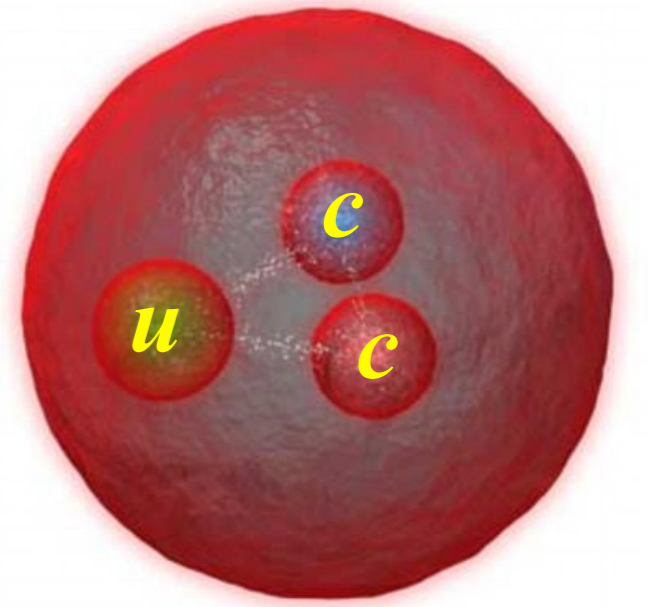


Weak Decays of Ξ_{cc}

— discovery potentials



Fu-Sheng Yu
Lanzhou University



第十屆高能物理大會 @ 上海, 2018.06.19 - 06.24

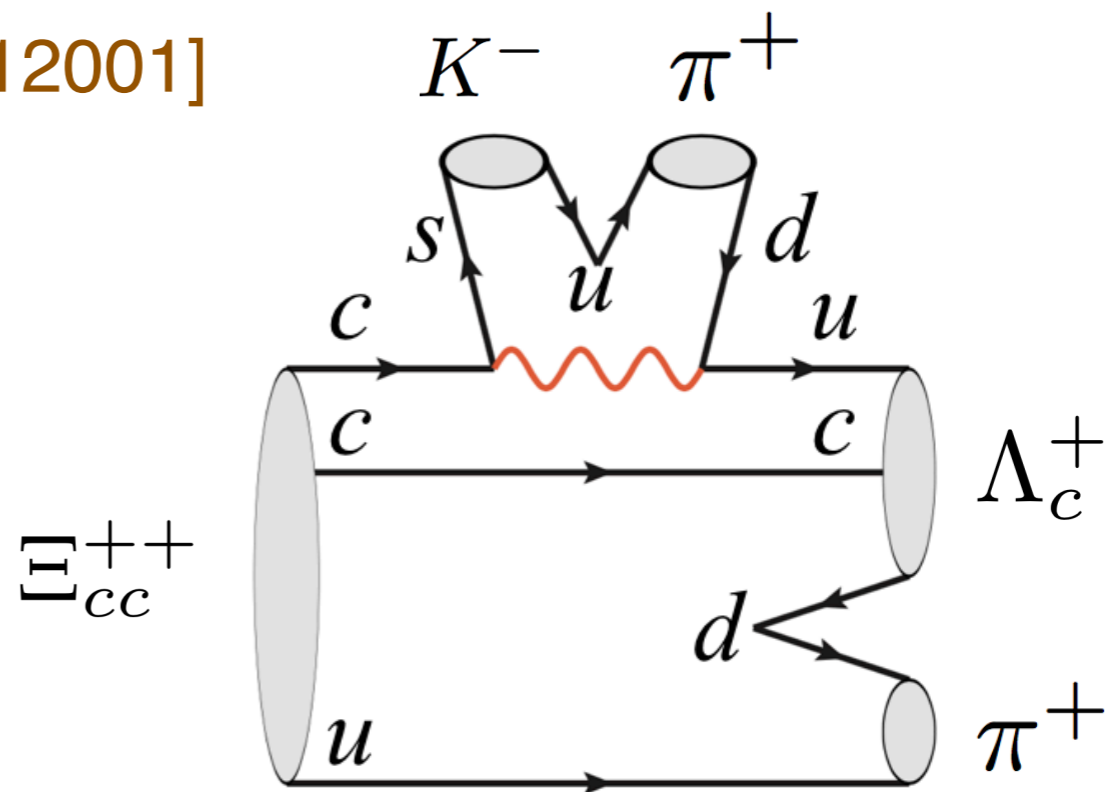
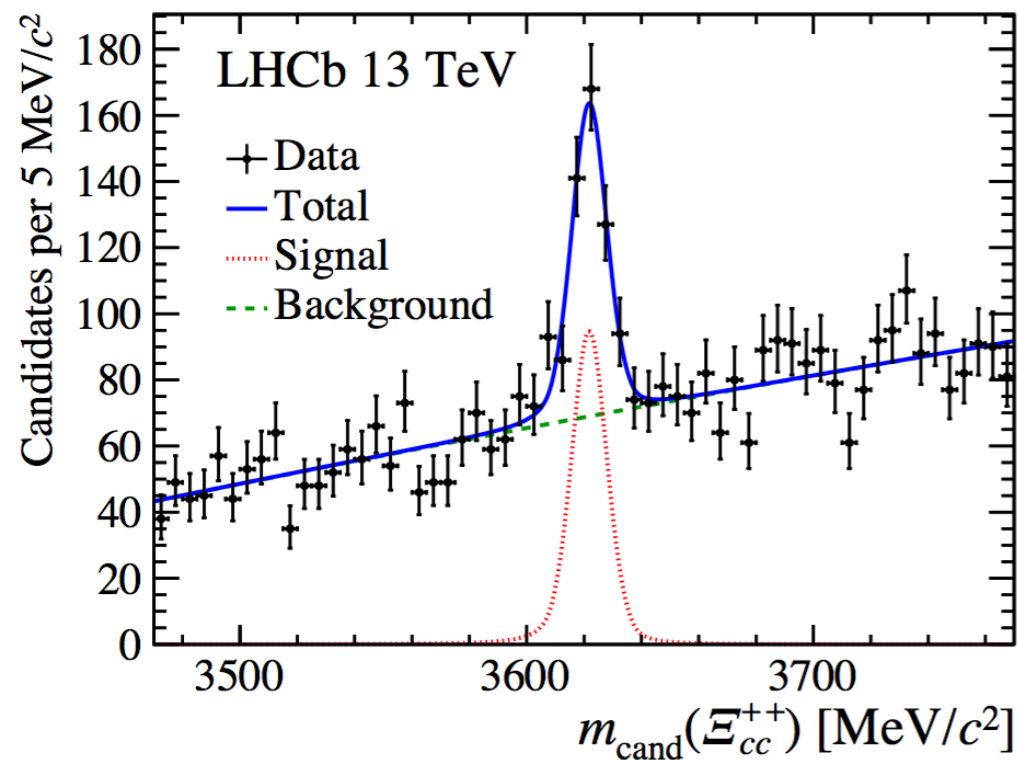
In collaboration with Hua-Yu Jiang, Run-Hui Li, Ying Li, Cai-Dian Lü,
Wei Wang, Zhen-Xing Zhao, Zhi-Tian Zou

Outline

1. Introduction
2. Theoretical Framework and results
3. Outlook
4. Summary

LHCb observed Ξ_{cc}^{++}

[LHCb, PRL119,112001]



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

first reported on July 6, 2017

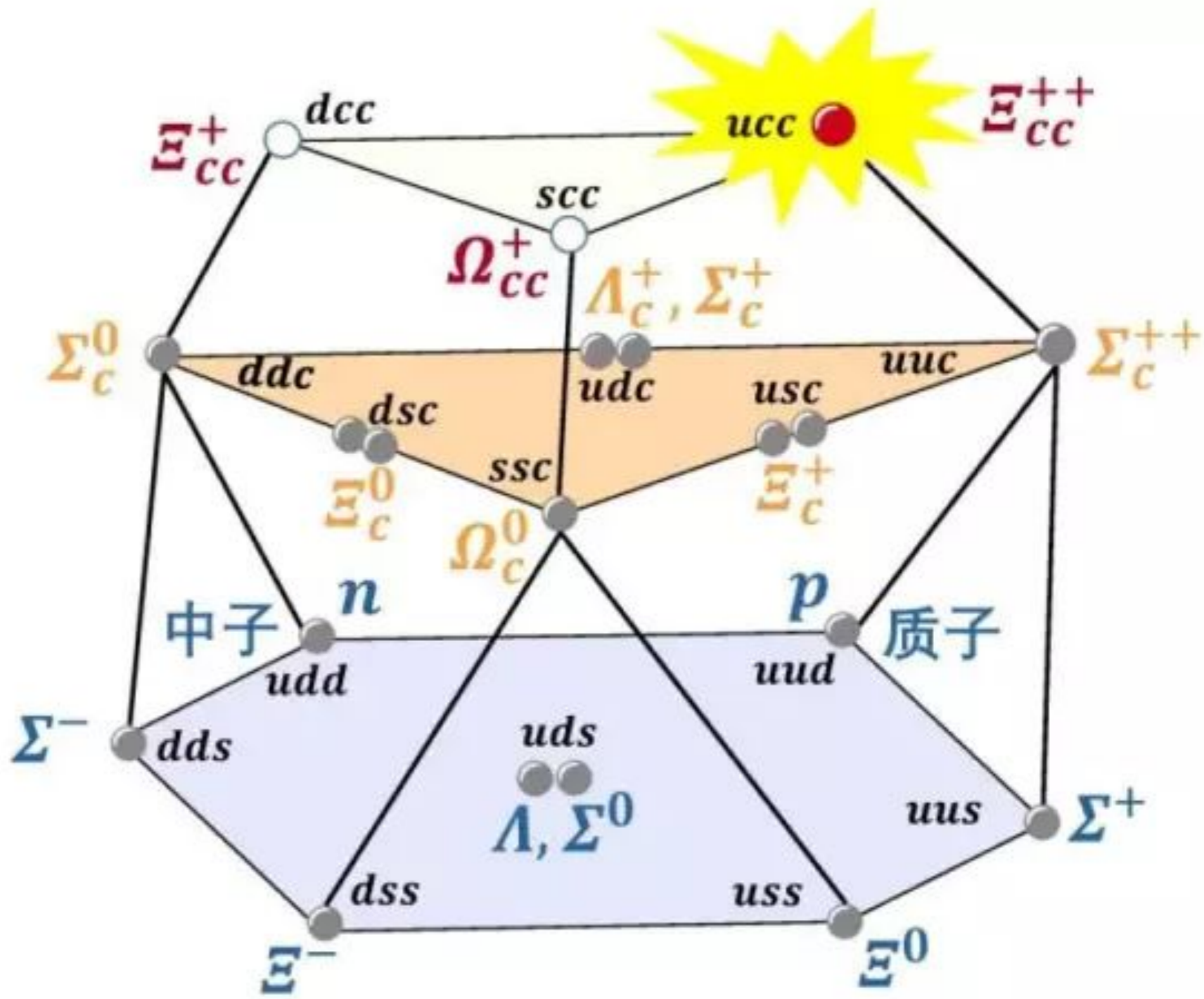
$$m_{\Xi_{cc}^{++}} = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14 \text{ MeV}$$

$$\tau_{\Xi_{cc}^{++}} = 0.256_{-0.022}^{+0.024} \pm 0.014 \text{ ps}$$

[See Liang Sun's talk on Friday]

The discovery channel
of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$
was suggested by

[FSY, Jiang, Li, Lü, Wang,
Zhao, CPC42(2018)05001,
[arXiv:1703.09086]]

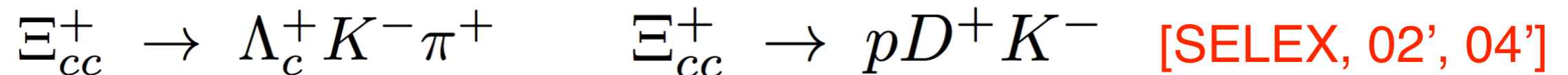


SU(4) flavor symmetry

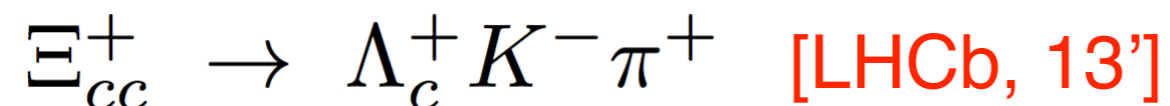
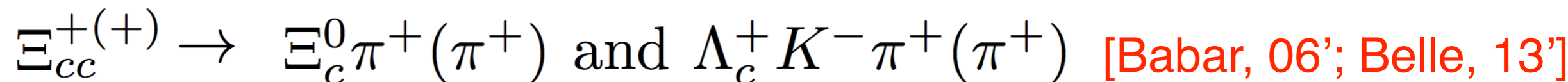
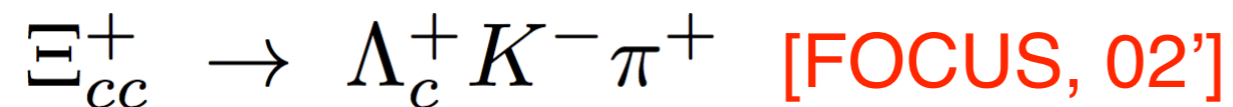
Searching History

- In experiments

- The only evidence was found for Ξ_{cc}^+ by SELEX



- But not confirmed by other experiments

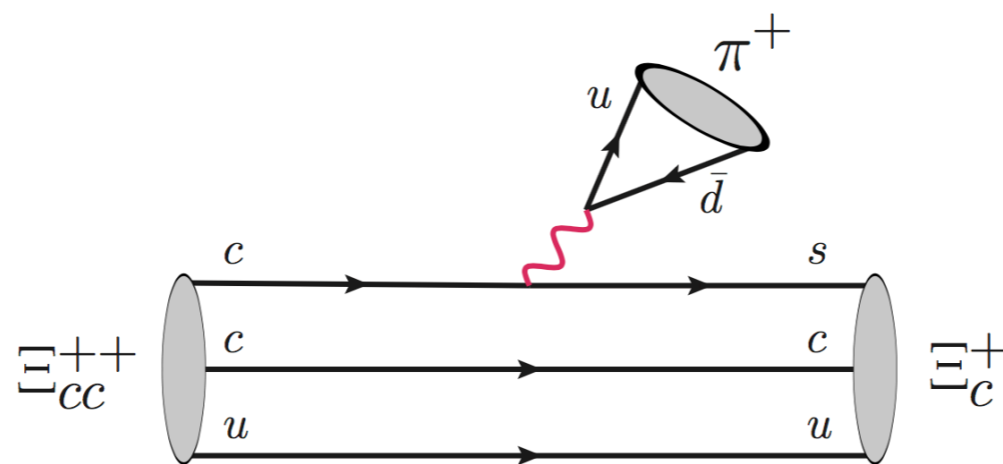


Theory Framework for weak decays of charmed baryons

Short + Long distance contributions

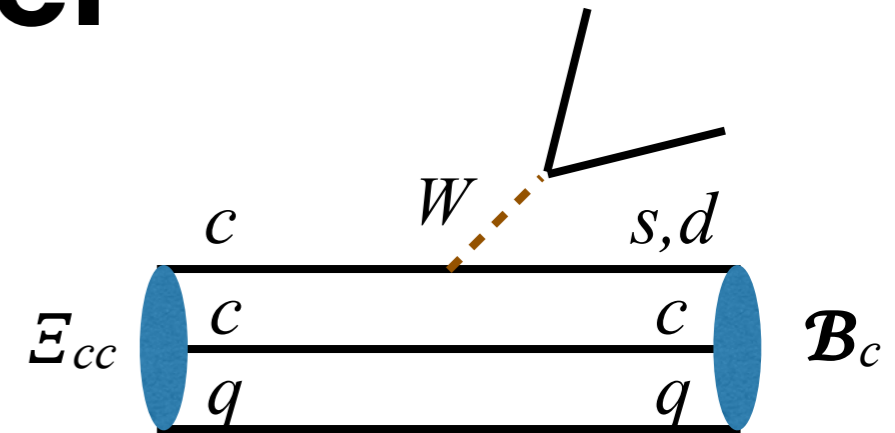
Short-distance contributions

- 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

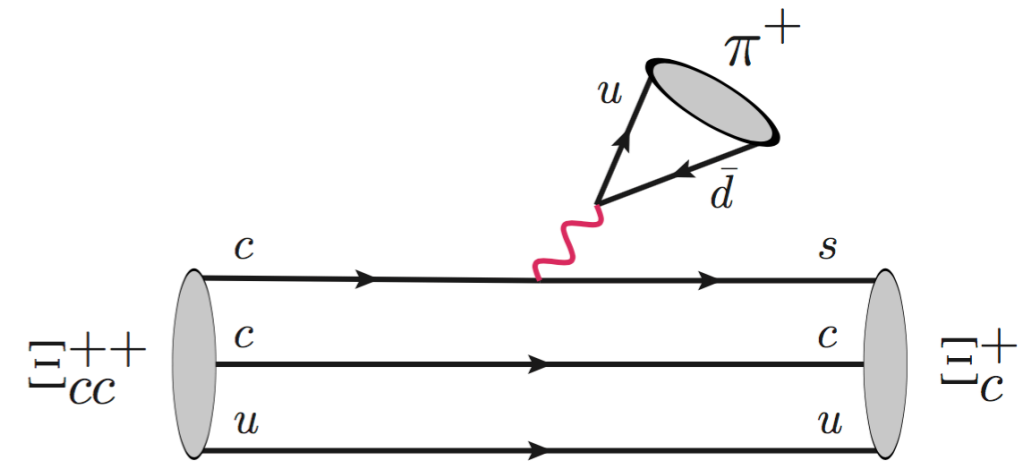
- **Isospin symmetry** relates FF's of Ξ_{cc}^{++} and Ξ_{cc}^+
- **Flavor SU(3) symmetry** relates FF's of $c \rightarrow s$ and $c \rightarrow d$ transitions
- **Uncertainties in FFs are mostly cancelled in the relative branching fractions.**



$c \rightarrow s$	$\Xi_{cc} \rightarrow \Xi_c/\Xi'_c(0^+)$				$\Xi_{cc} \rightarrow \Xi_c/\Xi'_c(1^+)$			
	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_{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
$c \rightarrow d$	$\Xi_{cc} \rightarrow \Lambda_c/\Sigma_c(0^+)$				$\Xi_{cc} \rightarrow \Lambda_c/\Sigma_c(1^+)$			
	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_{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

[W.Wang, FSY, Z.X.Zhao, '17]

Short-Distance Contributions



- External W -emission processes using factorization approach

$$A(\Xi_{cc} \rightarrow \mathcal{B}_c M)_{\text{SD}}$$

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

- Relative branching fractions are reliable

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

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

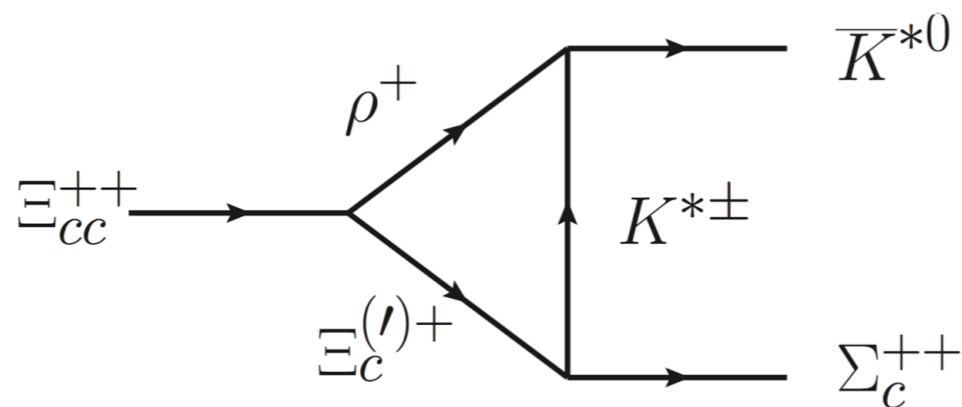
$$\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ \ell^+ \nu) / \mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+) = 0.71,$$

Uncertainties of form factors are mostly cancelled

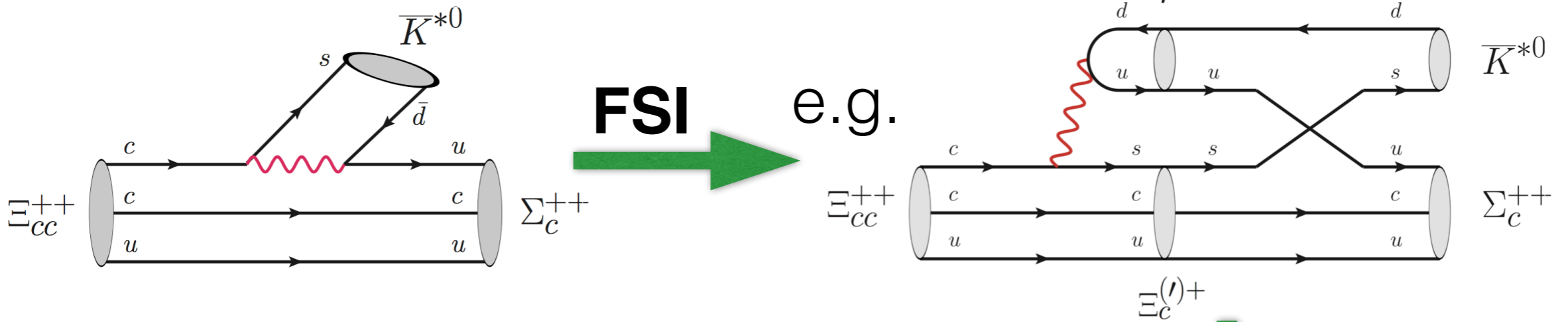
$\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+)$ is the largest one

Long-distance contributions

- final-state interacting (FSI) effects
 - significantly large in charm decays
- Calculate rescattering effects



$$\Xi_{cc}^{+++} \rightarrow \Sigma_c^{++} \bar{K}^{*0}$$

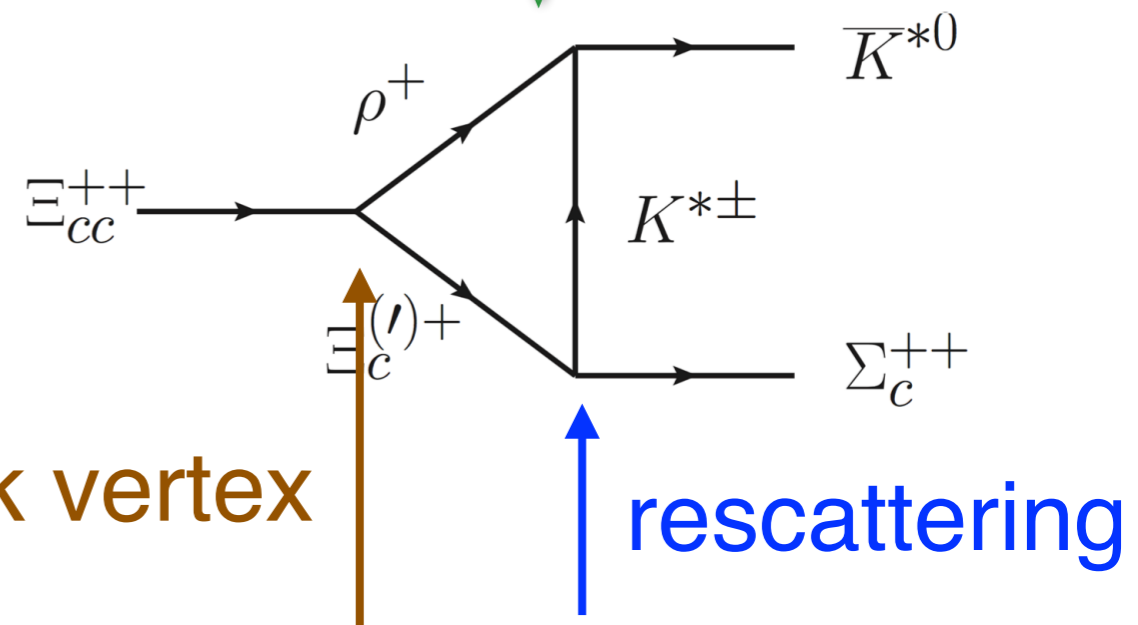


Rescattering mechanism of the final-state interacting effects

Absorptive part:

$$\text{Abs}\mathcal{M}(p_i \rightarrow p_f q) =$$

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



[See Jiang's talk in April 24] 11

Relative Branching Fractions with long-distance contributions

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

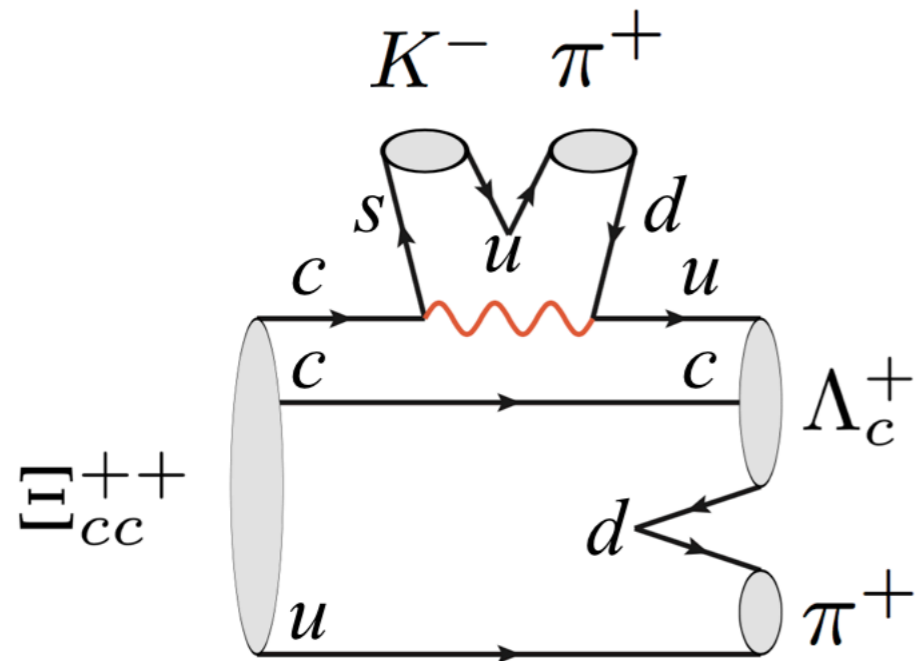
Uncertainties of the relative branching fractions induced by the parameter of η are less than 10%

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

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

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

is actually a four-body decay



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

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

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

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

$$\Xi_{cc}^{+++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+ \quad \mathbf{v.s.} \quad \Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$$

SELEX's discovery channel,
LHCb measured

Baryons	Modes	\mathcal{B}_{LD}	
$\Xi_{cc}^{+++} (ccu)$	$\Sigma_c^{+++} (2455) \bar{K}^{*0}$	defined as 1	$\Lambda_c^+ K^- \pi^+ \pi^+$
	pD^{*+}	0.04	Br \times 5
	pD^+	0.0008	
$\Xi_{cc}^+ (ccd)$	$\Lambda_c^+ \bar{K}^{*0}$	$(\mathcal{R}_\tau/0.3) \times 0.22$	$\Lambda_c^+ K^- \pi^+$
	$\Sigma_c^{++} (2455) K^-$	$(\mathcal{R}_\tau/0.3) \times 0.008$	
	$\Xi_c^+ \rho^0$	$(\mathcal{R}_\tau/0.3) \times 0.04$	
	ΛD^+	$(\mathcal{R}_\tau/0.3) \times 0.004$	
	pD^0	$(\mathcal{R}_\tau/0.3) \times 0.002$	

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

$$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+ \quad \mathbf{v.s.} \quad \Xi_{cc}^+ \rightarrow p D^+ K^-$$

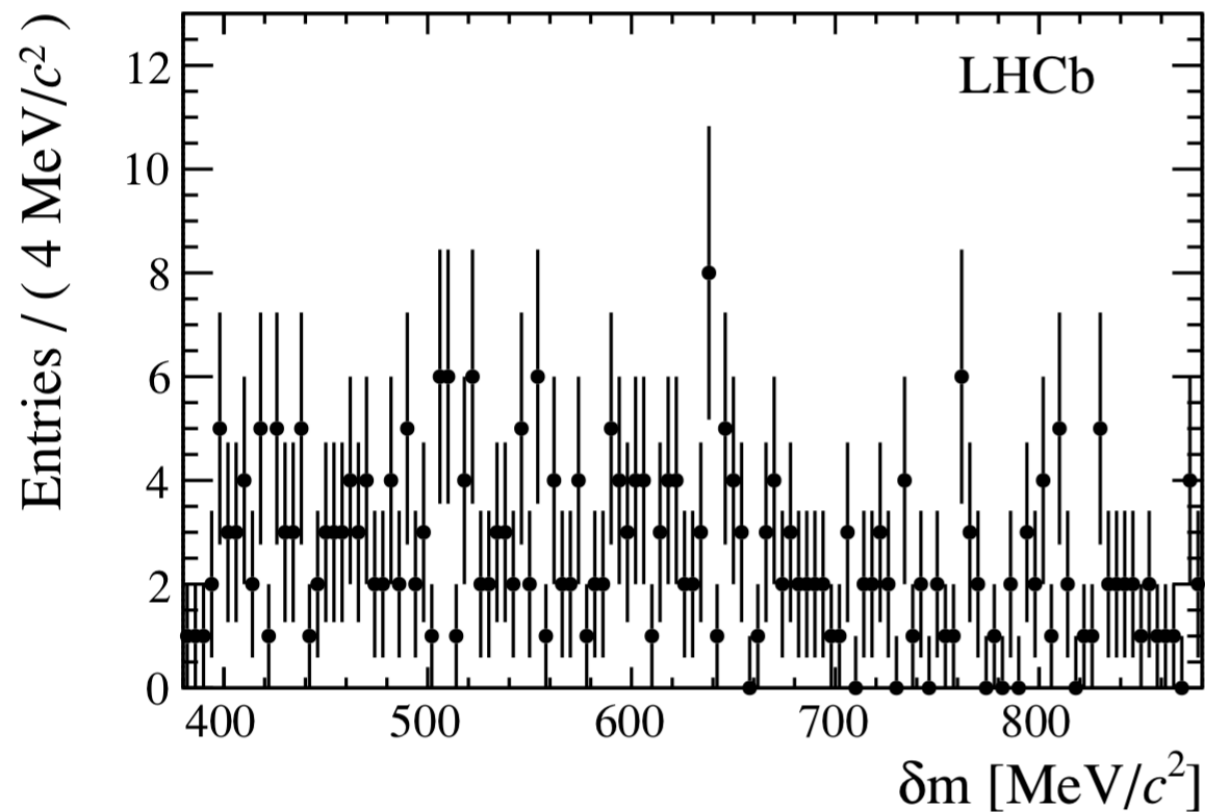
SELEX's discovery channel

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

We recommend to measure $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ to search for doubly heavy baryons

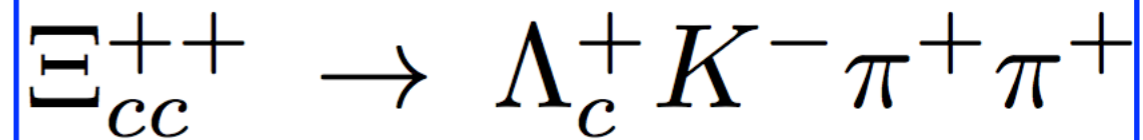
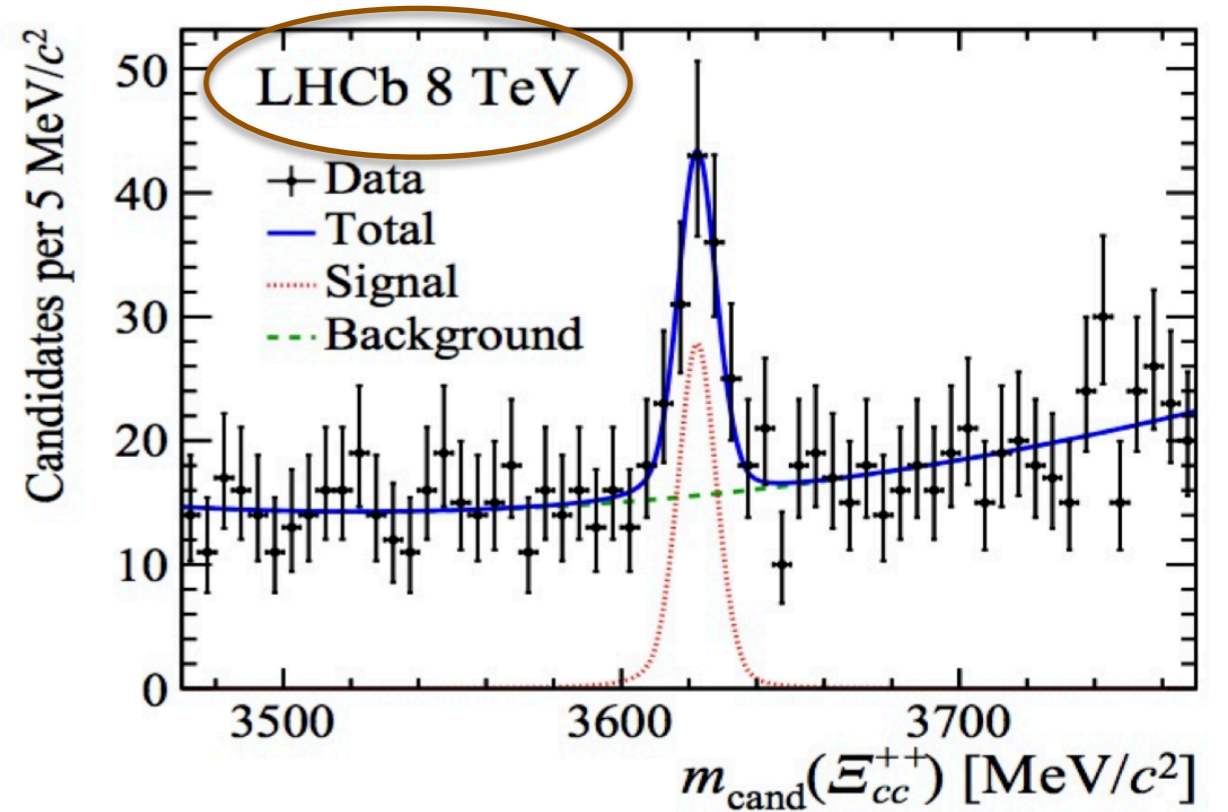
[FSY, *et al*, 1703.09086]

LHCb Run-I Data Analysis



No signal

[LHCb, JHEP 12 (2013)090]



Observation

[See Liang Sun's talk on Friday]

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

Weak Decays of Ξ_{cc}



Fu-Sheng Yu (于福升)

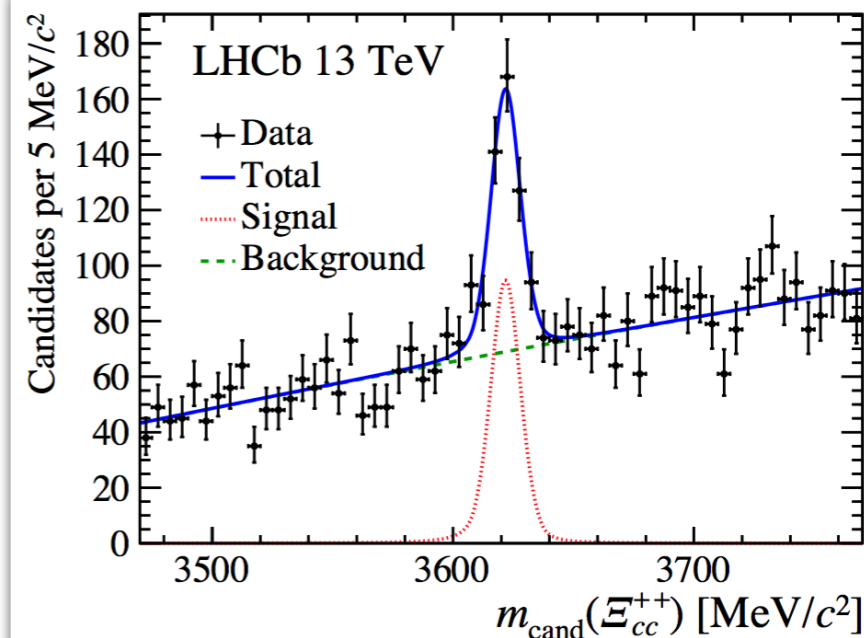
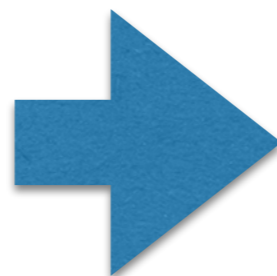
Lanzhou University

15.03.2017 @ LHCb Charm WG

Thank Ji-Bo and Andrea for invitation to give a talk!

Based on [arXiv:1703.09086]

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



Theory talks on decays
@ LHCb-China, Dec 2016
@ LHCb-Charm, Mar 2017

Observation reported
by LHCb, Jul 2017

LHCb发言人Passaleva:
“中国的理论家的关键建议
引导该分析在正确的方向
上取得了突破。”

高原宁教授:
双粲重子的发现
是理论和实验结
合的典范。

List of studies on weak decays

1. Doubly heavy baryon weak decays: $\Xi_{bc}^0 \rightarrow pK^-$, $\Xi_{cc}^+ \rightarrow \Sigma_c(2520)^{++}K^-$
[arXiv:1701.03284]
2. Discovery potentials of doubly charmed baryons: $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$
[arXiv:1703.09086]
3. Weak decays of doubly heavy baryons: the $1/2 \rightarrow 1/2$ case
[arXiv:1707.02834]
4. Weak decays of doubly heavy baryons : SU(3) analysis
[arXiv:1707.06570]
5. Weak decays of doubly heavy baryons : decay constant
[arXiv:1711.10289]
6. Weak decays of doubly heavy baryons : Multi-body decay channels
[arXiv:1712.03830]
7. Weak decays of triply heavy baryons
[arXiv:1803.01476]
8. Weak decays of doubly heavy baryons: the $1/2 \rightarrow 3/2$ case
[arXiv:1805.10878]

List of studies on weak decays

Prospect



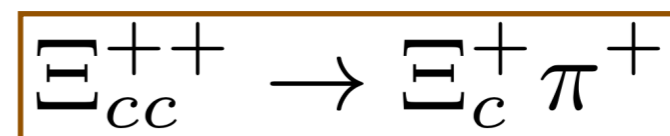
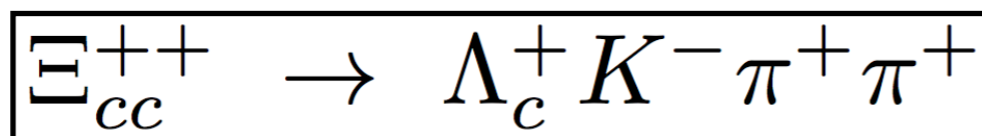
- Study Ξ_{cc}^{++} in more channels?
- lifetime?
- Ξ_{cc}^+ ?
- $J^P = 1/2^+$?
- Semi-leptonic decay modes?
- CP Violation?
- ...

A long long list...

[W. Wang's talk @ Implication of LHCb, 2017]

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



- And LHCb observed it via the first process.
- Outlook: similar analysis to search for other particles.

Thank you !

Backup

cross sections of production @ LHC

$\sigma(\Xi_{cc})$ is close to
 $\sigma(B_c)$ @ LHC

Ξ_{cc}

-	$\sqrt{S} = 7.0\text{TeV}$	$\sqrt{S} = 14.0\text{TeV}$
$[^3S_1]$	38.11	69.40
$[^1S_0]$	9.362	17.05
Total	47.47	86.45

in unit of nb

$$p_t \geq 4\text{GeV} \quad |y| \leq 1.5$$

[J.-W. Zhang, X.-G. Wu, T. Zhong, Y. Yu, Z.-Y. Fang, Phys.Rev. D 83, 034026 (2011)]

B_c

-	$ (^1S_0)_1\rangle$	$ (^3S_1)_1\rangle$	$ (^1S_0)_{8g}\rangle$	$ (^3S_1)_{8g}\rangle$	$ (^1P_1)_1\rangle$	$ (^3P_0)_1\rangle$	$ (^3P_1)_1\rangle$	$ (^3P_2)_1\rangle$
LHC	71.1	177.	(0.357, 3.21)	(1.58, 14.2)	9.12	3.29	7.38	20.4

LHC ($\sqrt{S} = 14.0$ TeV)

in unit of nb

[C.-H. Chang, C.-F. Qiao, J.-X. Wang, X.-G. Wu, Phys.Rev. D71 (2005) 074012]

B_c well studied at LHCb,
discovery and establishment of Ξ_{cc} would not be far

The key issue
is to select the decaying processes
with the largest possibilities of
observing doubly charmed baryons

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

But much less ambiguity of ratio of lifetimes

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

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



Effect of destructive Pauli interference

Longer lifetime of Ξ_{cc}^{++}

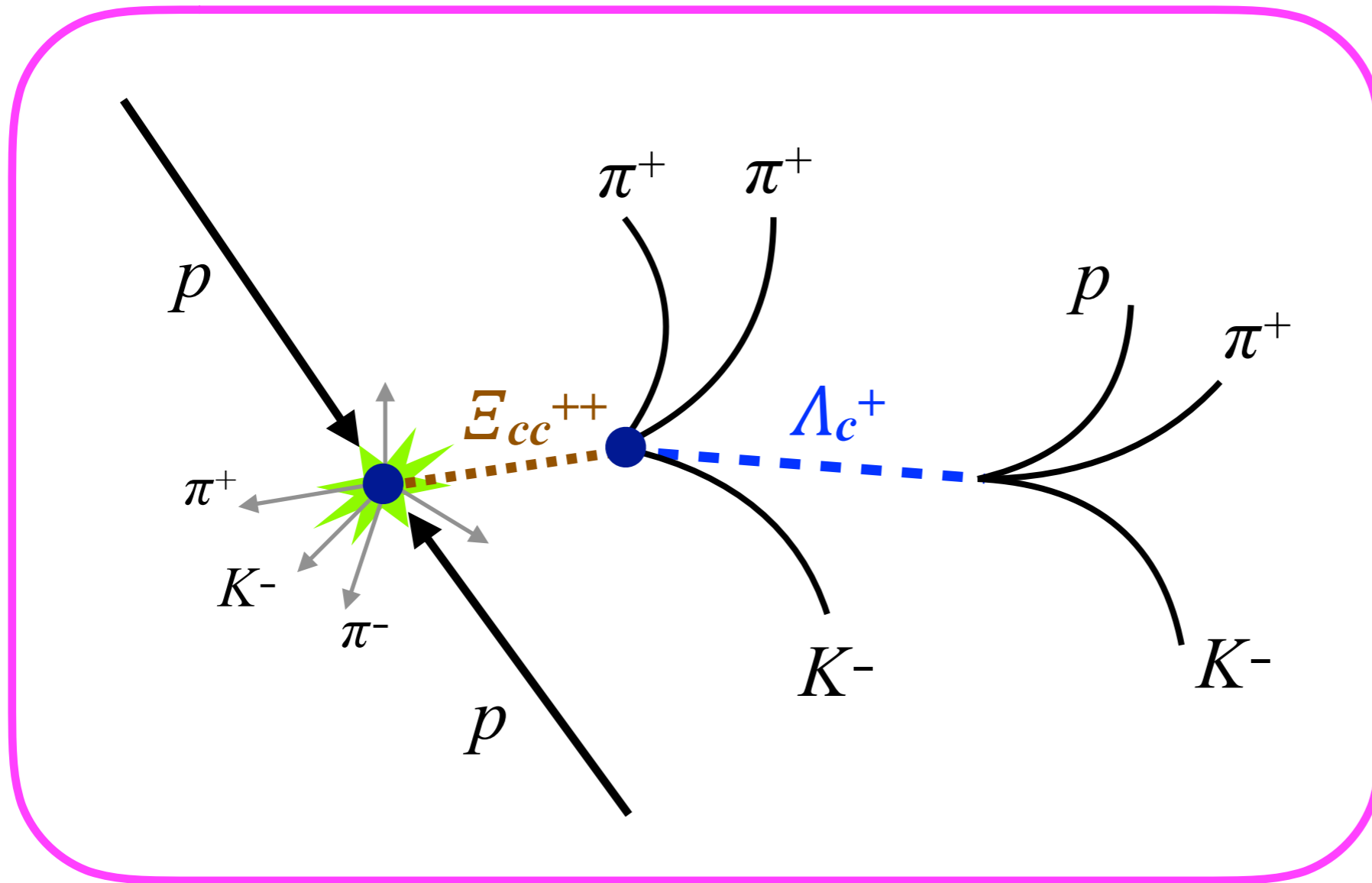
$$\mathcal{R}_\tau \equiv \frac{\tau_{\Xi_{cc}^+}}{\tau_{\Xi_{cc}^{++}}} = 0.25 \sim 0.37 \quad \tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^+)$$

- Longer lifetime \Rightarrow Larger branching fractions

$$\mathcal{B}_i = \Gamma_i \cdot \tau$$

- Longer lifetime \Rightarrow Higher efficiency of identification at hadron colliders

We recommend to search for Ξ_{cc}^{++} rather than Ξ_{cc}^+



**Longer
Lifetime**

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)]

small lifetime

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

Cabibbo-suppressed

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

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

missing energy

Other processes with large branching fractions, but

- either have neutral final-state particles

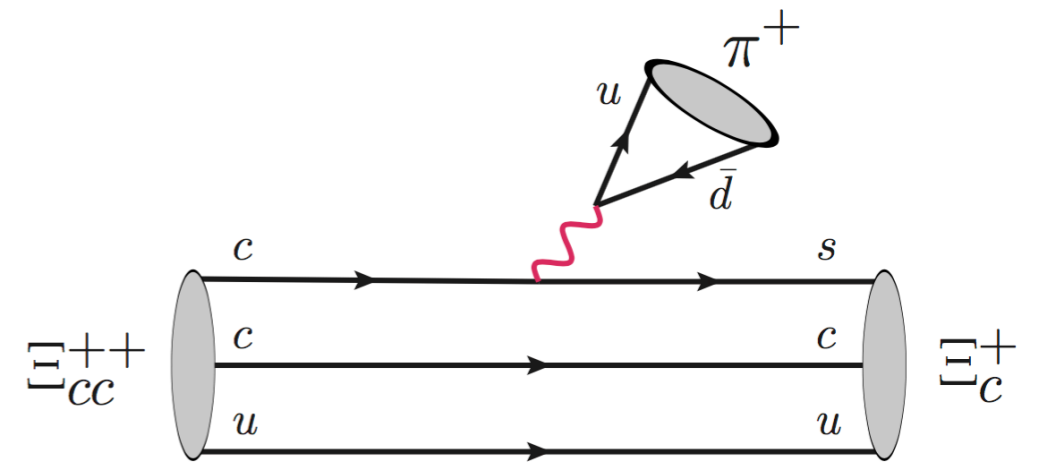
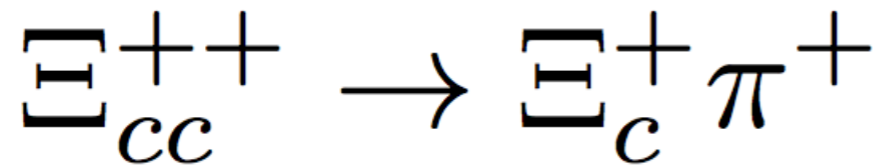
$$\Xi_c^+ \rho^+ (\rightarrow \pi^+ \pi^0)$$

$$\Xi_c'^+ (\rightarrow \Xi_c^+ \gamma) \pi^+$$

- or have more tracks

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

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



Absolute branching fractions:

$$\mathcal{B}(\Xi_{cc}^{+++} \rightarrow \Xi_c^+ \pi^+) = \left(\frac{\tau_{\Xi_{cc}^{+++}}}{300 \text{ fs}} \right) \times 3.4\%$$

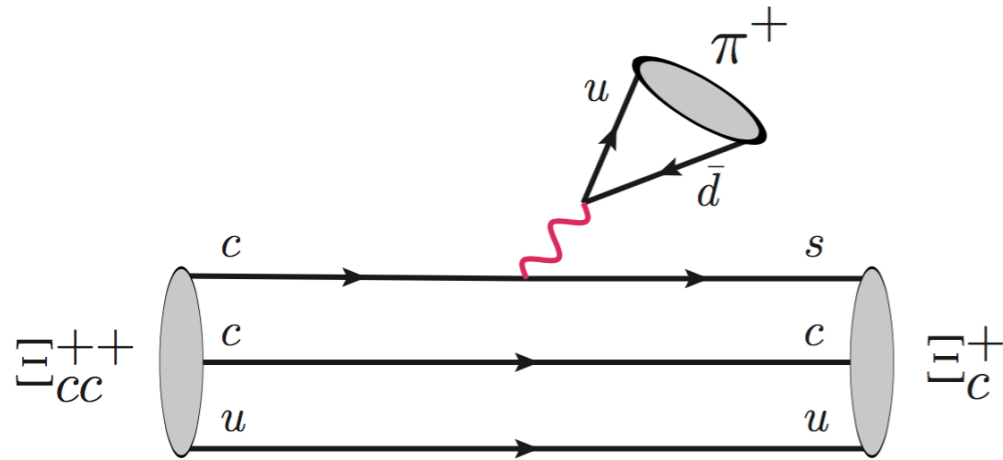
large enough for measurement

We suggest to measure $\Xi_{cc}^{+++} \rightarrow \Xi_c^+ \pi^+$ with the reconstruction of $\Xi_c^+ \rightarrow pK^- \pi^+$

[FSY, *et al*, 1703.09086]

$\mathcal{B}(\Xi_c^+ \rightarrow pK^- \pi^+)$ has never been directly measured
but predicted to be $(2.2 \pm 0.8)\%$

Short-distance v.s. Long-distance Contributions

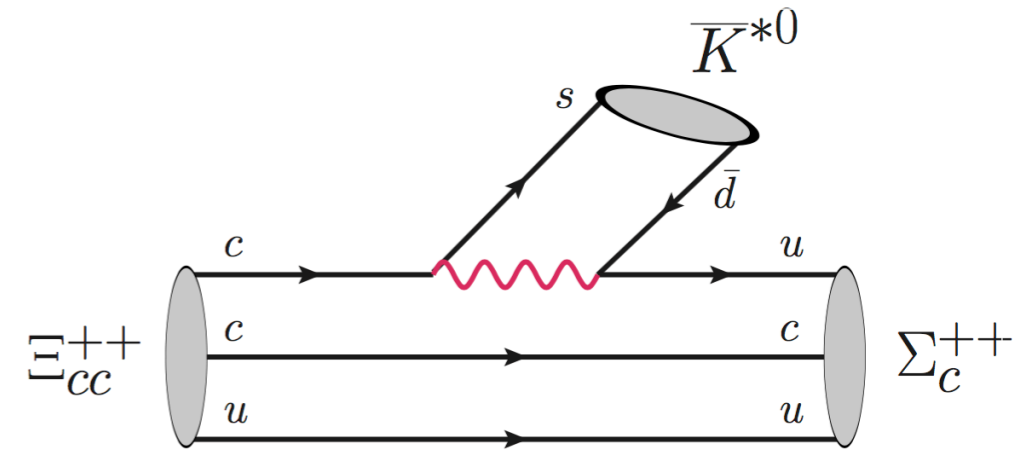


Br=3.4%

short-distance
branching fractions

external W-emission
color-favored

$$a_1(\mu_c) = 1.07$$



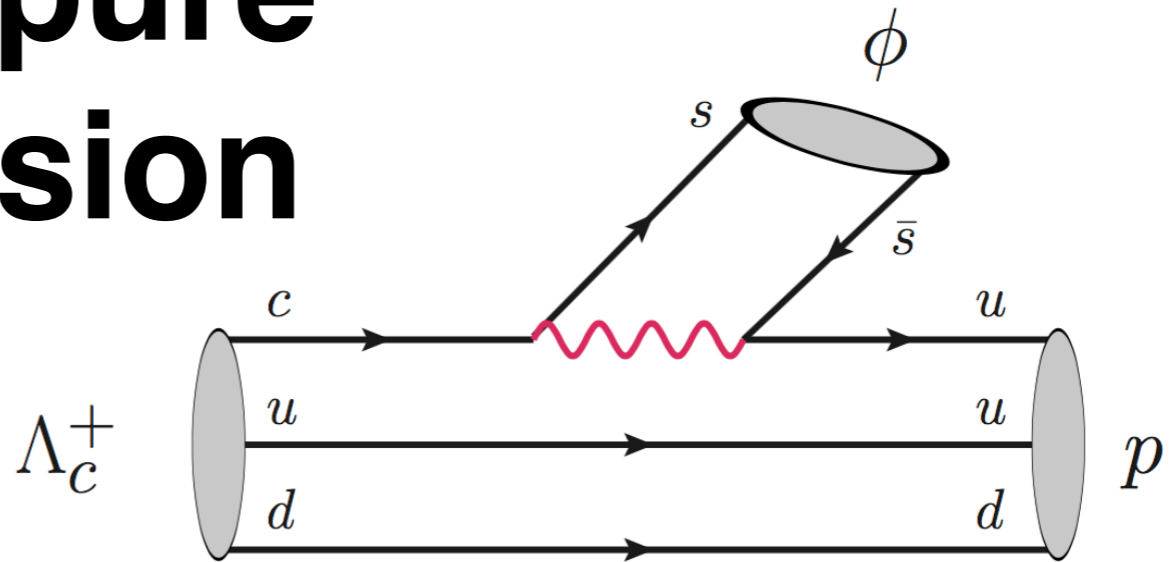
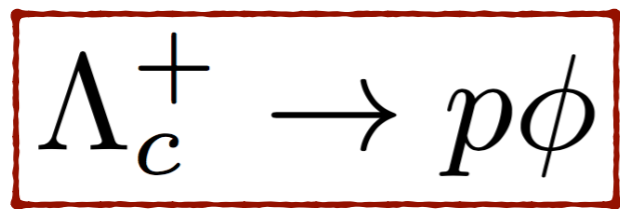
Br=0.003%

internal W-emission
color-suppressed

$$a_2(\mu_c) = -0.02$$

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

Indication from pure internal W-emission



Short-distance

v.s.

Long-distance

$$\text{Br}(\text{SD}) = 10^{-6}$$

$$|a_2(\mu_c)| = 0.02$$

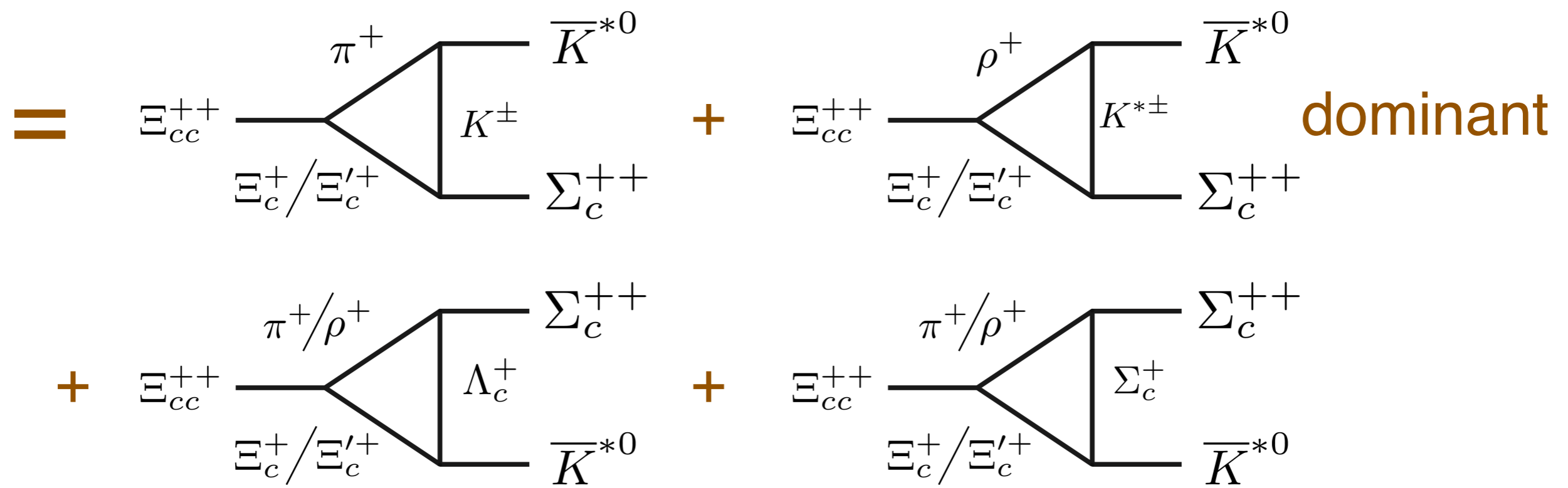
$$\text{Br}(\text{exp}) = (1.04 \pm 0.21) \times 10^{-3}$$

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

large- N_c limit

**Understanding long-distance contributions
is essential to find a best process
for the searches for doubly heavy baryons**

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



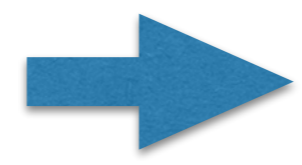
$$\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+) = 3.4\%$$

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

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

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

$$\eta = 1.0 \sim 2.0$$



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

Large enough for measurements

Effective Lagrangian

$$\begin{aligned}
\mathcal{L}_{\text{eff}} = & i \frac{g_{VPP}}{\sqrt{2}} \text{Tr}\{V^\mu [P, \partial_\mu P]\} + i \frac{g_{VVV}}{\sqrt{2}} \text{Tr}\{(\partial_\nu V_\mu - \partial_\mu V_\nu) V^\mu V^\nu\} - ig_{DDV} (D_i \partial_\mu D^{j\dagger} - \partial_\mu D_i D^{j\dagger}) (V^\mu)^i_j \\
& + ig_{VD^*D^*} (D_i^{*\nu} \partial_\mu D_\nu^{*j\dagger} - \partial_\mu D_i^{*\nu} D_\nu^{*j\dagger}) (V^\mu)^i_j + 4if_{VD^*D^*} D_{i\mu}^{*\dagger} (\partial^\mu V^\nu - \partial^\nu V^\mu)^i_j D_\nu^{*j} \\
& - ig_{PDD^*} (D^i \partial^\mu P_{ij} D_\mu^{*j\dagger} - h.c.) + g_{PB\mathcal{B}} \text{Tr}[\bar{\mathcal{B}} i \gamma_5 P \mathcal{B}] + g_{1V\mathcal{B}\mathcal{B}} \text{Tr}[\bar{\mathcal{B}} \gamma_\mu V^\mu \mathcal{B}] + \frac{g_{2V\mathcal{B}\mathcal{B}}}{2m_{\mathcal{B}}} \text{Tr}[\bar{\mathcal{B}} \sigma_{\mu\nu} \partial^\mu V^\nu \mathcal{B}] \\
& + \{g_{P\mathcal{B}_{c\bar{3}}\mathcal{B}_{c\bar{3}}} \text{Tr}[\bar{\mathcal{B}}_{c\bar{3}} i \gamma_5 P \mathcal{B}_{c\bar{3}}] + (\mathcal{B}_{c\bar{3}} \rightarrow \mathcal{B}_{c6})\} + \{g_{P\mathcal{B}_{c6}\mathcal{B}_{c\bar{3}}} \text{Tr}[\bar{\mathcal{B}}_{c6} i \gamma_5 P \mathcal{B}_{c\bar{3}}] + h.c.\}, \\
& + \{g_{1V\mathcal{B}_{c\bar{3}}\mathcal{B}_{c\bar{3}}} \text{Tr}[\bar{\mathcal{B}}_{c\bar{3}} \gamma_\mu V^\mu \mathcal{B}_{c\bar{3}}] + \frac{g_{2V\mathcal{B}_{c\bar{3}}\mathcal{B}_{c\bar{3}}}}{2m_{c\bar{3}}} \text{Tr}[\bar{\mathcal{B}}_{c\bar{3}} \sigma_{\mu\nu} \partial^\mu V^\mu \mathcal{B}_{c\bar{3}}] + (\mathcal{B}_{c\bar{3}} \rightarrow \mathcal{B}_{c6})\} \\
& + \{g_{1V\mathcal{B}_{c6}\mathcal{B}_{c\bar{3}}} \text{Tr}[\bar{\mathcal{B}}_{c6} \gamma_\mu V^\mu \mathcal{B}_{c\bar{3}}] + \frac{g_{2V\mathcal{B}_{c6}\mathcal{B}_{c\bar{3}}}}{m_{c6} + m_{c\bar{3}}} \text{Tr}[\bar{\mathcal{B}}_{c6} \sigma_{\mu\nu} \partial^\mu V^\mu \mathcal{B}_{c\bar{3}}] + h.c.\} + g_{\Lambda_c(\Sigma_c)ND_q} \{\bar{\Lambda}_c(\bar{\Sigma}_c) i \gamma_5 D_q N + h.c.\} \\
& + g_{1\Lambda_c(\Sigma_c)ND_q^*} \{\bar{\Lambda}_c(\bar{\Sigma}_c) \gamma_\mu D_q^{*\mu} N + h.c.\} + \frac{g_{2\Lambda_c(\Sigma_c)ND_q^*}}{m_{\Lambda_c(\Sigma_c)} + m_N} \{\bar{\Lambda}_c(\bar{\Sigma}_c) \sigma_{\mu\nu} \partial^\mu D_q^{*\nu} N + h.c.\}
\end{aligned}$$

Hadronic coupling constants are related under the flavor SU(3) symmetry and the chiral and heavy quark symmetries

Uncertainties are mostly cancelled in relative Br's

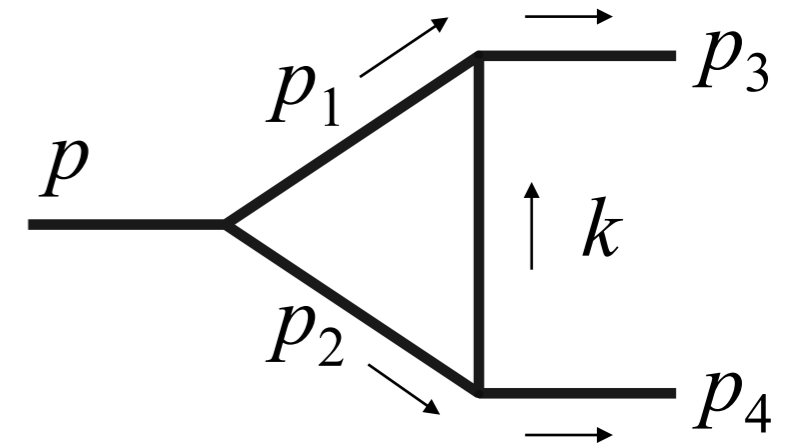
[Yan, *et al*, PRD46,1148(1992)]

[Casalbuoni, *et al*, Phys.Rept.281,145(1997)]

[Meissner, Phys.Rept.161,213(1988)]

Theoretical Uncertainties

- Transition form factors —cancelled in relative Br's
- Hadronic coupling constants —cancelled in relative Br's
- Off-shell effects of intermediate states



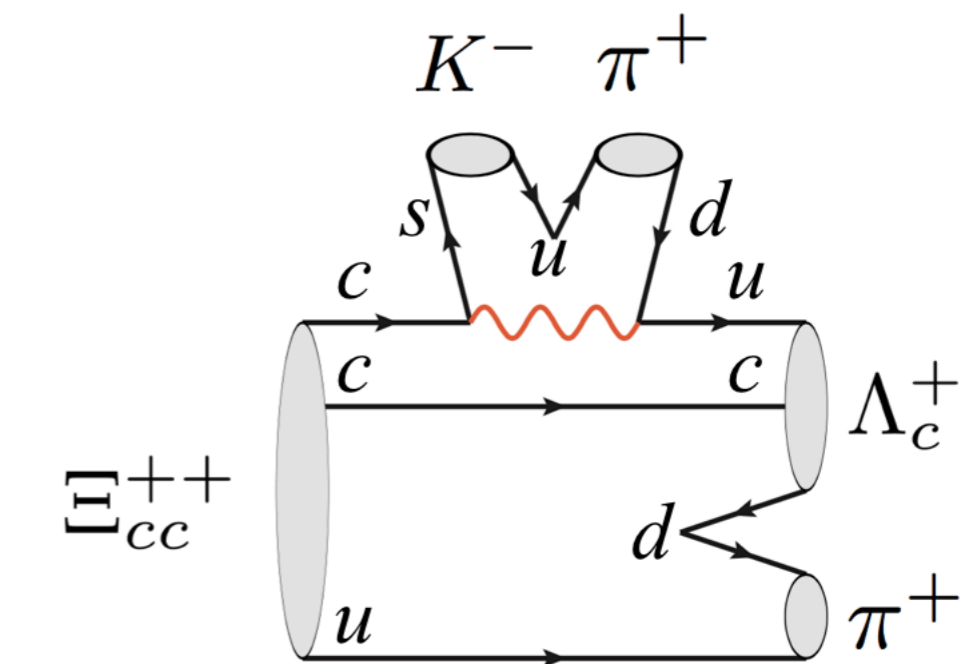
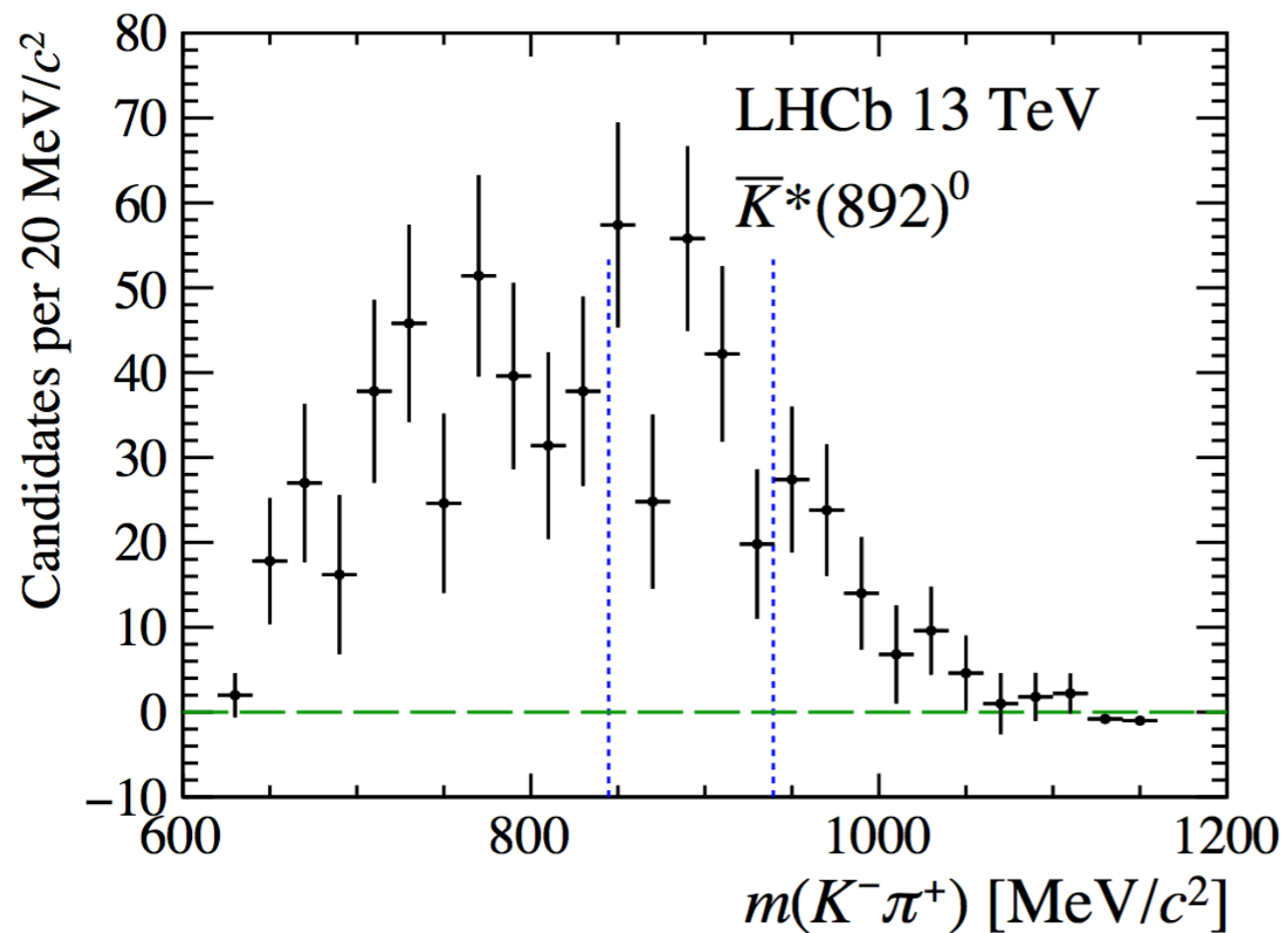
$$F(t, m) = \left(\frac{\Lambda^2 - m^2}{\Lambda^2 - t} \right)^n \quad t \equiv (p_1 - p_3)^2 \quad n=1$$

$$\Lambda = m_{\text{exc}} + \eta \Lambda_{\text{QCD}} \quad [\text{Cheng, Chua, Soni, PRD 71, 014030 (2005)}]$$

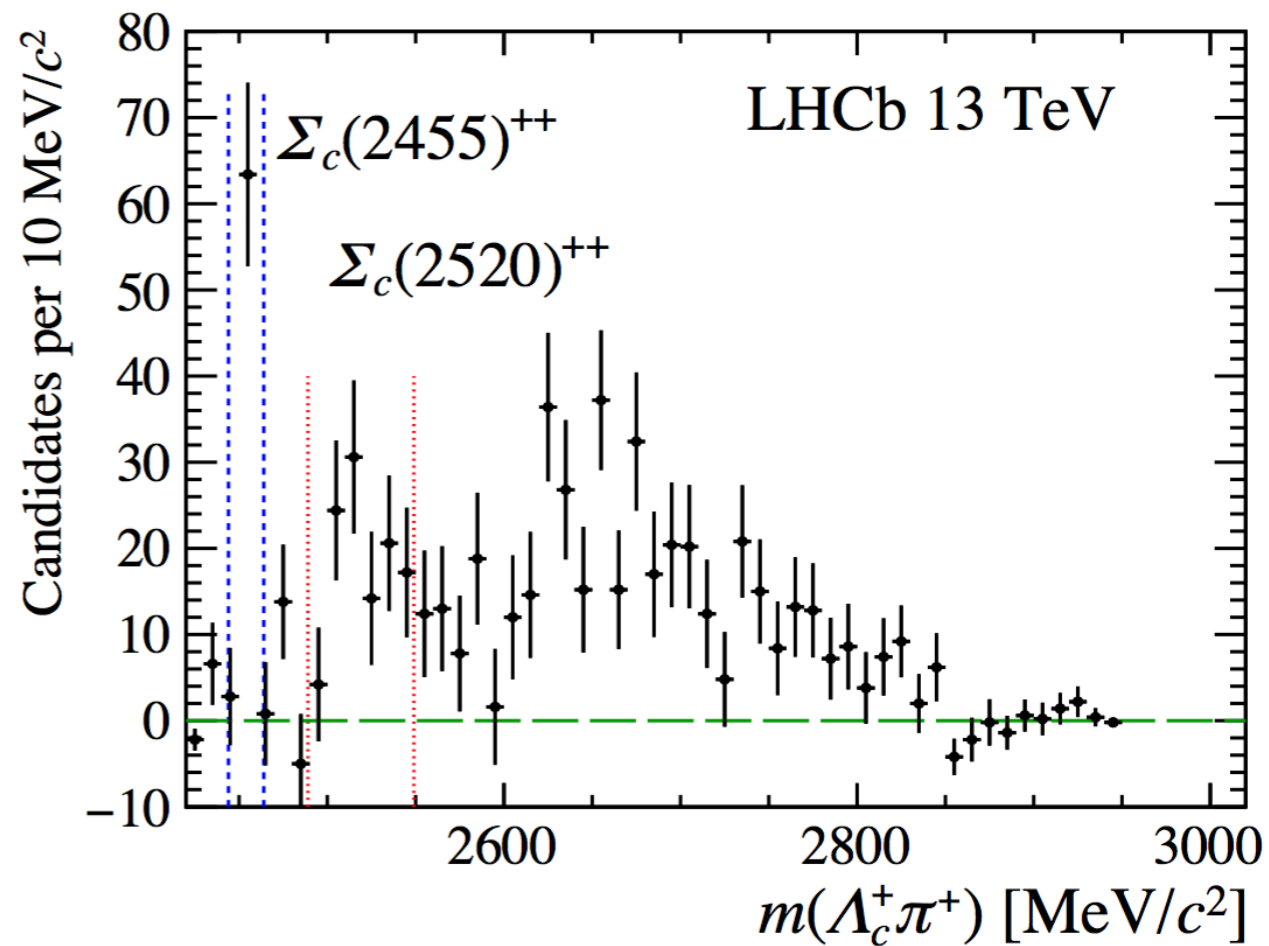
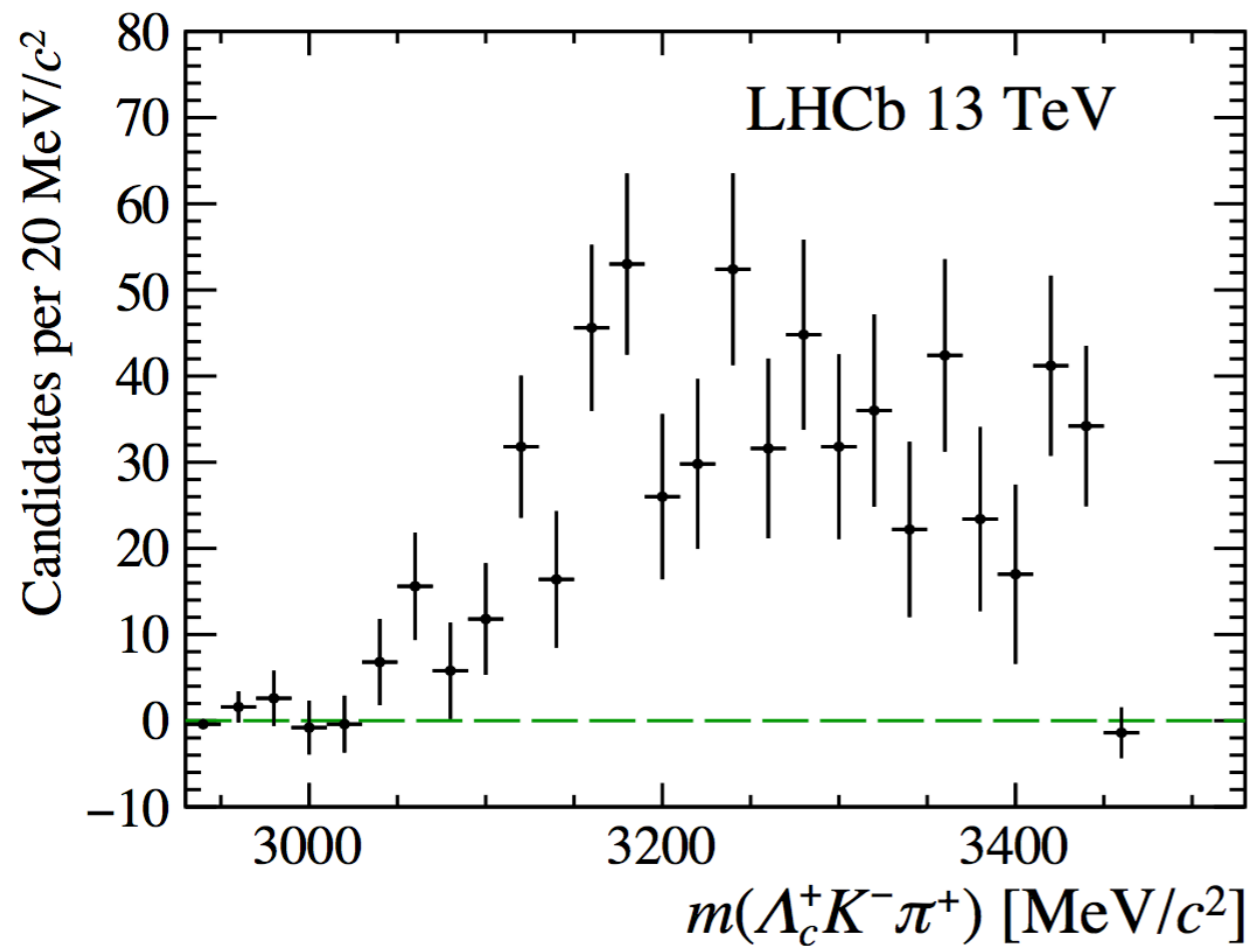
Results are very sensitive to the value of η

No first-principle calculations for η

We take η from 1.0 to 2.0

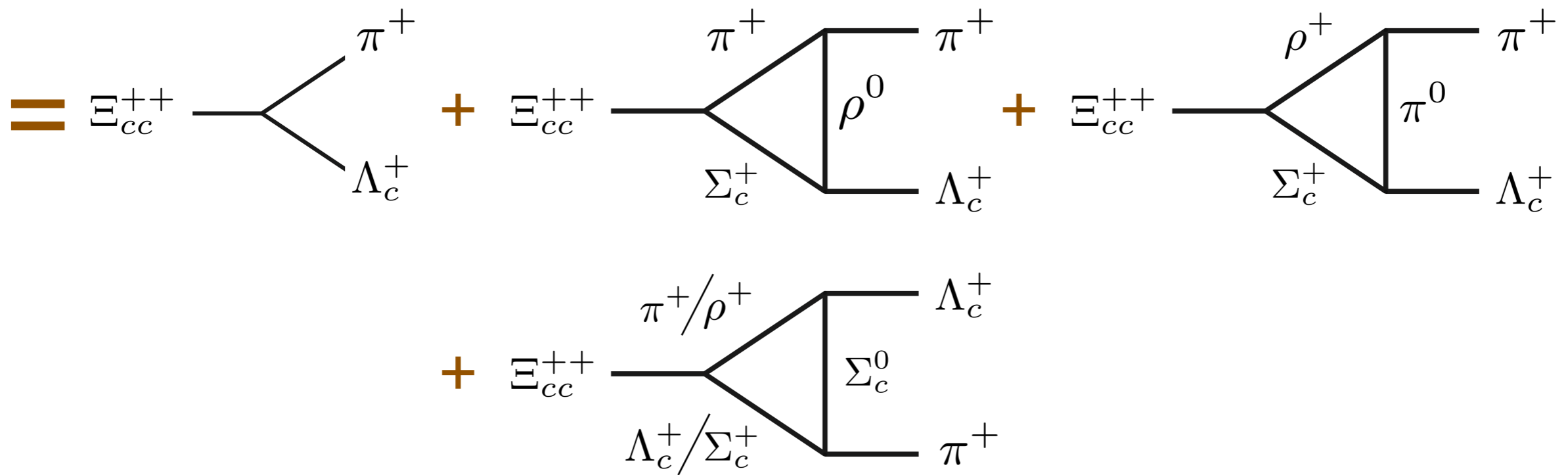
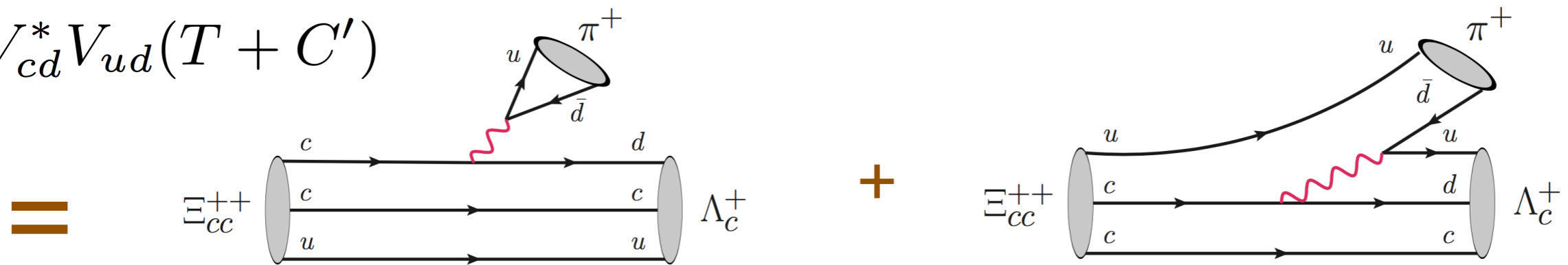


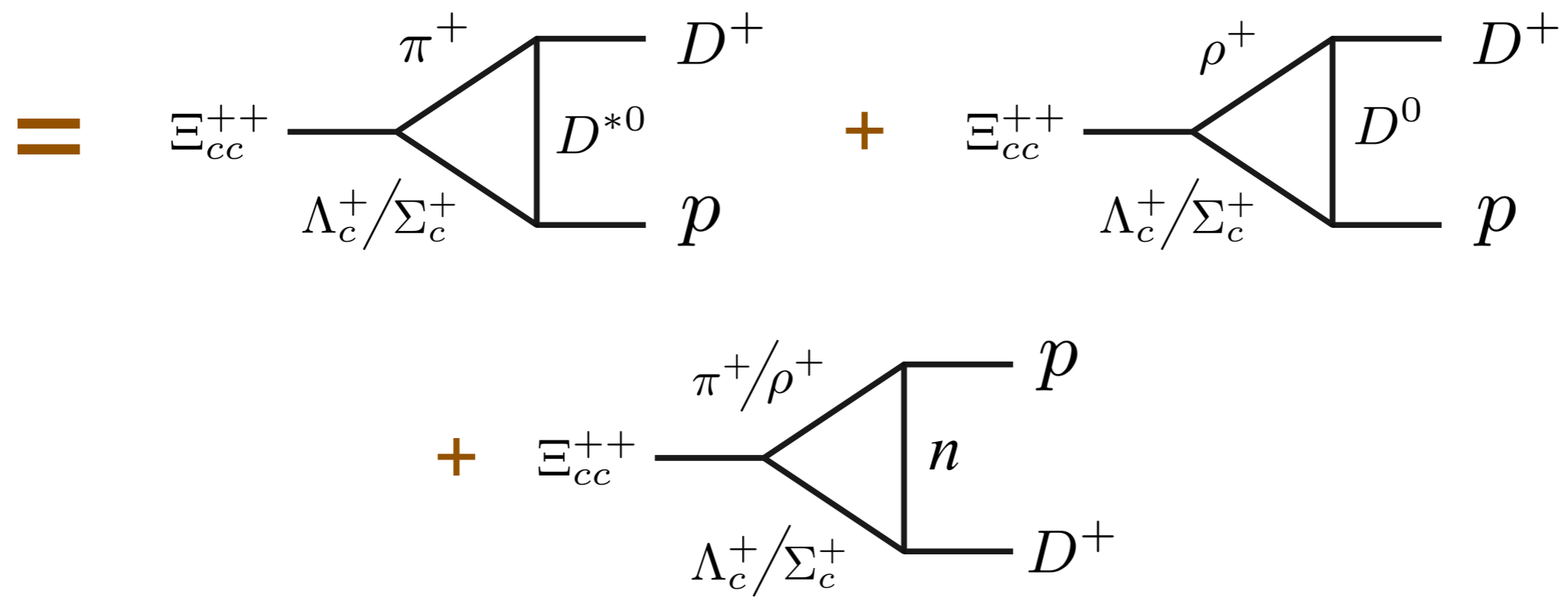
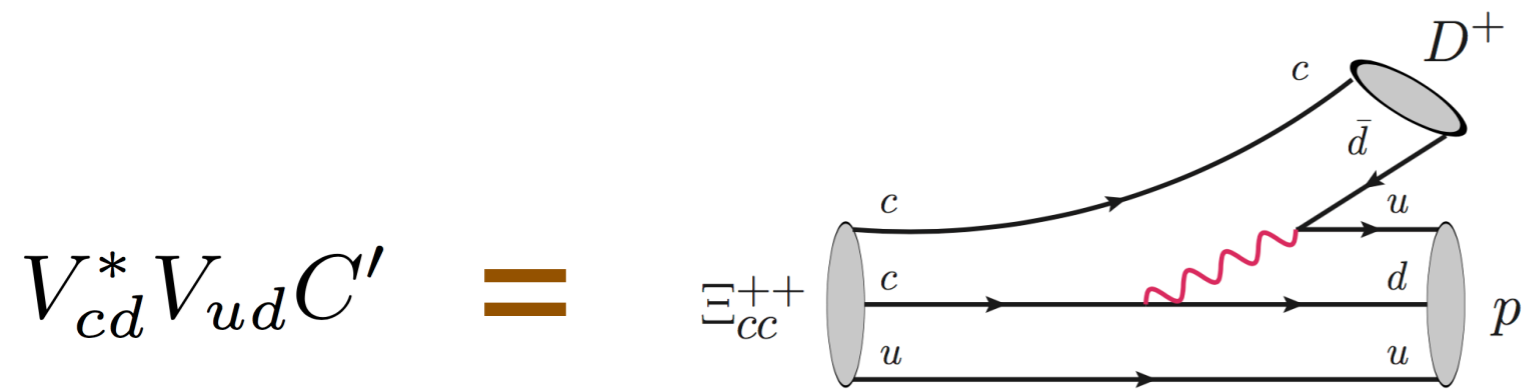
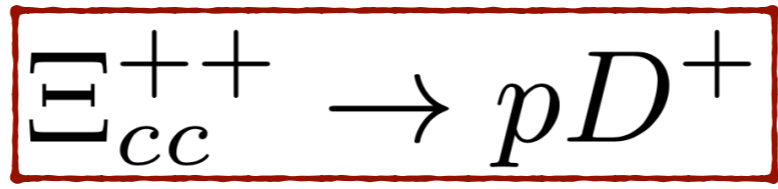
Resonances dominated

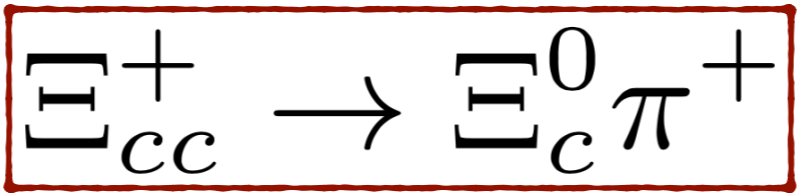


$$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ \pi^+$$

$$V_{cd}^* V_{ud} (T + C')$$

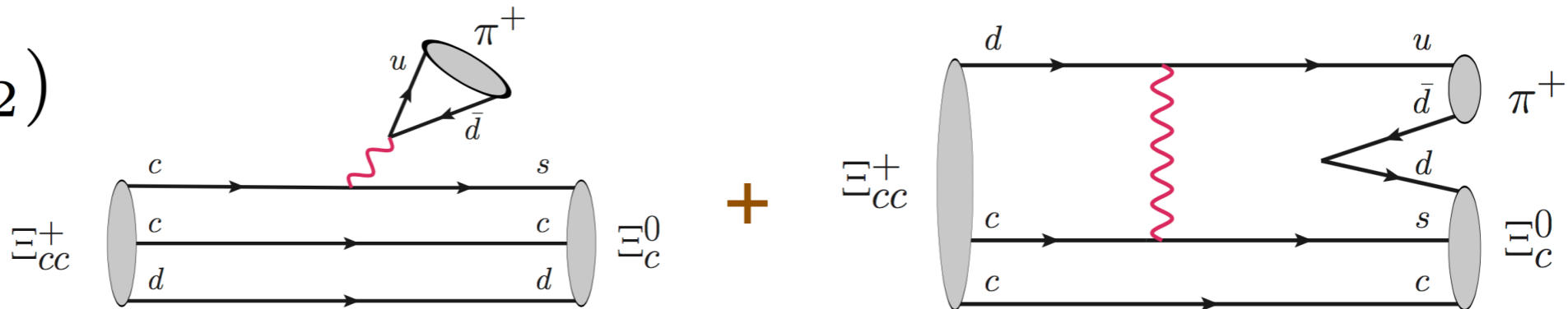




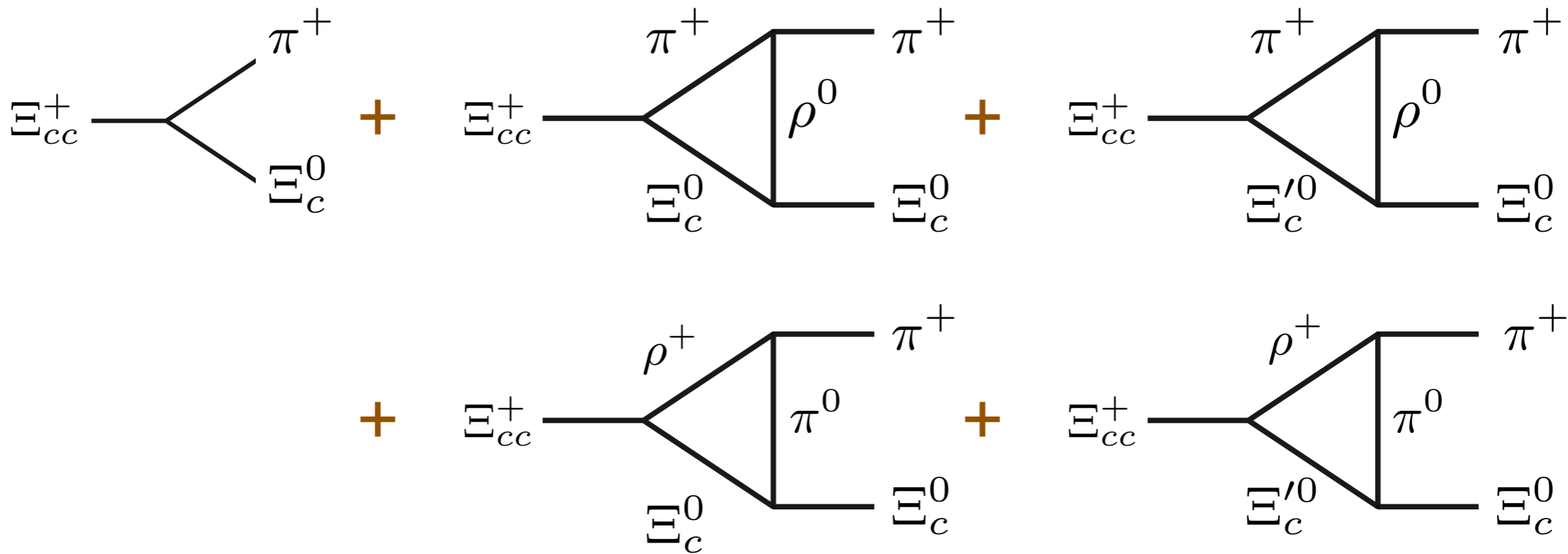


$$V_{cs}^* V_{ud} (T + E_2)$$

=



=

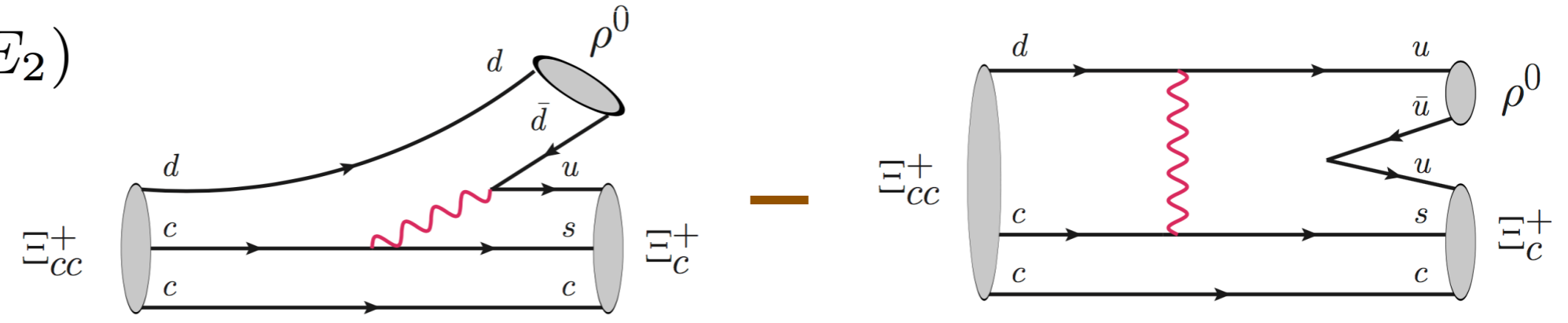


$$\boxed{\Xi_{cc}^+ \rightarrow \Xi_c^+ \rho^0}$$

$$\rightarrow \Xi_c^+ \pi^+ \pi^-$$

$$\frac{1}{\sqrt{2}} V_{cs}^* V_{ud} (C' - E_2)$$

=



=

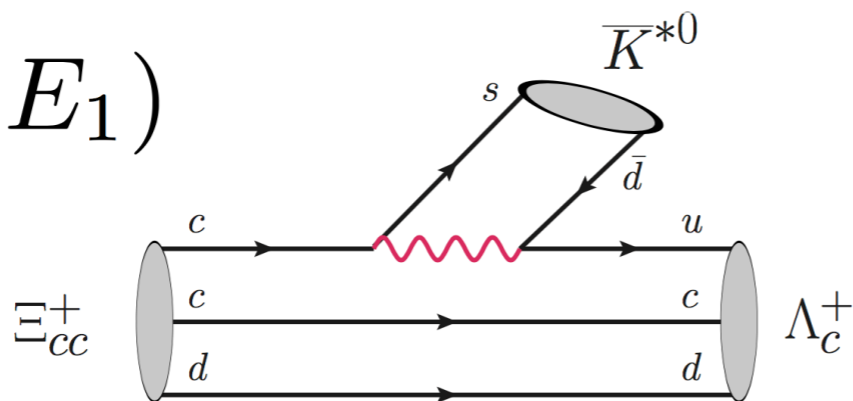


$$\boxed{\Xi_{cc}^+ \rightarrow \Lambda_c^+ \bar{K}^{*0}}$$

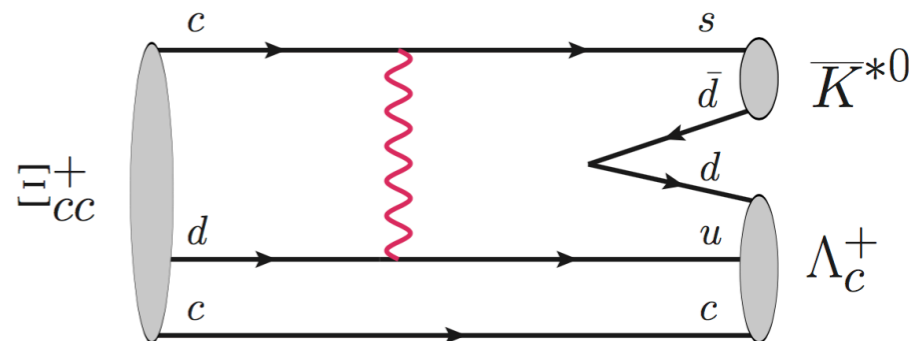
$$\rightarrow \Lambda_c^+ K^- \pi^+$$

$$V_{cs}^* V_{ud} (C + E_1)$$

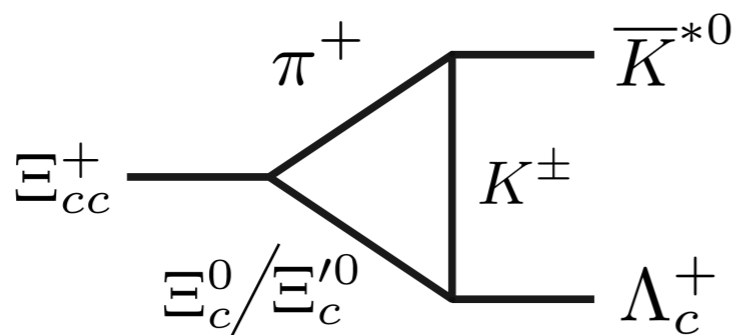
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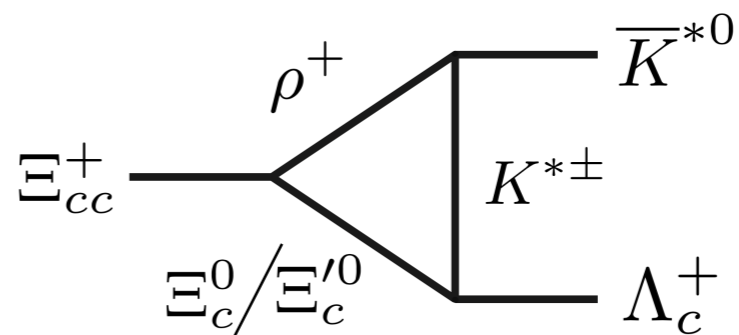
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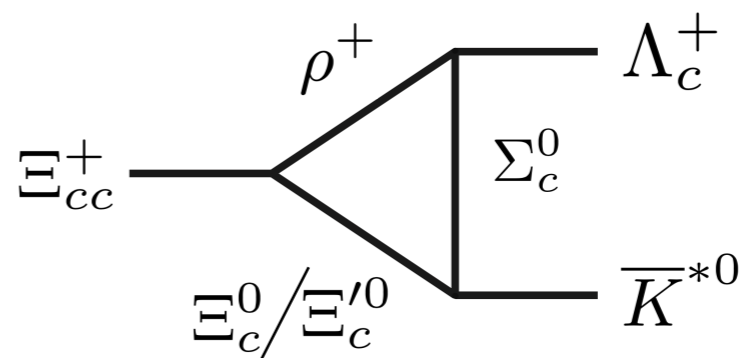
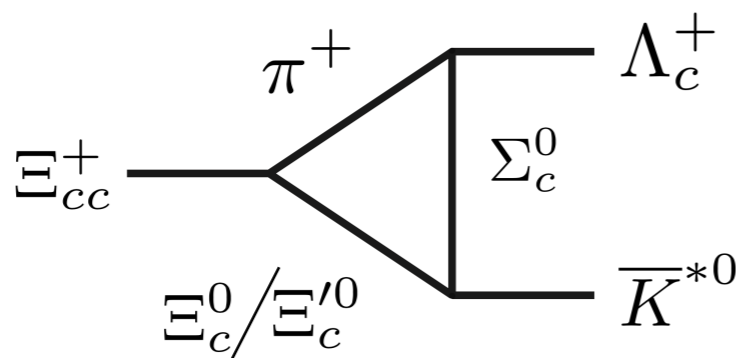
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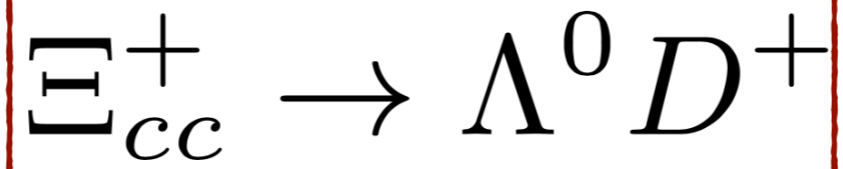


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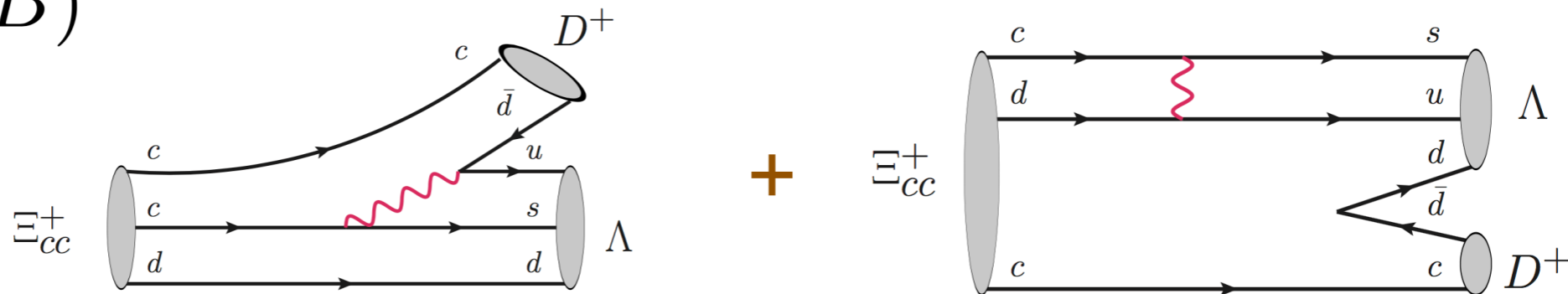
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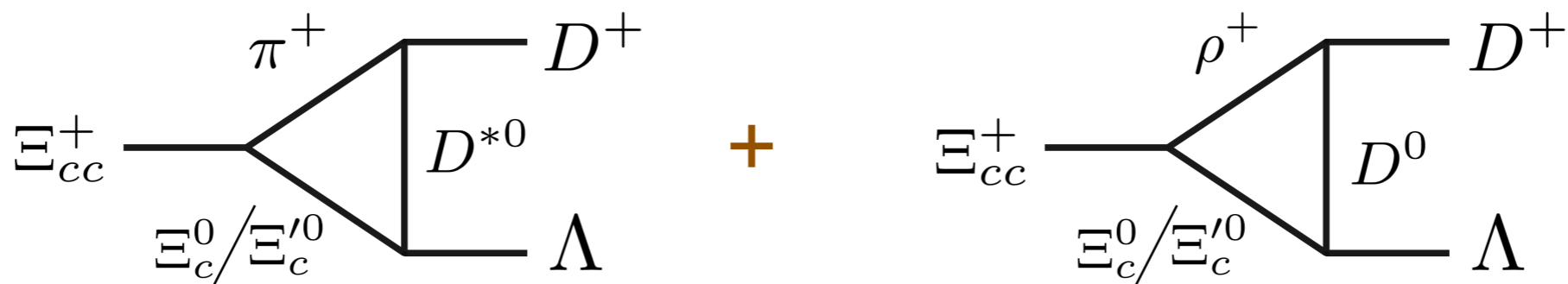


$$V_{cs}^* V_{ud} (C' + B)$$

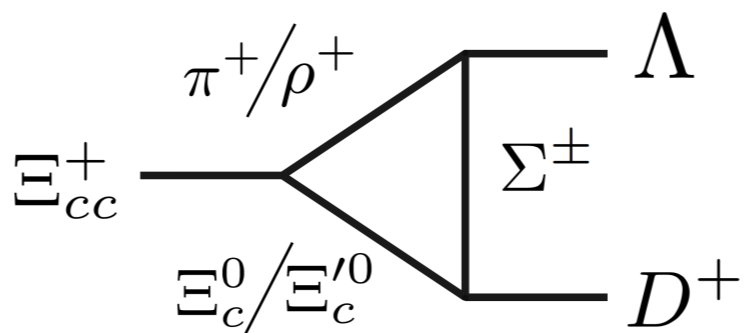
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Branching Ratio of $\Xi_c^+ \rightarrow pK^- \pi^+$

Under U-spin symmetry, $d \leftrightarrow s$

$$\mathcal{A}(\Xi_c^+ \rightarrow p\bar{K}^{*0}) = \mathcal{A}(\Lambda_c^+ \rightarrow \Sigma^+ K^{*0})$$

$$\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^+ K^{*0}) = (0.36 \pm 0.10)\% \quad [\text{FOCUS, 01}']$$

$$\mathcal{B}(\Xi_c^+ \rightarrow p\bar{K}^{*0}) / \mathcal{B}(\Xi_c^+ \rightarrow pK^- \pi^+) = 0.54 \pm 0.10$$

[FOCUS, 02']

$$Br(\Xi_c^+ \rightarrow pK^- \pi^+) = (2.2 \pm 0.8)\%$$

[FSY, *et al*, 1703.09086]