Weak decays of doubly heavy baryon

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[PLB767 (2017) 232,arXiv:1701.03284]
[arXiv:1703.09086]

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Outline

1. **Introduction to doubly heavy baryons**

   masses, lifetimes and productions

2. Semi-leptonic decays

   form factors in the light-front quark model

3. Non-leptonic decays

   topologies and hierarchy

4. Suggestions on the discovery channels

Summary

Motivations

- Doubly heavy baryons are predicted in quark model and QCD

Baryons	quarks	$I(J^P)$	Baryons	quarks	$I(J^P)$
Ξ_{cc}^{++}	ucc	$\frac{1}{2}(\frac{1}{2}^+)$	Ξ_{cb}^{+}	ucb	$\frac{1}{2}(\frac{1}{2}^+)$
Ξ_{cc}^{+}	dcc	$\frac{1}{2}(\frac{1}{2}^+)$	Ξ_{cb}^{0}	dcb	$\frac{1}{2}(\frac{1}{2}^+)$
Ω_{cc}^{+}	scc	$0(\frac{1}{2}^+)$	Ω_{cb}^{0}	scb	$0(\frac{1}{2}^+)$

- But not established so far
  - The only evidence was found for Ξ_{cc}^{+} by SELEX

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

[SELEX, 02'; 04']

  - But not confirmed by other experiments

[Babar, 06'; Belle, 13'; LHCb, 13']

- Searching for them is one of the most important purposes of particle physics, to understand the hadron spectroscopy, the perturbative and non-perturbative QCD dynamics of the productions and decays.

Masses of Ξ_{cc}

$M(\Xi_{cc}^{++})=M(\Xi_{cc}^{+})$

$\sim 3.6\text{GeV}$

$\pm 100\text{MeV}$

Quark model:

2 m_c+1GeV

=(2×1.3+1)GeV

=3.6 GeV

$M(\Omega_{cc}^{+})\sim M(\Xi_{cc})+0.1\text{GeV}$

Table from [Karliner, Rosner, 14']

Reference	Value (MeV)	Method
[Karliner, Rosner, 14']	3627 ± 12	
[23]	3550–3760	QCD-motivated quark model
[25]	3668 ± 62	QCD-motivated quark model
[28]	3651	QCD-motivated quark model
[43]	3613	Potential and bag models
[44]	3630	Potential model
[45]	3610	Heavy quark effective theory
[46]	3660 ± 70	Feynman-Hellmann + semi-empirical
[47]	3676	Mass sum rules
[48]	3660	Relativistic quasipotential quark model
[49]	3607	Three-body Faddeev equations.
[50]	3527	Bootstrap quark model + Faddeev eqs.
[51]	ucc: 3649 ± 12, dcc: 3644 ± 12	Quark model
[52]	3480 ± 50	Potential approach + QCD sum rules
[53]	3690	Nonperturbative string
[54]	3620	Relativistic quark-diquark
[55]	3520	Bag model
[56]	3643	Potential model
[57]	3642	Relativistic quark model + Bethe-Salpeter
[58]	3612^{+17}	Variational
[59]	3678	Quark model
[61]	3540 ± 20	Instantaneous approx. + Bethe-Salpeter
[62]	4260 ± 190	QCD sum rules
[63]	$3608(15)(^{13}_{35})$, $3595(12)(^{21}_{22})$	Quenched lattice
[64]	3549(13)(19)(92)	Quenched lattice
[65]	$3665 \pm 17 \pm 14^{+0}_{-78}$	Lattice, domain-wall + KS fermions
[66]	3603(15)(16)	Lattice, $N_f = 2+1$
[67]	3513(23)(14)	LGT, twisted mass ferm., m_π=260 MeV
[68]	3595(39)(20)(6)	LGT, $N_f = 2+1$, $m_\pi = 200$ MeV
[69]	3568(14)(19)(1)	LGT, $N_f = 2+1$, $m_\pi = 210$ MeV

Masses of bc baryons

[Karliner, Rosner, 14']

$M(\Xi_{bc}^{+})=M(\Xi_{bc}^{0}) \sim 6.9\text{GeV} \quad \pm 100\text{MeV}$

Quark model:

mb+mc+1GeV

= (4.6+1.3+1)GeV

= 6.9 GeV

Reference	Value (MeV)	Method
Present work	6914 ± 13	
[25]	6916 ± 139	QCD-motivated quark model
[28]	6938	QCD-motivated quark model
[44]	6930	Potential models
[46]	6990 ± 90	Feynman-Hellmann + semi-empirical formulas
[47]	7029	Mass sum rules
[48]	6950	Relativistic quasipotential quark model
[49]	6915	Three-body Faddeev equations.
[52]	6820 ± 50	Potential approach and QCD sum rules
[53]	6960	Nonperturbative string
[54]	6933	Relativistic quark-diquark
[55]	6800	Bag model
[58]	6919	Variational
[59]	7011	Quark model
[60]	6789	Coupled channel formalism
[61]	6840 ± 10	Instantaneous approx. + Bethe-Salpeter
[62]	6750 ± 50	QCD sum rules

$M(\Omega_{bc}^{0}) \sim M(\Xi_{bc}) + 0.1\text{GeV}$

5

Lifetimes

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

Priority to search for Ξ_{cc}^{++}

Literatures	Ξ_{cc}^{++}	Ξ_{cc}^{+}	Ω_{cc}^{+}
Karliner, Rosner, 2014	185	53	
Kiselev, Likhoded, Onishchenko, 1998	430±100	110±10	
Kiselev, Likhoded, 2002	460±50	160±50	270±60
Guberina, Melic, Stefancic, 1998	1550	220	250
Chang, Li, Li, Wang, 2007	670	250	210

(fs)

Large ambiguity of lifetimes

SELEX collaboration: $\tau(\Xi_{cc}^{+}) < 33 \text{ fs}$ @ 90% confidence

Compared to

$$\tau(\Lambda_c^+) = (200 \pm 6) \times 10^{-15} s, \qquad \tau(\Xi_c^+) = (442 \pm 26) \times 10^{-15} s,$$

$$\tau(\Xi_c^0) = (112^{+13}_{-10}) \times 10^{-15} s, \qquad \tau(\Omega_c^0) = (69 \pm 12) \times 10^{-15} s.$$

Lifetimes

[Karliner, Rosner, 14']

Baryon	This work	[28]	[52]	[71]	[72]
$\Xi_{cc}^{++} = ccu$	185	430±100	460±50	500	~ 200
$\Xi_{cc}^{+} = ccd$	53	120±100	160±50	150	~ 100
$\Xi_{bc}^{+} = bcu$	244	330±80	300±30	200	–
$\Xi_{bc}^{0} = bcd$	93	280±70	270±30	150	–

$\times 10^{-15} s$

b-hadron species	average lifetime	lifetime ratio
B^0	1.520 ± 0.004 ps	
B^+	1.638 ± 0.004 ps	$B^+/B^0 = 1.076 \pm 0.004$
B_s^0	1.504 ± 0.005 ps	$B_s^0/B^0 = 0.990 \pm 0.004$
B_{sL}	1.413 ± 0.006 ps	
B_{sH}	1.608 ± 0.010 ps	
B_c^+	0.507 ± 0.009 ps	
Λ_b	1.466 ± 0.010 ps	$\Lambda_b/B^0 = 0.965 \pm 0.007$
Ξ_b^-	1.567 ± 0.040 ps	

charm decay dominated

charm: Vcs ~ 1

bottom: Vcb ~ λ^2~0.04

$$\tau(\Lambda_c^+) = (200 \pm 6) \times 10^{-15} s, \qquad \tau(\Xi_c^+) = (442 \pm 26) \times 10^{-15} s,$$
$$\tau(\Xi_c^0) = (112^{+13}_{-10}) \times 10^{-15} s, \qquad \tau(\Omega_c^0) = (69 \pm 12) \times 10^{-15} s.$$

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

$p_t \geq 4GeV \qquad |y| \leq 1.5$

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

B_c

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

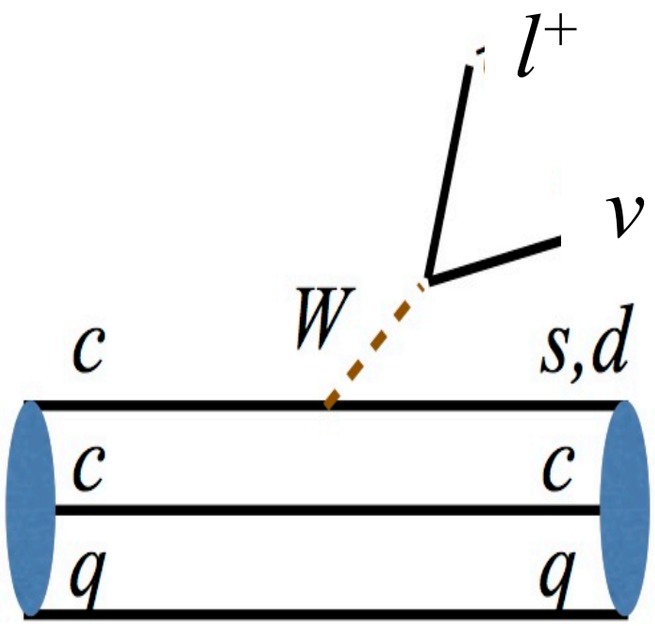
LHC ($\sqrt{S} = 14.0$ TeV) in unit of nb

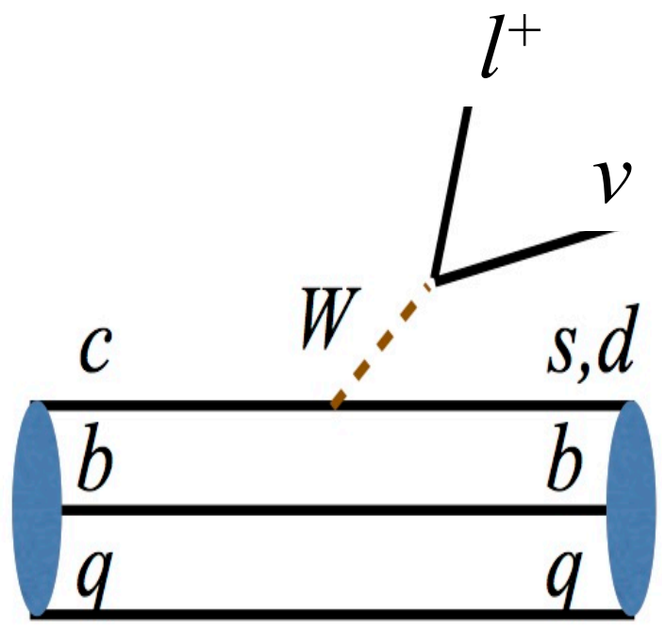
[C.-H. Chang, C.-F. Qiao, J.-X. Wang, X.-G. Wu, Phys.Rev. D71 (2005) 074012]

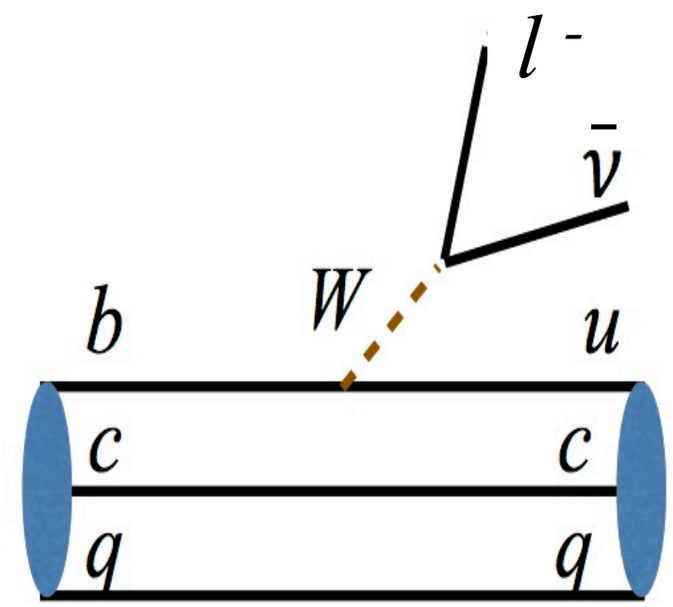
B_c well studied at LHCb,

discovery and establishment of Ξ_{cc} would not be far

2. Semi-leptonic decays





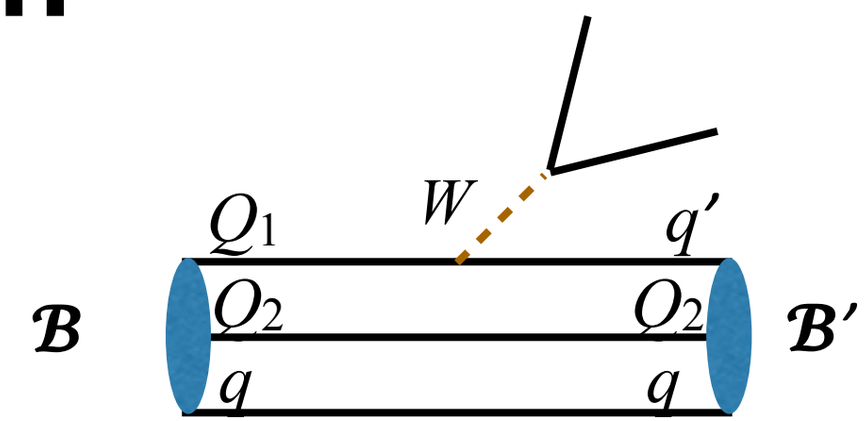


Key point is to calculate form factors

First try in the light-front quark model

Wei Wang, Fu-Sheng Yu, Zhen-Xing Zhao, arXiv: 1707.02834

Form factors with di-quark assumption

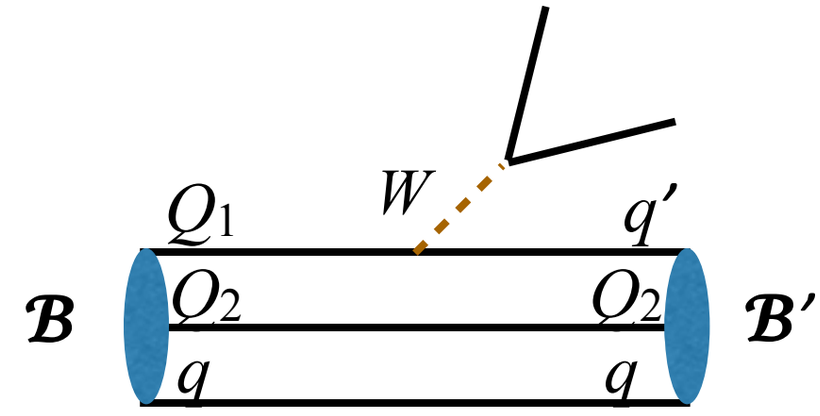


- $Q_1Q_2q \to q'Q_2q$
- weak decays of $Q_1 \to q'$
- diquark assumption: spectators $[Q_2q]$
- diquark is dominated by $J^P=0^+$

$$\langle B'(P',S'_z)|(V-A)_\mu|B(P,S_z)\rangle = \bar{u}(P',S'_z)\left[\gamma_\mu f_1(q^2) + i\sigma_{\mu\nu}\frac{q^\nu}{M}f_2(q^2) + \frac{q_\mu}{M}f_3(q^2)\right]u(P,S_z)$$
$$- \bar{u}(P',S'_z)\left[\gamma_\mu g_1(q^2) + i\sigma_{\mu\nu}\frac{q^\nu}{M}g_2(q^2) + \frac{q_\mu}{M}g_3(q^2)\right]\gamma_5 u(P,S_z)$$

Form factors in light-front quark model

$$|B(P,S,S_z)\rangle = \int \{d^3p_1\}\{d^3p_2\}2(2\pi)^3\delta^3(\tilde{P}-\tilde{p}_1-\tilde{p}_2)$$
$$\times \sum_{\lambda_1} \Psi^{SS_z}(\tilde{p}_1,\tilde{p}_2,\lambda_1)|q_\alpha(p_1,\lambda_1)[di](p_2)\rangle$$



light-front wave function

diquark

- LRQM: all particles are on-shell

m_u	m_d	m_s	m_c	m_b	$m_{[cu]}$	$m_{[cd]}$
0.25	0.25	0.37	1.4	4.8	$1.4+0.25$	$1.4+0.25$

Form factors in LFQM

$$F(q^2) = \frac{F(0)}{1 - \frac{q^2}{m^2_{\rm pole}}}$$

	channels	$f_1(0)$	$f_2(0)$	$g_1(0)$	$g_2(0)$	$m_{\rm pole}$
c decay	$\Xi_{cc}^{++} \to \Lambda_c^+$	0.653	−0.739	0.533	−0.053	D^*
	$\Xi_{cc}^{++} \to \Sigma_c^+$	0.653	−0.739	0.533	−0.053	D^*
	$\Xi_{cc}^{++} \to \Xi_c^+$	0.754	−0.783	0.620	−0.080	D_s^*
	$\Xi_{cc}^{+} \to \Sigma_c^0$	0.653	−0.739	0.533	−0.053	D^*
	$\Xi_{cc}^{+} \to \Xi_c^0$	0.754	−0.783	0.620	−0.080	D_s^*
b decay	$\Xi_{bc}^{+} \to \Sigma_c^{++}$	0.136	−0.081	0.130	−0.009	B^*
	$\Xi_{bc}^{0} \to \Lambda_c^+$	0.136	−0.081	0.130	−0.009	B^*
	$\Xi_{bc}^{0} \to \Sigma_c^+$	0.136	−0.081	0.130	−0.009	B^*
c decay	$\Xi_{bc}^{+} \to \Lambda_b^0$	0.639	−1.707	0.499	−0.232	D^*
	$\Xi_{bc}^{+} \to \Xi_b^0$	0.725	−1.801	0.571	−0.269	D_s^*
	$\Xi_{bc}^{0} \to \Xi_b^-$	0.725	−1.801	0.571	−0.269	D_s^*

Semi-leptonic decays

	channels	$\mathcal{B}$	
c decay	$\Xi_{cc}^{++} \to \Lambda_c^+$	5.16×10^{-3}	$\lvert V_{cd}\rvert^2 \sim \lambda^2 \sim 0.05$
	$\Xi_{cc}^{++} \to \Sigma_c^+$	2.50×10^{-3}	
	$\Xi_{cc}^{++} \to \Xi_c^+$	5.58×10^{-2}	$\lvert V_{cs}\rvert^2 \sim 1$
	$\Xi_{cc}^{+} \to \Sigma_c^0$	7.13×10^{-4}	$\lvert V_{cd}\rvert^2 \sim \lambda^2 \sim 0.05$
	$\Xi_{cc}^{+} \to \Xi_c^0$	1.58×10^{-2}	$\lvert V_{cs}\rvert^2 \sim 1$
b decay	$\Xi_{bc}^{+} \to \Sigma_c^{++}$	3.11×10^{-5}	$\lvert V_{ub}\rvert^2 \sim \lambda^6 \sim 10^{-5}$
	$\Xi_{bc}^{0} \to \Lambda_c^{+}$	1.53×10^{-5}	phase space $\left(\frac{m_b}{m_c}\right)^5 \sim 300$
	$\Xi_{bc}^{0} \to \Sigma_c^{+}$	1.19×10^{-5}	
c decay	$\Xi_{bc}^{+} \to \Lambda_b^0$	6.53×10^{-3}	$\lvert V_{cd}\rvert^2 \sim \lambda^2 \sim 0.05$
	$\Xi_{bc}^{+} \to \Xi_b^0$	6.79×10^{-2}	$\lvert V_{cs}\rvert^2 \sim 1$
	$\Xi_{bc}^{0} \to \Xi_b^-$	2.56×10^{-2}	

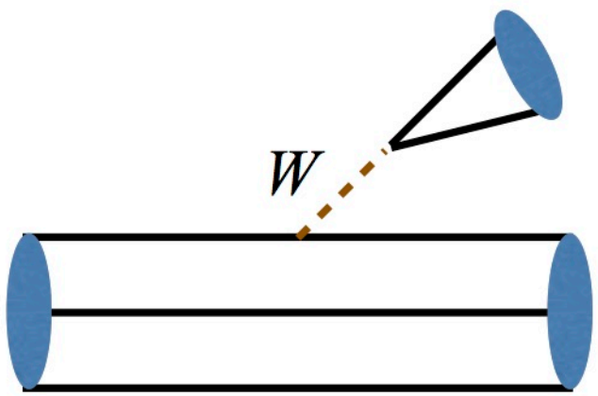
Semi-leptonic decays are not competitive

with missing energy
😱😱😱

	channels	$\mathcal{B}$	
c decay	$\Xi_{cc}^{++} \to \Lambda_c^+$	5.16×10^{-3}	$\times 10^{-2}$ $\sim 10^{-4}$
	$\Xi_{cc}^{++} \to \Sigma_c^+$	2.50×10^{-3}	
	$\Xi_{cc}^{++} \to \Xi_c^+$	5.58×10^{-2}	
	$\Xi_{cc}^{+} \to \Sigma_c^0$	7.13×10^{-4}	Non-leptonic: $10^{-3\sim-4}$
	$\Xi_{cc}^{+} \to \Xi_c^0$	1.58×10^{-2}	
b decay	$\Xi_{bc}^{+} \to \Sigma_c^{++}$	3.11×10^{-5}	
	$\Xi_{bc}^{0} \to \Lambda_c^+$	1.53×10^{-5}	$\times 10^{-2}$ $\sim 10^{-7}$
	$\Xi_{bc}^{0} \to \Sigma_c^+$	1.19×10^{-5}	Non-leptonic: $10^{-6\sim-8}$
c decay	$\Xi_{bc}^{+} \to \Lambda_b^0$	6.53×10^{-3}	
	$\Xi_{bc}^{+} \to \Xi_b^0$	6.79×10^{-2}	$\times 10^{-4}$ $\sim 10^{-6}$
	$\Xi_{bc}^{0} \to \Xi_b^-$	2.56×10^{-2}	Non-leptonic: $10^{-6\sim-8}$

3. Non-leptonic decays

- Only **two-body** decays are available in theory
- Estimate branching fractions using **topological diagrammatic approach**



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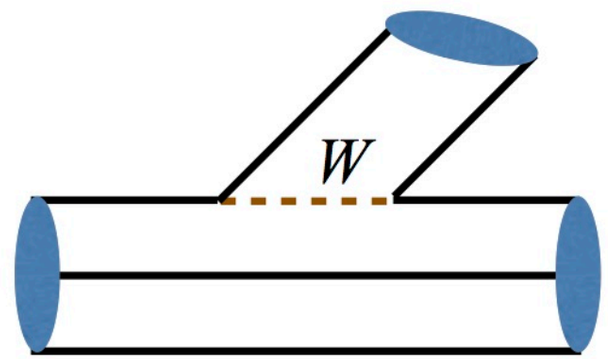
color-favored tree



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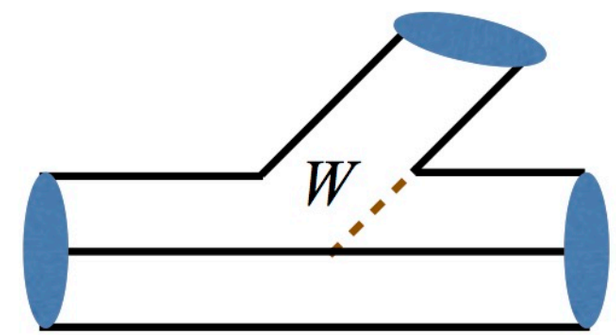

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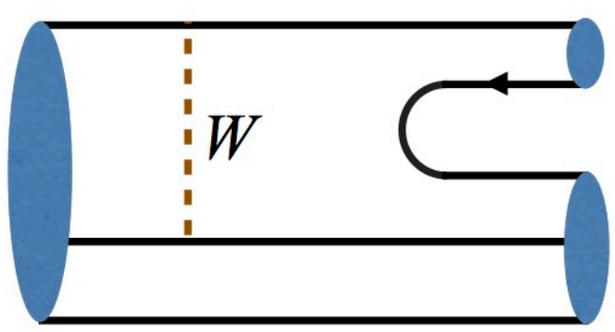
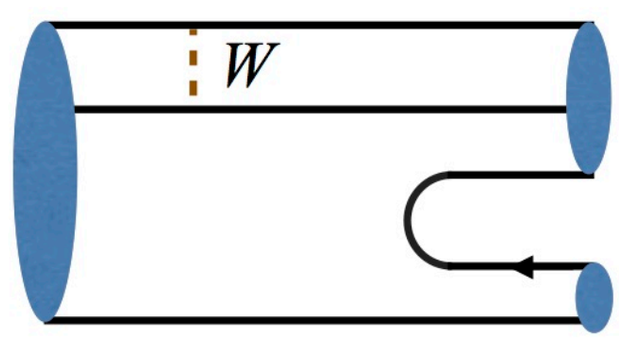
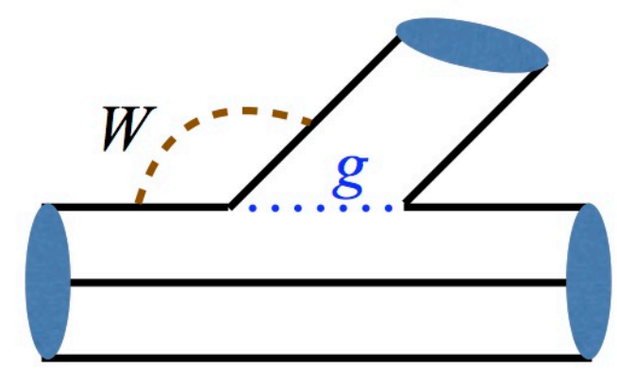


(E)
W-exchange



(B)
Bow tie



(P)
penguin

Difficulties in theory

- It is always difficult to understand the dynamics of charm decays, due to large non-perturbative contributions
- Heavy quark effective theory does not work for $1/m_c$
- Topological diagrammatic approach works well in D decays. ΔA_{CP} was predicted to be (-0.06 ~ -0.19)% in 2012 [Li, Lu, **Yu**, PRD86,036012], and confirmed by recent LHCb measurements.
- But it does not work in charmed baryon decays so far, due to less data to fix parameters.

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

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

$|P| \sim 0$

- Large error
- Strong phases neglected, largest interference

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: $|C/T| \sim |C'/T| \sim |E/T| \sim |P/T| \sim O(\Lambda_{QCD}/m_Q) \sim 0.3$

$|B/E| \sim O(\Lambda_{QCD}/m_Q) \sim 0.3$

Factorization-assisted topological-amplitude approach

$B \to \pi\pi$ $\quad T^{\pi\pi} : C^{\pi\pi} : E^{\pi\pi} : P^{\pi\pi} = 1 : 0.47 : 0.29 : 0.32$

[S.H. Zhou, Q.A. Zhang, C.D. Lu, 16']

Hierarchy in heavy quark expansion

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

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

b decay: |C/T|~|C'/T|~|E/T|~|P/T|~O(Λ_{QCD}/m_Q)~0.3

|B/E|~|PE/E|~O(Λ_{QCD}/m_Q)~0.3

PQCD approach

$\Lambda_b \to p\pi$

	A	B
T	$-2.42 \times 10^{-9} - i2.07 \times 10^{-9}$	$-1.74 \times 10^{-9} - i1.22 \times 10^{-9}$
C'	$2.05 \times 10^{-10} - i4.60 \times 10^{-10}$	$-2.35 \times 10^{-10} + i4.77 \times 10^{-10}$
B	$2.89 \times 10^{-11} - i8.95 \times 10^{-12}$	$1.11 \times 10^{-11} - i4.36 \times 10^{-12}$
E	$-7.00 \times 10^{-11} + i3.33 \times 10^{-10}$	$2.21 \times 10^{-10} - i4.04 \times 10^{-11}$
PE	$-6.84 \times 10^{-12} + i4.85 \times 10^{-11}$	$7.00 \times 10^{-12} - i4.75 \times 10^{-11}$
P	$1.37 \times 10^{-10} + i1.71 \times 10^{-11}$	$-1.60 \times 10^{-10} + i2.01 \times 10^{-10}$

[C.D. Lu, Y.M. Wang, H. Zou, Ali, Kramer, 09']

Hierarchy in heavy quark expansion

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

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

c decay: |C/T|~|C'/T|~|E/T|~O(Λ_{QCD}/m_Q)~1

|B/E|~O(Λ_{QCD}/m_Q)~1

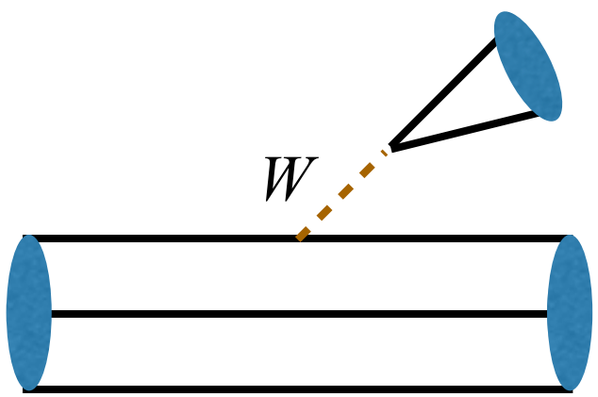
|P|~0

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

	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

Topologies of two-body non-leptonic charmed baryon decays



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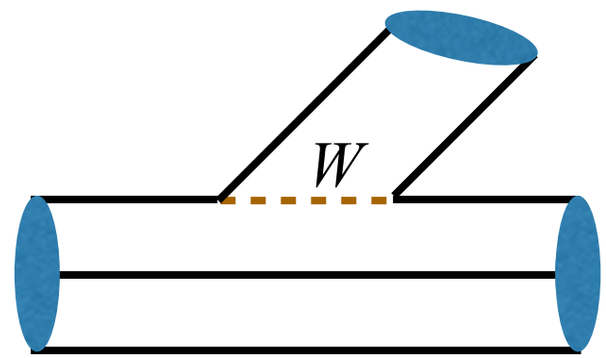
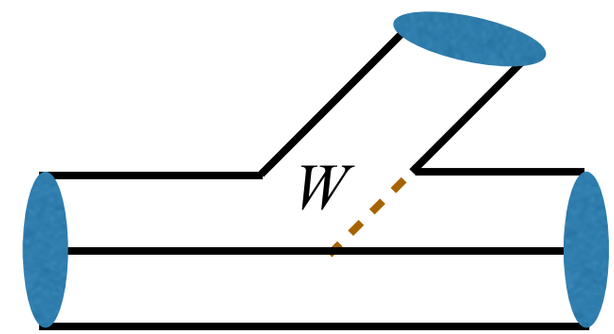
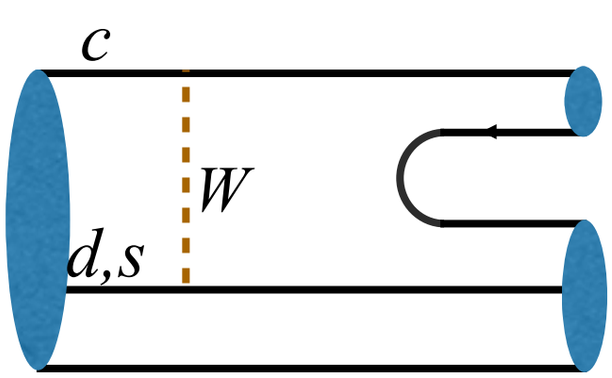


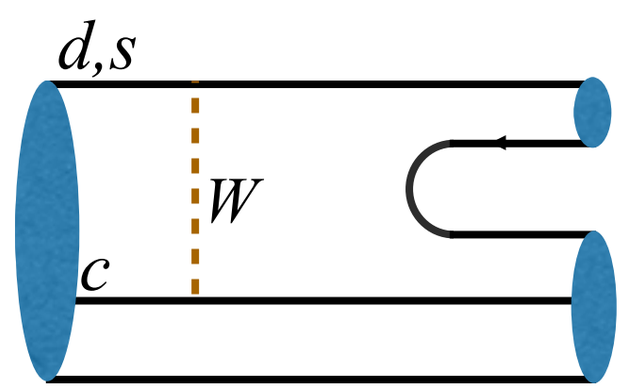
(C)
color-suppressed emitted



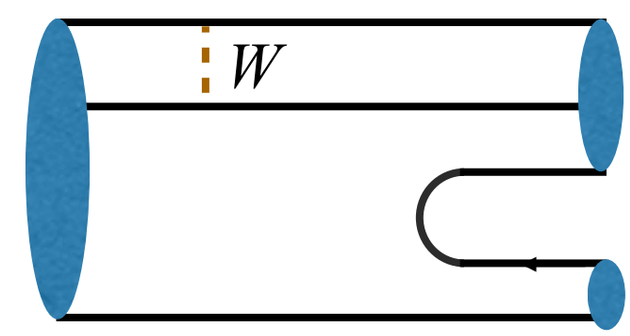
(C')
color-commensurate



(E_1)
W-exchange 1



(E_2)
W-exchange 2



(B)
Bow tie

Theoretical Framework

1. To understand factorizable contributions

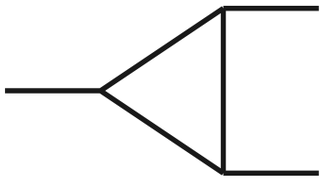
   — tree emitted (T) diagrams

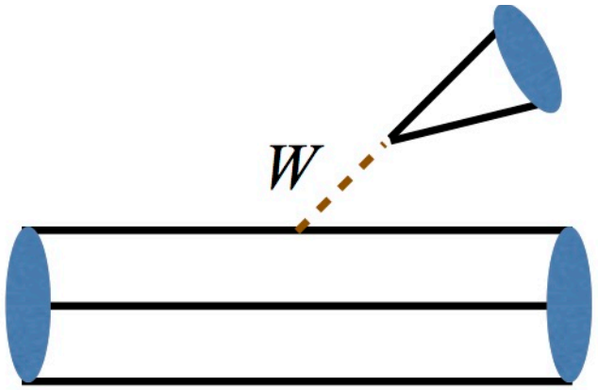
   - Form factors calculated in light-front quark model

2. To understand non-factorizable contributions

   — final-state interacting effects

   - Calculate rescattering effects





(T)

T diagrams

$$A = -\lambda f_P (M - M') f_1(m^2)$$

$$B = -\lambda f_P (M + M') g_1(m^2)$$

Under SU(3) symmetry

channels	$f_1(0)$	$f_2(0)$	$g_1(0)$	$g_2(0)$	$m_{\rm pole}$
$\Xi_{cc}^{++} \to \Lambda_c^+$	0.653	−0.739	0.533	−0.053	D^*
$\Xi_{cc}^{++} \to \Sigma_c^+$	0.653	−0.739	0.533	−0.053	D^*
$\Xi_{cc}^{++} \to \Xi_c^+$	0.754	−0.783	0.620	−0.080	D_s^*
$\Xi_{cc}^{+} \to \Sigma_c^0$	0.653	−0.739	0.533	−0.053	D^*
$\Xi_{cc}^{+} \to \Xi_c^0$	0.754	−0.783	0.620	−0.080	D_s^*
$\Xi_{bc}^{+} \to \Sigma_c^{++}$	0.136	−0.081	0.130	−0.009	B^*
$\Xi_{bc}^{0} \to \Lambda_c^+$	0.136	−0.081	0.130	−0.009	B^*
$\Xi_{bc}^{0} \to \Sigma_c^+$	0.136	−0.081	0.130	−0.009	B^*
$\Xi_{bc}^{+} \to \Lambda_b^0$	0.639	−1.707	0.499	−0.232	D^*
$\Xi_{bc}^{+} \to \Xi_b^0$	0.725	−1.801	0.571	−0.269	D_s^*
$\Xi_{bc}^{0} \to \Xi_b^-$	0.725	−1.801	0.571	−0.269	D_s^*

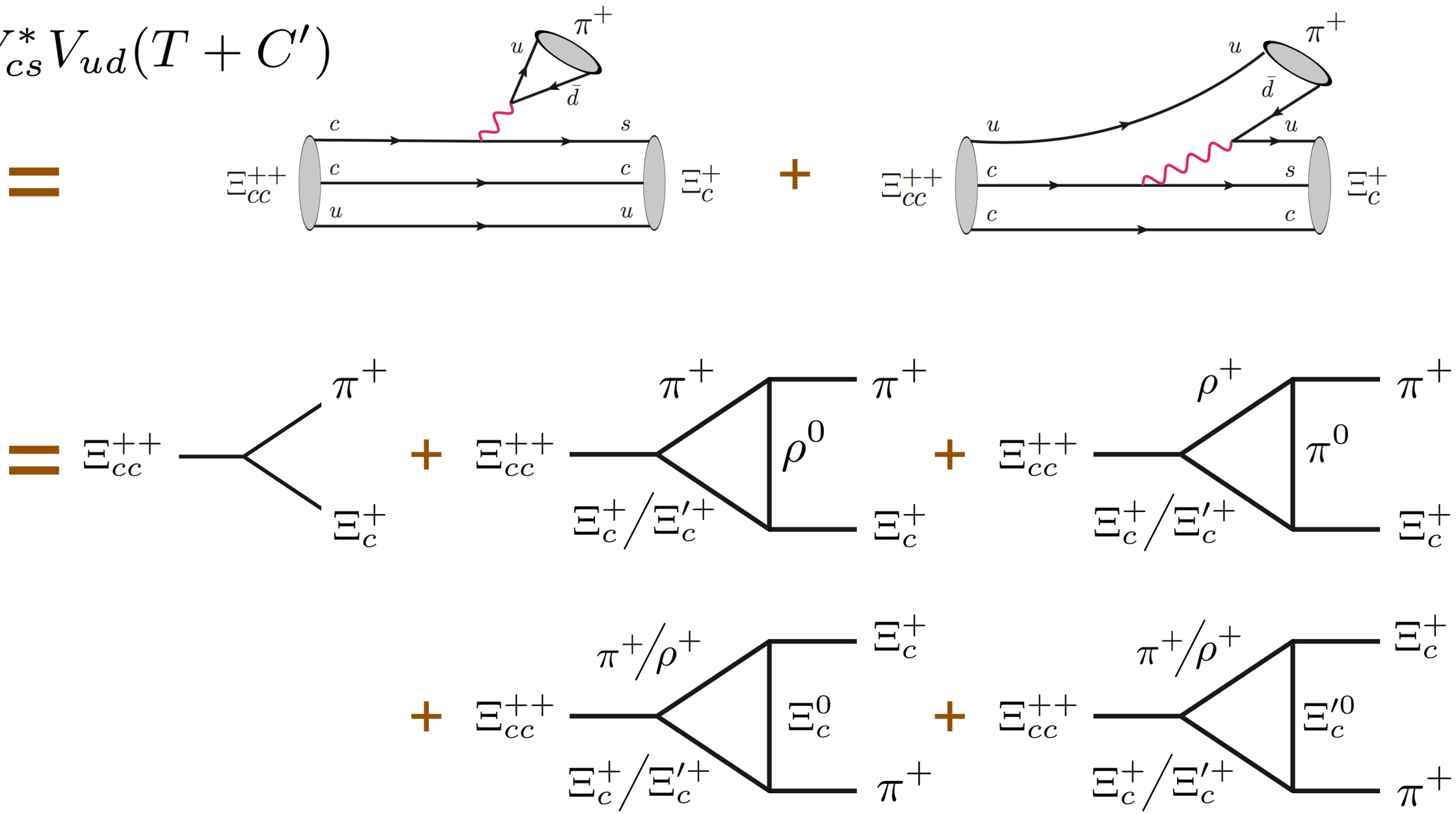
T_A=0.14, T_B=0.50

T_A=0.10, T_B=0.18

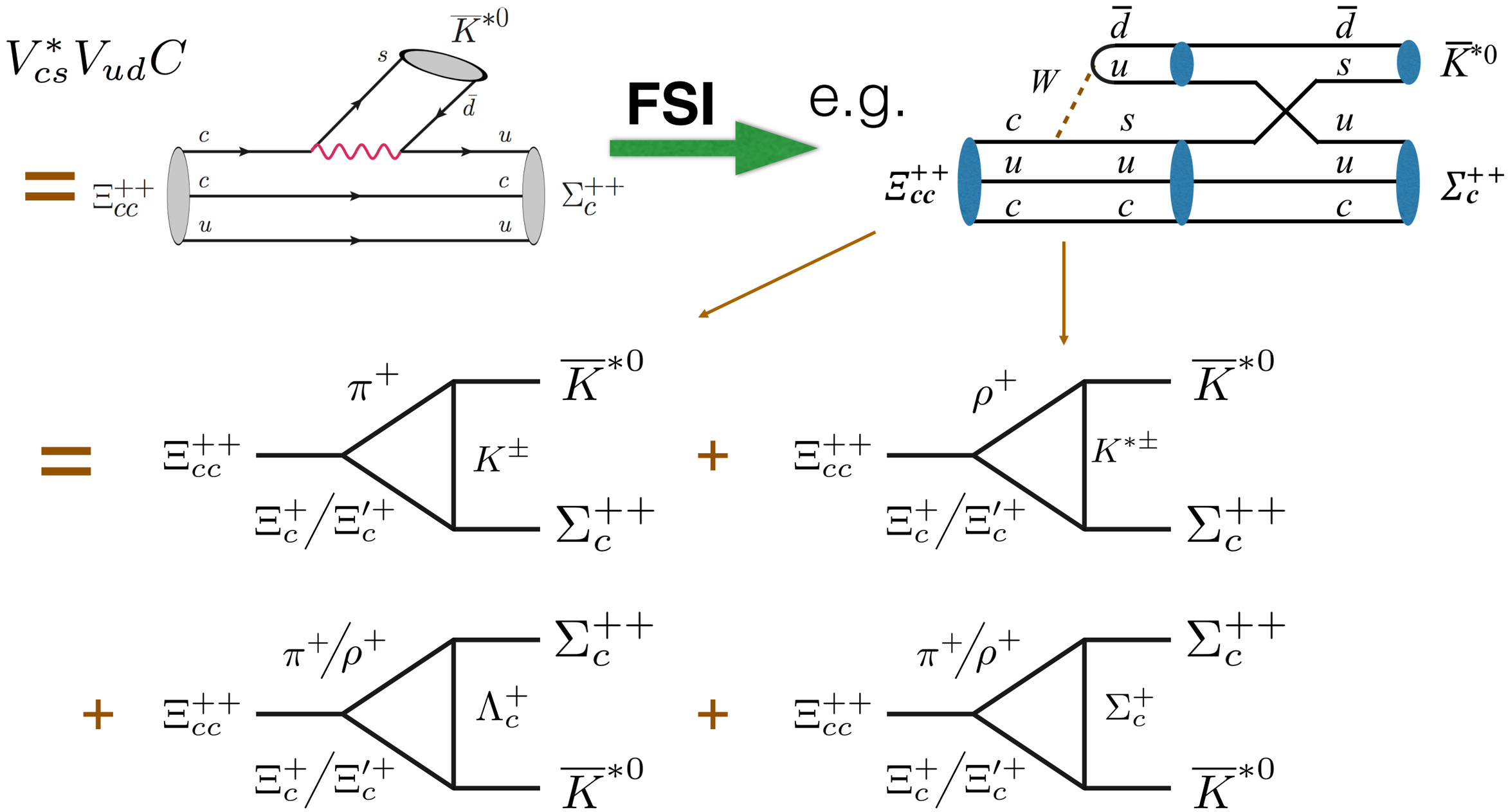
T_A=0.13, T_B=1.0

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

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

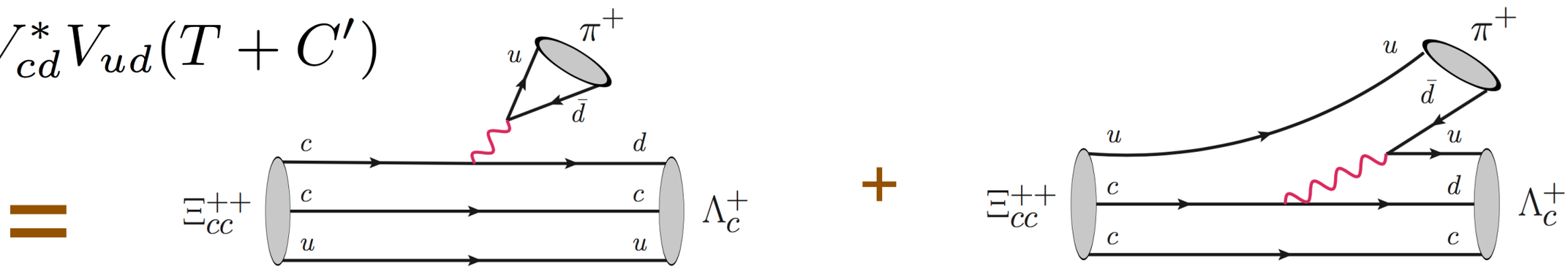


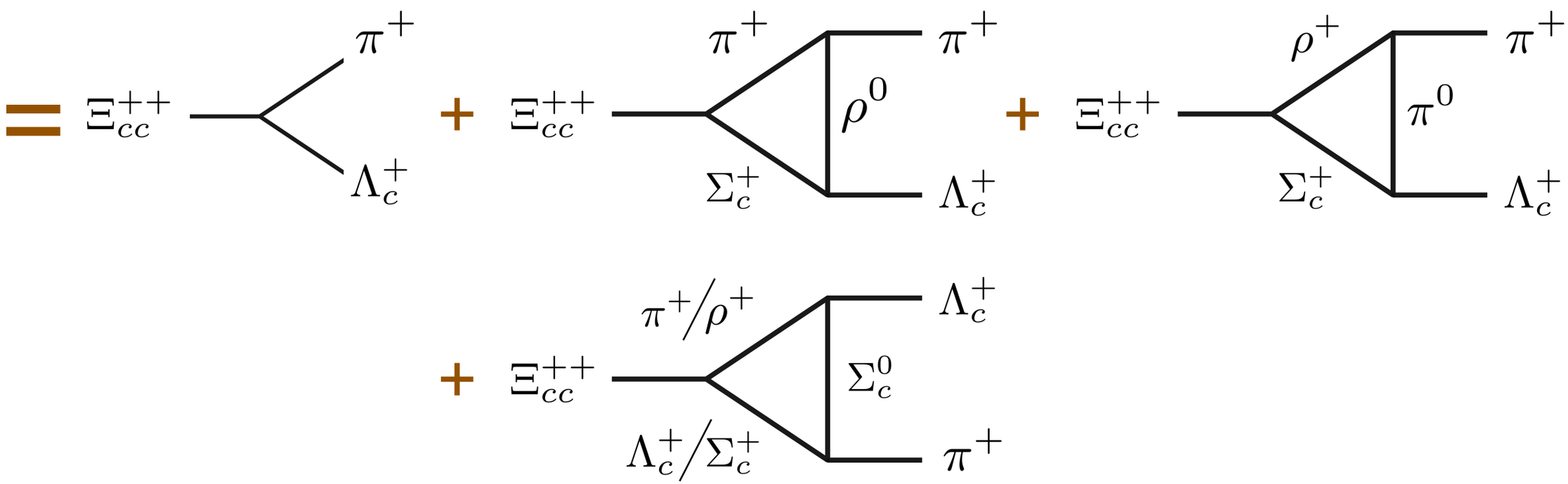
$$\Xi_{cc}^{++} \to \Sigma_c^{++}\overline{K}^{*0} \to \Lambda_c^+ K^- \pi^+ \pi^+$$



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

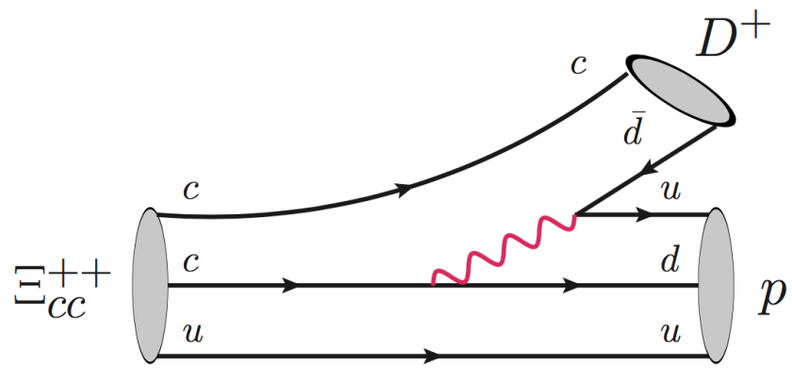
$V_{cd}^* V_{ud}(T + C')$





$\Xi_{cc}^{++} \to pD^+$

$V_{cd}^* V_{ud} C'$ =



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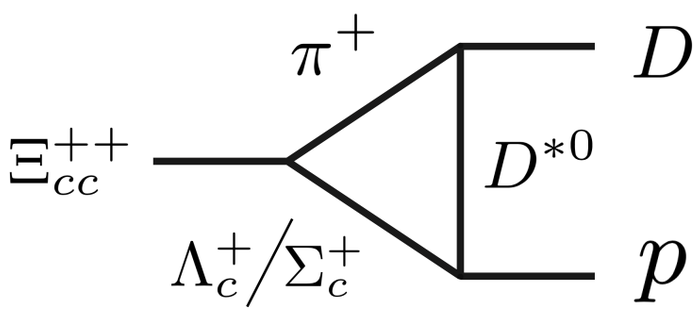

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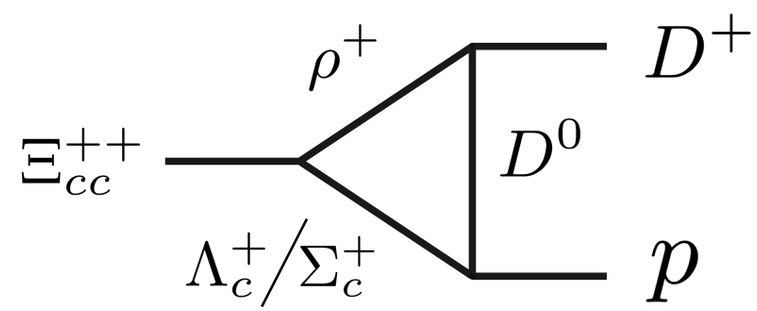

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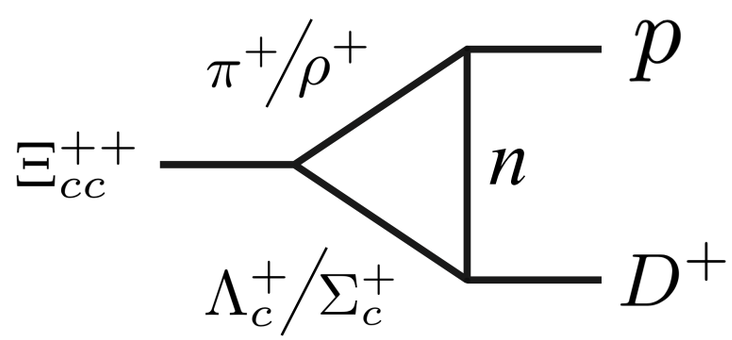
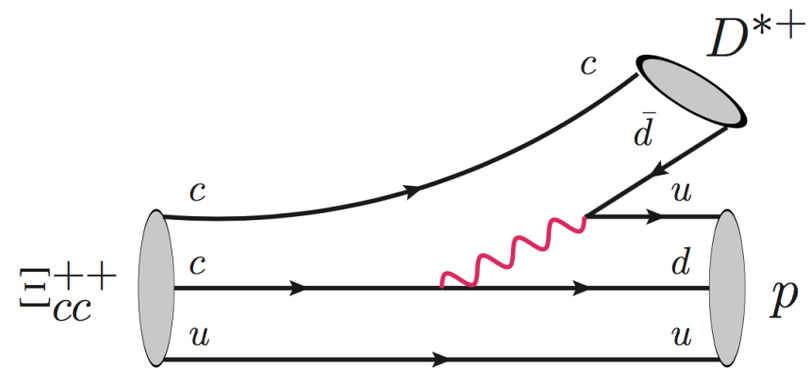


$$\boxed{\Xi_{cc}^{++} \to pD^{*+}} \quad \to pD^0\pi^+$$

$$V_{cd}^* V_{ud} C' =$$



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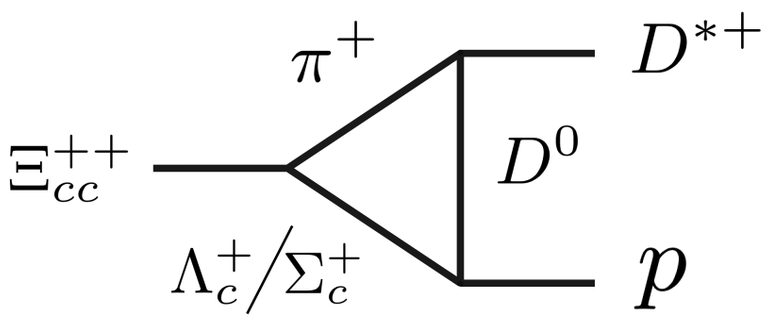

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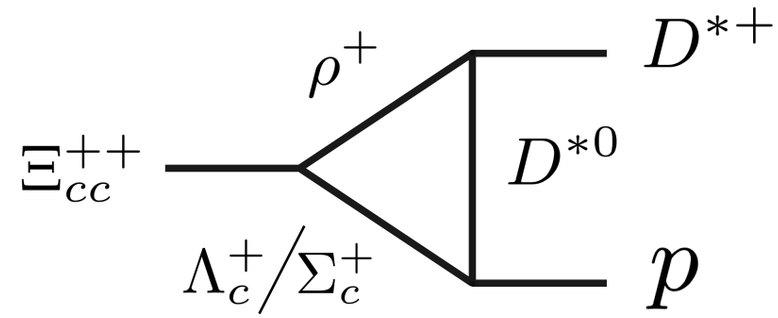

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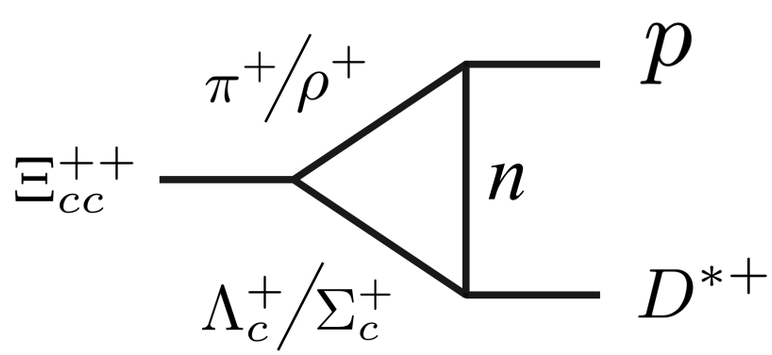
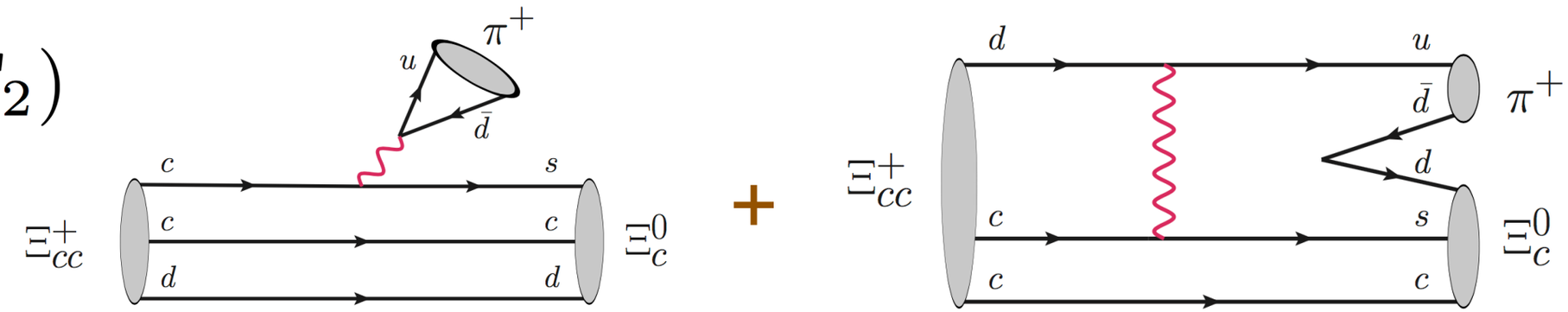


$\Xi_{cc}^{+} \to \Xi_{c}^{0}\pi^{+}$

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

$=$



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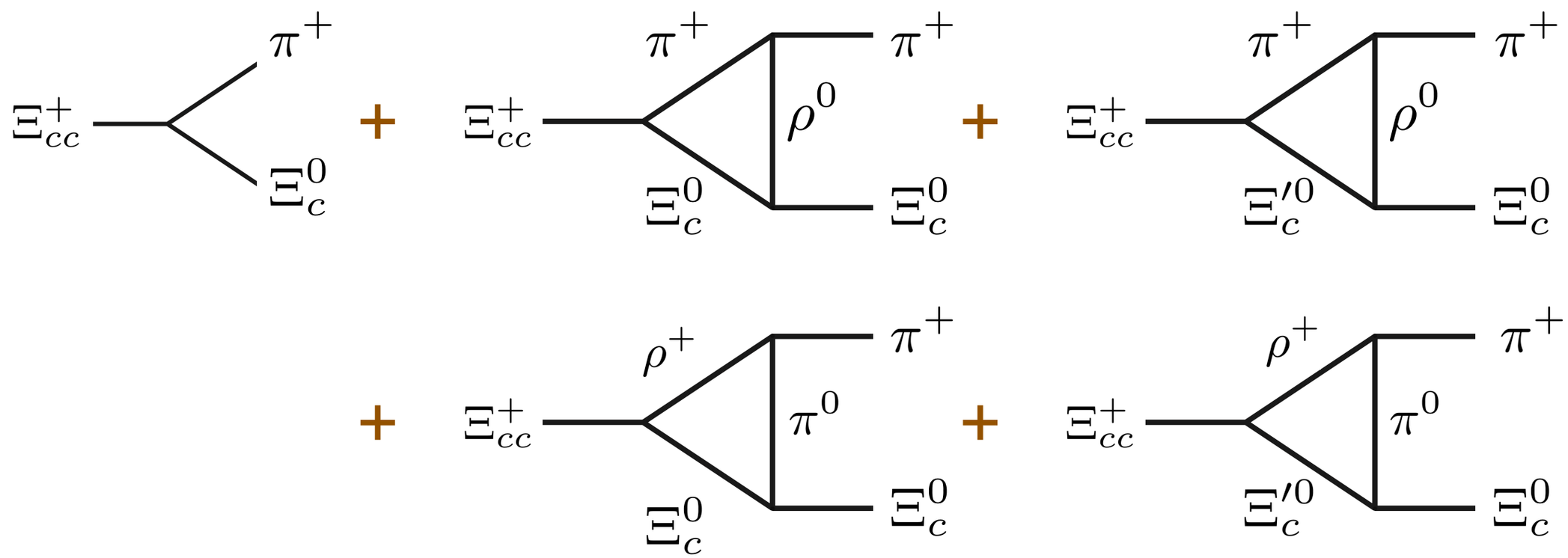
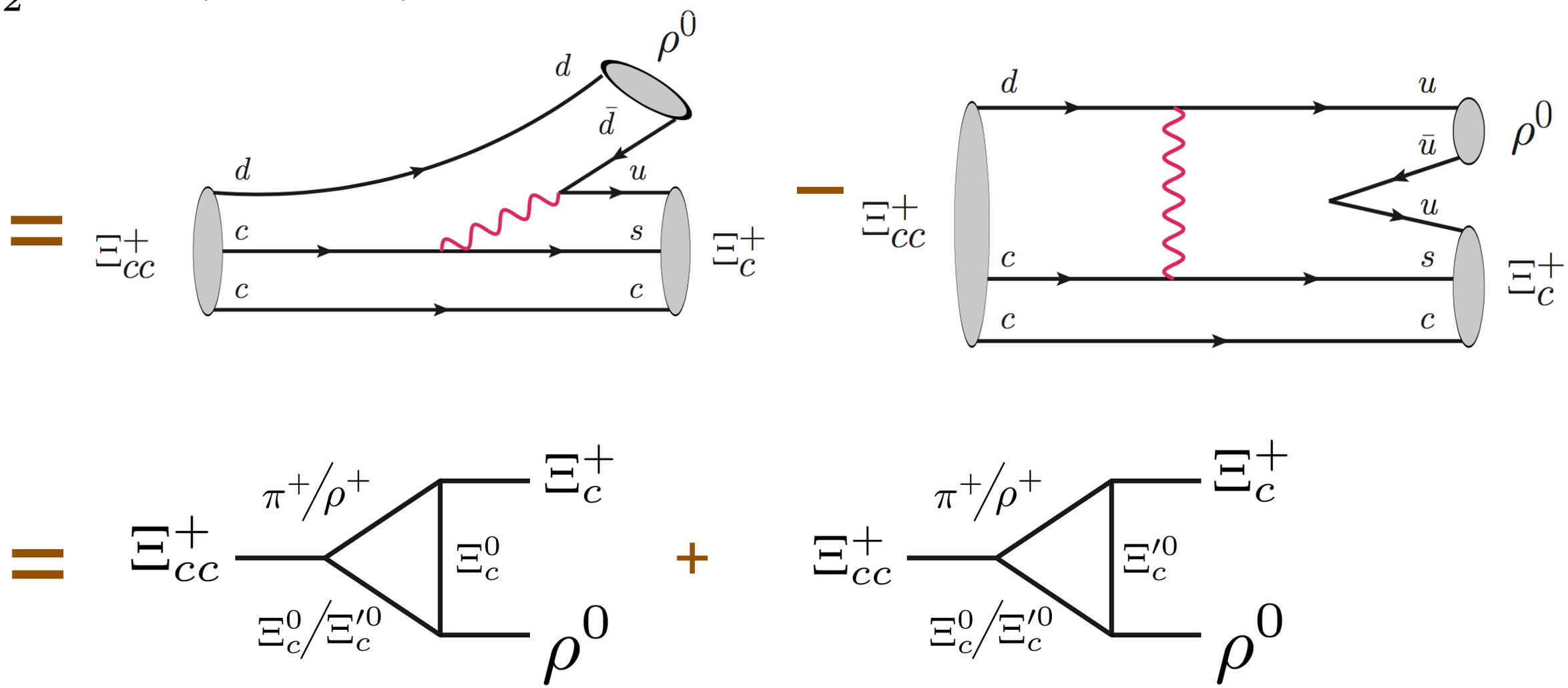


$$\boxed{\Xi_{cc}^{+} \to \Xi_{c}^{+}\rho^{0}} \to \Xi_{c}^{+}\pi^{+}\pi^{-}$$

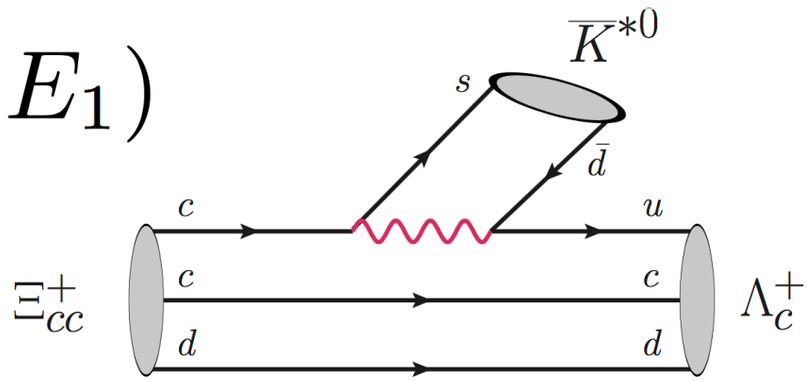
$$\frac{1}{\sqrt{2}} V_{cs}^{*} V_{ud} (C' - E_2)$$



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

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

$=$



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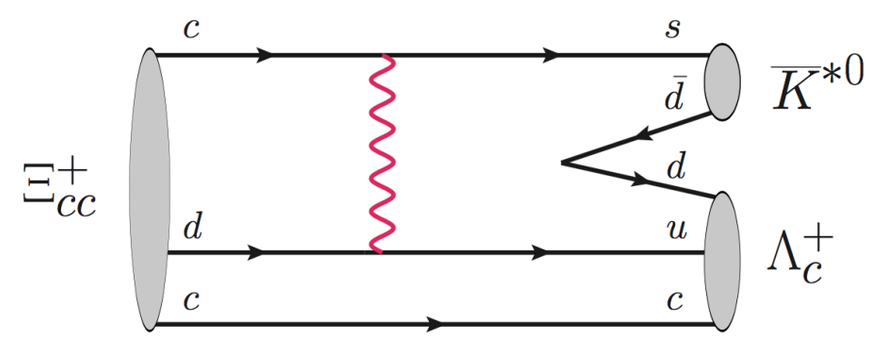

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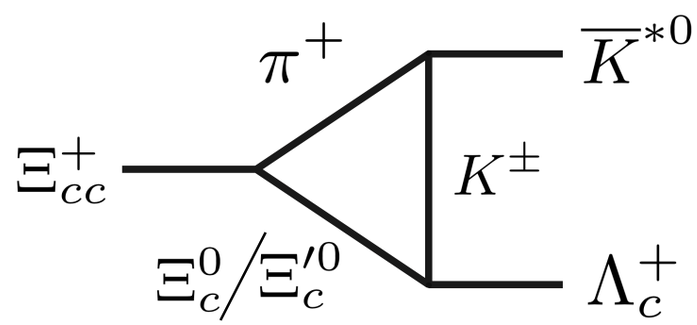

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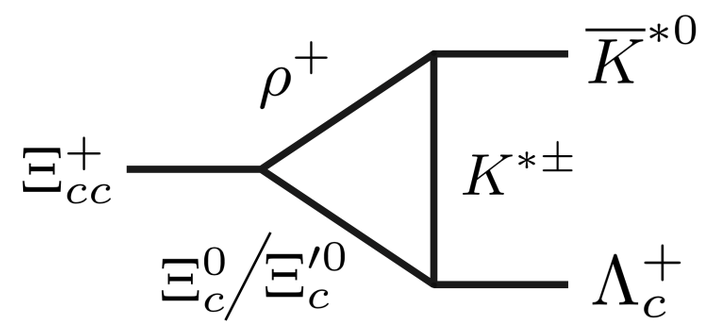

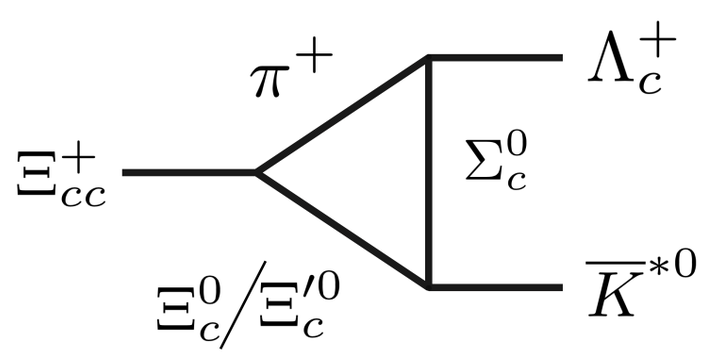

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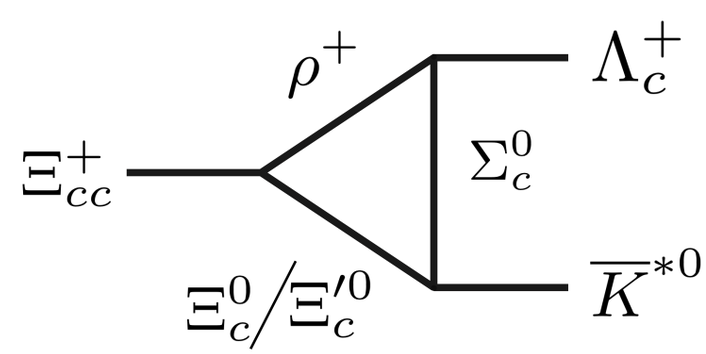
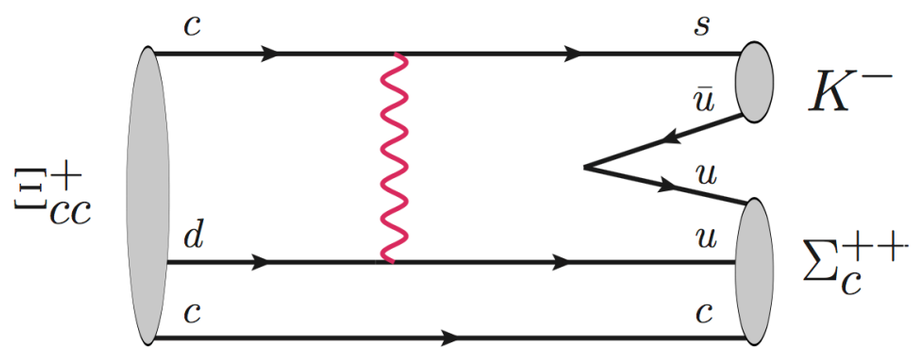


SELEX exp. ever found evidence in this channel

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

$V_{cs}^* V_{ud} E_1$ =



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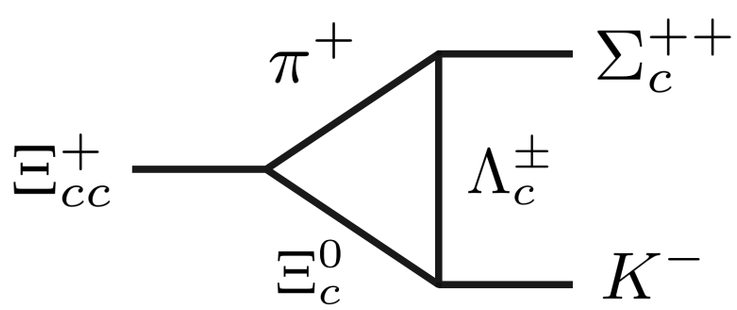

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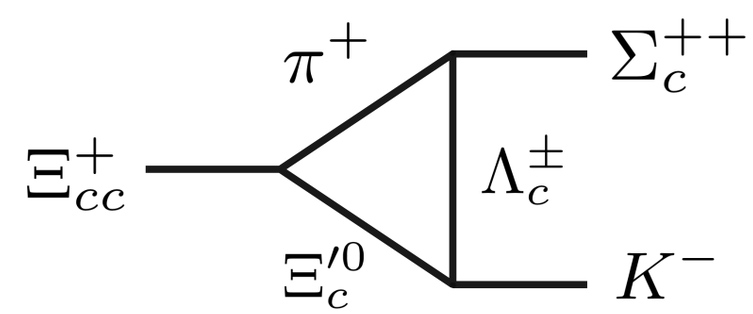

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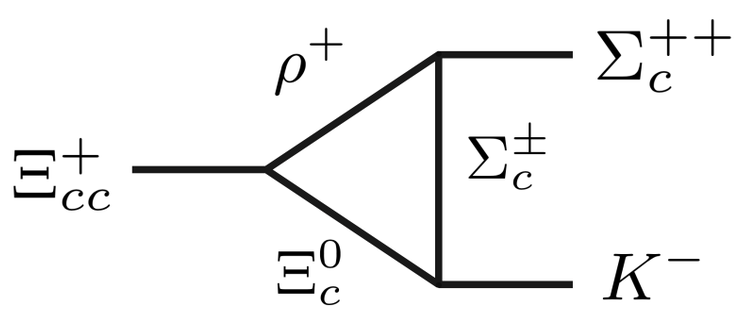

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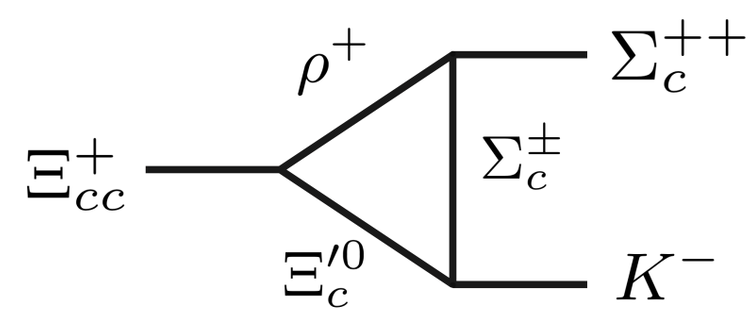
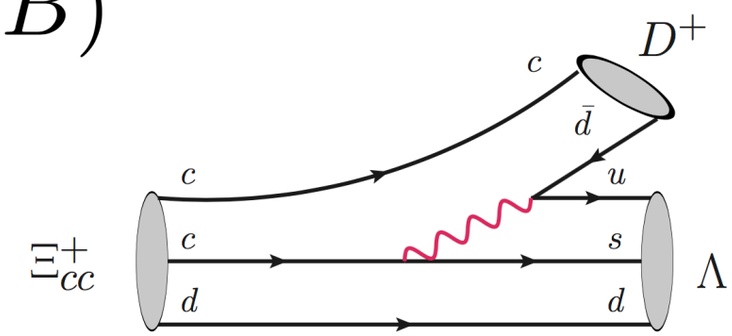


SELEX exp. ever found evidence in this channel

$\Xi_{cc}^{+} \to \Lambda^{0} D^{+}$

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

=



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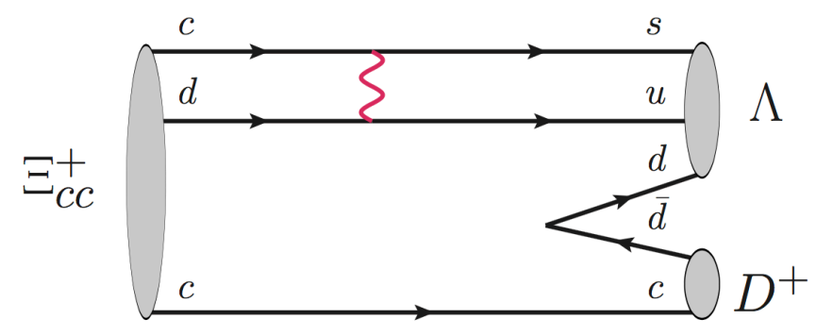

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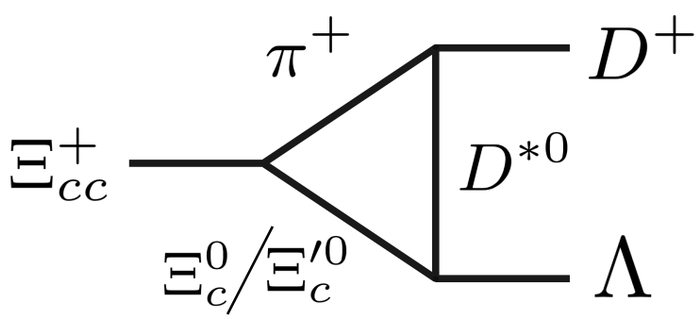

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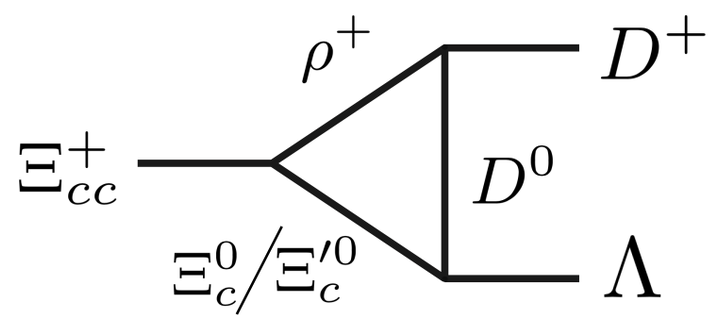

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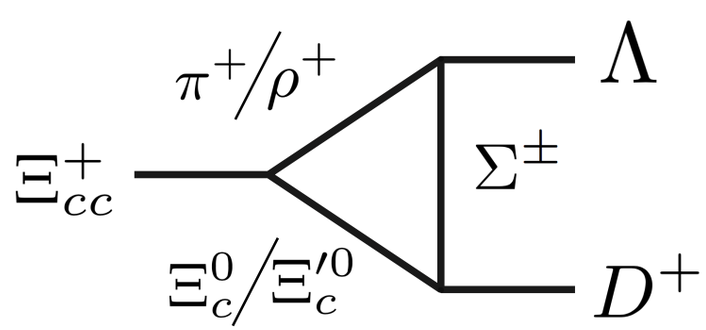
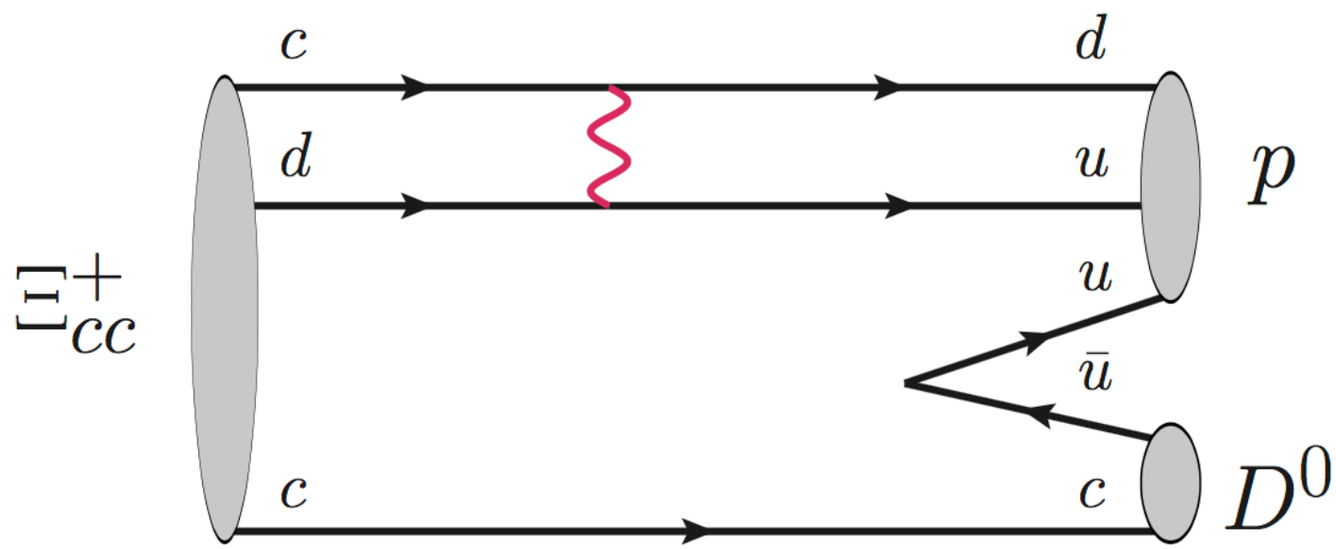


$$\Xi_{cc}^{+} \to p D^{0}$$

$$V_{cd}^{*} V_{ud} B =$$



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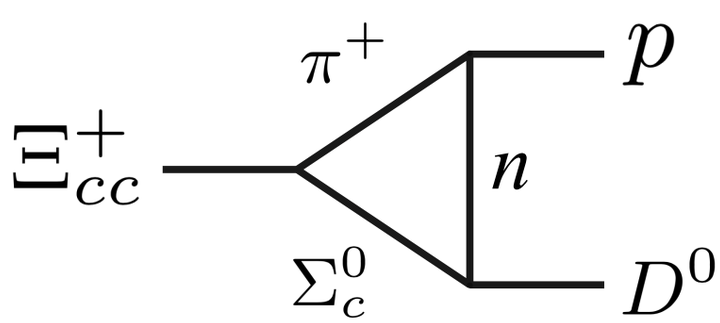

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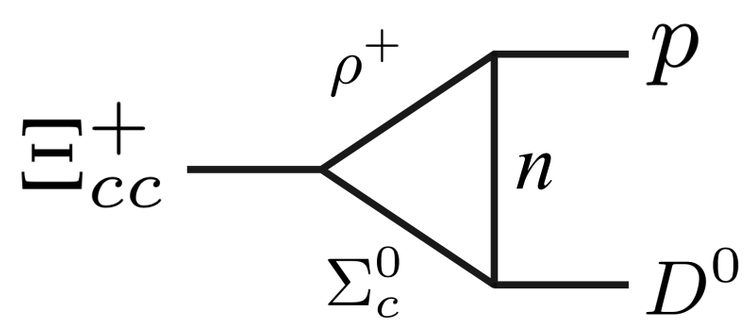
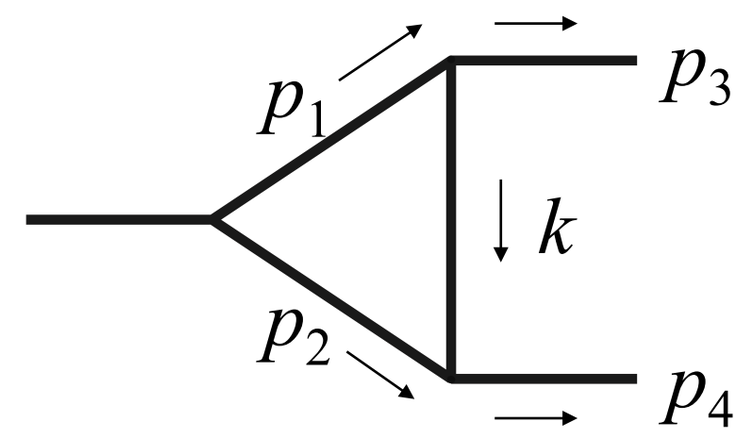


Theoretical Uncertainties

- Strong couplings between hadrons

  — Large ambiguities in literatures

- Off-shell effects of intermediate states



$$F(t, m) = \left(\frac{\Lambda^2 - m^2}{\Lambda^2 - t}\right)^n$$

$$t \equiv (p_1 - p_3)^2 \qquad n=1$$

$$\Lambda = m_{\rm exc} + \eta \Lambda_{\rm QCD}$$

[Cheng, Chua, Soni, PRD 71, 014030 (2005)]

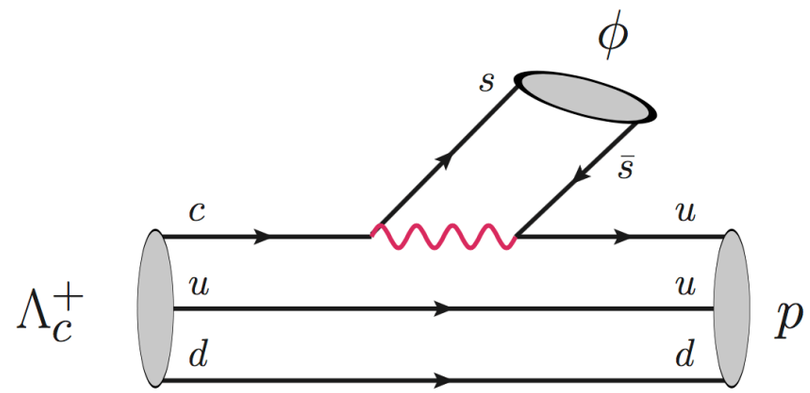
Results are very sensitive to the value of η

No first-principle calculations for η

We take η from 1.0 to 2.0

Checked with $\boxed{\Lambda_c^+ \to p\phi}$

$V_{cd}^* V_{ud} C$ =



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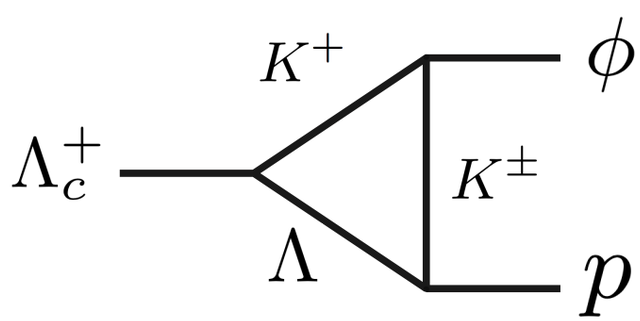

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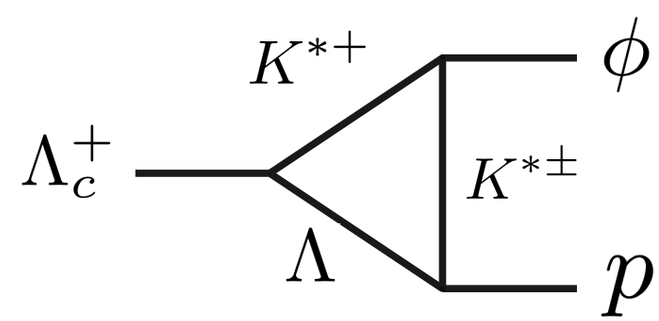

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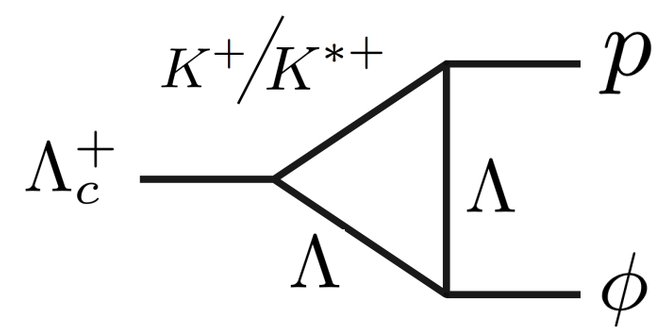


PDG $\mathcal{B}(\Lambda_c^+ \to p\phi) = (1.04 \pm 0.21) \times 10^{-3}$

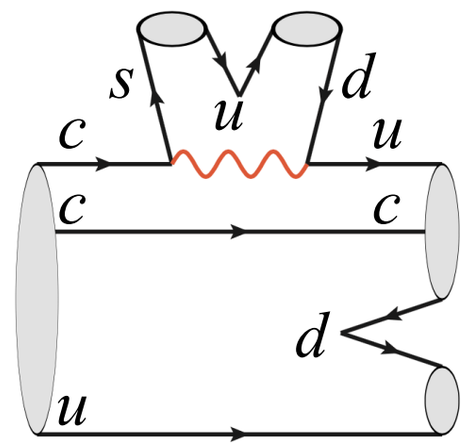
$\eta \sim 1.3$

Results of Branching Fractions

Baryons	Modes	Representation	Br	
Ξ_{cc}^{++}	$\Sigma_c^{++}\overline{K}^{*0}$	$V_{cs}^* V_{ud} C$	$(1.6 \sim 11)\%$	$\Lambda_c^+ K^- \pi^+ \pi^+$
	$\Xi_c^+ \pi^+$	$V_{cs}^* V_{ud}(T + C')$	$(9.0 \sim 9.4)\%$	
	$\Lambda_c^+ \pi^+$	$V_{cd}^* V_{ud}(T + C')$	$(0.6 \sim 1.3)\%$	
	pD^+	$V_{cd}^* V_{ud} C'$	$(0.01 \sim 0.08)\%$	
	pD^{*+}	$V_{cd}^* V_{ud} C'$	$(0.3 \sim 2.8)\%$	$pD^0\pi^+$
Ξ_{cc}^+	$\Xi_c^0 \pi^+$	$V_{cs}^* V_{ud}(T + E_2)$	$(2.9 \sim 3.8)\%$	
	$\Xi_c^+ \rho^0$	$\frac{1}{\sqrt{2}} V_{cs}^* V_{ud}(C' - E_2)$	$(0.2 \sim 1.8)\%$	$\Xi_c^+ \pi^+ \pi^-$
	$\Lambda_c^+ \overline{K}^{*0}$	$V_{cs}^* V_{ud}(C + E_1)$	$(0.14 \sim 0.5)\%$	$\Lambda_c^+ K^- \pi^+$
	$\Sigma_c^{++} K^-$	$V_{cs}^* V_{ud} E_1$	$(0.02 \sim 0.1)\%$	
	ΛD^+	$V_{cs}^* V_{ud}(C' + B)$	$(0.1 \sim 0.7)\%$	
	pD^0	$V_{cd}^* V_{ud} B$	$(0.0002 \sim 0.001)\%$	

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

K^{*0}, $(K\pi)_{\text{S-wave}}$, $K_0^*(1430)$

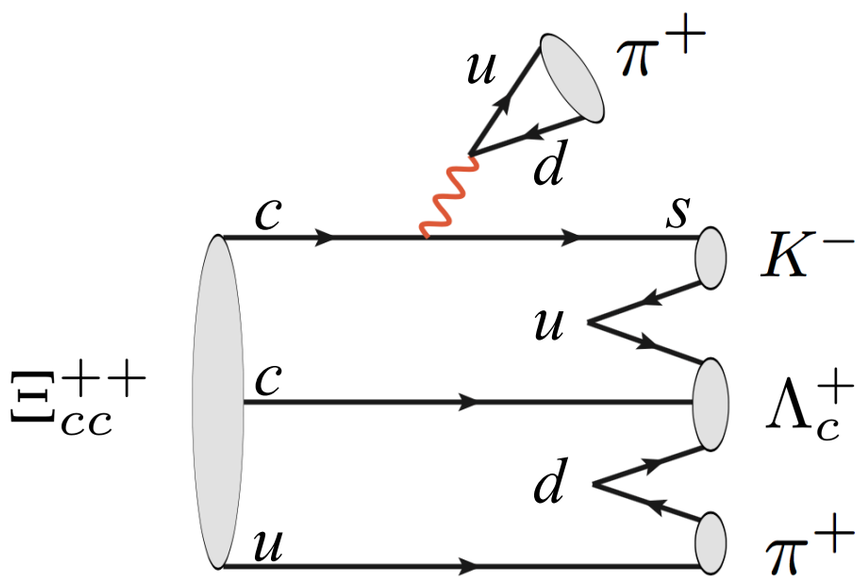


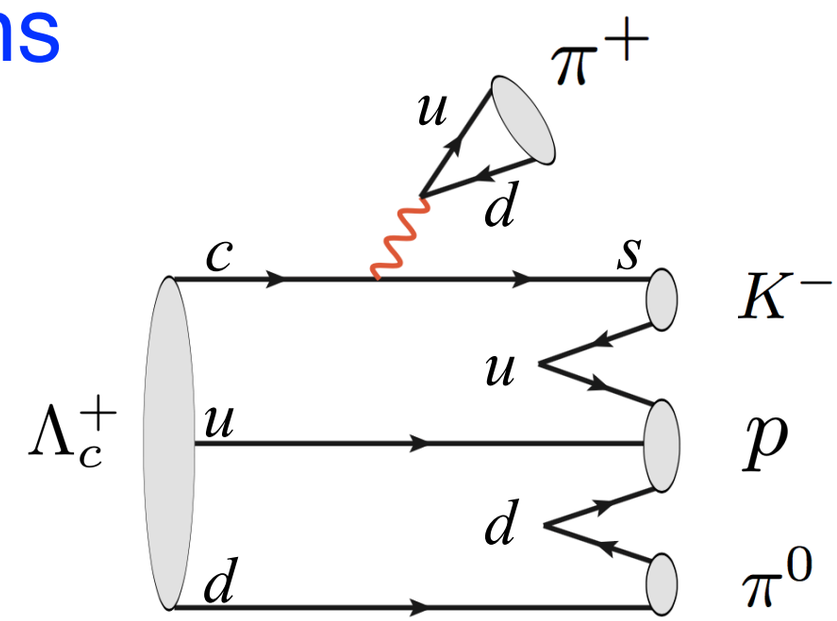
$\Sigma_c^{++}(2455)$, $\Sigma_c^{++}(2520)$

1. Many resonances

$$Br(\Sigma_c^{++} K^{*0}) = (1.6 \sim 11)\%$$

2. Large non-resonant contributions





$$Br(\Lambda_c^+ \to pK^-\pi^+\pi^0) = (4.9 \pm 0.4)\%$$

$$Br(\Lambda_c^+ \to p(K^-\pi^+)_{\text{nonresonant}}\pi^0) = (4.6 \pm 0.9)\%$$

$$Br(\Lambda_c^+ \to \Lambda\pi^+) = (1.30 \pm 0.07)\%$$

multi-body > two-body

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

- In theory, we can only calculate two-body non-leptonic decays.

- For multi-body processes, we can only give a rough estimation.

- Similarly to $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, it can also be expected that the branching fractions of $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^+ \to \Xi_c^+ \pi^+ \pi^-$ could reach $\mathcal{O}(10\%)$

Prediction on Br of $\Xi_c^+ \to pK^-\pi^+$

Ξ_c^+ detecting mode, Br not directly measured

Under U-spin symmetry

$$\mathcal{A}(\Xi_c^+ \to p\overline{K}^{*0}) = -\mathcal{A}(\Lambda_c^+ \to \Sigma^+ K^{*0})$$

PDG

$\Lambda_c^+ \to \Sigma^+ K^{*0}$ saturates $Br(\Lambda_c^+ \to \Sigma^+ K^-\pi^+) = (0.21 \pm 0.06)\%$

$$Br(\Xi_c^+ \to p\overline{K}^{*0})/Br(\Xi_c^+ \to pK^-\pi^+) = 0.54 \pm 0.10$$

Averaged: $Br(\Xi_c^+ \to pK^-\pi^+) = (1.6 \pm 0.5)\%$

It can be widely used

$\tau(\Xi_c^+) = (442 \pm 26) \times 10^{-15} s$

Precision can be improved by measurements of Λ_c^+ and Ξ_c^+ decays

Priorities to measure

1. Ξ_{cc}^{++} > Ξ_{cc}^{+}, due to $\tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^{+})$

2. $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ has the largest branching fraction in Ξ_{cc}^{++} decays. And large $Br(\Lambda_c^+ \to pK^-\pi^+)$ But suffer 6 tracks. LHCb, **PRL 119 (2017) 112001**

3. $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ has only 4 tracks. Its branching fraction has large ambiguity. Small $Br(\Xi_c^+ \to pK^-\pi^+)$

4. $\Xi_{cc}^{++} \to pD^+$ has only 4 tracks. Branching fraction and lifetime of D^+ are large

5. For Ξ_{cc}^{+}, $\Lambda_c^+ K^- \pi^+$ has the largest priority.

Non-leptonic decays of Ω_{cc}^{+}

Modes	Br(first)($\times 10^{-3}$)	Br(final)($\times 10^{-3}$)	Representation
pD^0	0.3	0.008	Bc Vcd Vus
$(p\pi^-)(D^+/D^0\pi^+)$	0.2	0.006	Bc Vcd Vus
$(pK^-\pi^+/\Sigma^+)D^0$	3.	0.08	Bc Vcs Vus
$(pK^-/\Lambda)(D^+/D^0\pi^+)$	10.	0.3	Ccm Vcd Vud + Bc Vcs Vus
$(pK^-/\Lambda)(D_s^+/D^0K^+)$	0.5	0.01	Bc Vcd Vus + Ccm Vcd Vus
$(pK^-\pi^+K^-/\Xi^0)(D^+/D^0\pi^+)$	50.	2.	Ccm Vcs Vud
$(pK^-\pi^+K^-/\Xi^0)(D_s^+/D^0K^+)$	9.	0.3	Bc Vcs Vus + Ccm Vcs Vus
$(\Lambda_c^+\pi^+)\pi^-$	0.2	0.01	-(Ec Vcd Vus)
$(\Lambda_c^+\pi^+)K^-$	3.	0.2	-(Ec Vcs Vus)
$\Lambda_c^+(\pi^+\pi^-)$	0.8	0.04	2 Ec Vcd Vus
$\Lambda_c^+(K^-\pi^+)$	10.	0.7	Ccb Vcd Vud - Ec Vcs Vus
$\Lambda_c^+(K^+K^-)$	0.1	0.006	Ccb Vcd Vus
$(\Lambda_c^+\pi^-)\pi^+$	0.2	0.01	Ec Vcd Vus
$(\Lambda_c^+\pi^+K^-/\Xi_c^+)(\pi^+\pi^-)$	9.	0.5	-(Ct Vcd Vud) + Ec Vcs Vus
$(\Lambda_c^+\pi^+K^-/\Xi_c^+)(K^+\pi^-)$	0.4	0.02	Ct Vcd Vus - Ec Vcd Vus
$(\Lambda_c^+\pi^+K^-/\Xi_c^+)(K^-\pi^+)$	100.	7.	Ccb Vcs Vud + Ct Vcs Vud
$(\Lambda_c^+\pi^+K^-/\Xi_c^+)(K^+K^-)$	10.	0.5	Ccb Vcs Vus + Ct Vcs Vus - Ec Vcs Vus
$(\Lambda_c^+K^-/\Xi_c^0)\pi^+$	10.	0.6	T Vcd Vud + Ec Vcs Vus
$(\Lambda_c^+K^-/\Xi_c^0)K^+$	0.6	0.03	Ec Vcd Vus + T Vcd Vus
$(\Lambda_c^+\pi^+K^-K^-/\Omega_c^0)\pi^+$	50.	2.	T Vcs Vud
$(\Lambda_c^+\pi^+K^-K^-/\Omega_c^0)K^+$	8.	0.4	Ec Vcs Vus + T Vcs Vus

Non-leptonic *b*-decays of Ξ_{bc}^{+}

Modes	Br(first)	Br(final)($\times 10^{-7}$)	Representation
$p(\pi^+\pi^-)$	0.1×10^{-7}	0.1	Bq Vcd Vub + 2 Eq Vcd Vub
$p(K^-\pi^+)$	0.6×10^{-7}	0.6	-(Eq Vcs Vub)
pD^0	$6. \times 10^{-7}$	0.2	Eq Vcb Vcd + Bc Vub Vud + Cbm Vub Vud
pJ/Ψ	0.02×10^{-7}	0.001	Cbm Vcd Vub
$(p\pi^-)\pi^+$	0.04×10^{-7}	0.04	Bq Vcd Vub + Eq Vcd Vub
$(p\pi^-)(D^+/D^0\pi^+)$	$3. \times 10^{-7}$	0.08	Eq Vcb Vcd + Bc Vub Vud
$(p\pi^+)\pi^-$	0.03×10^{-7}	0.03	-(Eq Vcd Vub)
$(p\pi^+)K^-$	0.5×10^{-7}	0.5	-(Eq Vcs Vub)
$(pK^-\pi^+/\Sigma^+)(\pi^+\pi^-)$	0.8×10^{-7}	0.8	Bq Vcs Vub + Eq Vcs Vub
$(pK^-\pi^+/\Sigma^+)(K^+\pi^-)$	0.03×10^{-7}	0.03	-(Eq Vcd Vub)
$(pK^-\pi^+/\Sigma^+)(K^+K^-)$	0.5×10^{-7}	0.5	-(Eq Vcs Vub)
$(pK^-\pi^+/\Sigma^+)D^0$	$60. \times 10^{-7}$	2.	Eq Vcb Vcs + Bc Vub Vus + Cbm Vub Vus
$(pK^-\pi^+/\Sigma^+)J/\Psi$	0.4×10^{-7}	0.02	Cbm Vcs Vub
$(pK^-/\Lambda)\pi^+$	0.8×10^{-7}	0.8	Bq Vcs Vub + Eq Vcs Vub
$(pK^-/\Lambda)K^+$	0.04×10^{-7}	0.04	Bq Vcd Vub + Eq Vcd Vub
$(pK^-/\Lambda)(D^+/D^0\pi^+)$	$60. \times 10^{-7}$	2.	Eq Vcb Vcs + Bc Vub Vus
$(pK^-/\Lambda)(D_s^+/D^0K^+)$	$2. \times 10^{-7}$	0.07	Eq Vcb Vcd + Bc Vub Vud
$(pK^-\pi^+K^-/\Xi^0)K^+$	0.8×10^{-7}	0.8	Bq Vcs Vub + Eq Vcs Vub
$(pK^-\pi^+K^-/\Xi^0)(D_s^+/D^0K^+)$	$60. \times 10^{-7}$	2.	Eq Vcb Vcs + Bc Vub Vus
$(\Lambda_c^+\pi^+)\pi^-$	$30. \times 10^{-7}$	2.	-(Eq Vcb Vcd) + Ec Vub Vud + Tb Vub Vud
$(\Lambda_c^+\pi^+)K^-$	$70. \times 10^{-7}$	3.	-(Eq Vcb Vcs) + Ec Vub Vus + Tb Vub Vus
$\Lambda_c^+(K^-\pi^+)$	$50. \times 10^{-7}$	3.	-(Eq Vcb Vcs) + Ec Vub Vus
$(\Lambda_c^+\pi^-)\pi^+$	$1. \times 10^{-7}$	0.05	Bq Vcb Vcd - Ec Vub Vud
$(\Lambda_c^+\pi^-)(D^+/D^0\pi^+)$	$20. \times 10^{-7}$	0.04	Bc Vcb Vud - Ec Vcb Vud
$(\Lambda_c^+\pi^+K^-/\Xi_c^+)(K^+\pi^-)$	$5. \times 10^{-7}$	0.3	-(Eq Vcb Vcd) + Ec Vub Vud
$(\Lambda_c^+\pi^+K^-/\Xi_c^+)(K^+K^-)$	$50. \times 10^{-7}$	2.	-(Eq Vcb Vcs) + Ec Vub Vus
$(\Lambda_c^+K^-/\Xi_c^0)\pi^+$	$2. \times 10^{-7}$	0.1	Bq Vcb Vcs - Ec Vub Vus
$(\Lambda_c^+K^-/\Xi_c^0)K^+$	0.9×10^{-7}	0.05	Bq Vcb Vcd - Ec Vub Vud
$(\Lambda_c^+K^-/\Xi_c^0)(D^+/D^0\pi^+)$	$1. \times 10^{-7}$	0.002	Bc Vcb Vus - Ec Vcb Vus
$(\Lambda_c^+K^-/\Xi_c^0)(D_s^+/D^0K^+)$	$20. \times 10^{-7}$	0.03	Bc Vcb Vud - Ec Vcb Vud
$(\Lambda_c^+\pi^+K^-K^-/\Omega_c^0)K^+$	$2. \times 10^{-7}$	0.1	Bq Vcb Vcs - Ec Vub Vus
$(\Lambda_c^+\pi^+K^-K^-/\Omega_c^0)(D_s^+/D^0K^+)$	$1. \times 10^{-7}$	0.002	Bc Vcb Vus - Ec Vcb Vus

Non-leptonic *c*-decays of Ξ_{bc}^{+}

Modes	Br(first)	Br(final)($\times 10^{-7}$)	Representation
$(\Lambda_b^0\pi^+)(K^+\pi^-)$	0.07×10^{-3}	0.07	Cct Vcd Vus
$(\Lambda_b^0\pi^+)(K^-\pi^+)$	$30. \times 10^{-3}$	30.	Cct Vcs Vud
$(\Lambda_b^0\pi^+)(K^+K^-)$	0.8×10^{-3}	0.8	Cct Vcs Vus
$\Lambda_b^0\pi^+$	$7. \times 10^{-3}$	7.	Ccb Vcd Vud + Tc Vcd Vud
$\Lambda_b^0K^+$	0.3×10^{-3}	0.3	Ccb Vcd Vus + Tc Vcd Vus
$(\Lambda_b^0\pi^+K^-/\Xi_b^0)\pi^+$	$100. \times 10^{-3}$	100.	Ccb Vcs Vud + Tc Vcs Vud
$(\Lambda_b^0\pi^+K^-/\Xi_b^0)K^+$	$4. \times 10^{-3}$	4.	Ccb Vcs Vus + Tc Vcs Vus
$p\bar{B}^0$	$3. \times 10^{-3}$	3.	Ccm Vcd Vud
$p\bar{B}_s^0$	0.1×10^{-3}	0.1	Ccm Vcd Vus
$(pK^-\pi^+/\Sigma^+)\bar{B}^0$	$20. \times 10^{-3}$	20.	Ccm Vcs Vud
$(pK^-\pi^+/\Sigma^+)\bar{B}_s^0$	0.8×10^{-3}	0.8	Ccm Vcs Vus

Non-leptonic *b*-decays of Ξ_{bc}^0

Modes	Br(first)($\times 10^{-7}$)	Br(final)($\times 10^{-7}$)	Representation
$p\pi^-$	0.007×10^{-7}	0.007	Bq Vcd Vub - Eq Vcd Vub
pK^-	0.2×10^{-7}	0.2	-(Eq Vcs Vub)
$(p\pi^-)(\pi^+\pi^-)$	0.03×10^{-7}	0.03	-(Bq Vcd Vub) + 2 Eq Vcd Vub
$(p\pi^-)(K^-\pi^+)$	0.2×10^{-7}	0.2	-(Eq Vcs Vub)
$(p\pi^-)D^0$	$2. \times 10^{-7}$	0.07	Eq Vcb Vcd + Cbm Vub Vud
$(p\pi^-)J/\Psi$	0.009×10^{-7}	0.0005	Cbm Vcd Vub
$(p\pi^-\pi^-)\pi^+$	0.01×10^{-7}	0.01	Eq Vcd Vub
$(p\pi^-\pi^-)(D^+/D^0\pi^+)$	$1. \times 10^{-7}$	0.03	Eq Vcb Vcd
$(pK^-\pi^+/\Sigma^+)\pi^-$	0.009×10^{-7}	0.009	Bq Vcs Vub
$(pK^-/\Lambda)(\pi^+\pi^-)$	0.1×10^{-7}	0.1	-(Bq Vcs Vub) + Eq Vcs Vub
$(pK^-/\Lambda)(K^+\pi^-)$	0.006×10^{-7}	0.006	Bq Vcd Vub - Eq Vcd Vub
$(pK^-/\Lambda)(K^+K^-)$	0.2×10^{-7}	0.2	-(Eq Vcs Vub)
$(pK^-/\Lambda)D^0$	$20. \times 10^{-7}$	0.7	Eq Vcb Vcs + Cbm Vub Vus
$(pK^-/\Lambda)J/\Psi$	0.2×10^{-7}	0.009	Cbm Vcs Vub
$(pK^-\pi^-/\Sigma^-)\pi^+$	0.2×10^{-7}	0.2	Eq Vcs Vub
$(pK^-\pi^-/\Sigma^-)K^+$	0.01×10^{-7}	0.01	Eq Vcd Vub
$(pK^-\pi^-/\Sigma^-)(D^+/D^0\pi^+)$	$20. \times 10^{-7}$	0.7	Eq Vcb Vcs
$(pK^-\pi^-/\Sigma^-)(D_s^+/D^0K^+)$	$1. \times 10^{-7}$	0.03	Eq Vcb Vcd
$(pK^-\pi^+K^-/\Xi^0)(K^+\pi^-)$	0.009×10^{-7}	0.009	Bq Vcs Vub
$(pK^-K^-/\Xi^-)K^+$	0.2×10^{-7}	0.2	Eq Vcs Vub
$(pK^-K^-/\Xi^-)(D_s^+/D^0K^+)$	$20. \times 10^{-7}$	0.6	Eq Vcb Vcs
$\Lambda_c^+\pi^-$	$10. \times 10^{-7}$	0.6	Bq Vcb Vcd - Eq Vcb Vcd + Cbb Vub Vud + Tb Vub Vud
$\Lambda_c^+K^-$	$30. \times 10^{-7}$	1.	-(Eq Vcb Vcs) + Tb Vub Vus
$(\Lambda_c^+\pi^-)(K^-\pi^+)$	$20. \times 10^{-7}$	1.	-(Eq Vcb Vcs)
$(\Lambda_c^+\pi^+K^-/\Xi_c^+)\pi^-$	$1. \times 10^{-7}$	0.06	Bq Vcb Vcs + Cbb Vub Vus
$(\Lambda_c^+K^-/\Xi_c^0)(K^+\pi^-)$	0.6×10^{-7}	0.03	Bq Vcb Vcd - Eq Vcb Vcd
$(\Lambda_c^+K^-/\Xi_c^0)(K^+K^-)$	$20. \times 10^{-7}$	1.	-(Eq Vcb Vcs)
$(\Lambda_c^+\pi^+K^-K^-/\Omega_c^0)(K^+\pi^-)$	0.9×10^{-7}	0.05	Bq Vcb Vcs

Non-leptonic *c*-decays of Ξ_{bc}^0

Modes	Br(first)	Br(final)($\times 10^{-7}$)	Representation
$(\Lambda_b^0\pi^+)\pi^-$	0.6×10^{-3}	0.6	Eb Vcd Vud
$(\Lambda_b^0\pi^+)K^-$	$10. \times 10^{-3}$	10.	Eb Vcs Vud
$\Lambda_b^0(\pi^+\pi^-)$	$10. \times 10^{-3}$	10.	-(Ccb Vcd Vud) - Cct Vcd Vud - 2 Eb Vcd Vud
$\Lambda_b^0(K^+\pi^-)$	0.1×10^{-3}	0.1	Ccb Vcd Vus + Cct Vcd Vus
$\Lambda_b^0(K^-\pi^+)$	$40. \times 10^{-3}$	40.	Cct Vcs Vud + Eb Vcs Vud
$\Lambda_b^0(K^+K^-)$	0.3×10^{-3}	0.3	Cct Vcs Vus
$(\Lambda_b^0\pi^-)\pi^+$	$2. \times 10^{-3}$	2.	-(Eb Vcd Vud) + Tc Vcd Vud
$(\Lambda_b^0\pi^-)K^+$	0.03×10^{-3}	0.03	Tc Vcd Vus
$(\Lambda_b^0\pi^+K^-/\Xi_b^0)(\pi^+\pi^-)$	$40. \times 10^{-3}$	40.	-(Ccb Vcs Vud) - Eb Vcs Vud
$(\Lambda_b^0\pi^+K^-/\Xi_b^0)(K^+\pi^-)$	$2. \times 10^{-3}$	2.	Eb Vcd Vud + Ccb Vcs Vus
$(\Lambda_b^0\pi^+K^-/\Xi_b^0)(K^+K^-)$	$3. \times 10^{-3}$	3.	Eb Vcs Vud
$(\Lambda_b^0K^-/\Xi_b^-)\pi^+$	$40. \times 10^{-3}$	40.	-(Eb Vcs Vud) + Tc Vcs Vud
$(\Lambda_b^0K^-/\Xi_b^-)K^+$	$2. \times 10^{-3}$	2.	-(Eb Vcd Vud) + Tc Vcs Vus
$(\Lambda_b^0\pi^+K^-K^-/\Omega_b^-)K^+$	$6. \times 10^{-3}$	6.	-(Eb Vcs Vud)
pB^-	$1. \times 10^{-3}$	1.	Bb Vcd Vud
$(p\pi^-)\bar{B}^0$	$3. \times 10^{-3}$	3.	Bb Vcd Vud + Ccm Vcd Vud
$(p\pi^-)\bar{B}_s^0$	0.03×10^{-3}	0.03	Ccm Vcd Vus
$(pK^-\pi^+/\Sigma^+)B^-$	$8. \times 10^{-3}$	8.	Bb Vcs Vud
$(pK^-/\Lambda)\bar{B}_s^0$	$1. \times 10^{-3}$	1.	Bb Vcd Vud + Ccm Vcs Vus
$(pK^-\pi^+K^-/\Xi^0)\bar{B}_s^0$	$6. \times 10^{-3}$	6.	Bb Vcs Vud
$(pK^-/\Lambda)\bar{B}^0$	$30. \times 10^{-3}$	30.	Bb Vcs Vud + Ccm Vcs Vud

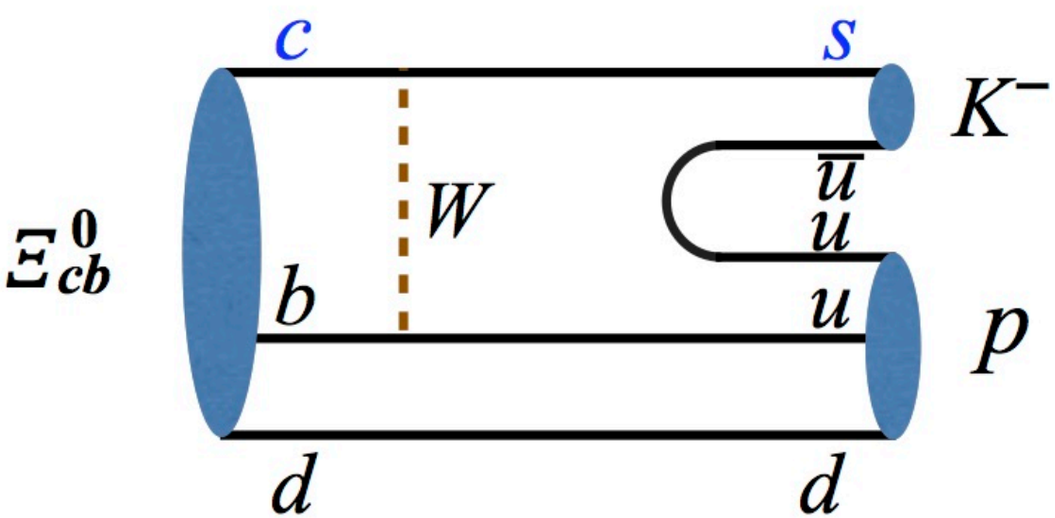
Non-leptonic *b*-decays of Ω_{bc}^0

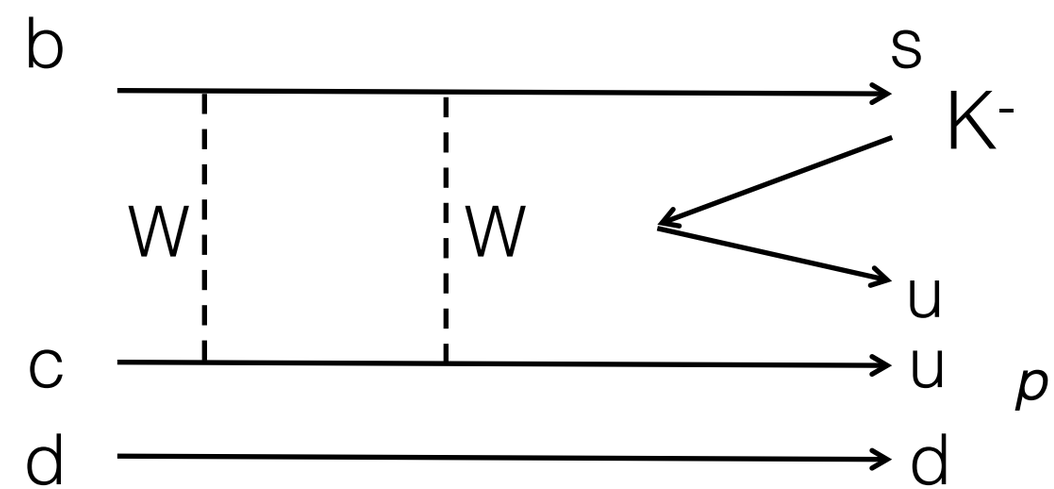
Modes	Br(first)($\times 10^{-7}$)	Br(final)($\times 10^{-7}$)	Representation
pK^-	0.001×10^{-7}	0.001	Bq Vcd Vub
$(p\pi^-)(K^-\pi^+)$	0.001×10^{-7}	0.001	Bq Vcd Vub
$(pK^-\pi^+/\Sigma^+)\pi^-$	0.02×10^{-7}	0.02	-(Eq Vcd Vub)
$(pK^-\pi^+/\Sigma^+)K^-$	0.3×10^{-7}	0.3	Bq Vcs Vub - Eq Vcs Vub
$(pK^-/\Lambda)(\pi^+\pi^-)$	0.09×10^{-7}	0.09	2 Eq Vcd Vub
$(pK^-/\Lambda)(K^-\pi^+)$	0.3×10^{-7}	0.3	Bq Vcs Vub - Eq Vcs Vub
$(pK^-/\Lambda)(K^+K^-)$	0.001×10^{-7}	0.001	Bq Vcd Vub
$(pK^-/\Lambda)D^0$	$5. \times 10^{-7}$	0.2	Eq Vcb Vcd + Cbm Vub Vud
$(pK^-/\Lambda)J/\Psi$	0.02×10^{-7}	0.001	Cbm Vcd Vub
$(pK^-\pi^-/\Sigma^-)\pi^+$	0.02×10^{-7}	0.02	Eq Vcd Vub
$(pK^-\pi^-/\Sigma^-)(D^+/D^0\pi^+)$	$2. \times 10^{-7}$	0.07	Eq Vcb Vcd
$(pK^-\pi^+K^-/\Xi^0)(\pi^+\pi^-)$	0.4×10^{-7}	0.4	Eq Vcs Vub
$(pK^-\pi^+K^-/\Xi^0)(K^+\pi^-)$	0.02×10^{-7}	0.02	-(Eq Vcd Vub)
$(pK^-\pi^+K^-/\Xi^0)(K^+K^-)$	0.3×10^{-7}	0.3	Bq Vcs Vub - Eq Vcs Vub
$(pK^-\pi^+K^-/\Xi^0)D^0$	$50. \times 10^{-7}$	2.	Eq Vcb Vcs + Cbm Vub Vus
$(pK^-\pi^+K^-/\Xi^0)J/\Psi$	0.4×10^{-7}	0.02	Cbm Vcs Vub
$(pK^-K^-/\Xi^-)\pi^+$	0.4×10^{-7}	0.4	Eq Vcs Vub
$(pK^-K^-/\Xi^-)K^+$	0.02×10^{-7}	0.02	Eq Vcd Vub
$(pK^-K^-/\Xi^-)(D^+/D^0\pi^+)$	$50. \times 10^{-7}$	1.	Eq Vcb Vcs
$(pK^-K^-/\Xi^-)(D_s^+/D^0K^+)$	$2. \times 10^{-7}$	0.07	Eq Vcb Vcd
Ω^-K^+	0.4×10^{-7}	0.4	Eq Vcs Vub
$\Omega^-(D_s^+/D^0K^+)$	$50. \times 10^{-7}$	1.	Eq Vcb Vcs
$\Lambda_c^+K^-$	$1. \times 10^{-7}$	0.05	Bq Vcb Vcd + Cbb Vub Vud
$(\Lambda_c^+\pi^-)(K^-\pi^+)$	0.1×10^{-7}	0.006	Bq Vcb Vcd
$(\Lambda_c^+\pi^+K^-/\Xi_c^+)\pi^-$	$20. \times 10^{-7}$	1.	-(Eq Vcb Vcd) + Tb Vub Vud
$(\Lambda_c^+\pi^+K^-/\Xi_c^+)K^-$	$40. \times 10^{-7}$	2.	Bq Vcb Vcs - Eq Vcb Vcs + Cbb Vub Vus + Tb Vub Vus
$(\Lambda_c^+K^-/\Xi_c^0)(K^-\pi^+)$	$30. \times 10^{-7}$	1.	Bq Vcb Vcs - Eq Vcb Vcs
$(\Lambda_c^+K^-/\Xi_c^0)(K^+K^-)$	0.1×10^{-7}	0.005	Bq Vcb Vcd
$(\Lambda_c^+\pi^+K^-K^-/\Omega_c^0)(K^+\pi^-)$	$2. \times 10^{-7}$	0.1	-(Eq Vcb Vcd)
$(\Lambda_c^+\pi^+K^-K^-/\Omega_c^0)(K^+K^-)$	$30. \times 10^{-7}$	1.	Bq Vcb Vcs - Eq Vcb Vcs

Non-leptonic *c*-decays of Ω_{bc}^0

Modes	Br(first)	Br(final)($\times 10^{-7}$)	Representation
$(\Lambda_b^0\pi^+)\pi^-$	0.07×10^{-3}	0.07	Eb Vcd Vus
$(\Lambda_b^0\pi^+)K^-$	$1. \times 10^{-3}$	1.	Eb Vcs Vus
$\Lambda_b^0(\pi^+\pi^-)$	0.3×10^{-3}	0.3	-2 Eb Vcd Vus
$\Lambda_b^0(K^-\pi^+)$	$5. \times 10^{-3}$	5.	Ccb Vcd Vud + Eb Vcs Vus
$\Lambda_b^0(K^+K^-)$	0.04×10^{-3}	0.04	Ccb Vcd Vus
$(\Lambda_b^0\pi^-)\pi^+$	0.07×10^{-3}	0.07	-(Eb Vcd Vus)
$(\Lambda_b^0\pi^+K^-/\Xi_b^0)(\pi^+\pi^-)$	$5. \times 10^{-3}$	5.	-(Cct Vcd Vud) - Eb Vcs Vus
$(\Lambda_b^0\pi^+K^-/\Xi_b^0)(K^+\pi^-)$	0.2×10^{-3}	0.2	Cct Vcd Vus + Eb Vcd Vus
$(\Lambda_b^0\pi^+K^-/\Xi_b^0)(K^-\pi^+)$	$80. \times 10^{-3}$	80.	Ccb Vcs Vud + Cct Vcs Vud
$(\Lambda_b^0\pi^+K^-/\Xi_b^0)(K^+K^-)$	$4. \times 10^{-3}$	4.	Ccb Vcs Vus + Cct Vcs Vus + Eb Vcs Vus
$(\Lambda_b^0K^-/\Xi_b^-)\pi^+$	$5. \times 10^{-3}$	5.	Tc Vcd Vud - Eb Vcs Vus
$(\Lambda_b^0K^-/\Xi_b^-)K^+$	0.2×10^{-3}	0.2	-(Eb Vcd Vus) + Tc Vcd Vus
$(\Lambda_b^0\pi^+K^-K^-/\Omega_b^-)\pi^+$	$20. \times 10^{-3}$	20.	Tc Vcs Vud
$(\Lambda_b^0\pi^+K^-K^-/\Omega_b^-)K^+$	$3. \times 10^{-3}$	3.	-(Eb Vcs Vus) + Tc Vcs Vus
pB^-	0.2×10^{-3}	0.2	Bb Vcd Vus
$(p\pi^-)\bar{B}^0$	0.1×10^{-3}	0.1	Bb Vcd Vus
$(pK^-\pi^+/\Sigma^+)B^-$	$1. \times 10^{-3}$	1.	Bb Vcs Vus
$(pK^-/\Lambda)\bar{B}^0$	$5. \times 10^{-3}$	5.	Ccm Vcd Vud + Bb Vcs Vus
$(pK^-/\Lambda)\bar{B}_s^0$	0.2×10^{-3}	0.2	Bb Vcd Vus + Ccm Vcd Vus
$(pK^-\pi^+K^-/\Xi^0)\bar{B}^0$	$30. \times 10^{-3}$	30.	Ccm Vcs Vud
$(pK^-\pi^+K^-/\Xi^0)\bar{B}_s^0$	$4. \times 10^{-3}$	4.	Bb Vcs Vus + Ccm Vcs Vus

Example of Two body decays



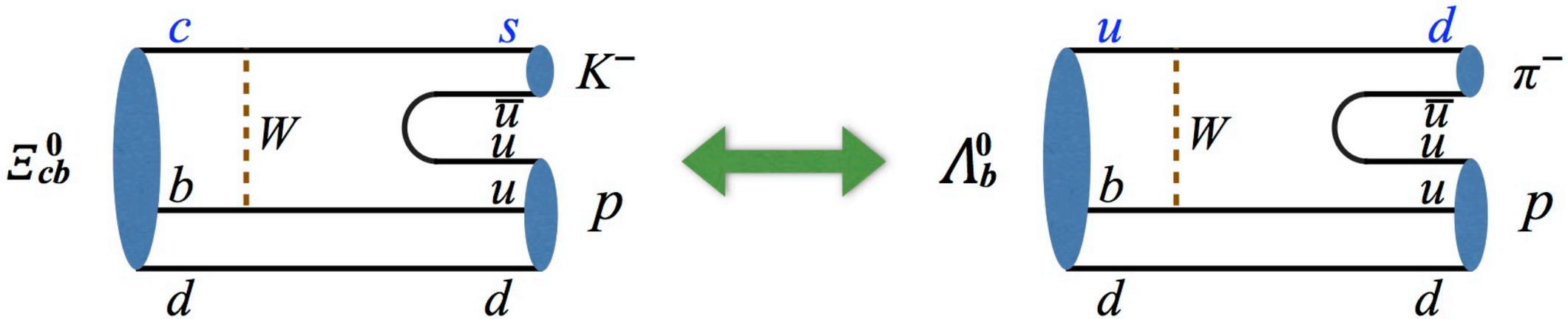


Vcs Vud CKM
enhanced
large

G_F^2
suppressed
negligible

Charged final states, easy to measure, but theoretically difficult to calculate

Cross Check via Similarity
W-exchange diagram



- pure W-exchange process
- possible discovery channel

- Calculated by PQCD

[C.D.Lu, Y.M. Wang, H. Zou, Ali, Kramer, 09']

They are the same at the leading order

$m_c/m_b << 1$ $m_u/m_b << 1$

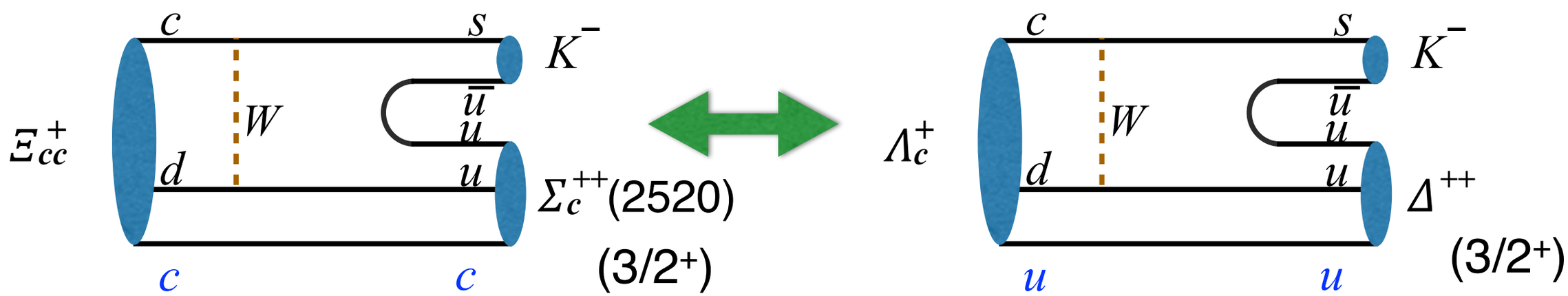
$\mathcal{R}_f \equiv f_{\Xi_{bc}}/f_{\Lambda_b}$ ~1

$\mathcal{R}_\tau = \tau_{\Xi_{bc}}/\tau_{\Lambda_b}$ ~0.1

$$\mathcal{BR}(\Xi_{bc}^0 \to p^+K^-) = 3.38 \times \mathcal{R}_f^2 \times \mathcal{R}_\tau \times 10^{-7} \sim 10^{-8}$$

[Li, Lu, Wang, **Yu**, Zou, PLB767,232(2017), 1701.03284]

W-exchange via similarity



- pure W-exchange process
- possible discovery channel

$\Xi_{cc}^+ \to (\Lambda_c^+ \pi^+) K^-$ $\boxed{c \text{ v.s. } u}$

- pure W-exchange process
- measured [PDG]

$$Br(\Lambda_c^+ \to \Delta^{++} K^-) = (1.09 \pm 0.25)\%$$

Experimentally, $\Sigma_c^{++}(2520)$ is found to decay into $\Lambda_c^+\pi^+$ with branching ratio 100%.

$$\mathcal{BR}(\Xi_{cc}^+ \to \Sigma_c^{++}(2520) K^-) \approx \mathcal{BR}(\Lambda_c^+ \to \Delta^{++} K^-) \times 0.66 \times 4 \times \frac{1}{2} \times \frac{\tau_{\Xi_{cc}}}{\tau_{\Lambda_c}} \in [0.36\%, 1.80\%]$$

[Li, Lu, Wang, **Yu**, Zou, PLB767,232(2017), 1701.03284]

Summary

- We estimate the branching fractions of many channels of doubly heavy baryon weak decays
- We suggest to measure the following processes with the largest possibilities to be observed.

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

- $$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$$
  $$\Xi_{cc}^{++} \to p D^+$$
- Ξ_{cc} has been discovered by LHCb, through the first channel

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

- Also predict branching fraction of $\Xi_c^+ \to p K^- \pi^+$

Thank you !