Weak Decays of doubly heavy baryons

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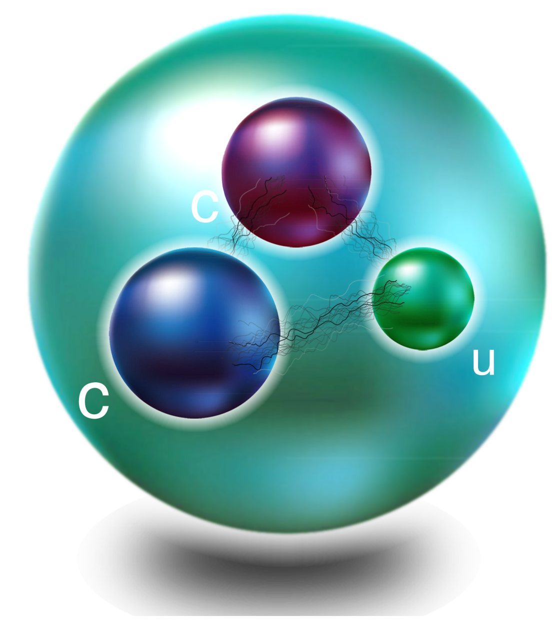
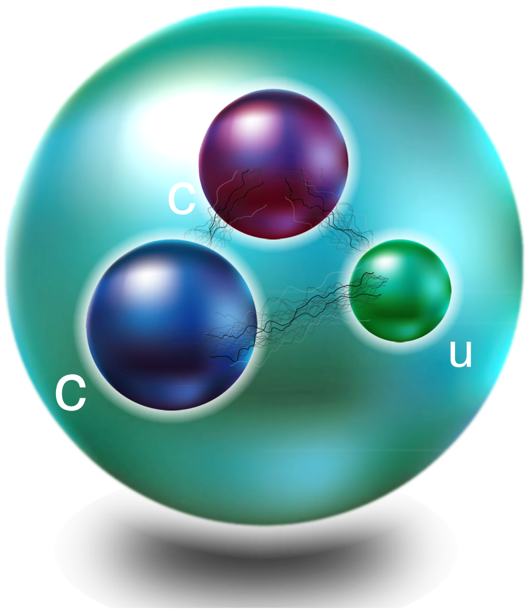


HADRON2019 @ Guilin, 16-21 August, 2019

In collaboration with Hua-Yu Jiang, Run-Hui Li, Cai-Dian Lü, Wei Wang, Zhen-Xing Zhao, Zhi-Tian Zou

Outline



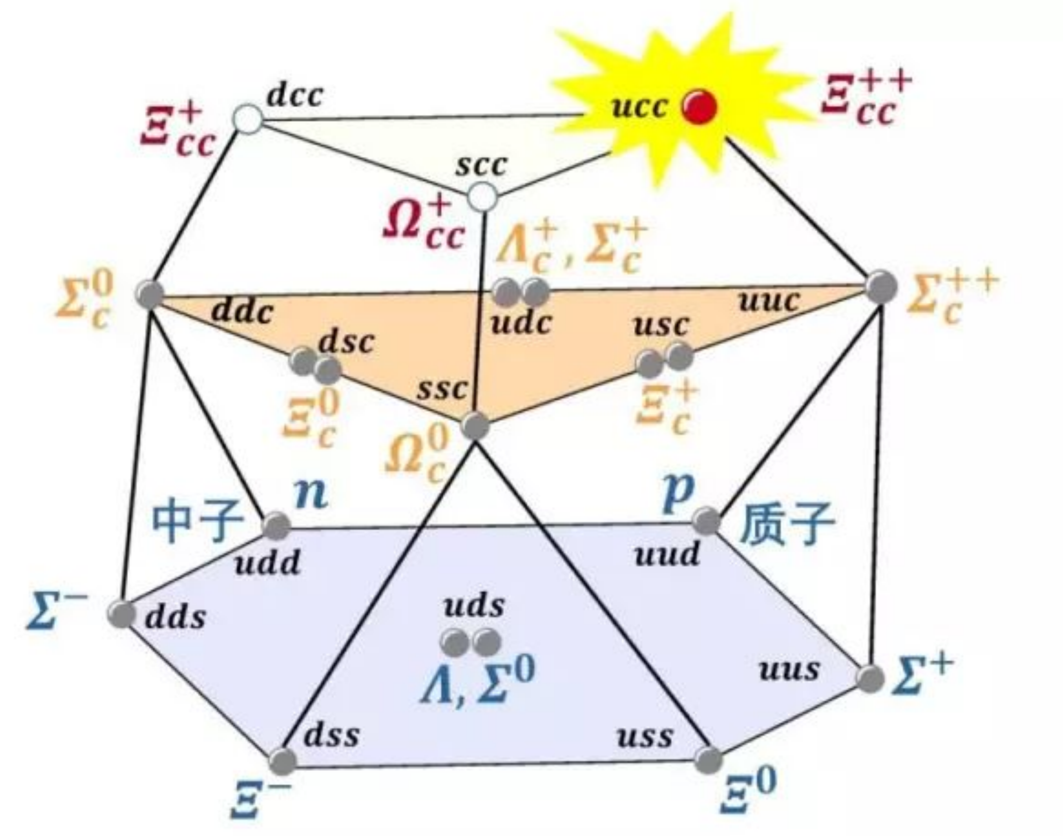
1. Introduction
2. Weak decays of doubly charmed baryons
    - Semileptonic decays **See Xiaohui Hu's talk**
    - ✓ Hadronic decays
3. Summary

LHCb observed

doubly charmed baryon via

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

LHCb, '17, '18



with

$$m(\Xi_{cc}^{++}) = (3621.40 \pm 0.78)\ \text{MeV}$$

$$\tau(\Xi_{cc}^{++}) = (2.56^{+0.24}_{-0.22} \pm 0.14) \times 10^{-13}\ s$$

LHCb, '18

Double-charm-baryon Searches

- History

- **Evidence**

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

- **But not confirmed**

$\Xi_{cc}^{+} \rightarrow \Lambda_c^+ K^- \pi^+$ FOCUS, '02

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

$\Xi_{cc}^{+} \rightarrow \Lambda_c^+ K^- \pi^+$ LHCb, '13

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Misleading !!

Double-charm-baryon Searches

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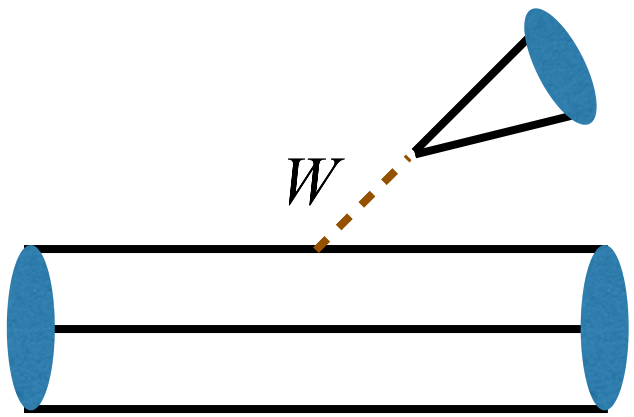
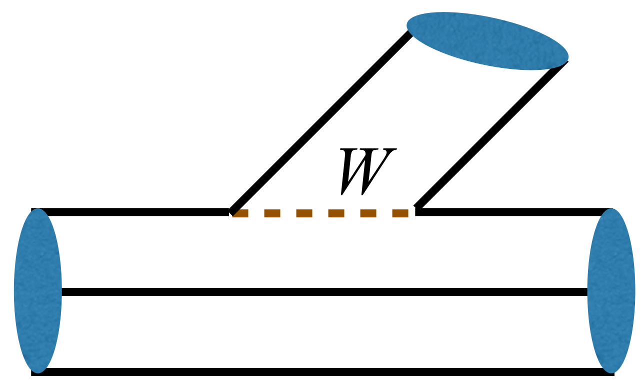
Misleading !!

2016, LHCb Run II, What discovery channel?

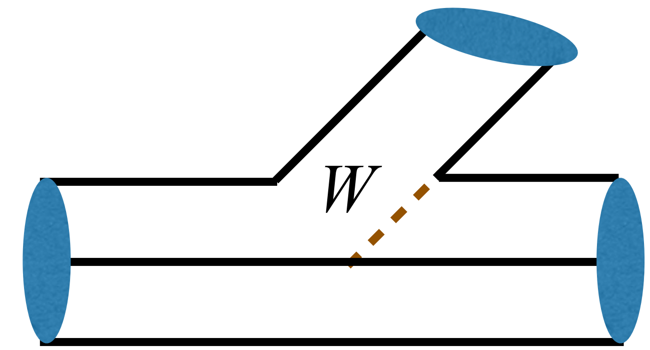
Topologies of two-body non-leptonic charmed baryon decays



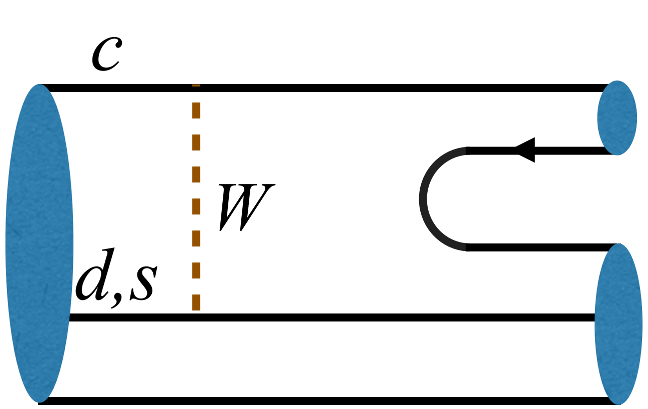
(T)
color-favored tree emitted



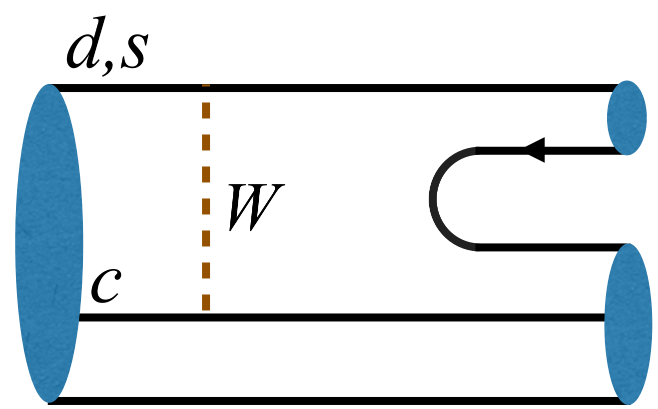
(C)
color-suppressed emitted



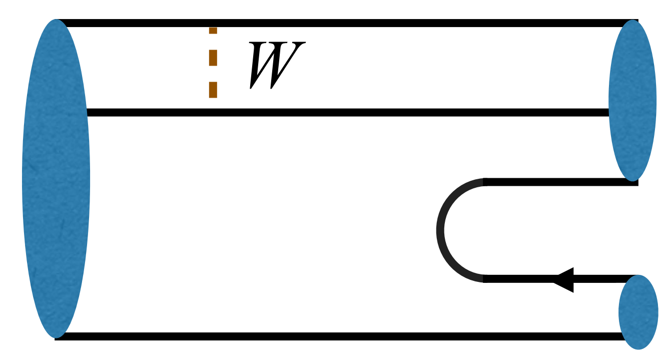
(C′)
color-commensurate



(E_1)
W-exchange 1



(E_2)
W-exchange 2



(B)
Bow tie

Dynamics is challenging in charmed baryon decays

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

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

$|P| \sim 0$

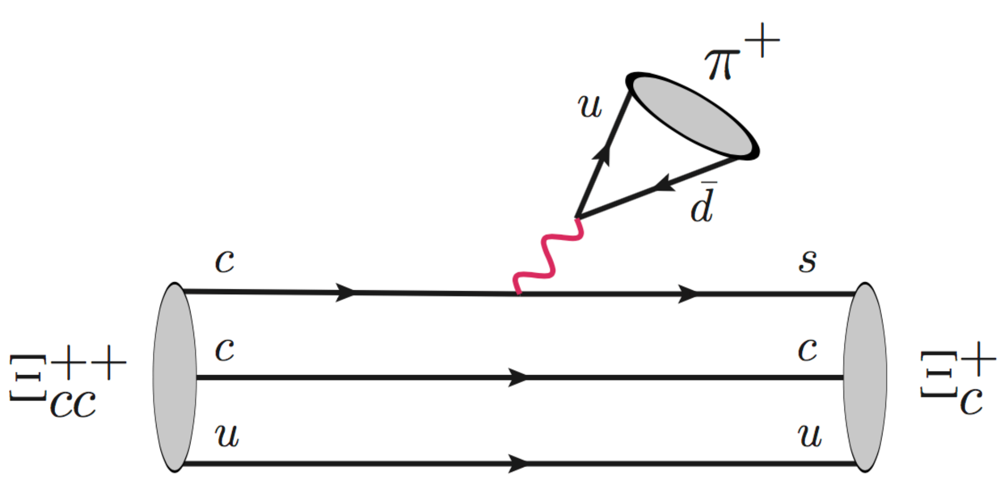
Theoretical Framework for weak decays of charmed baryons

Short + Long distance contributions

Short-distance contributions

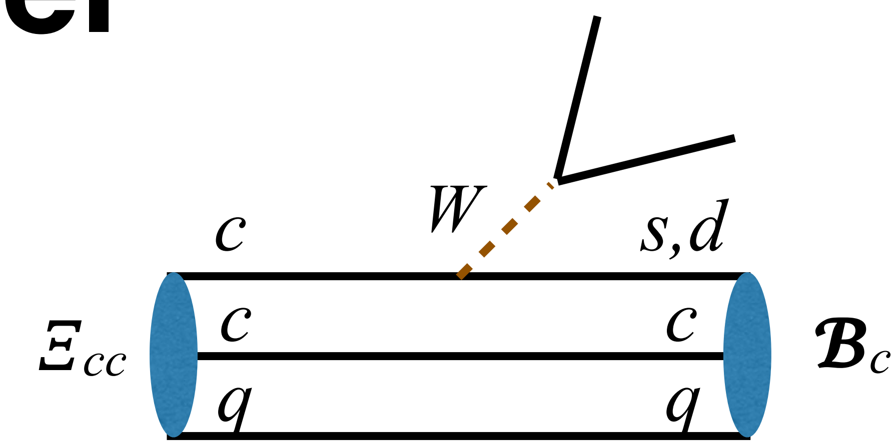
— external W-emission diagrams

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



Transition form factors (FF) in light-front quark model

- Isospin symmetry relates FF's of Ξ_{cc}^{++} and Ξ_{cc}^{+}
- Flavor SU(3) symmetry relates FF's of $c \to s$ and $c \to d$ transitions
- Uncertainties in FFs are mostly cancelled in the relative branching fractions.



$c \to s$

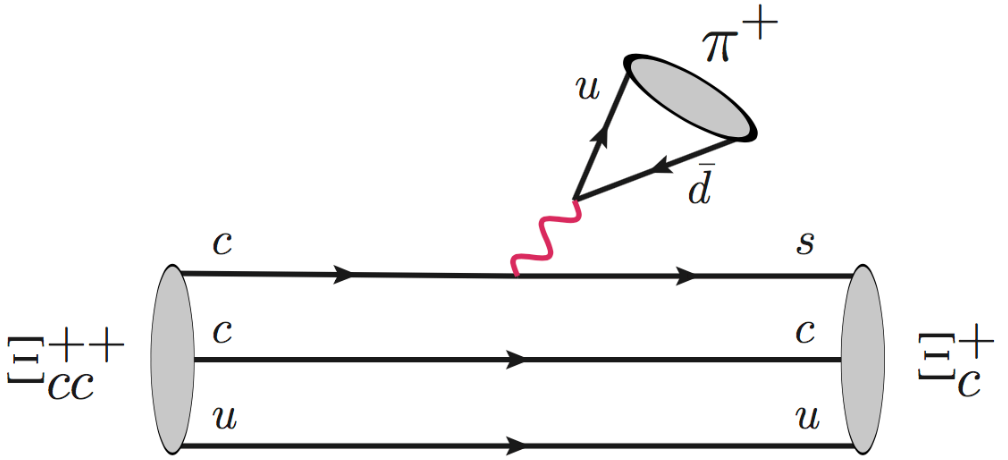
	$\Xi_{cc} \to \Xi_c/\Xi_c'(0^+)$				$\Xi_{cc} \to \Xi_c/\Xi_c'(1^+)$			
	f_1	g_1	f_2	g_2	f_1	g_1	f_2	g_2^*
$F(0)$	0.75	0.62	−0.78	−0.08	0.74	−0.20	0.80	−0.02
$m_{\rm fit}$	1.84	2.16	1.67	1.29	1.58	2.10	1.62	1.62
δ	0.25	0.35	0.30	0.52	0.36	0.21	0.31	1.37

$c \to d$

	$\Xi_{cc} \to \Lambda_c/\Sigma_c(0^+)$				$\Xi_{cc} \to \Lambda_c/\Sigma_c(1^+)$			
	f_1	g_1	f_2	g_2	f_1	g_1	f_2	g_2^*
$F(0)$	0.65	0.53	−0.74	−0.05	0.64	−0.17	0.73	−0.03
$m_{\rm fit}$	1.72	2.03	1.56	1.12	1.49	1.99	1.53	2.03
δ	0.27	0.38	0.32	1.10	0.37	0.23	0.32	2.62

Wang, **FSY**, Zhao, '17

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** small lifetime

Cabibbo-suppressed

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

$$\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+\pi^+)/\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+\pi^+) = 0.056,$$

$$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+\ell^+\nu)/\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+\pi^+) = 0.71,$$

missing energy

Other processes with large branching fractions, but

- either have neutral final-state particles

$$\Xi_c^+\rho^+(\to \pi^+\pi^0) \qquad \Xi_c'^+(\to \Xi_c^+\gamma)\pi^+$$

- or have more tracks

$$\Xi_c^+a_1^+(\to \pi^+\pi^+\pi^-)$$

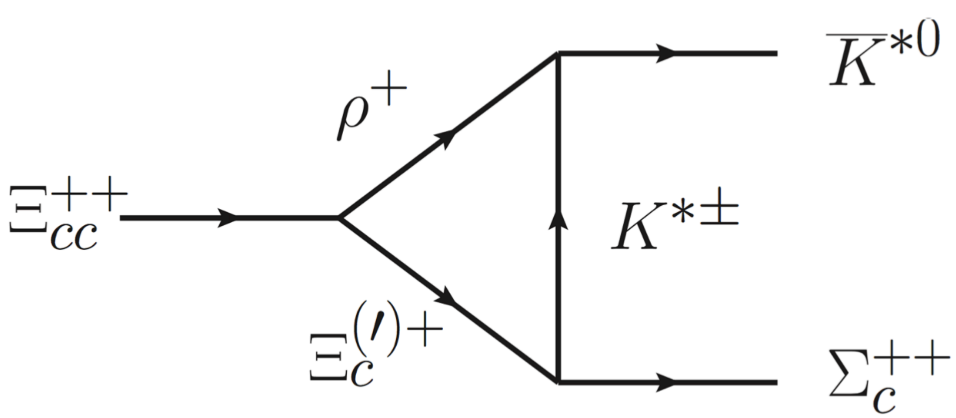
$\Xi_{cc}^{++} \to \Xi_c^+\pi^+$ is the best one to search for doubly heavy baryons among external W-emission processes

Long-distance contributions

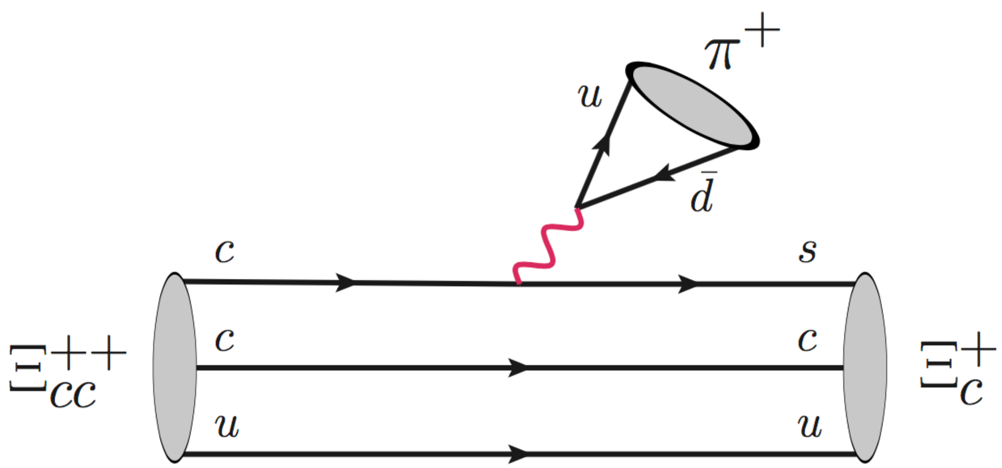
— final-state interacting (FSI) effects

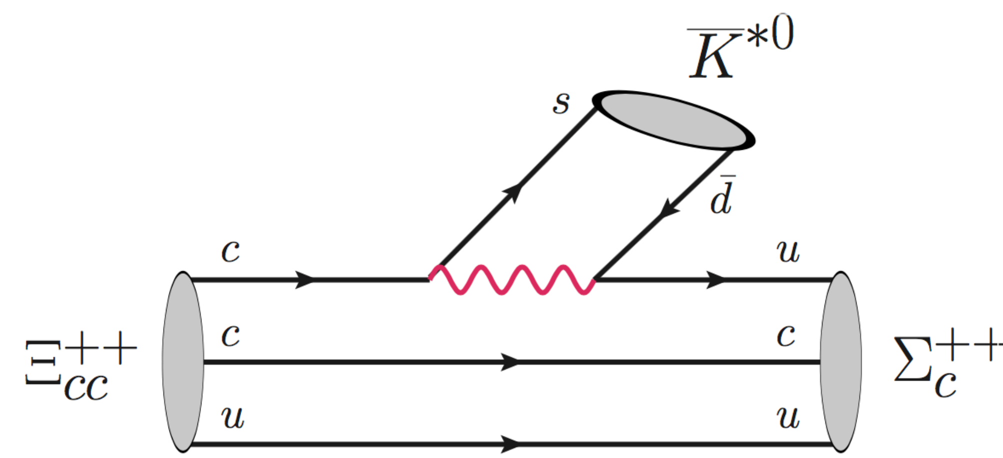
— significantly large in charm decays

- Calculate rescattering effects



Short-distance v.s. Long-distance Contributions





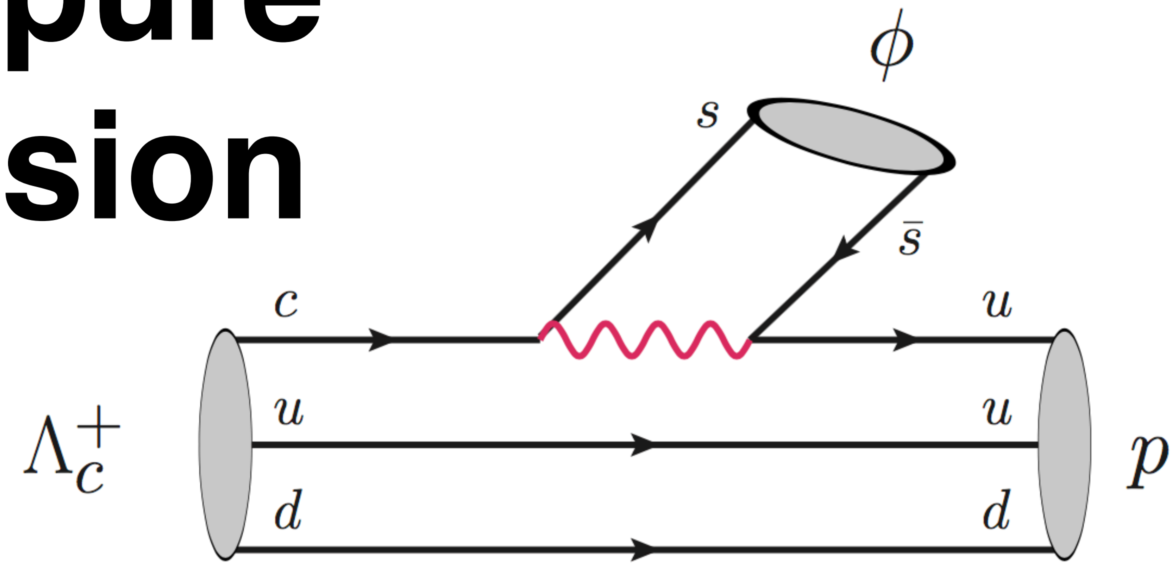
short-distance branching fractions

external W-emission	internal W-emission
Br=3.4%	Br=0.003%
color-favored	color-suppressed
$a_1(\mu_c)=1.07$	$a_2(\mu_c)= - 0.02$

But long-distance contributions are significantly enhanced in charmed hadron decays

Indication from pure internal W-emission

$$\Lambda_c^+ \to p\phi$$



Short-distance v.s. Long-distance

Br(SD)=10^{-6}

$|a_2(\mu_c)|=0.02$

Br(exp)=$(1.04\pm0.21)\times10^{-3}$

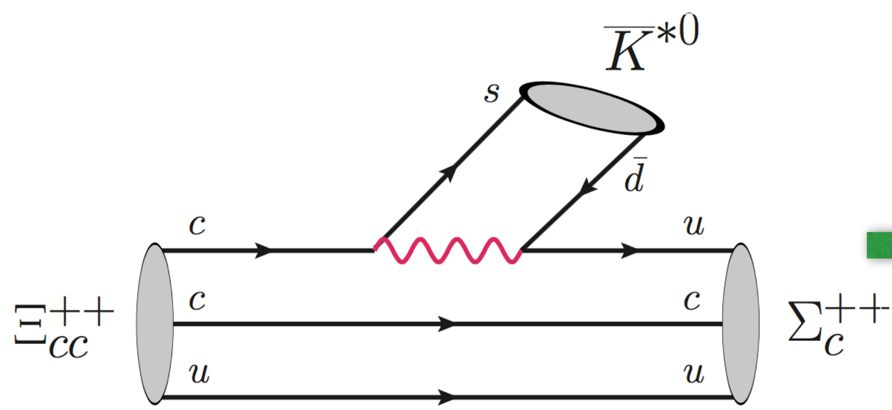
$|a_2^{eff}(\mu_c)|=0.7$

large-N_c limit

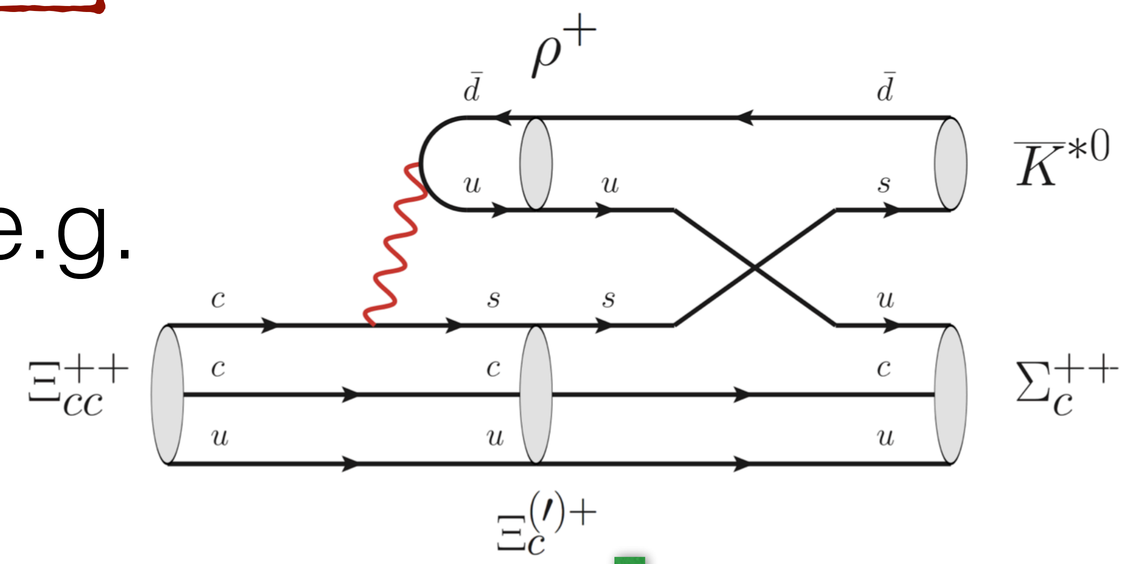
Understanding long-distance contributions is essential to find a best process

for the searches for doubly heavy baryons

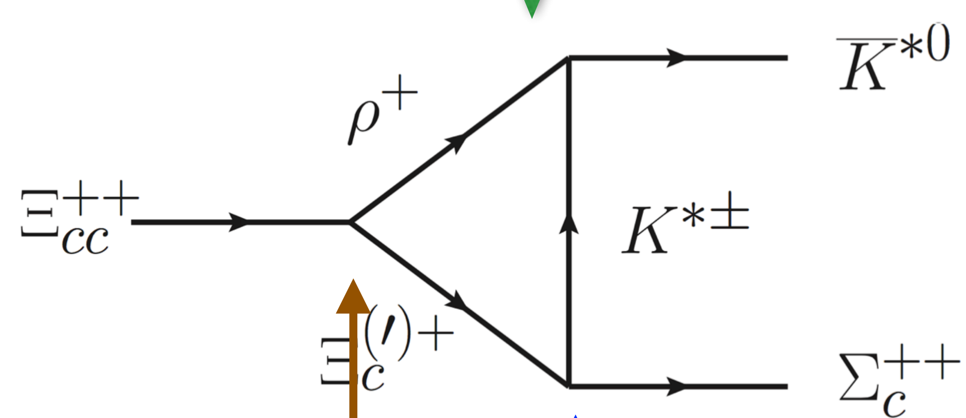
$\Xi_{cc}^{++} \to \Sigma_c^{++} \overline{K}^{*0}$



FSI e.g.



Rescattering mechanism of the final-state interacting effects



Absorptive part:

weak vertex

rescattering

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

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

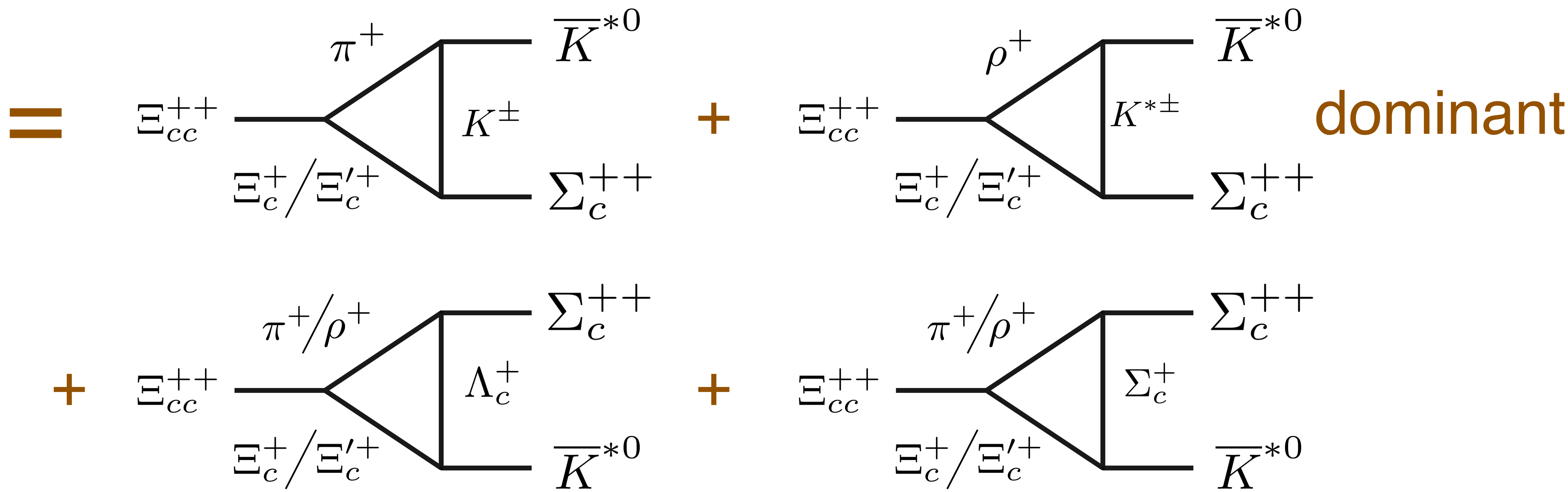
Relative Branching Fractions with long-distance contributions

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

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



$$\eta = 1.0 \sim 2.0$$

$$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) = 3.4\%$$

$$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \rho^+) = 6.3\%$$

$$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c'^+ \pi^+) = 2.4\%$$

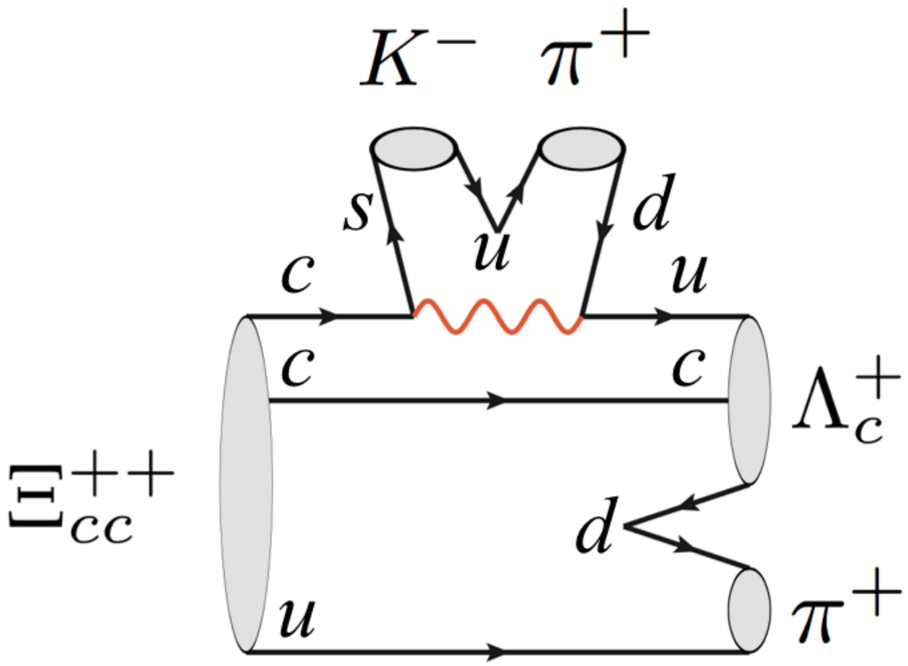
$$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c'^+ \rho^+) = 8.7\%$$

$$\Rightarrow \quad \boxed{\mathcal{B}(\Xi_{cc}^{++} \to \Sigma_c^{++} \overline{K}^{*0}) = (3.8 \sim 24.6)\% \times \frac{\tau_{\Xi_{cc}^{++}}}{300\ \mathrm{fs}}}$$

Large enough for measurements

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

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



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

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

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

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

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

$\tau \times (\sim 3)$

Br × 5

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

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

$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ has larger branching fraction than $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$

Lifetimes

Literatures	Ξ_{cc}^{++} (fs)	Ξ_{cc}^{+} (fs)
Cheng, Shi, 2018	298	45
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

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

- Longer lifetime ⇒ Higher efficiency to reject backgrounds in hadron colliders

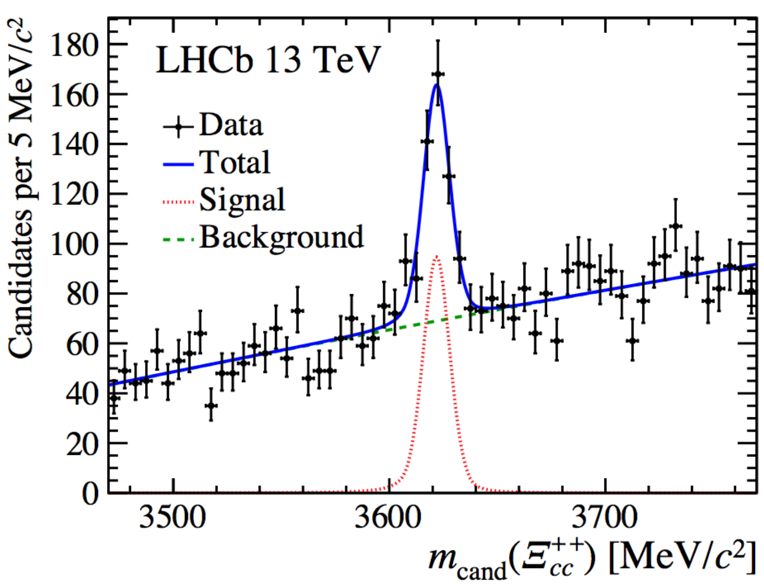
Discovery Potentials of Doubly Charmed Baryons

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.

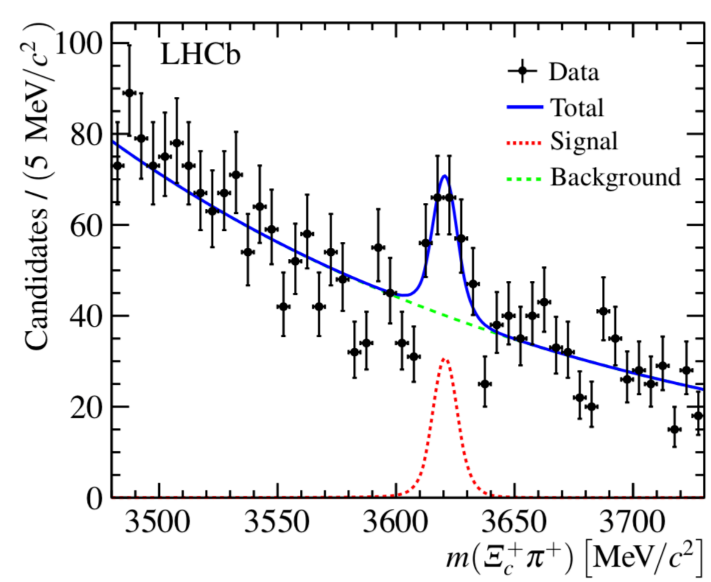
FSY, Jiang, Li, Lü, Wang, Zhao, 1703.09086

July 2017



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

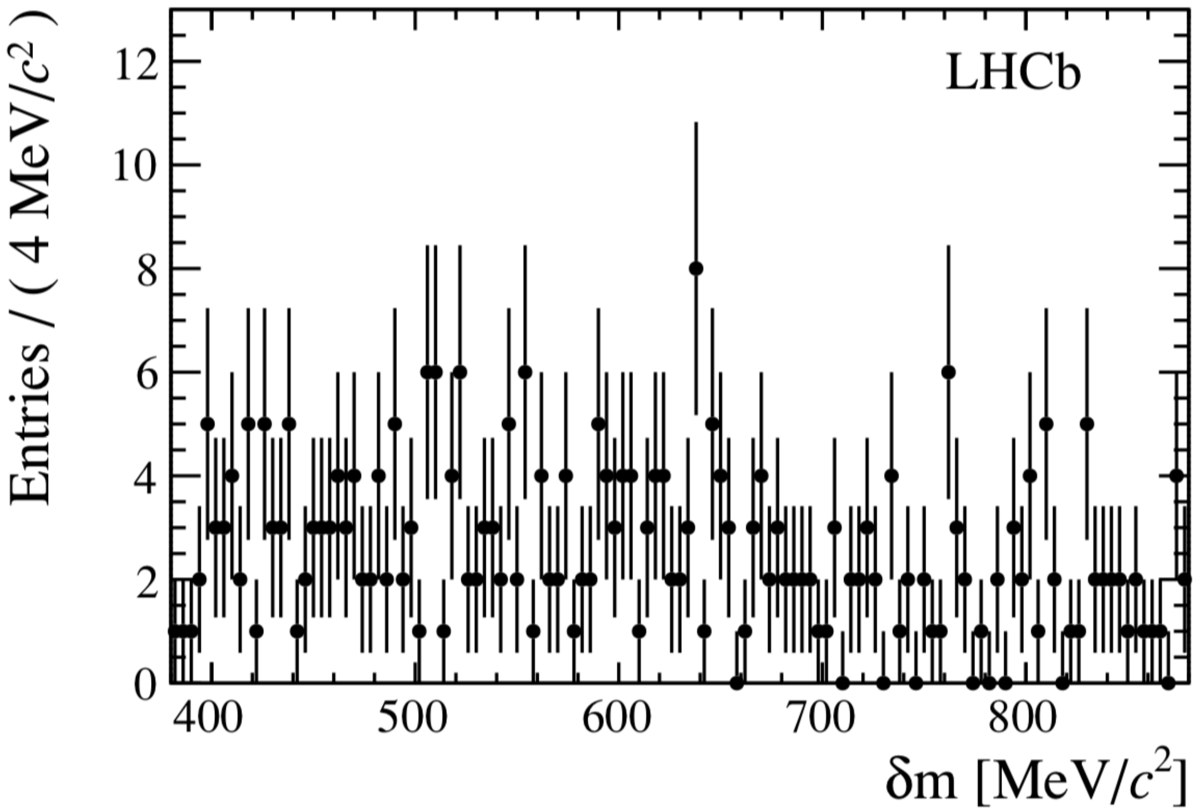
July 2018

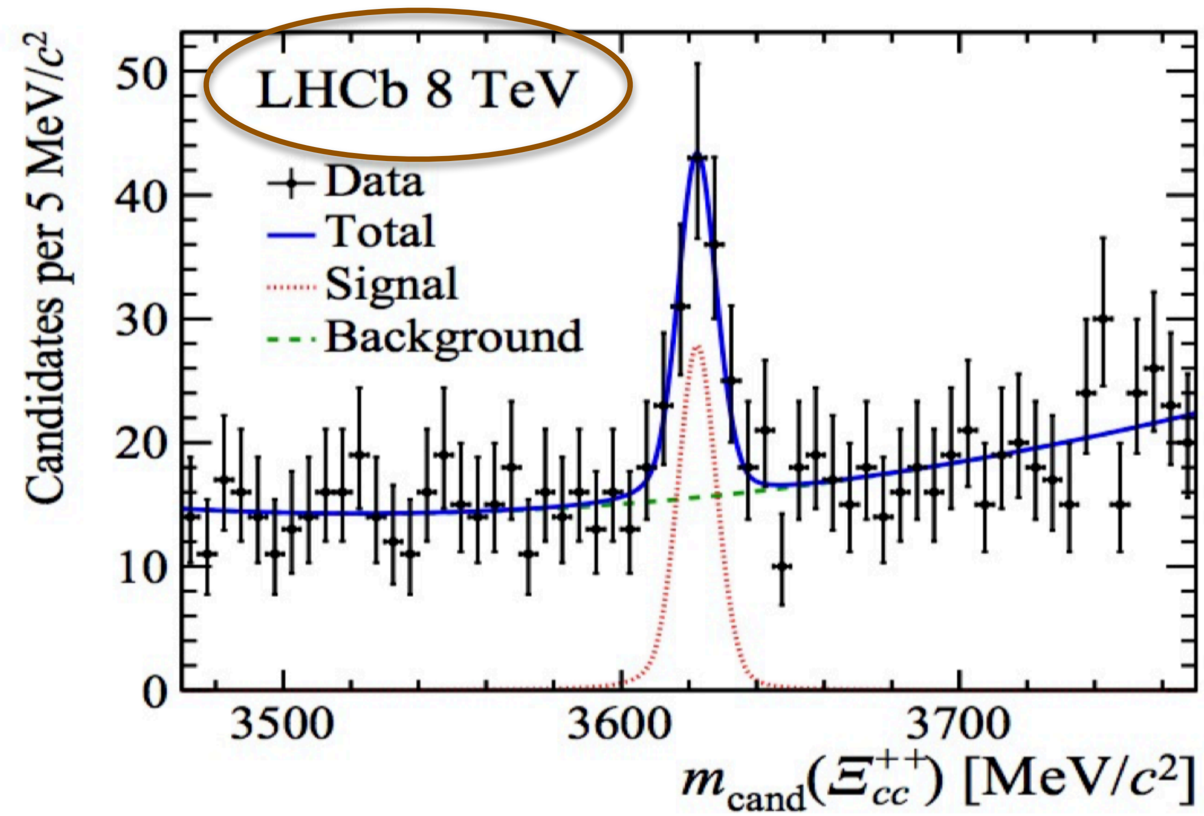


$$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$$

LHCb observed Ξ_{cc}^{++}

LHCb 2012 Data





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

No signal

[LHCb, JHEP 12 (2013)090]

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

Observation

LHCb talks

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

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

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: the FCNC processes 1807.03101

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

10. Weak decays of triply heavy baryons 1803.01476

11. QCD sum rules analysis of weak decays of doubly heavy baryons 1902.01092

12. Light-cone sum rules analysis of $\Xi_{QQ'q} \to \Lambda_{Q'}$ weak decays 1903.03921

……

Prospect of theoretical studies

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

……

Summary

- We systematically study the weak decays of doubly charmed baryons
- By comparing all the decay modes, we recommend to measure the following processes to search for doubly heavy baryons

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

- **And LHCb observed it via the both processes!**
- Outlook: similar analysis to search for other particles.

Thank you!