Double-heavy baryons

Fu-Sheng Yu

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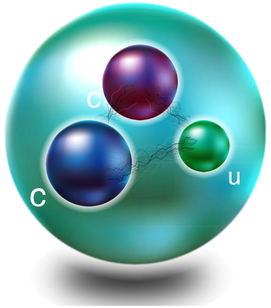
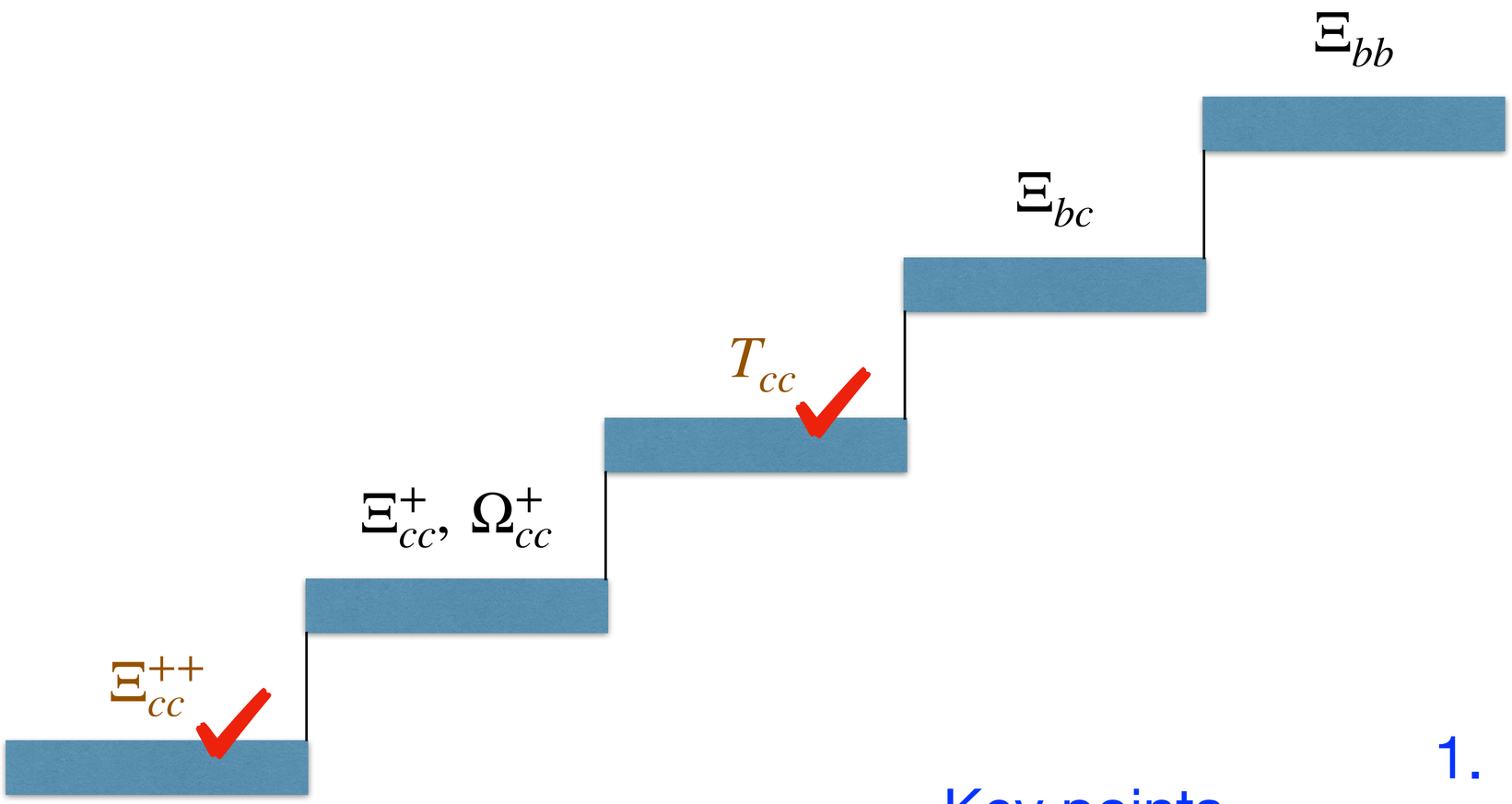


LHCb implications, 19.10.2021



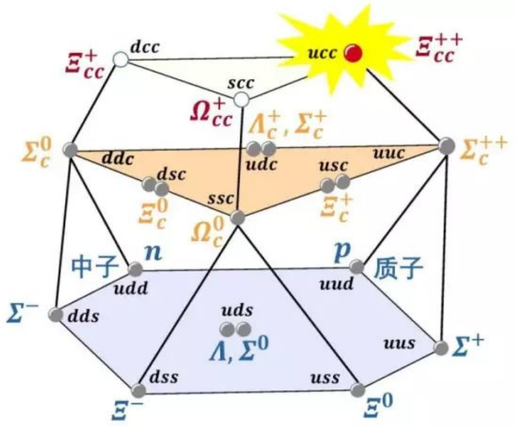
Key points of observations:

1. productions
2. branching fractions
3. lifetimes

Why double-heavy baryons?

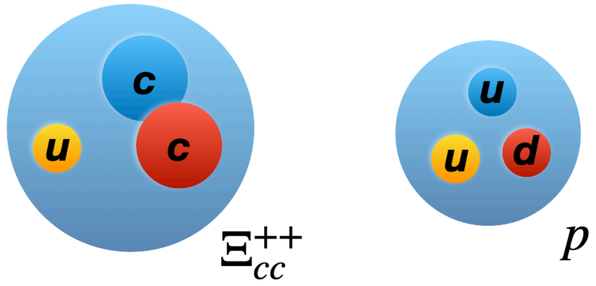
- Double-charm baryons are predicted in SU(4) quark model

  De Rujula, Georgi and Glashow, 1975;
  Jaffe, J. E. Kiskis, 1976; Ponce, 1979



- A heavy ‘double-star’ system with an attached light ‘planet’, much different from light baryons

- Open a new window for QCD properties



Role of Decay in the observation

- Two problems in the exp searches: Production and Decay

$$N \propto \sigma \cdot BR$$

- Production problem was solved at the beginning of LHC running

$$\sigma(pp \to \Xi_{cc}) \sim \sigma(pp \to B_c)$$

C.H.Chang, C.F.Qiao, J.X.Wang, X.G.Wu, 2005, 2006

X.G.Wu, Sci.China.PMA, 2020

- Decay properties are the key problem in the LHCb searches of doubly charmed baryons.

FSY, Sci.China.PMA, 2020

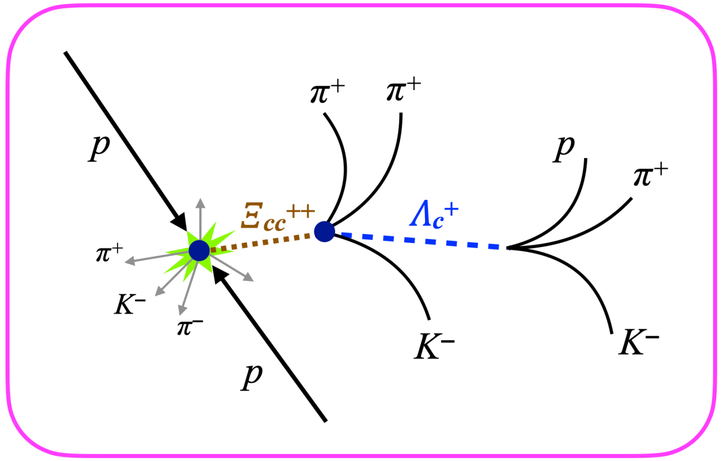
- Statistics requires: largest branching ratios and easily detected

Lifetime is important

1. Longer lifetime ⇒ Larger branching ratios

$$BR_i = \Gamma_i \cdot \tau$$

2. Longer lifetime ⇒ Higher efficiency to reject backgrounds in hadron colliders



- Large ambiguity in predictions
- But less ambiguity in the ratio

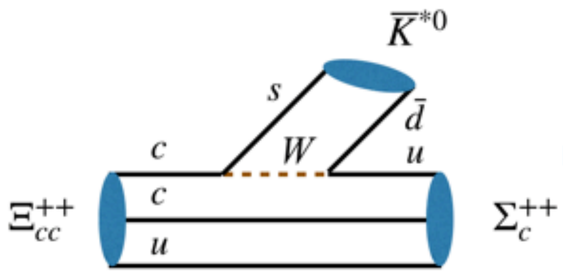
$$\boxed{\tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^{+})}$$

- Recommend Ξ_{cc}^{++} rather than Ξ_{cc}^{+}

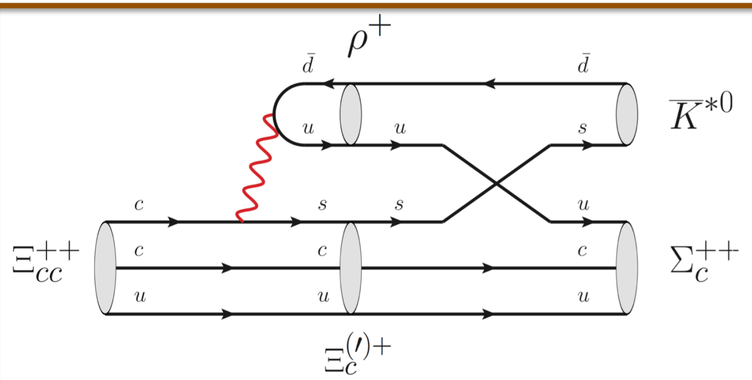
Literatures	Ξ_{cc}^{++} (fs)	Ξ_{cc}^{+} (fs)
Karliner, Rosner, 2014	185	53
Kiselev, Likhoded, 2002	460±50	160±50
Chang, Li, Li, Wang, 2007	670	250
Cheng, Shi, 2018	250	45

Decay amplitudes

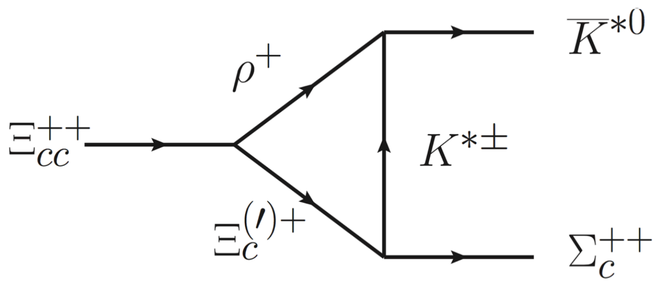
- Short-distance contributions: factorization
- Long-distance contributions: FSI rescattering



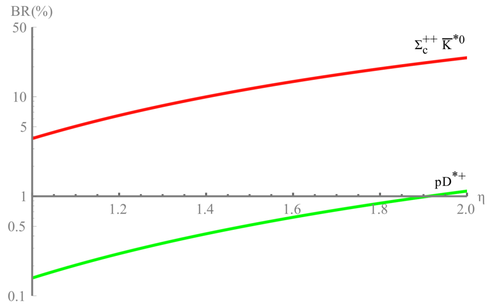
Topology: C



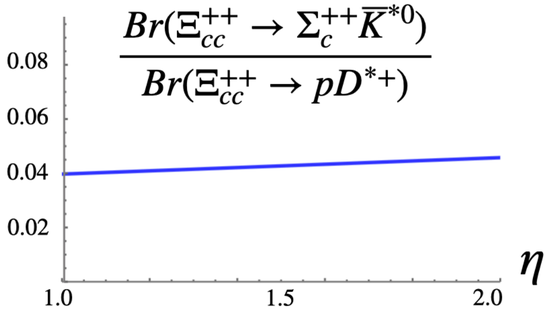
quark exchange



hadronic triangle



- Theoretical uncertainty is under control in the **ratio** of branching fractions of different processes



1703.09086

2102.00961

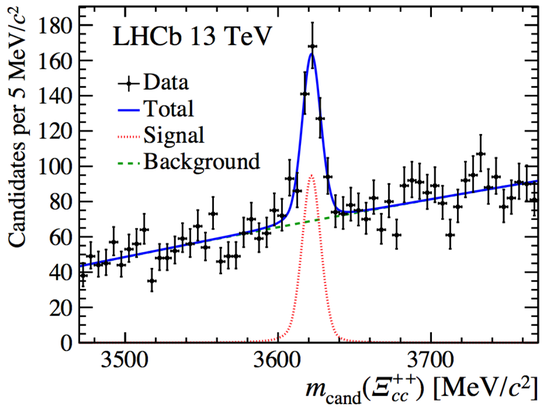
Chinese Physics C Vol. 42, No. 5 (2018) 051001

Discovery potentials of doubly charmed baryons*

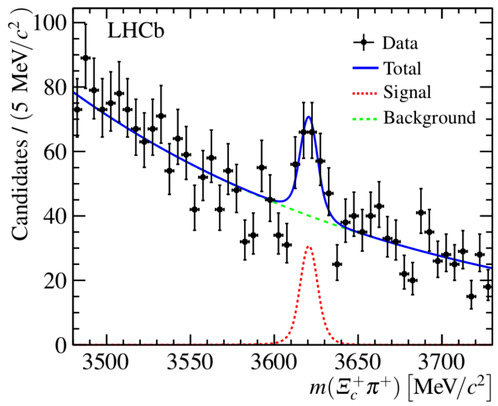
Fu-Sheng Yu(于福升)[1,2;1)] Hua-Yu Jiang(蒋华玉)[1,2] Run-Hui Li(李润辉)[3] Cai-Dian Lü(吕才典)[4,5;2)]
Wei Wang(王伟)[6;3)] Zhen-Xing Zhao(赵振兴)[6]

$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ are the most favorable decay modes

July 2017

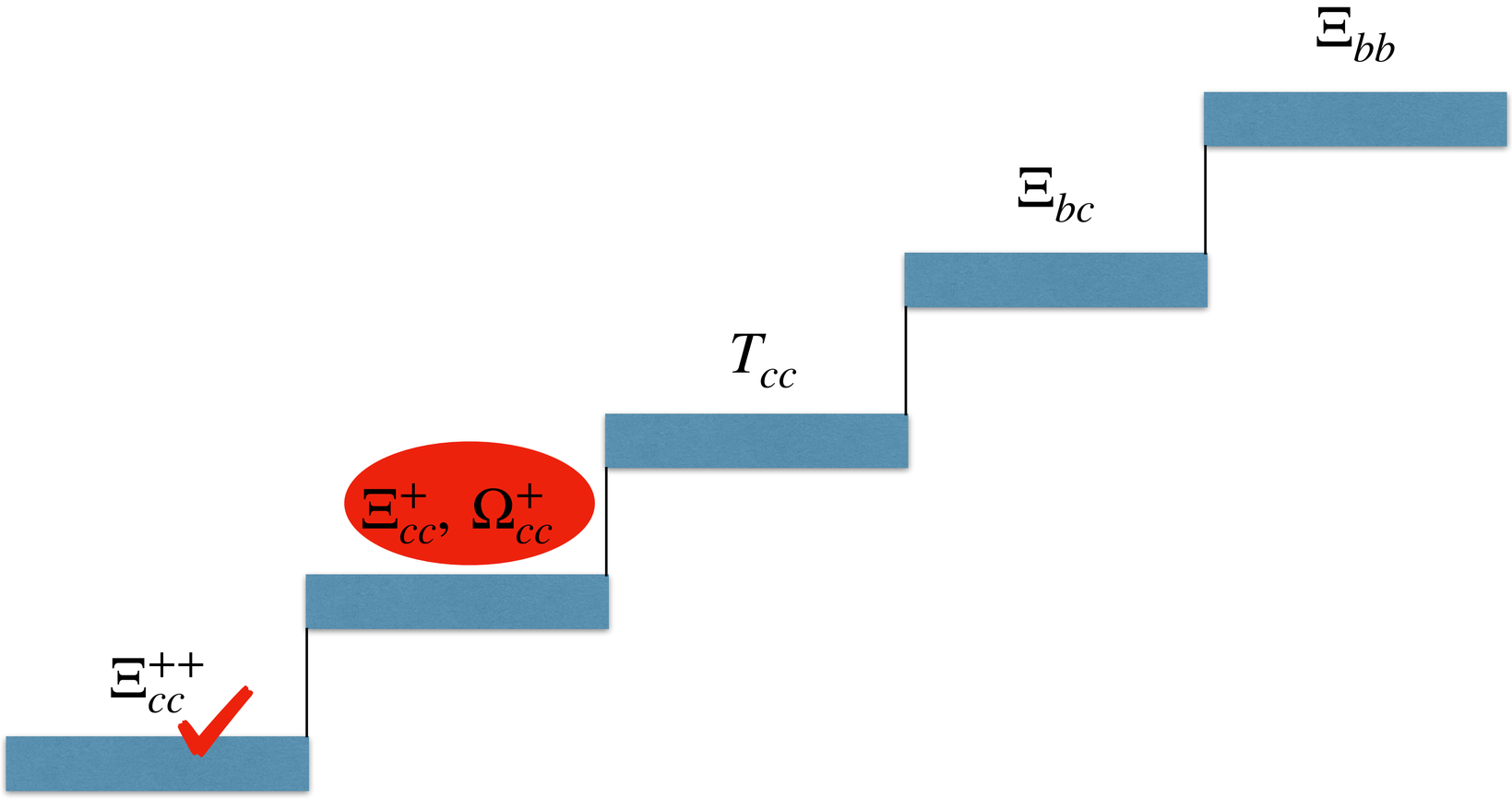


$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$$



July 2018

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


Ξ_{bb}
Ξ_{bc}
T_{cc}
$\Xi_{cc}^{+}, \Omega_{cc}^{+}$
Ξ_{cc}^{++}

Double-charm baryons: Ξ_{cc}^+, Ω_{cc}^+

- Decaying processes for Ξ_{cc}^+ and Ω_{cc}^+ $\quad$ $\mathrm{B}_{cc} \to \mathrm{B}_c P,\ \mathrm{B}_c V, \mathrm{B}_8 D^{(*)}$

H.Y.Cheng, F.R.Xu, 2019

R.H.Li, et al, 2017-2020

$\mathcal{BR}(\Xi_{cc}^+ \to \Xi_c^+ \rho^0) \in [0.4\%, 2.5\%]$ $\quad$ $\mathcal{BR}(\Omega_{cc}^+ \to \Xi_c^+ \overline{K}^{*0}) \in [0.5\%, 3.3\%]$

- Suggestion for measurements

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

$$\Omega_{cc}^+ \to \Xi_c^+ K^- \pi^+$$

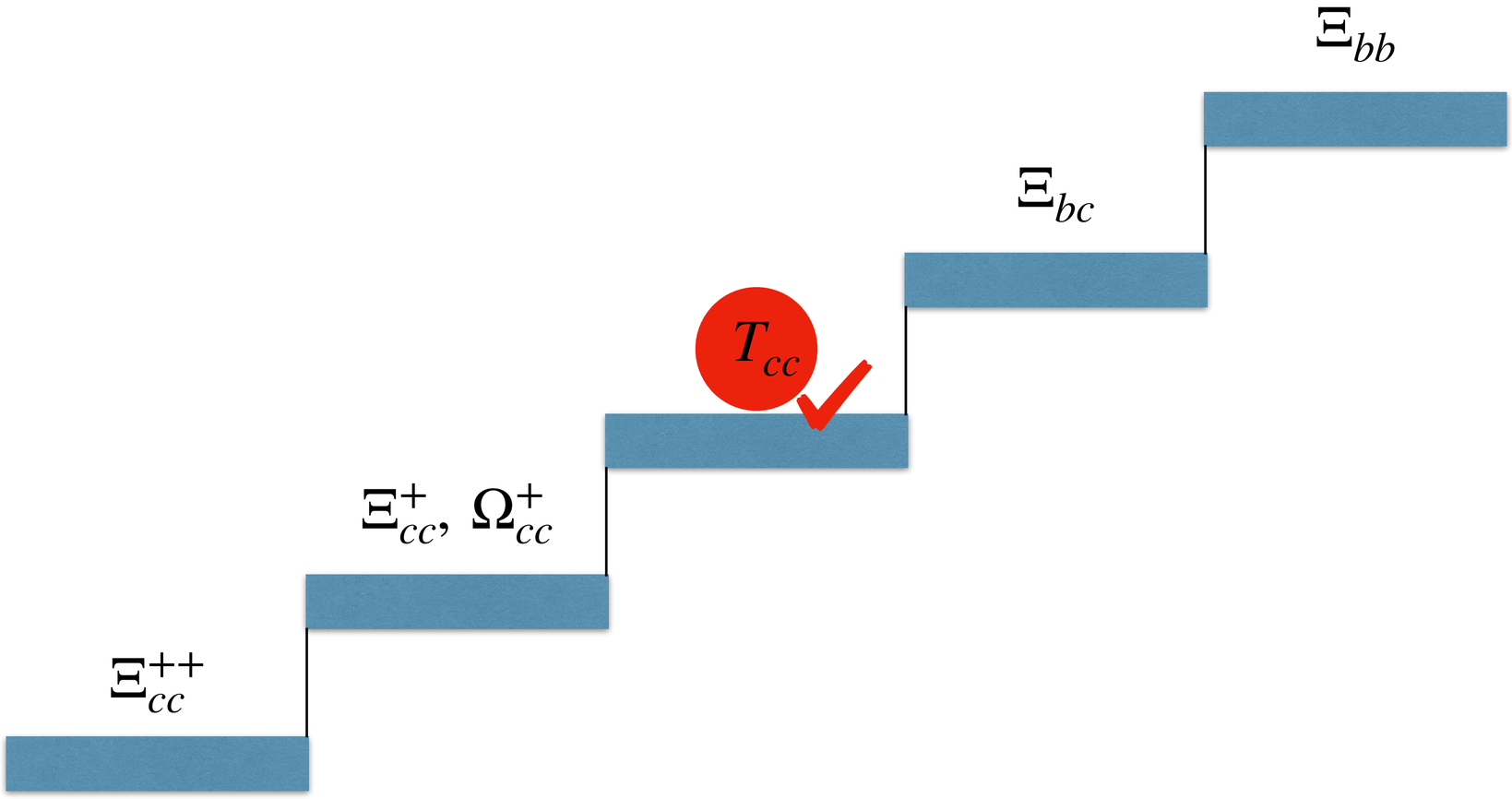
Run-Hui Li, 2017, 2018

Lifetimes: $\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^+) > \tau(\Xi_{cc}^+)$

298fs $\quad$ 200fs $\quad$ 45fs

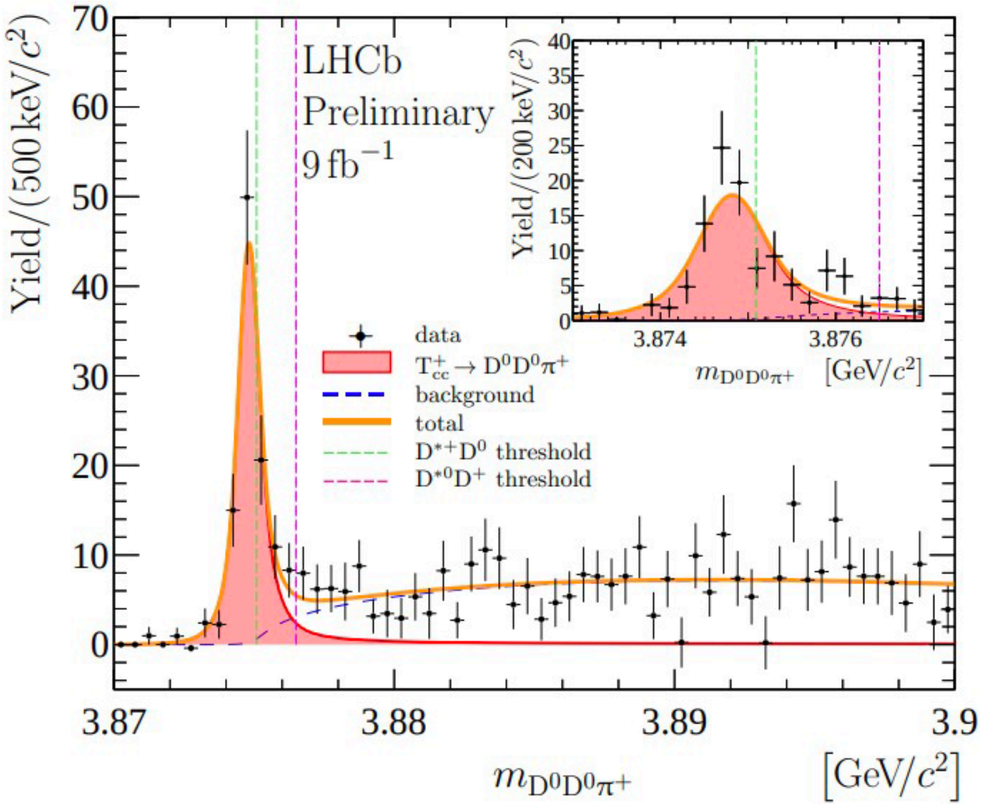
Cheng, Shi, 2018

To be observed


Ξ_{bb}
Ξ_{bc}
T_{cc}
Ξ_{cc}^{+}, Ω_{cc}^{+}
Ξ_{cc}^{++}

Discovery of T_{cc}

$N_s = 117 \pm 16$



"Highlights from the LHCb Experiment" ——Franz Muheim
"Recent LHCb results on exotic meson candidates" —— Ivan Polyakov

@ European Physical Society Conference on high energy physics 2021

Discovery potentials of double-charm tetraquarks

We find that their production cross sections at the LHCb with $\sqrt{s} = 13$ TeV reach $\mathcal{O}(10^4)$ pb, which indicate that the LHCb has collected $\mathcal{O}(10^8)$ such particles. Through the decay channels of $T^{\{cc\}}_{[\bar{u}\bar{d}]} \to D^+K^-\pi^+$ or $D^0D^+\gamma$ (if stable) or $T^{\{cc\}}_{[\bar{u}\bar{d}]} \to D^0D^{*+}$ (if unstable), it is highly hopeful that they get discovered at the LHCb in the near future. We also discuss the productions and decays of the double-charm tetraquarks at future Tera-Z factories.

branching fractions of $T^{\{cc\}}_{[\bar{u}\bar{d}]}$ decays is the same as the observed Ξ_{cc}^{++}. Comparing with the production rates between double-charm tetraquarks and baryons, and considering around 2×10^3 events of Ξ_{cc}^{++} with the current LHCb data, the signal yields of $T^{\{cc\}}_{[\bar{u}\bar{d}]}$ would be $\mathcal{O}(10^2)$ at LHCb, and will reach $\mathcal{O}(10^3)$ at LHCb Run III. Thus it is hopefully expected that the double-charm tetraquark will be observed in the near future. Although the production rates are smaller at the future Z factories, it is also expected to be observed at the Tera-Z factories due to the smaller backgrounds.

- Correct discovery channel
- Correct signal yields

Qin, Shen, **FSY**, 2008.08026

Fully reconstructed: $T_{cc}^{+} \to D^0 D^{*+}$

Compared with $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ $\quad u \leftrightarrow \bar{u}\bar{d}$

Production

final prod $\quad f_{\Lambda_b} / f_{B_u} \sim 0.5$

primarily prod $\quad f_{\Sigma_b^{(*)}} / f_{\Lambda_b} \sim 1$

$\Rightarrow \dfrac{f_{T_{cc}}}{f_{\Xi_{cc}}} \sim \dfrac{1}{4}$

Decay $\quad Br(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)\, Br(\Lambda_c^+ \to p K^- \pi^+)$

10% $\quad$ 6% $\quad$ one track more 1/3

$$\sim Br(T_{cc} \to D^0 D^{*+})\, Br(D^{*+} \to D^0 \pi^+)\, Br(D^0 \to K^- \pi^+)^2$$

1/2 $\quad$ 2/3 $\quad$ $(4\%)^2$

$$\longrightarrow \quad Br(T_{cc})/Br(\Xi_{cc}^{++}) \sim 1/4$$

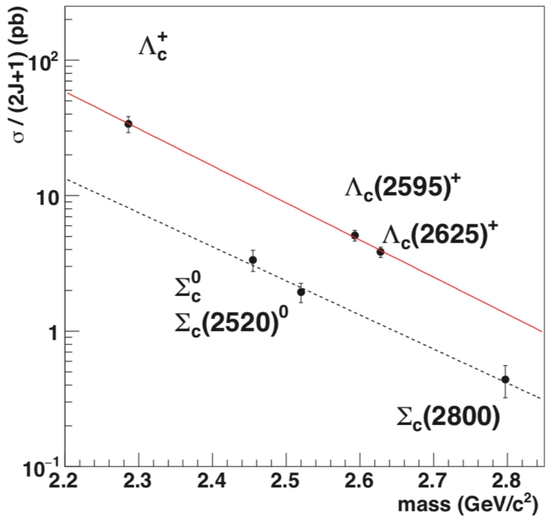
1500 events of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+ \longrightarrow$ 100 events of Tcc

Qin, Shen, **FSY**, 2008.08026

Fragmentation

- Different from ordinary heavy mesons and baryons with excited states decaying into the ground states,
- The excited cc-tetraquarks would directly decay into DD mesons, but not the ground states
- Primarily production *v.s.* final production
- The ground-state fragmentation fraction is

$$\frac{f_{T_{cc}}}{f_{\Xi_{cc}}} \approx \frac{f_{ud}(\text{primary})}{f_{ud}(\text{final})} \times \frac{f_{ud}(\text{final})}{f_u}$$

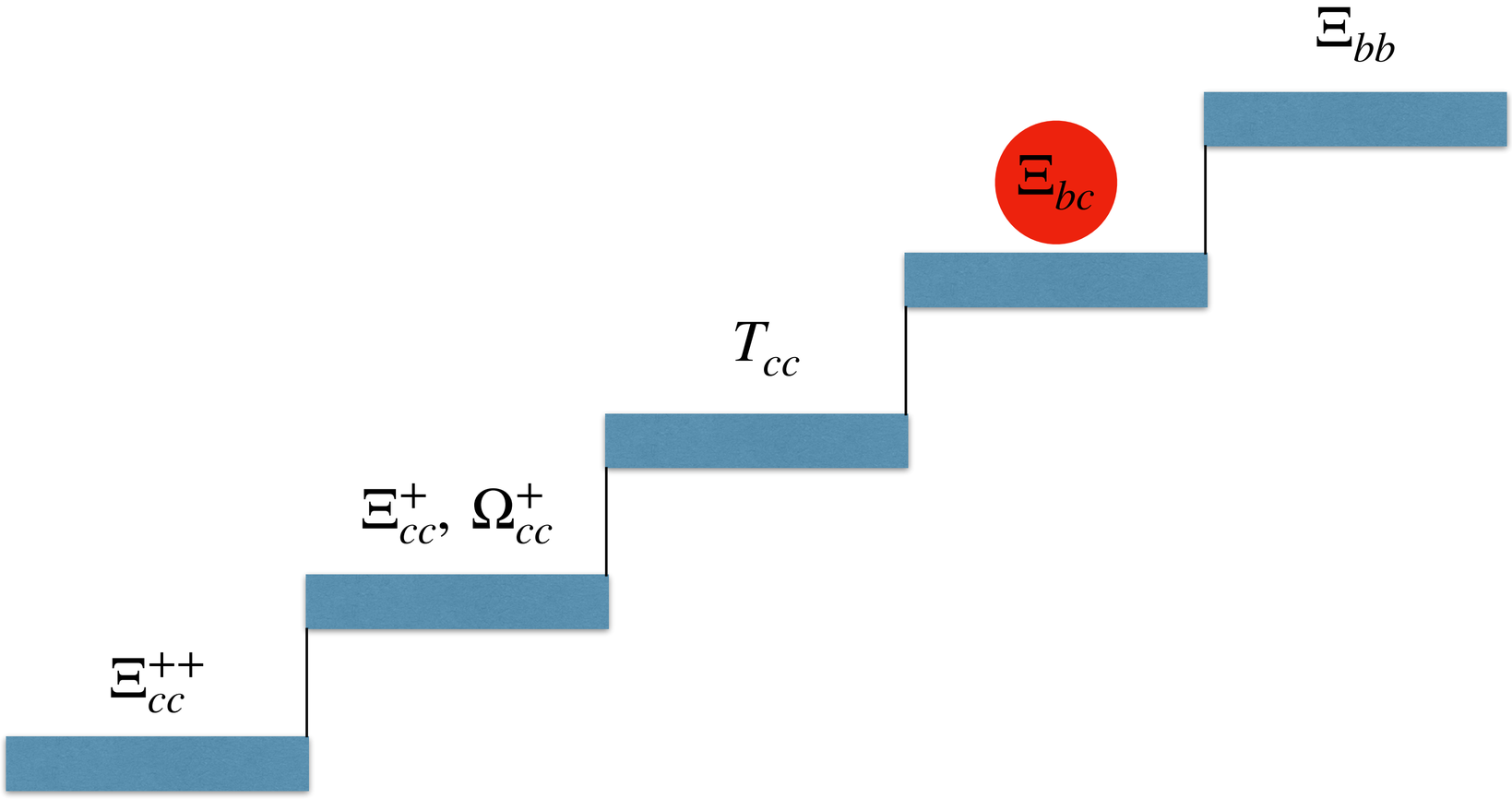


$$\frac{f_{\Lambda_c}}{f_{\Lambda_c+\Sigma_c+\Lambda_c^*}} = 0.48 \pm 0.08$$

Belle, arXiv:1706.06791

$$\frac{f_{\Lambda_b^0}}{f_u + f_d}(p_T) = (1 \pm 0.061)\left[(0.0793 \pm 0.0141) + e^{(-1.022\pm0.047)+(-0.107\pm0.002)\times p_T}\right]$$

LHCb, 1902.06794


Ξ_{bb}
Ξ_{bc}
T_{cc}
Ξ_{cc}^{+}, Ω_{cc}^{+}
Ξ_{cc}^{++}

Difficulties in experimental searches for Ξ_{bc}

- Detection efficiency —— small exclusive branching ratios

channels	Γ/ GeV	$\mathcal{B}$	channels	Γ/ GeV	$\mathcal{B}$
$\Xi_{bc}^0 \to \Lambda_c^+ \pi^-$	1.13×10^{-18}	1.60×10^{-7}	$\Xi_{bc}^0 \to \Lambda_c^+ \rho^-$	3.31×10^{-18}	4.68×10^{-7}
$\Xi_{bc}^0 \to \Lambda_c^+ a_1^-$	4.42×10^{-18}	6.24×10^{-7}	$\Xi_{bc}^0 \to \Lambda_c^+ K^-$	9.36×10^{-20}	1.32×10^{-8}
$\Xi_{bc}^0 \to \Lambda_c^+ K^{*-}$	1.70×10^{-19}	2.41×10^{-8}	$\Xi_{bc}^0 \to \Lambda_c^+ D^-$	2.27×10^{-19}	3.21×10^{-8}
$\Xi_{bc}^0 \to \Lambda_c^+ D^{*-}$	2.42×10^{-19}	3.42×10^{-8}	$\Xi_{bc}^0 \to \Lambda_c^+ D_s^-$	6.23×10^{-18}	8.80×10^{-7}
$\Xi_{bc}^0 \to \Lambda_c^+ D_s^{*-}$	5.82×10^{-18}	8.22×10^{-7}			
$\Xi_{bc}^0 \to \Sigma_c^+ \pi^-$	1.12×10^{-18}	1.58×10^{-7}	$\Xi_{bc}^0 \to \Sigma_c^+ \rho^-$	3.53×10^{-18}	4.99×10^{-7}
$\Xi_{bc}^0 \to \Sigma_c^+ a_1^-$	5.24×10^{-18}	7.41×10^{-7}	$\Xi_{bc}^0 \to \Sigma_c^+ K^-$	9.16×10^{-20}	1.29×10^{-8}
$\Xi_{bc}^0 \to \Sigma_c^+ K^{*-}$	1.86×10^{-19}	2.63×10^{-8}	$\Xi_{bc}^0 \to \Sigma_c^+ D^-$	1.96×10^{-19}	2.77×10^{-8}
$\Xi_{bc}^0 \to \Sigma_c^+ D^{*-}$	3.85×10^{-19}	5.44×10^{-8}	$\Xi_{bc}^0 \to \Sigma_c^+ D_s^-$	5.34×10^{-18}	7.55×10^{-7}
$\Xi_{bc}^0 \to \Sigma_c^+ D_s^{*-}$	9.73×10^{-18}	1.38×10^{-6}			

Wang, **FSY**, Zhao, 1707.02834
Han, Zhang, Jiang, Xiao, **FSY**, 2102.00961

- First experimental attempts

(LHCb, 13 TeV, ~ 5 fb^{-1})

$$\frac{\sigma(\Xi_{bc}^0)}{\sigma(\Lambda_b^0)} \frac{B(\Xi_{bc}^0 \to D^0 p K^-)}{B(\Lambda_b^0 \to D^0 p K^-)} < [1.7,30]\,\%$$

[LHCb, 2009.02481]

$< [0.6, 3] \times 10^{-4}$

$$\frac{\sigma(\Xi_{bc}^0)}{\sigma(\Lambda_b^0)} \frac{B(\Xi_{bc}^0 \to \Lambda_c^+ \pi^-)}{B(\Lambda_b^0 \to \Lambda_c^+ \pi^-)} < [0.5,2.5] \times 10^{-4}$$

$$\frac{\sigma(\Xi_{bc}^0)}{\sigma(\Lambda_b^0)} \frac{B(\Xi_{bc}^0 \to \Xi_c^+ \pi^-)}{B(\Lambda_b^0 \to \Xi_c^+ \pi^-)} < [1.4,6.9] \times 10^{-3}$$

[LHCb, 2104.04759]

$$\left(B(\Lambda_b^0 \to \Lambda_c^+ \pi^-) = 4.9 \times 10^{-3}, \sigma(\Lambda_b^0) \sim 10\ \mu b, \sigma(\Xi_{bc}^0) \sim\ 40\ nb\right)$$

Proposal: inclusive Ξ_{bc} search

- Generally, inclusive decays have (1) larger branching ratios but (2) lower detection efficiencies

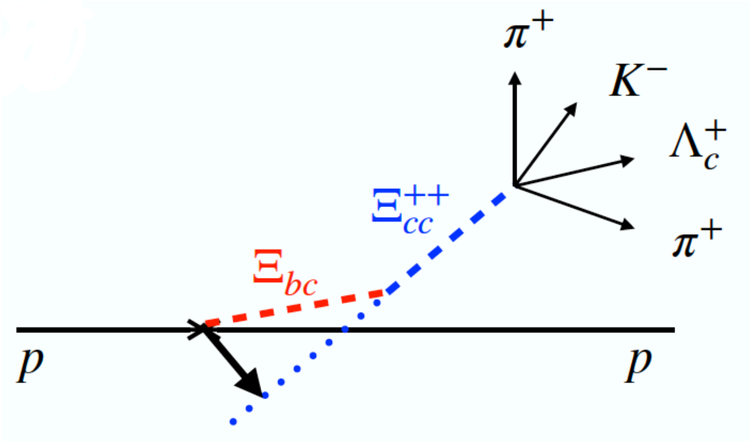
  Basically impossible at hadron colliders

- However, for $\Xi_{bc} \to \Xi_{cc}^{++} + X$, the efficiency can be large by making use of the inform of displaced vertex

  Inspired by the proposal to search for Ξ_{bb} via $\Xi_{bb} \to B_c + X$
  [Gershon,Poluektov,1810.06657]

- Ξ_{bc} is (almost) the only source for displaced Ξ_{cc}'s

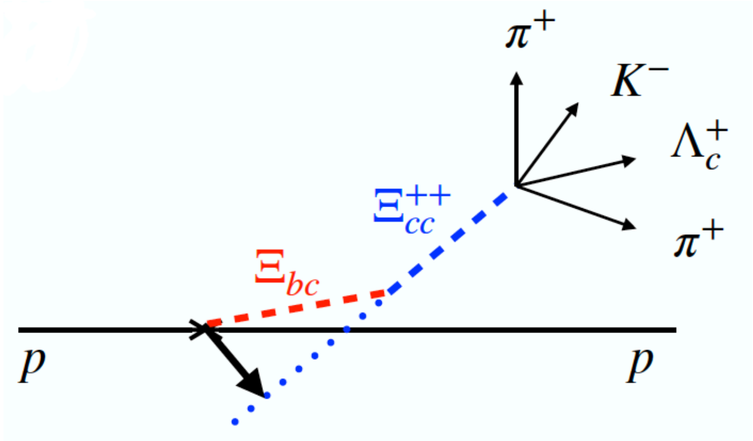
- The $B_c \to \Xi_{cc}^{++} + X$ decay is highly suppressed



Calculation of $\Xi_{bc} \to \Xi_{cc} + X$

- First important fact: $\Xi_{bc} \to \Xi_{cc} + X \;=\; \Xi_{bc} \to X_{cc}$

  X_{cc} include excited states of Ξ_{cc}, which still decay into Ξ_{cc}



- Regarding the heavy diquarks χ_{bc} and χ_{cc} as point-like particles, the decay at the quark-diquark diquark level is

$$\chi_{bc} \to \chi_{cc} + \ell^- \bar{\nu},\, \chi_{cc} + \bar{q} q'$$

It is reasonable because $r_{QQ'} \sim 1/(m_Q v) \ll 1/\Lambda_{\text{QCD}}$ [e.g.,Brodsky,Guo,Hanhart,Meissner,1101.1983]

- By making use of OPE, the inclusive decay rate is expanded by powers of $1/M_{QQ'}$ within the Heavy Diquark Effective Theory

[Y.J.Shi, W.Wang, Z.X.Zhao,Meissner,2002.02785]

- At the leading power

$$B(\Xi_{bc} \to X_{cc}) = B(\chi_{bc} \to \chi_{cc} + \ell^- \bar{\nu},\, \chi_{cc} + \bar{q} q') + \mathcal{O}(1/M_{QQ'})$$

Calculation of $\Xi_{bc} \to \Xi_{cc} + X$

- Numerical result for the decay width

$$\Gamma(\Xi_{bc} \to \Xi_{cc} + X) = (1.9 \pm 0.1 \pm 0.3 \pm 0.4) \times 10^{-13} \text{ GeV}$$

Uncertainties from model dependence, scale dependence, power correction

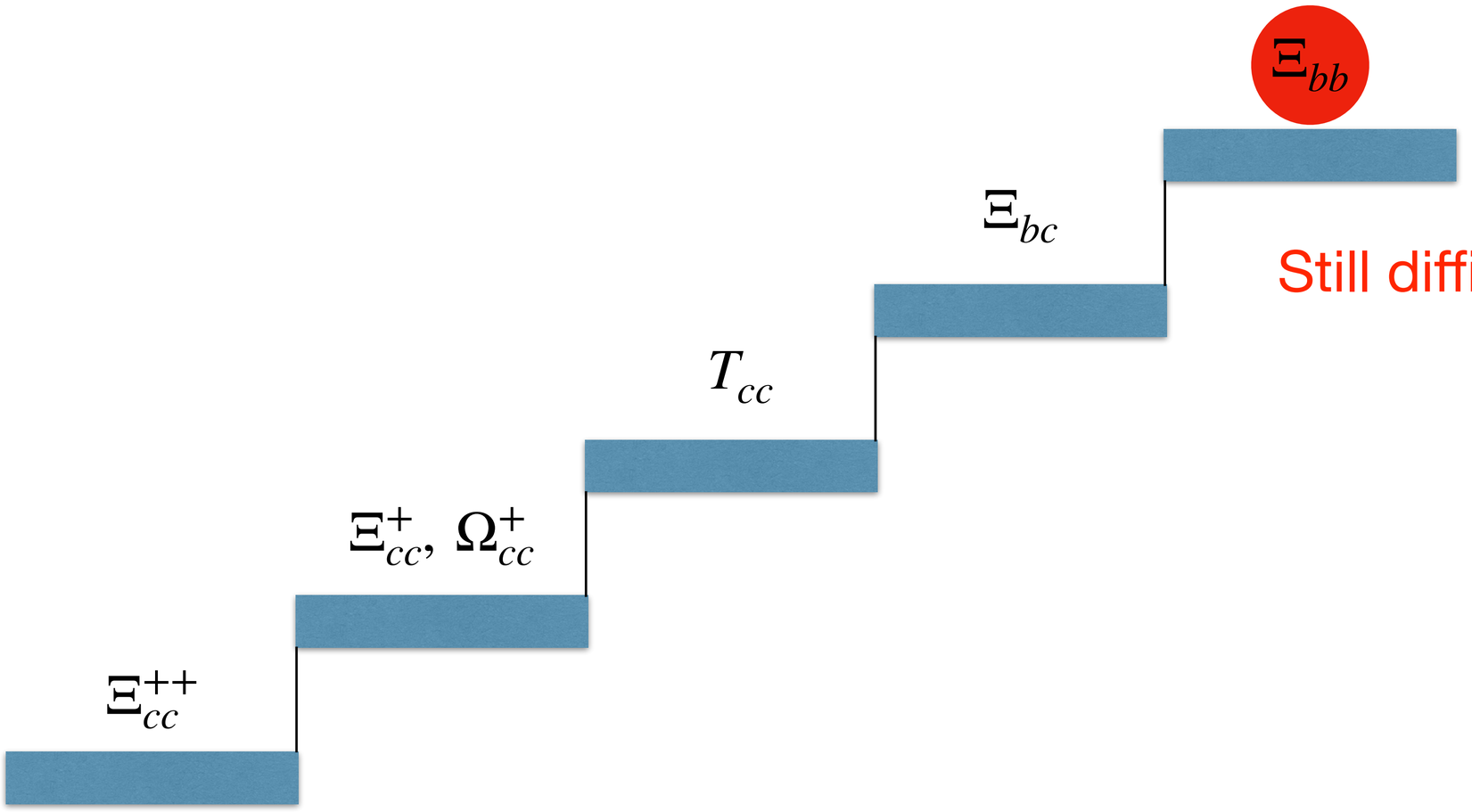
- The branching ratio is

$$B(\Xi_{bc}^{+} \to \Xi_{cc}^{++} + X) \approx 6\% \times \frac{\tau_{\Xi_{bc}^{+}}}{400\text{fs}}$$

Qin, Shi, Wang, Yang, **FSY**, Zhu, 2108.06716

- Lifetimes Cheng, Xu, 1903.08148

$$93\text{fs} < \tau(\Xi_{bc}^{0}) < 108 \text{ fs}, \quad 409 \text{ fs} < \tau(\Xi_{bc}^{+}) < 607 \text{ fs}$$



Still difficult at Run3

Summary

- The observation of double-charm baryon, Ξ_{cc}^{++}, opens a new window on the study of strong interaction.
- The decay properties, including the branching fractions and lifetimes, are very important in the experimental searches, as well as productions.
- Collaborations between experimentalists and theorists are helpful.
- Some suggestions are give to search for other double-heavy baryons.

Thank you!

Backups

Search for $\Xi_{bc} \to \Xi_{cc}^{++} + X$ with displaced Ξ_{cc}^{++}

- Estimated of signal signal events

$$N(\Xi_{bc} \to \Xi_{cc}^{++} + X) = N(\Xi_{cc}^{++}) \cdot \frac{2\sigma(\Xi_{bc})}{\sigma(\Xi_{cc})} \cdot B(\Xi_{bc} \to \Xi_{cc}^{++} + X)$$

(Both Ξ_{bc}^{0} and Ξ_{bc}^{+} decay equally to Ξ_{cc}^{++} and thus Identical detection efficiency)

Three ingredients:

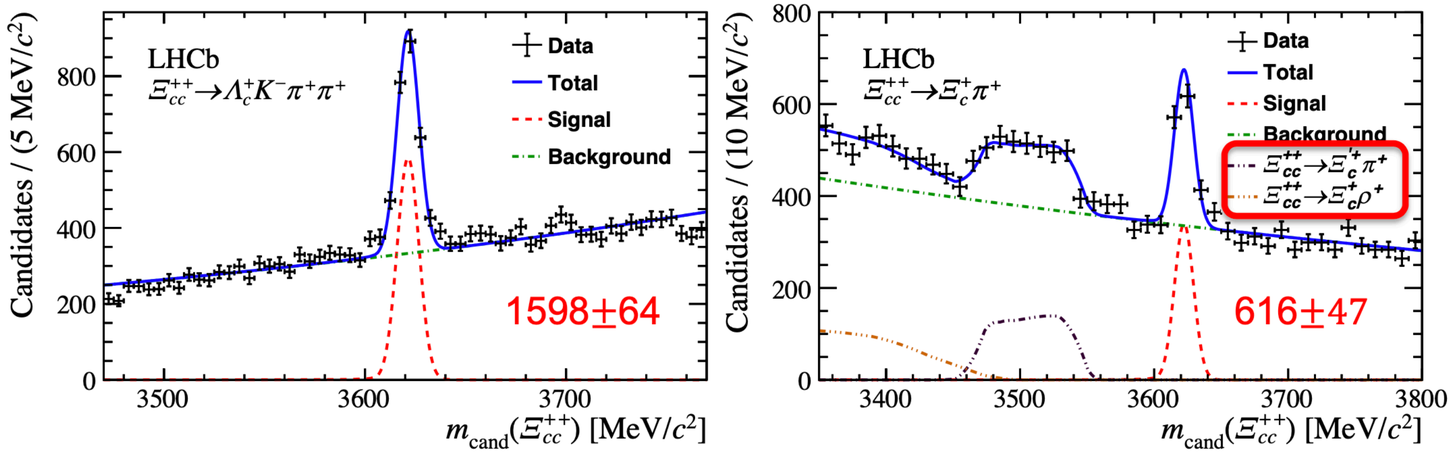
1. Number of signals of Ξ_{cc}^{++}

2. Production ratio $\sigma(\Xi_{bc})/\sigma(\Xi_{cc})$

3. Branching fraction of inclusive decay of $\Xi_{bc} \to \Xi_{cc}^{++} + X$

Search for $\Xi_{bc} \to \Xi_{cc}^{++} + X$ with displaced Ξ_{cc}^{++}

1.Number of signals of Ξ_{cc}^{++}



J.B.He

- Data of 9 fb^{-1} Run 1+2

	2011	2012	2018	2023	2029	2035
LHCb	Run I		Run II	Run III	Run IV	Run V
Integrated luminosity	1 fb-1	3 fb-1	9 fb-1	23 fb-1	50 fb-1	300 fb-1

- Events estimated for 23 fb^{-1} (Run III)

$$\frac{7000}{1600} \times (1600 + 600) \approx 10000$$

Decay mode	LHCb $23\,\mathrm{fb}^{-1}$	LHCb $50\,\mathrm{fb}^{-1}$	LHCb $300\,\mathrm{fb}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$	7k	15k	90k	<6k
$\Xi_{bc}^{+} \to J/\psi\, \Xi_c^+$	50	100	600	—

Z.W.Yang

Search for $\Xi_{bc} \to \Xi_{cc}^{++} + X$ with displaced Ξ_{cc}^{++}

2. Production ratio $\sigma(\Xi_{bc})/\sigma(\Xi_{cc})$

[X.G.Wu et al, 1101.1130]

TABLE VI. Comparison of the total cross section (in units nb) for the hadronic production of Ξ_{cc}, Ξ_{bc}, and Ξ_{bb} at $\sqrt{S} = 7.0$ TeV and $\sqrt{S} = 14.0$ TeV, where $[^3S_1]$ and $[^1S_0]$ stand for the combined results for the diquark in spin-triplet and spin-singlet states, respectively. In the calculations, we adopt $p_T > 4$ GeV and $|y| < 1.5$.

	Ξ_{cc}		Ξ_{bc}		Ξ_{bb}	
	$\sqrt{S} = 7.0$ TeV	$\sqrt{S} = 14.0$ TeV	$\sqrt{S} = 7.0$ TeV	$\sqrt{S} = 14.0$ TeV	$\sqrt{S} = 7.0$ TeV	$\sqrt{S} = 14.0$ TeV
$[^3S_1]$	38.11	69.40	16.7	28.55	0.503	1.137
$[^1S_0]$	9.362	17.05	3.72	6.315	0.100	0.226
Total	47.47	86.45	20.42	34.87	0.603	1.363

$$\sigma(\Xi_{bc})/\sigma(\Xi_{cc}) \approx 40\,\%$$

Search for $\Xi_{bc} \to \Xi_{cc}^{++} + X$ with displaced Ξ_{cc}^{++}

- Final number of estimated signal events @ LHCb Run3

$$N(\Xi_{bc} \to \Xi_{cc}^{++} + X) = N(\Xi_{cc}^{++}) \cdot \frac{2\sigma(\Xi_{bc})}{\sigma(\Xi_{cc})} \cdot B(\Xi_{bc} \to \Xi_{cc}^{++} + X)$$

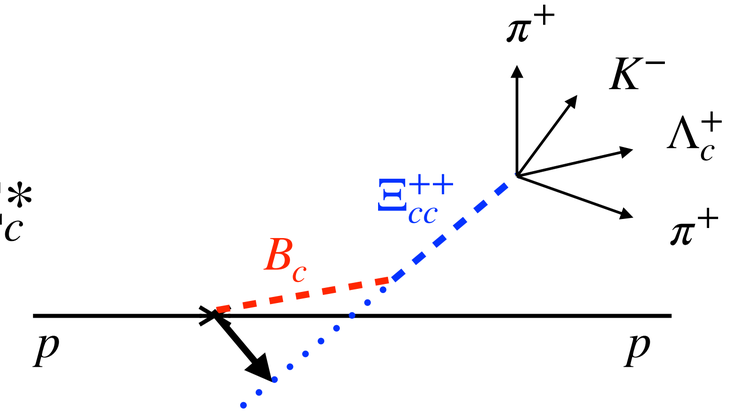
$$= 10^4 \cdot \frac{N(\Xi_{cc}^{++})}{10^4} \times 40\% \cdot \frac{2\sigma(\Xi_{bc})/\sigma(\Xi_{cc})}{40\,\%} \times 6\% \cdot \left(\frac{\tau_{\Xi_{bc}^+} + \tau_{\Xi_{bc}^0}}{400\text{fs}}\right)$$

$$= \mathbf{240} \times \frac{N(\Xi_{cc}^{++})}{10^4} \cdot \frac{\sigma(\Xi_{bc})/\sigma(\Xi_{cc})}{40\,\%} \cdot \left(\frac{\tau_{\Xi_{bc}^+} + \tau_{\Xi_{bc}^0}}{400\text{fs}}\right)$$

Small possibility from B_c decays

- The small phase space (0.18 GeV for $\Xi_{cc}\Xi_c$) only allows the processes of

  $B_c \to \Xi_{cc}\Xi_c$, or $\Xi_{cc}\Xi_c\gamma$, or $\Xi_{cc}\Xi_c\pi$, or $\Xi^*_{cc}\Xi_c$, or $\Xi_{cc}\Xi^*_c$

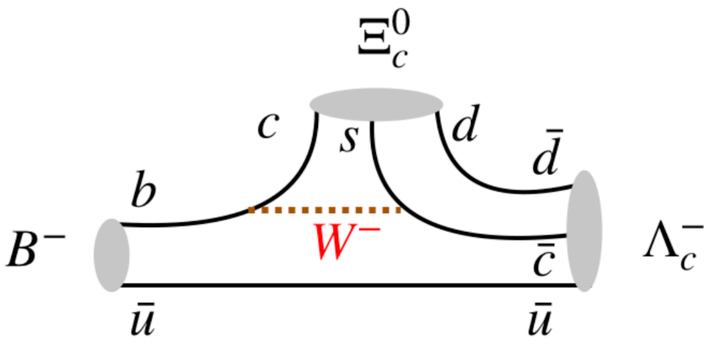


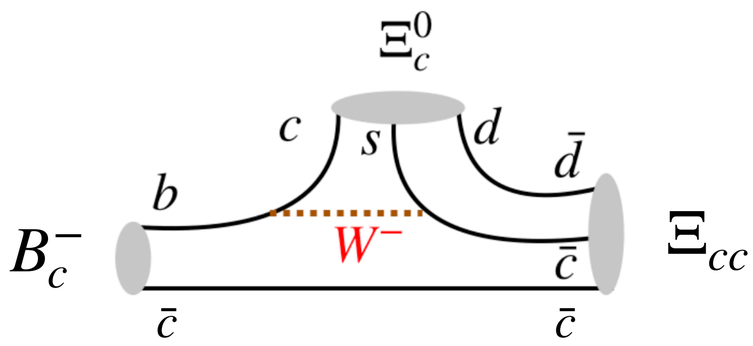
- Similar process but with a light spectator quark:

$$Br(B^0 \to \Xi_c^- \Lambda_c^+) = (1.2 \pm 0.8) \times 10^{-3}$$

$$Br(B^- \to \Xi_c^0 \Lambda_c^-) = (0.95 \pm 0.23) \times 10^{-3}$$

(0.5 GeV phase space)





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

SELEX's discovery channel,
LHCb measured

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	$(\mathcal{R}_\tau/0.3) \times 0.002$

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

$\tau \times (\sim 3)$

Br × 5

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

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