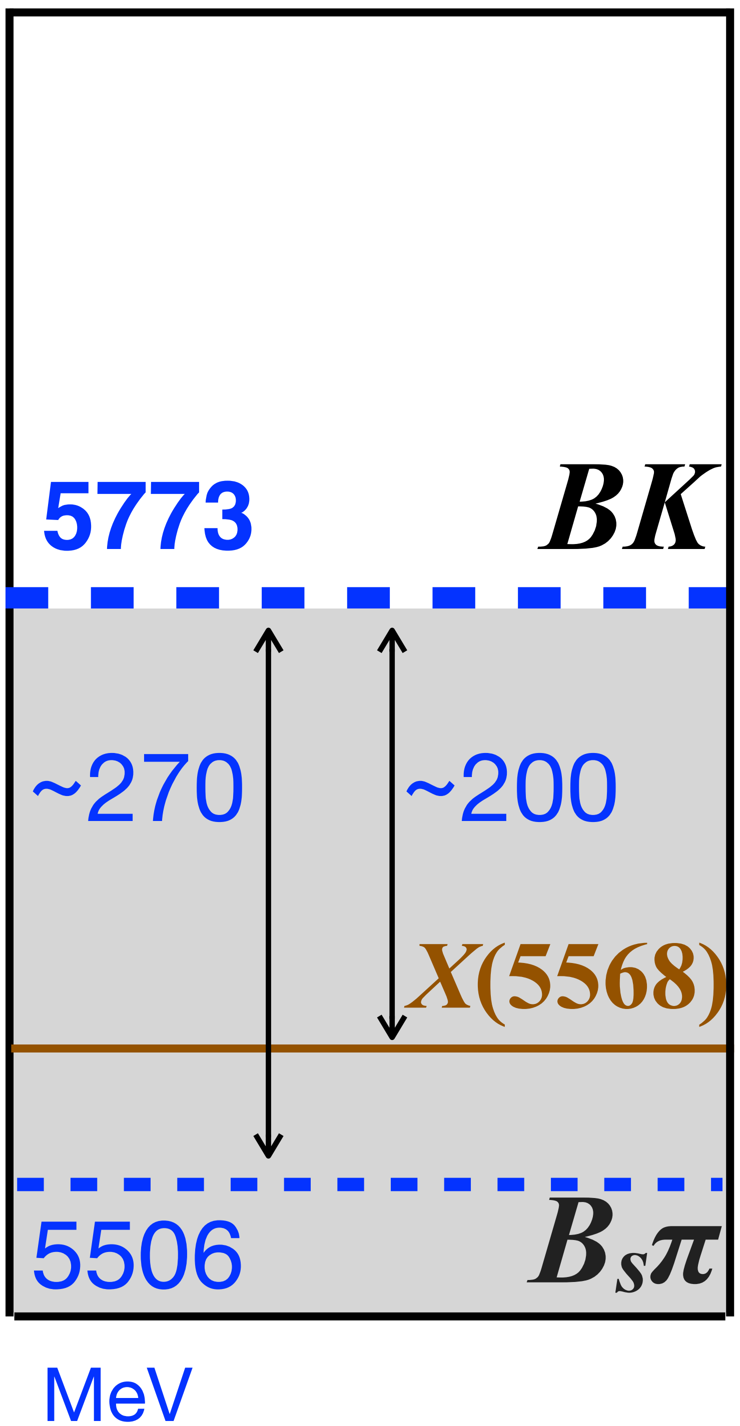
$$f_{B_c}/f_{B_u} \sim 0.1\%$$

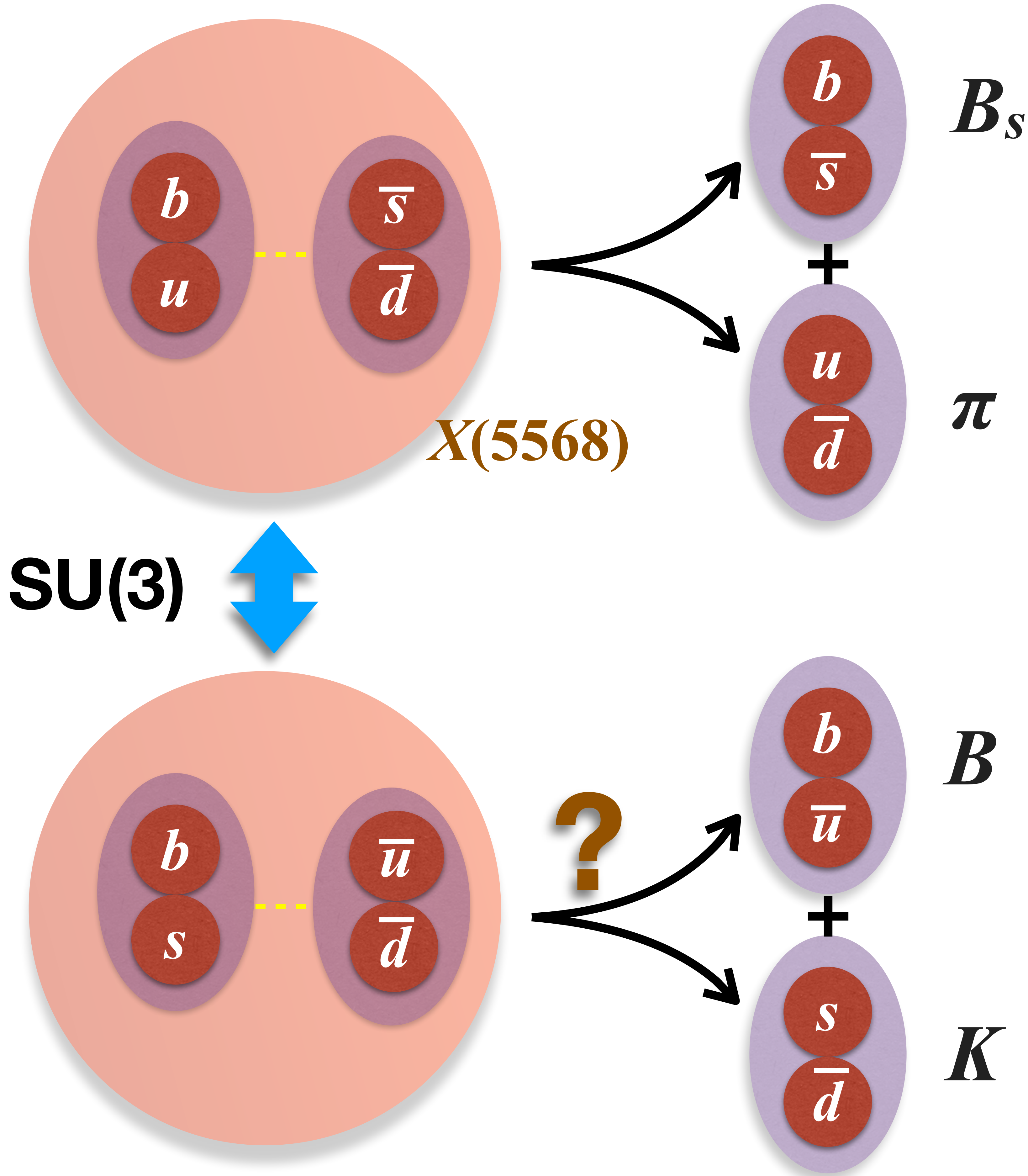
$$cc\bar{u}\bar{d} \to cu\bar{u}\bar{d},\ \ cd\bar{u}\bar{d},\ cs\bar{u}\bar{d} \qquad bs\bar{u}\bar{d}$$

Note that the question here is not whether tetraquarks exist.

But if exist, how to observe them?

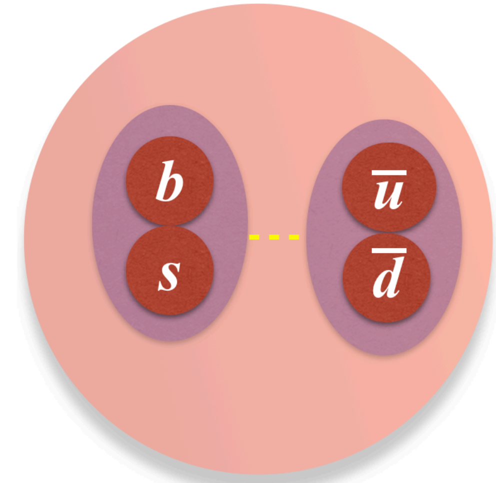
$[bs][\bar{u}\bar{d}]$



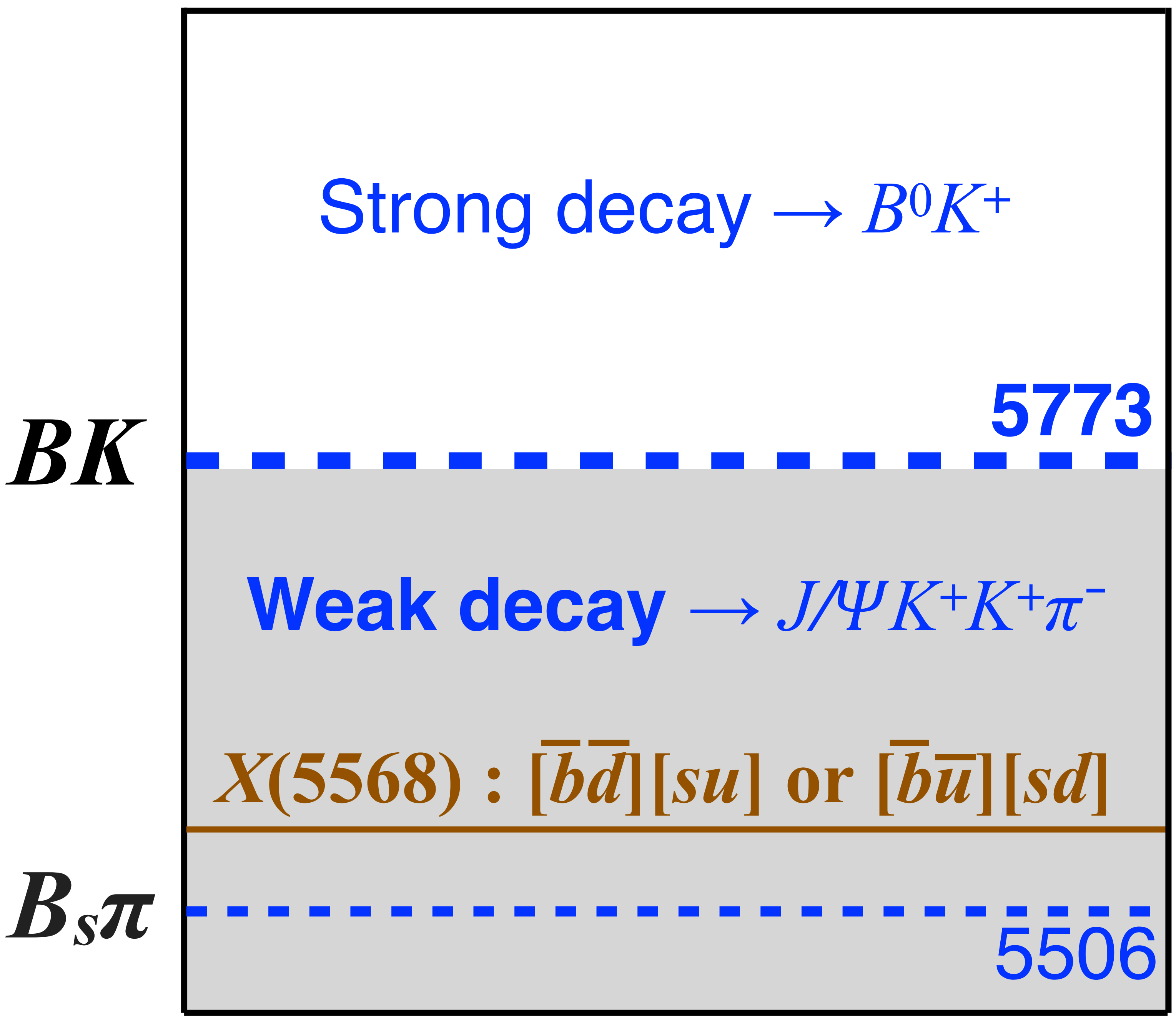


FSY, 1709.02571

$[bs][\bar{u}\bar{d}]$ Tetraquarks



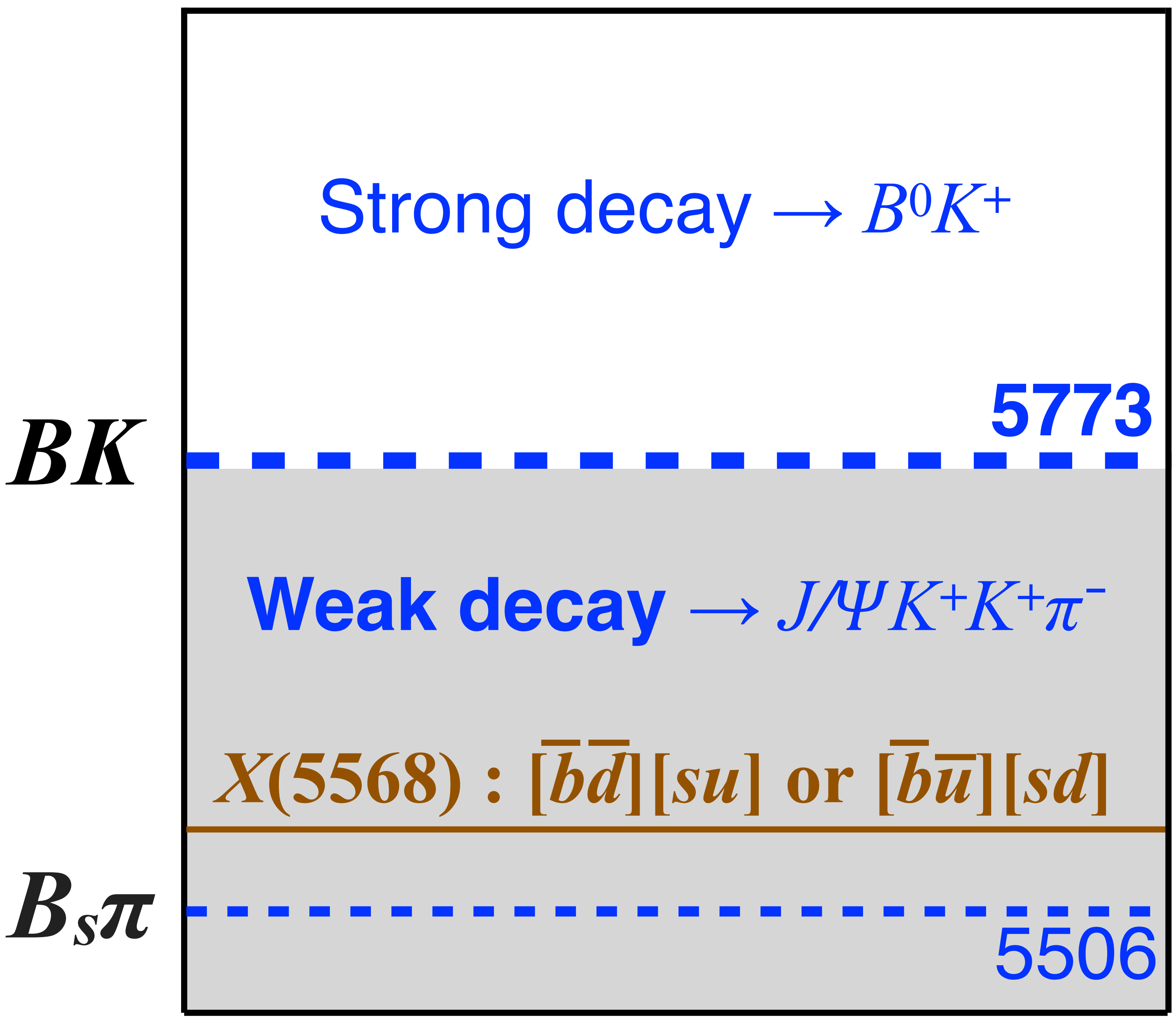
Lowest-lying state, 0^+



1. Higher threshold, BK is 270MeV over $B_s\pi$
2. If X(5568) exists, in SU(3) symmetry bs-tetraquark is below threshold, and weakly decay.
3. If above threshold, $Kaon$ suppresses background. better than $B_s\pi$

$[bs][\bar{u}\bar{d}]$ Tetraquarks

Lowest-lying state, 0^+



@ Tevatron

1. Production~X(5568)
2. Below threshold,
   weak decay,
   easier to observe by
   rejecting backgroud:
   - $\tau \sim \tau_B$ in heavy quark symmetry
   - J/Ψ involving.

If exists below threshold

heavy quark symmetry

Lifetime of

bs-tetraquark

is expected to be

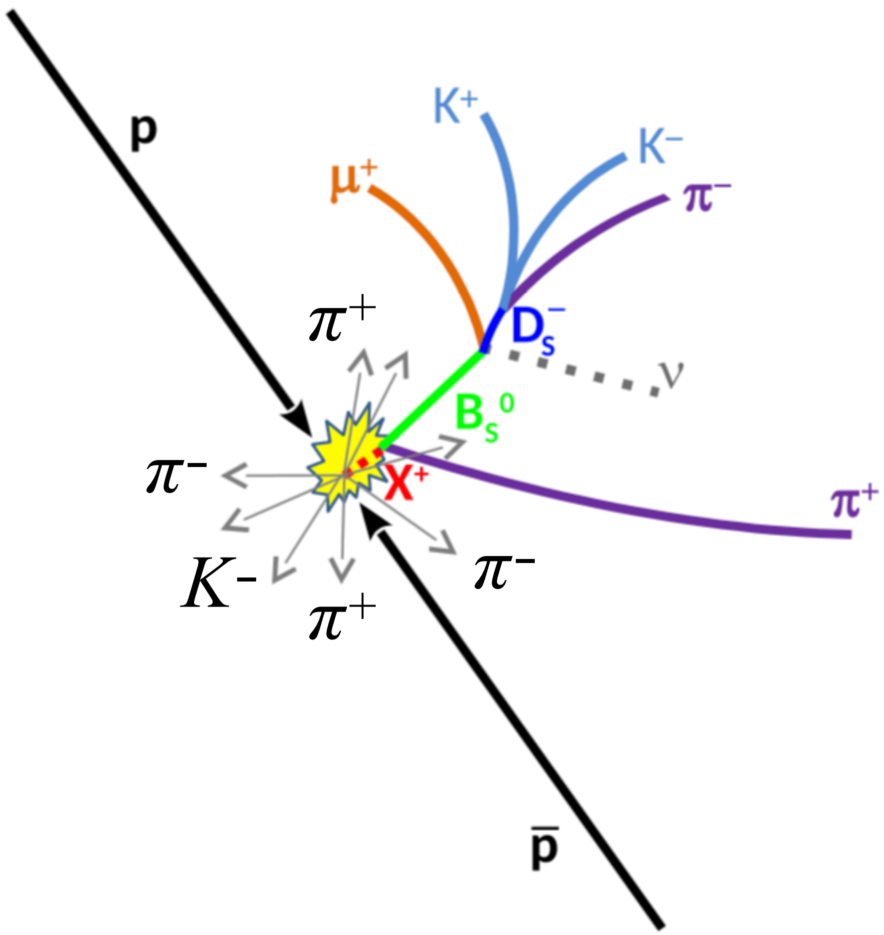
$\tau \approx 1.5$ps

Lifetimes of b-hadrons

Particle	Lifetime [ps]
B^+	1.638 ± 0.004
B^0	1.520 ± 0.004
B_s (flavor-specific)	1.511 ± 0.014
B_s $(1/\Gamma_s)$	1.510 ± 0.005
Λ_b^0	1.466 ± 0.010
Ξ_b^-	1.560 ± 0.040
Ξ_b^0	1.464 ± 0.031
Ω_b^-	$1.57^{+0.23}_{-0.20}$

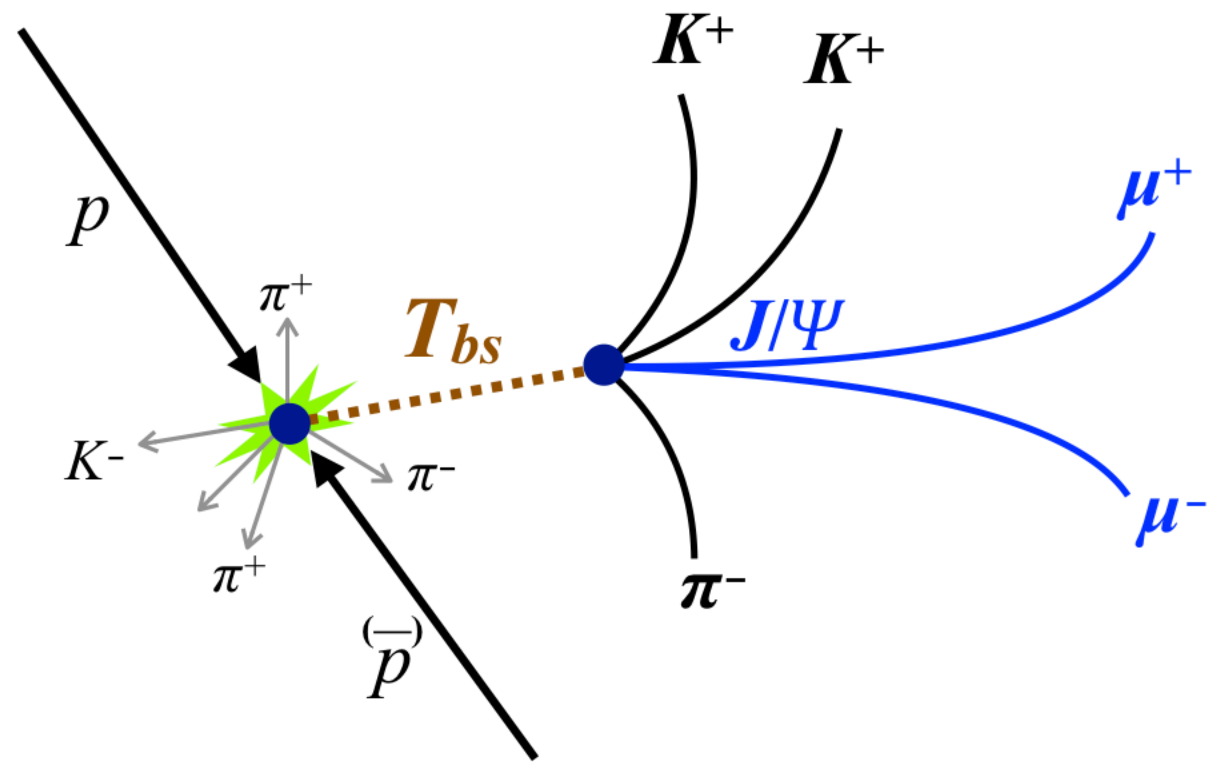
Long enough for observation

by **rejecting background** via real-time event selection



$X(5568) \rightarrow B_s{}^0\pi^{\pm}$

Large background



$T_{bs}{}^{+} \rightarrow J/\Psi K^{+}K^{+}\pi^{-}$

Suppressed background

$[bs][\bar{u}\bar{d}]$ Production and decay @ Tevatron

- Production is similar to X(5568)

$$X(5568) : [\bar{b}\bar{d}][su] \text{ or } [\bar{b}\bar{u}][sd]$$

- Decaying branching fractions:

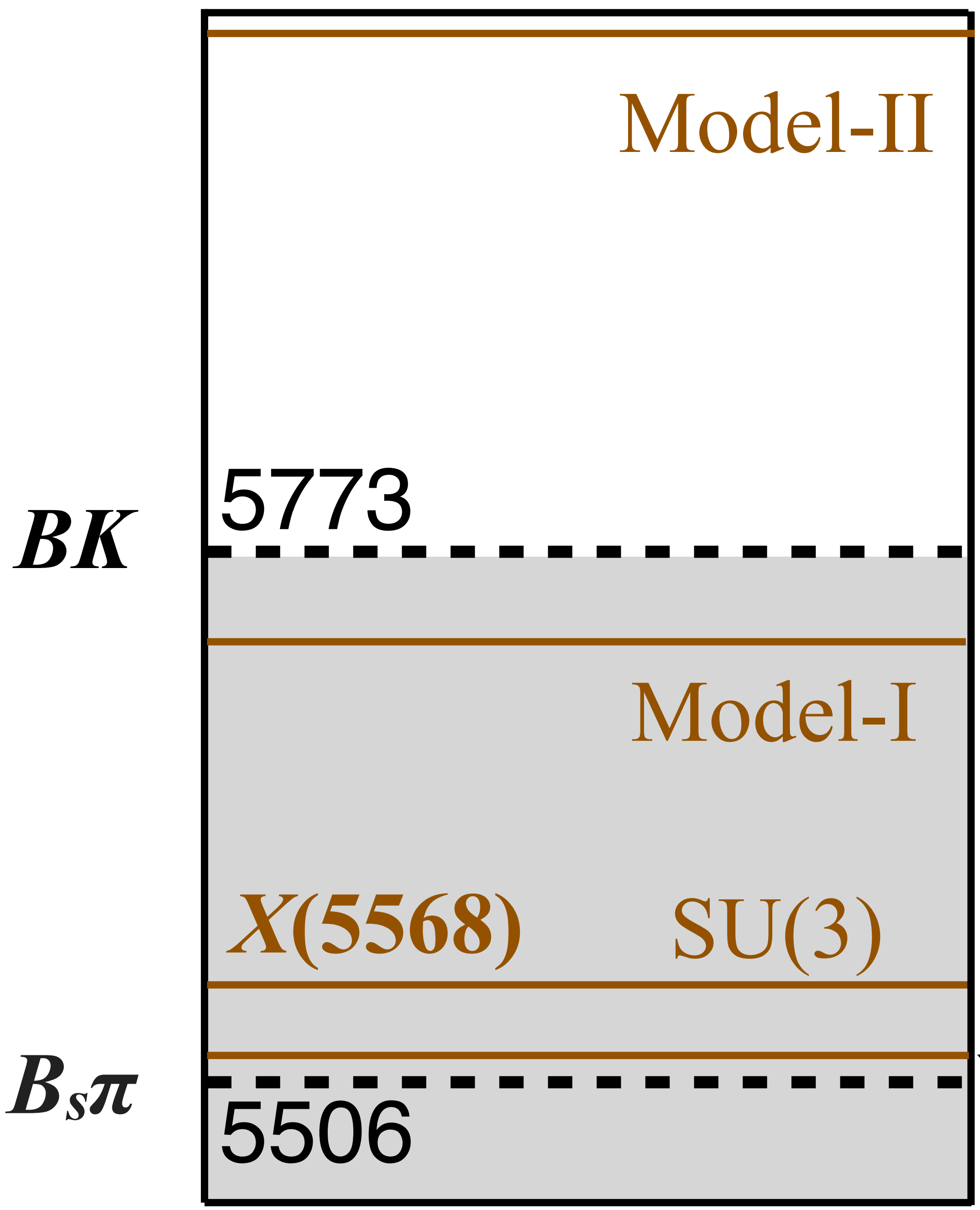
$$\mathrm{Br}(T_{bs} \to J/\Psi K^+ K^+ \pi^-) \sim \mathrm{Br}(b \to s\ J/\Psi) \sim \mathrm{Br}(B_s \to J/\Psi \phi)$$

T_{bs} is much easier to be observed than X(5568), due to rejection on background by longer lifetime

- **If T_{bs} is observed at D0 or CDF, X(5568) is confirmed**
- **If not, X(5568) is killed.**

$[bs][\bar{u}\bar{d}]$ Tetraquarks

Lowest-lying state, 0^+



Model-II: simple quark model

$$=m_b^b + m_s^b + 2m_q^b + a_{bs}/(m_b^b m_s^b) - 3a/(m_q^b)^2 + B(bs)$$

[Karliner, Rosner, PRD14']

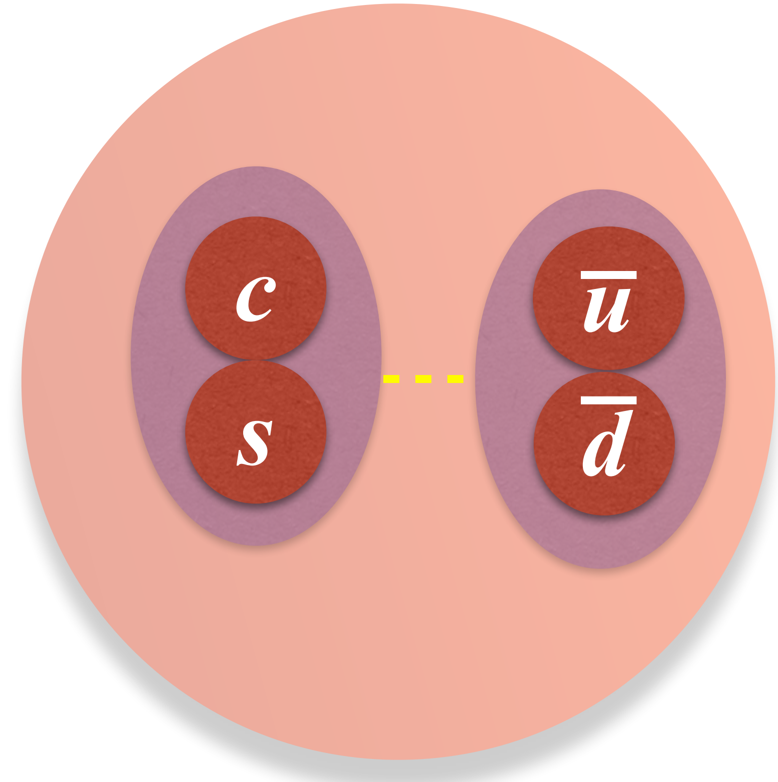
Model-I: diquark-antidiquark

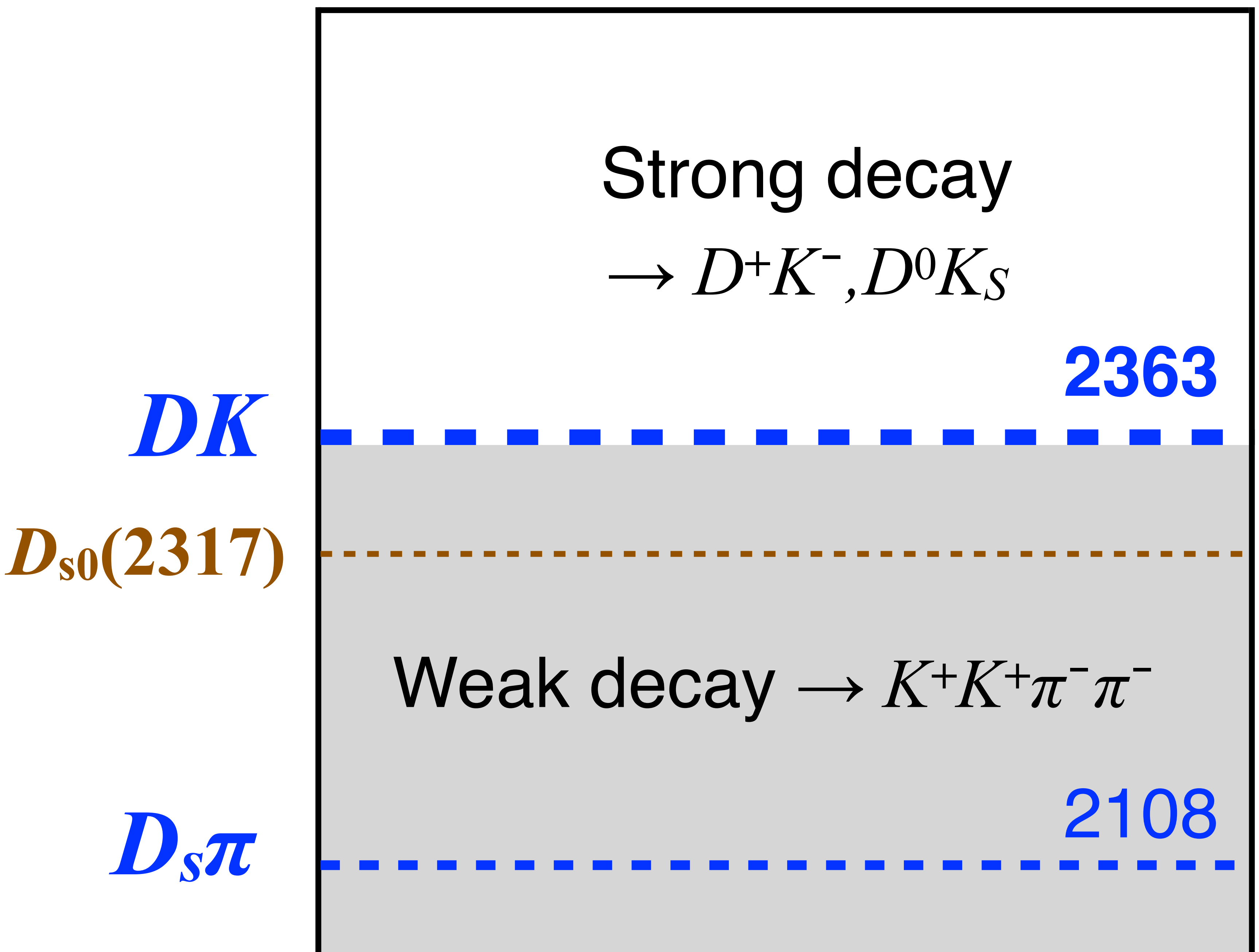
$$H = m_{[bs]} + m_{[ud]} + \sum_{i<j} 2\kappa_{ij}(\mathbf{S}_i \cdot \mathbf{S}_j)$$

[Maiani, Piccinini, Polosa, Riquer, PRD04']

[Y.R.Liu, X.Liu, S.L.Zhu, PRD93,074023]

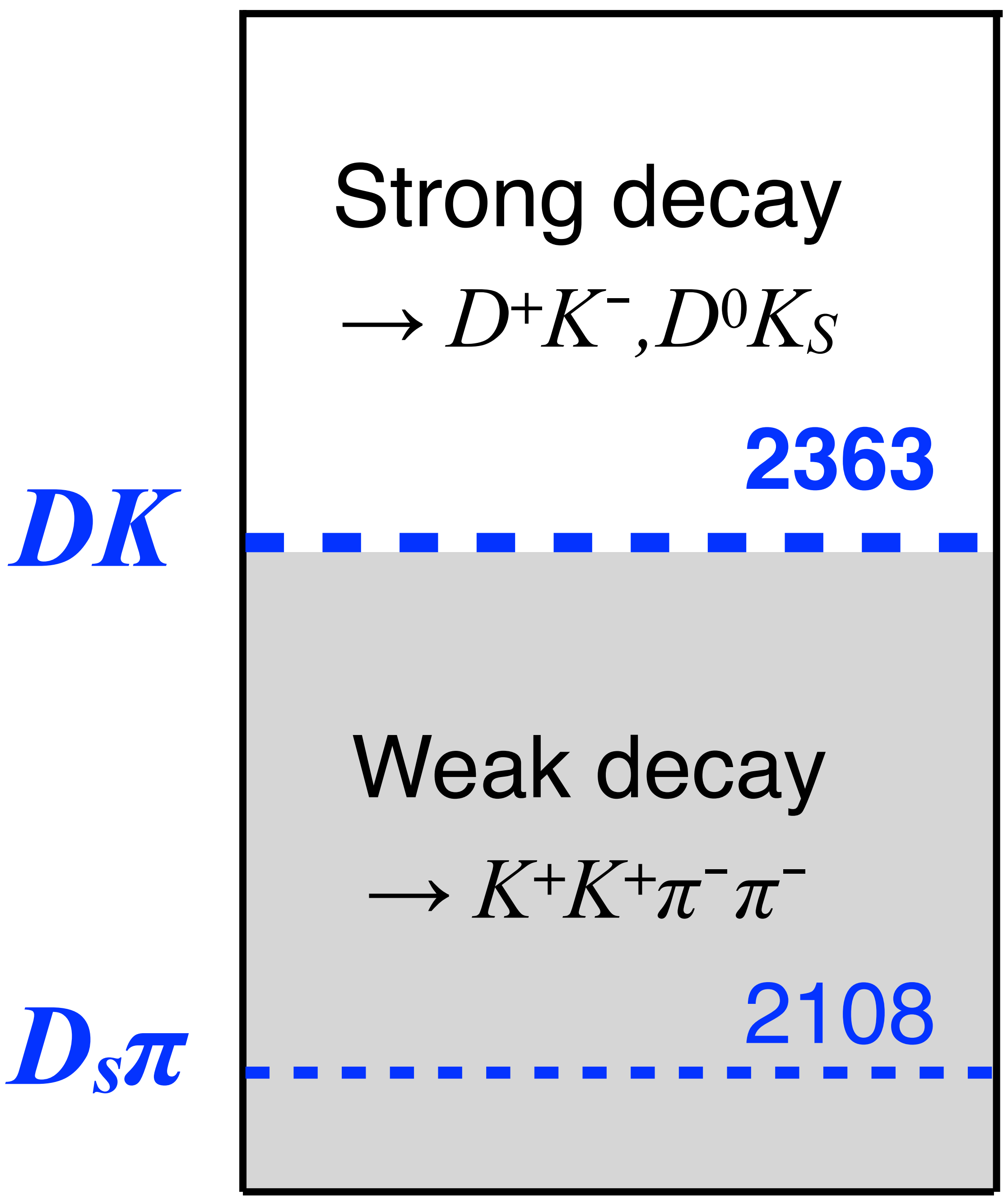
$b \to c$





$[cs][\bar{u}\bar{d}]$

$[cs][\bar{u}\bar{d}]$



FSY, 1709.02571

Advantages

★ **Larger production**

- Events of 3 orders larger than bs-tetraquark @ LHCb

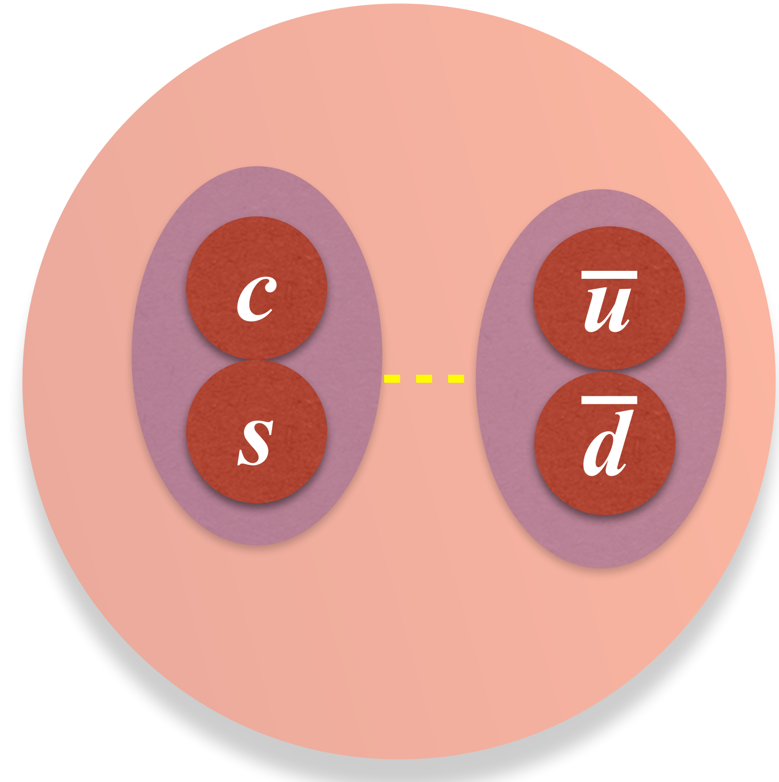
$$\sigma(pp \to c\bar{c}) \sim 20\ \sigma(pp \to b\bar{b})$$
$$Br(D^+ \to K^-\pi^+\pi^+) = 9\,\%$$
$$Br(B^- \to J/\Psi K^-) = 1 \times 10^{-3}$$
$$Br(J/\Psi \to \mu^+\mu^-) = 6\,\%$$

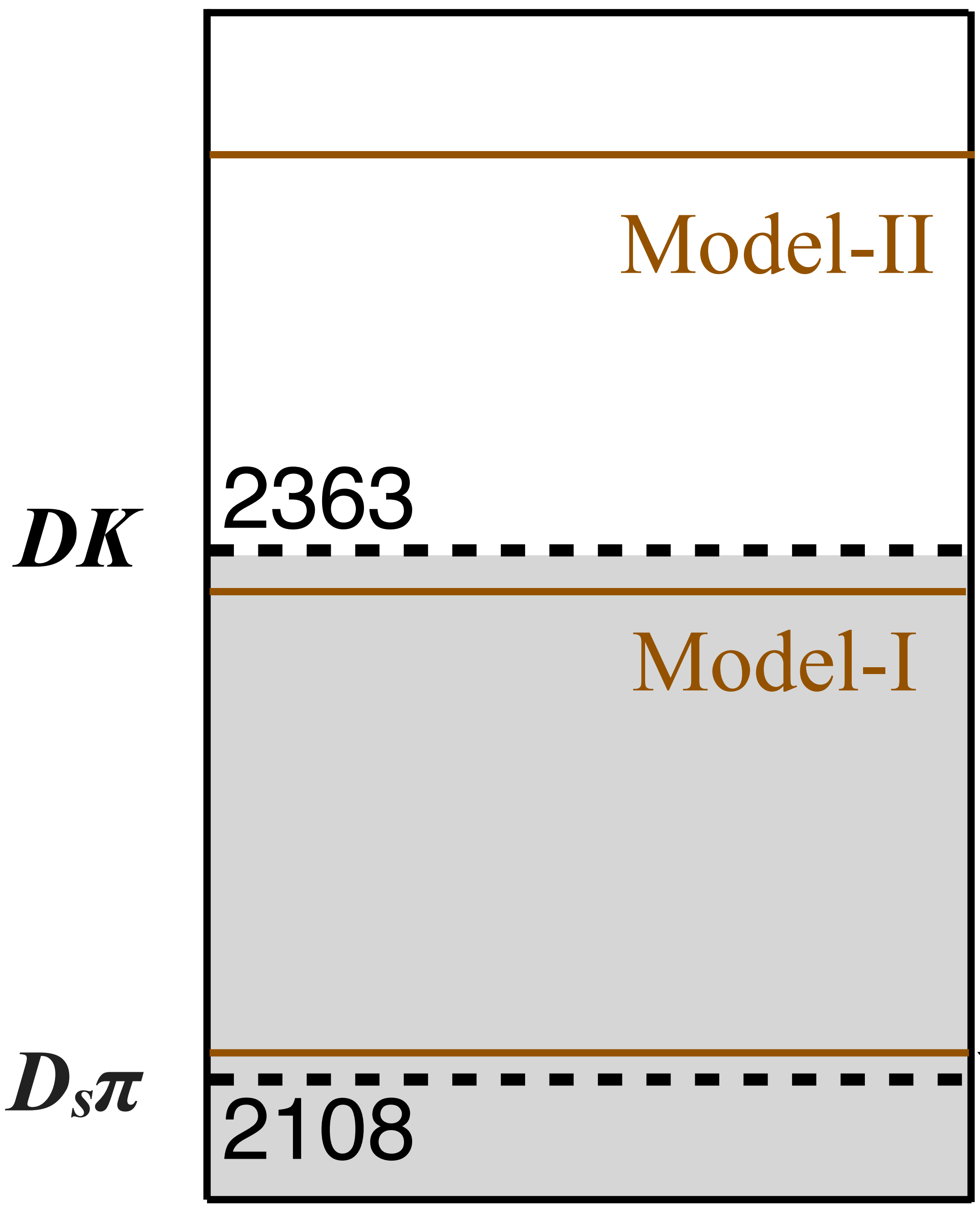
★ **Both @ LHCb and Belle (II)**

- Belle(II): lower background than LHCb
- Searching to be

$[cs][\bar{u}\bar{d}]$

Lowest-lying state, 0^+





Strong decay

$\to D^+K^-, D^0K_S$

[X.G.He, W.Wang, R.L.Zhu, JPG44,014003]

Weak decay

$\to K^+K^+\pi^-\pi^-$

[Y.R.Liu, X.Liu, S.L.Zhu, PRD93,074023]

Prompt Production

- **Might discriminate tetraquark or molecular**
  - Molecular states are difficult to be prompt produced,

    14 TeV @ LHCb & 10 GeV @ Belle (II)

    Moving fast, less possibility to be bounded
  - compared to B decays and Y(4260) decays

    B->X(3872), Y(4260)->Zc(3900)

- **Prompt production of Tetraquarks**

$$\frac{\sigma(T_{cs})}{\sigma(\Xi_c^+)} = \frac{\sigma([cs][\bar{u}\bar{d}])}{\sigma(csu)} = \frac{f'_{[ud]}}{f'_u} = \frac{f'_{\Lambda_c^+}}{f'_{D^0}}$$

Primarily production fractions

$[\boldsymbol{bs}][\boldsymbol{\bar{u}\bar{d}}]$ and $[\boldsymbol{cs}][\boldsymbol{\bar{u}\bar{d}}]$

are the most promising

detectable

open heavy flavor

tetraquark states

Summary

- Discovery channels of doubly charmed baryons
- bsud and csud are promising detectable tetraquarks

Thank you very much!