FPCP 2021

Lifetimes and non-leptonic decays of charmed baryons

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Lifetimes

- ❑ Singly charmed baryons
- ❑ Doubly charmed baryons
- ❑ Charm-bottom baryons

Evolution of lifetimes

PDG 2018

	10^{-13}s
Ξ_c^+	4.42 ± 0.26
Λ_c^+	2.00 ± 0.06
Ξ_c^0	$1.12^{+0.13}_{-0.10}$
Ω_c^0	0.69 ± 0.12

PDG 2020

	10^{-13}s	
Ξ_c^+	4.56 ± 0.05	
Λ_c^+	2.024 ± 0.031	
Ξ_c^0	1.53 ± 0.06	LHCb, 2019
Ω_c^0	2.68 ± 0.26	LHCb, 2018

How to understand

the dramatic change of lifetimes?

$$\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+)$$

$$\tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+)$$

$$\tau_{\Omega_c^0} = 276.5 \pm 13.4 \pm 4.4 \pm 0.7 \text{ fs (preliminary)}$$

$$\tau_{\Xi_c^0} = 148.0 \pm 2.3 \pm 2.2 \pm 0.2 \text{ fs (preliminary)}$$

LHCb, 2021

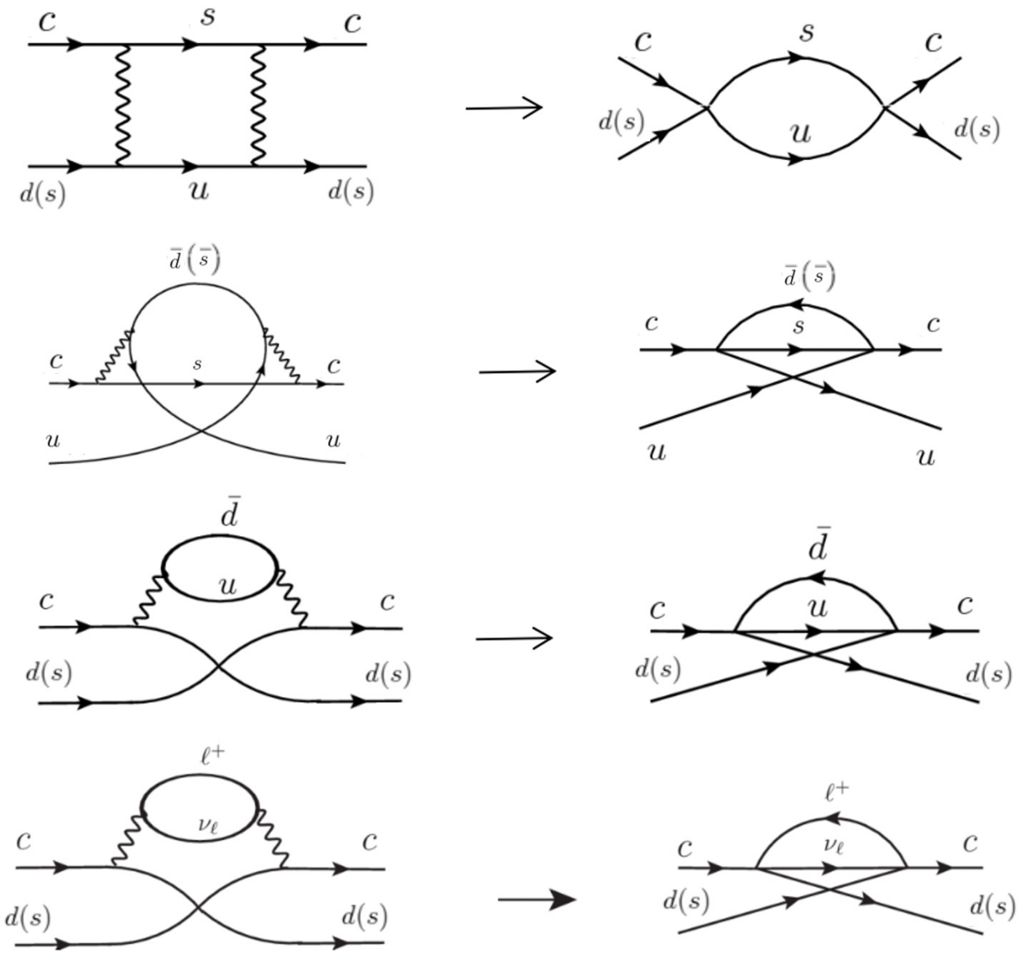
Theory: Heavy Quark Expansion

$$\Gamma(H_Q \to f) = \frac{G_F^2 m_Q^5}{192\pi^3}|V_{\mathrm{CKM}}|^2 \left(A_0 + \frac{A_2}{m_Q^2} + \frac{A_3}{m_Q^3} + \ldots\right)$$
$$= \frac{G_F^2 m_Q^5}{192\pi^3}|V_{\mathrm{CKM}}|^2 \left[c_{3,Q}\frac{\langle H_Q|\bar{Q}Q|H_Q\rangle}{2m_{H_Q}} + \frac{c_{5,Q}}{m_Q^2}\frac{\langle H_Q|\bar{Q}\sigma\cdot GQ|H_Q\rangle}{2m_{H_Q}} + \frac{c_{6,Q}}{m_Q^3}\frac{\langle H_Q|T_6|H_Q\rangle}{2m_{H_Q}}\right]$$

- ❑ A_0 term: decay of heavy quark
  In the limit of $m_Q \to \infty$, all heavy hadrons have identical lifetimes.
- ❑ Luke's theorem → lack of $1/m_Q$ corrections.
- ❑ A_2 term: interaction of heavy quark spin and gluon
- ❑ A_3 term: dim-6 four-quark operators inducing spectator effects responsible for lifetime differences.
- ❑ HQE in $1/m_Q$ expansion up to $1/m_Q^3$ works very well for B mesons and bottom baryons.

Spectator effects: dim-6 operators

$$\Gamma = \Gamma^{\text{dec}} + \Gamma^{\text{ann}} + \Gamma^{\text{int}} + \Gamma^{\text{semi}}$$



Γ^{ann} W-exchange
(or weak annihilation)

Γ^{int}_{-} Destructive P. I.,
(Pauli interference)

Γ^{int}_{+} Constructive P. I.

Γ^{semi} Additional constructive P. I.

	Dec	Ann	Int (-)	Int (+)	Semi	τ (10^{-13}s)	Expt (10^{-13}s)
Ξ_c^+	1	s^2	1	c^2	small P.I.	3.06	4.42 ± 0.26
Λ_c^+	1	c^2	1	s^2	no P.I.	2.91	2.00 ± 0.06
Ξ_c^0	1	1		c^2	small P.I.	1.62	$1.12^{+0.13}_{-0.10}$
Ω_c^0	1	$6s^2$		$10/3\ c^2$	large P.I.	1.06	0.69 ± 0.12

$s=\sin\theta_C$, $c=\cos\theta_C$

- Lifetime hierarchy (PDG 2018): $\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+)$
- It is difficult to explain

$$\frac{\tau(\Xi_c^+)}{\tau(\Lambda_c^+)} = 2.21 \pm 0.15 \qquad \frac{\tau(\Xi_c^+)}{\tau(\Xi_c^0)} = 3.95 \pm 0.47$$

- Ω_c has the shortest lifetime as it receives a large contribution from constructive Pauli interference.
- $1/m_c$ expansion not well convergent and sensible

Incorporating dim-7 operators

$$\Gamma(H_Q \to f) = \frac{G_F^2 m_Q^5}{192\pi^3}|V_{\rm CKM}|^2 \left(A_0 + \frac{A_2}{m_Q^2} + \frac{A_3}{m_Q^3} + \frac{A_4}{m_Q^4} + \ldots \right)$$

- Consider subleading $1/m_c$ corrections to spectator effects

$$P_1^q = \frac{m_q}{m_Q}\bar{Q}(1-\gamma_5)q\bar{q}(1-\gamma_5)Q, \qquad P_2^q = \frac{m_q}{m_Q}\bar{Q}(1+\gamma_5)q\bar{q}(1+\gamma_5)Q,$$

$$P_3^q = \frac{1}{m_Q^2}\bar{Q}\overleftarrow{D}_\rho\gamma_\mu(1-\gamma_5)D^\rho q\bar{q}\gamma^\mu(1-\gamma_5)Q, \qquad P_4^q = \frac{1}{m_Q^2}\bar{Q}\overleftarrow{D}_\rho(1-\gamma_5)D^\rho q\bar{q}(1+\gamma_5)Q$$

$$P_5^q = \frac{1}{m_Q}\bar{Q}\gamma_\mu(1-\gamma_5)q\bar{q}\gamma^\mu(1-\gamma_5)(i\not{D})Q, \qquad P_6^q = \frac{1}{m_Q}\bar{Q}(1-\gamma_5)q\bar{q}(1+\gamma_5)(i\not{D})Q,$$

Beneke, Buchalla, Dunietz ('96): width difference in B_s-$\underline{B}_s$ system
Gabbiani, Onishchenko, Petrov ('03,'04): lifetime difference of heavy hadrons
Lenz, Rauh ('13): D meson lifetimes

Charmed baryon lifetimes

- to $1/m_c^3$

	$\Gamma^{\rm dec}$	$\Gamma^{\rm ann}$	$\Gamma^{\rm int}_-$	$\Gamma^{\rm int}_+$	$\Gamma^{\rm semi}$	$\Gamma^{\rm tot}$	$\tau(10^{-13}s)$	$\tau_{\rm expt}(10^{-13}s)$
Λ_c^+	0.886	1.479	−0.400	0.042	0.215	2.221	2.96	2.00 ± 0.06
Ξ_c^+	0.886	0.085	−0.431	0.882	0.726	2.148	3.06	4.42 ± 0.26
Ξ_c^0	0.886	1.591		0.882	0.726	4.084	1.61	$1.12^{+0.13}_{-0.10}$
Ω_c^0	1.019	0.515		2.974	1.901	6.409	1.03	0.69 ± 0.12

- to $1/m_c^4$

	$\Gamma^{\rm dec}$	$\Gamma^{\rm ann}$	$\Gamma^{\rm int}_-$	$\Gamma^{\rm int}_+$	$\Gamma^{\rm semi}$	$\Gamma^{\rm tot}$	$\tau(10^{-13}s)$	$\tau_{\rm expt}(10^{-13}s)$
Λ_c^+	0.886	2.179	−0.211	0.022	0.215	3.091	2.12	2.00 ± 0.06
Ξ_c^+	0.886	0.133	−0.186	0.407	0.437	1.677	3.92	4.42 ± 0.26
Ξ_c^0	0.886	2.501		0.405	0.435	4.228	1.56	$1.12^{+0.13}_{-0.10}$
Ω_c^0	1.019	0.876		−0.559	−0.256	1.079	6.10	0.69 ± 0.12

- Right trend: $\Gamma(\Lambda_c^+)$ enhanced, $\Gamma(\Xi_c^+)$ suppressed

$$\frac{\tau(\Xi_c^+)}{\tau(\Lambda_c^+)} : \ 1.03 \ \rightarrow 1.84$$

- Lifetime of Ω_c: shortest ➡ longest

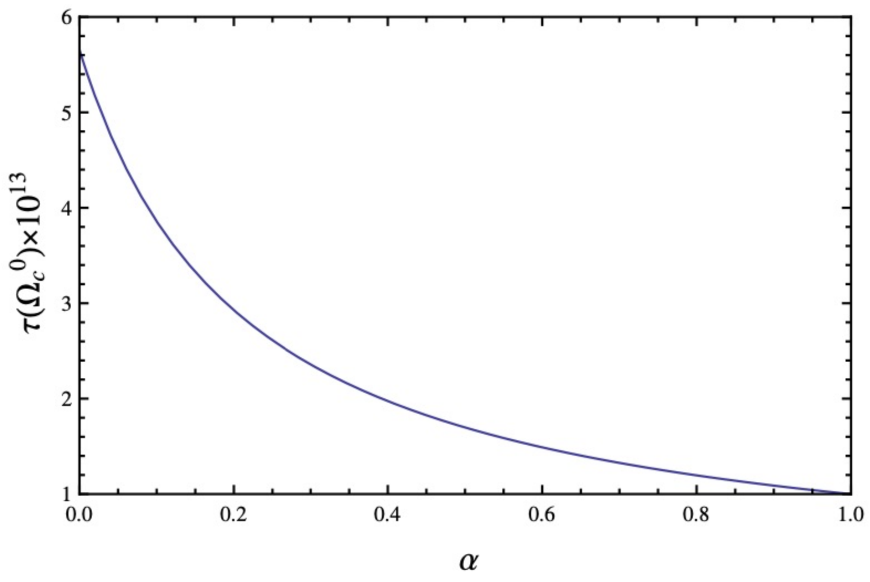
Ω_c^0	$\Gamma^{\rm dec}$	$\Gamma^{\rm ann}$	$\Gamma_-^{\rm int}$	$\Gamma_+^{\rm int}$	$\Gamma^{\rm semi}$	$\Gamma^{\rm tot}$	$\tau(10^{-13}s)$
$1/m_c^3$	1.019	0.515		2.974	1.901	6.409	1.03
$1/m_c^4$	1.019	0.876		−0.559	−0.256	1.079	6.10

- Destructive contributions from $\Gamma_7^{\rm int}$ & $\Gamma_7^{\rm semi}$ are too large to justify the validity of HQE

$$\Gamma_+^{\rm int} = \Gamma_{+,6}^{\rm int} + \Gamma_{+,7}^{\rm int}$$
$$\Gamma^{\rm semi} = \Gamma_6^{\rm semi} + \Gamma_7^{\rm semi}$$

prescription →

$$\Gamma_+^{\rm int} = \Gamma_{+,6}^{\rm int} + (1-\alpha)\Gamma_{+,7}^{\rm int}$$
$$\Gamma^{\rm semi} = \Gamma_6^{\rm semi} + (1-\alpha)\Gamma_7^{\rm semi}$$



The guideline for introducing α:

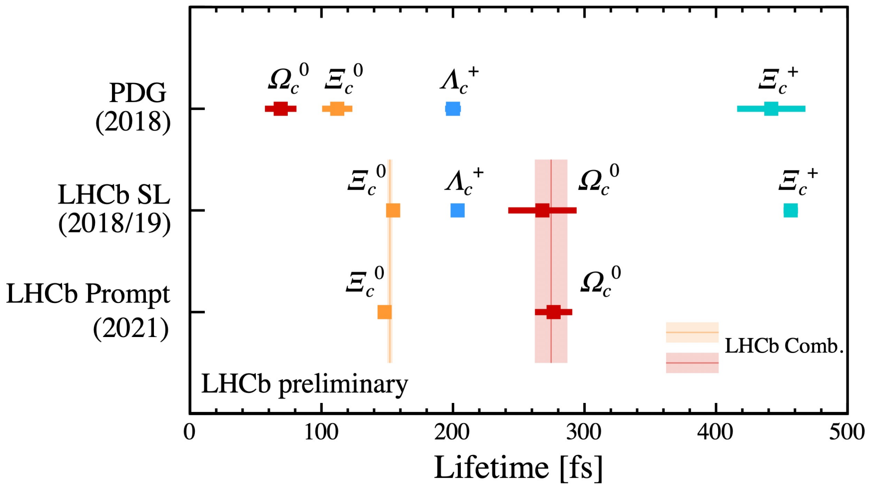
- positive $\Gamma_7^{\rm int}$ & $\Gamma_7^{\rm semi}$
- results close to that of Ξ_c^0

α	$\Gamma^{\rm dec}$	$\Gamma^{\rm ann}$	$\Gamma^{\rm int}_{+}$	$\Gamma^{\rm semi}$	$\Gamma^{\rm tot}$	$\tau(10^{-13}s)$
0	1.019	0.876	−0.559	−0.256	1.079	6.10
0.12	1.019	0.876	−0.135	0.003	1.762	3.73
0.16	1.019	0.876	0.006	0.089	1.990	3.31
0.22	1.019	0.876	0.218	0.219	2.331	2.82
0.32	1.019	0.876	0.571	0.435	2.900	2.27
1	1.019	0.876	2.974	1.901	6.770	0.97

Conjecture $0.16 < \alpha < 0.32$

$$2.3 \times 10^{-13}s < \tau(\Omega_c^0) < 3.3 \times 10^{-13}s$$

$$\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$$



Mon 07/06 | Tue 08/06 | **Wed 09/06** | Thu 10/06 | Fri 11/06 | All days

11:15 New charm results from LHCb

Presenter(s): Chen CHEN *(Tsinghua University)*
Room: 东方绿舟宾馆合欢厅
Location: Shanghai

	PDG(2018)	LHCb	Theory($1/m_c^3$)	Theory($1/m_c^4$)
Ξ_c^+	4.42±0.26	4.568±0.055	2.91	3.92
Λ_c^+	2.00±0.06	2.035±0.022	3.06	2.12
Ξ_c^0	$1.12^{+0.13}_{-0.10}$	1.545±0.025	1.62	1.56
Ω_c^0	0.69±0.12	2.68±0.26	1.06	2.3 ~ 3.3

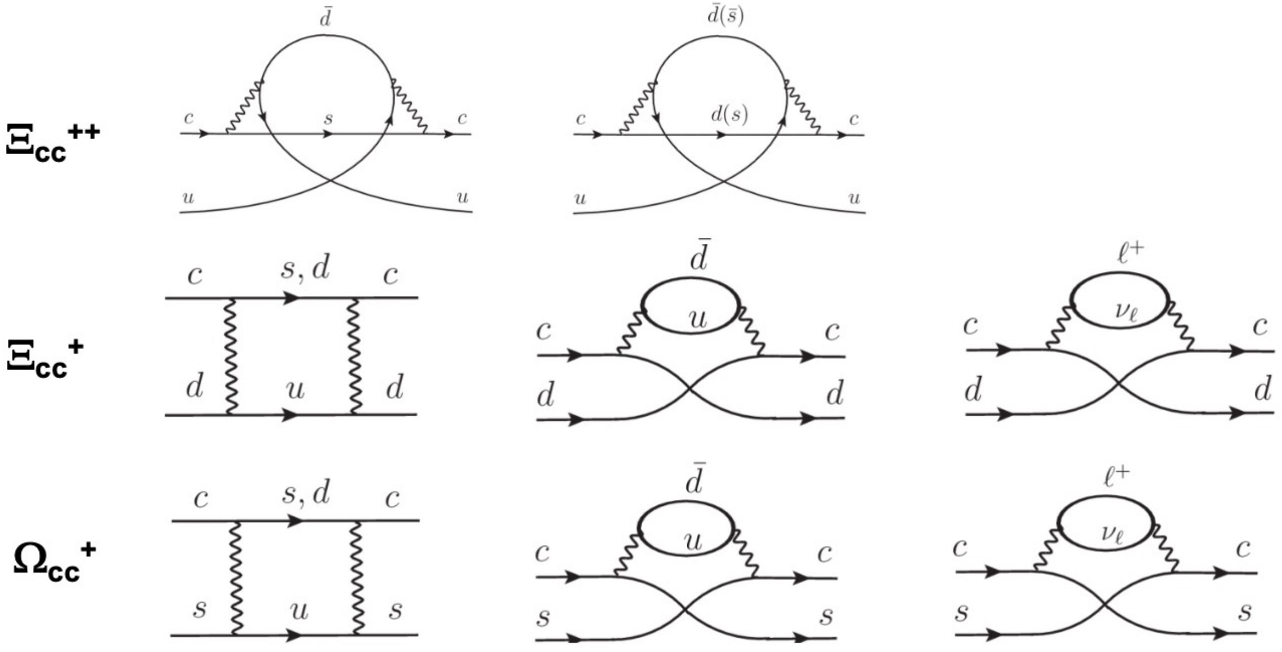
$$\mathcal{O}(1/m_c^3) \Rightarrow \tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0),$$

$$\mathcal{O}(1/m_c^4) \Rightarrow \tau(\Omega_c^0) > \tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$$

$$\mathcal{O}(1/m_c^4) \text{ with } \alpha \Rightarrow \tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$$

Lifetimes of doubly charmed baryons

	Dec	Ann	Int(-)	Int(+)	Semi	$\tau(10^{-13}$ s)
Ξ_{cc}^{++}	1		1		1	1.9~15.5
Ξ_{cc}^{+}	1	1		s^2	1 + s^2 P.I.	0.5~ 2.5
Ω_{cc}^{+}	1	s^2		1	1 + c^2 P.I.	2.1~ 2.8



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

Lifetimes of doubly charmed baryons

❑ to $1/m_c^3$

	$\Gamma^{\rm dec}$	$\Gamma^{\rm ann}$	$\Gamma^{\rm int}_-$	$\Gamma^{\rm int}_+$	$\Gamma^{\rm semi}$	$\Gamma^{\rm tot}$	$\tau(10^{-13}\ {\rm s})$	$\tau_{\rm expt}(10^{-13}\ {\rm s})$
Ξ_{cc}^{++}	2.198		-1.383		0.450	1.265	5.20	$2.56^{+0.28}_{-0.26}$
Ξ_{cc}^{+}	2.198	8.628		0.123	0.525	11.475	0.57	
Ω_{cc}^{+}	2.148	0.611		3.217	2.445	8.421	0.78	

$$\Gamma^{\rm ann} \gg \Gamma^{\rm int}_+ \;\Rightarrow\; \tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^{+}) > \tau(\Xi_{cc}^{+})$$

$$\Gamma^{\rm semi}(\Omega_{cc}^{+}) \gg \Gamma^{\rm semi}(\Xi_{cc}^{+}) > \Gamma^{\rm semi}(\Xi_{cc}^{++})$$

❑ to $1/m_c^4$

	$\Gamma^{\rm dec}$	$\Gamma^{\rm ann}$	$\Gamma^{\rm int}_-$	$\Gamma^{\rm int}_+$	$\Gamma^{\rm semi}$	$\Gamma^{\rm tot}$	$\tau(10^{-13}\ {\rm s})$	$\tau_{\rm expt}(10^{-13}\ {\rm s})$
Ξ_{cc}^{++}	2.198		-0.437		0.451	2.212	2.98	$2.56^{+0.28}_{-0.26}$
Ξ_{cc}^{+}	2.198	12.260		0.030	0.469	14.958	0.44	
Ω_{cc}^{+}	2.148	0.979		-0.246	0.318	3.200	2.06	

- $\tau(\Xi_{cc}^{++})$ becomes shorter, while $\tau(\Omega_{cc}^{+})$ becomes longer
- The use of HQE for constructive P.I. & semileptonic contribution is not valid

$$\Gamma_{+}^{\text{int}} = \Gamma_{+,6}^{\text{int}} + \Gamma_{+,7}^{\text{int}}$$
$$\Gamma^{\text{semi}} = \Gamma_{6}^{\text{semi}} + \Gamma_{7}^{\text{semi}}$$

prescription

$$\Gamma_{+}^{\text{int}} = \Gamma_{+,6}^{\text{int}} + (1-\alpha)\Gamma_{+,7}^{\text{int}}$$
$$\Gamma^{\text{semi}} = \Gamma_{6}^{\text{semi}} + (1-\alpha)\Gamma_{7}^{\text{semi}}$$

	α	Γ^{dec}	Γ^{ann}	Γ_{+}^{int}	Γ^{semi}	Γ^{tot}	$\tau(10^{-13}\ \text{s})$
Ω_{cc}^{+}	0	2.148	0.979	−0.246	0.318	3.200	2.06
	0.08	2.148	0.979	0.031	0.489	3.647	1.80
	0.30	2.148	0.979	0.792	0.956	4.876	1.35
	1	2.148	0.979	3.217	2.445	8.789	0.75

$$0.75 \times 10^{-13}\ \text{s} < \tau(\Omega_{cc}^{+}) < 1.80 \times 10^{-13}\ \text{s}$$

- Ξ_{cc}^{+}: insensitive to α (Cabibbo suppressed)

$$\tau(\Xi_{cc}^{++}) \sim 3.0 \times 10^{-13}\text{s} \qquad \tau(\Xi_{cc}^{+}) \sim 0.45 \times 10^{-13}\text{s}$$

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

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

LHCb ’18

Summary (I)

- HQE in $1/m_c$ fails to provide a satisfactory description of the lifetimes of charmed baryons to $O(1/m_c^3)$. Need to consider sub-leading $1/m_c$ corrections to spectator effects.

- Lifetime pattern of singly charmed baryon is dramatically changed in the presence of dim-7 effects: $\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$.

- For doubly charmed baryons, we found $\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^{+}) > \tau(\Xi_{cc}^{+})$ with $\tau(\Xi_{cc}^{++}) \sim 0.30$ ps, $\tau(\Xi_{cc}^{+}) \sim 0.05$ ps.

- The lifetime pattern of charm-bottom baryons are predicted as $\tau(\Xi_{bc}^{+}) > \tau(\Omega_{bc}^{0}) > \tau(\Xi_{bc}^{0})$.

Non-leptonic decays

- Antitriplet singly charmed baryons
- One sextet charmed baryon
- Doubly charmed baryons

Experimental progress

- BESIII
  - absolute branching ratio of $\Lambda_c^+ \to pK^-\pi^+$, 2016
  - observation of $\Lambda_c^+ \to nK_S^0\pi^+$, 2017
  - $\Lambda_c^+ \to p\pi^0$ and $\Lambda_c^+ \to p\pi^0$, 2017
  - absolute branching fraction for $\Lambda_c^+ \to \Xi^0 K^+$, 2018
  - decay asymmetries in $\Lambda_c \to PK_S, \Lambda\pi^+, \Sigma^+\pi^0, \Sigma^0\pi^+$, 2019
  - absolute branching fraction of inclusive decay $\Lambda_c^+ \to K_S^0 X$, 2020
  - absolute branching fraction for $\Lambda_c^+ \to pK_S^0\eta$, 2021
  - …
- Bell
  - Measurement of $\Xi_c^+ \to \Xi^-\pi^+\pi^+$, 2019
  - measurement of $\Xi_c^0 \to \Xi^-\pi^+$, 2019
  - asymmetry of $\Xi_c^0 \to \Xi^-\pi^+$, 2021
  - Branchng fractions of $\Lambda_c^+ \to p\eta$ and $\Lambda_c^+ \to p\pi^0$, 2021
  - …
- LHCb
  - Branching fraction of $\Lambda_c^+ \to p\,\pi^- K^+$, 2018
  - Observation of Ξ_{cc}^{++}, 2017
  - Observation of $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$,2018
  - Observation of $\Xi_c^+ \to p\phi$, 2019
  - Precision measurement of Ξ_{cc}^{++} mass, 2020
  - Search for Ξ_{cc}^+, 2020, 2021
  - Search for Ω_{cc}^+, 2021
  - …

Current situation

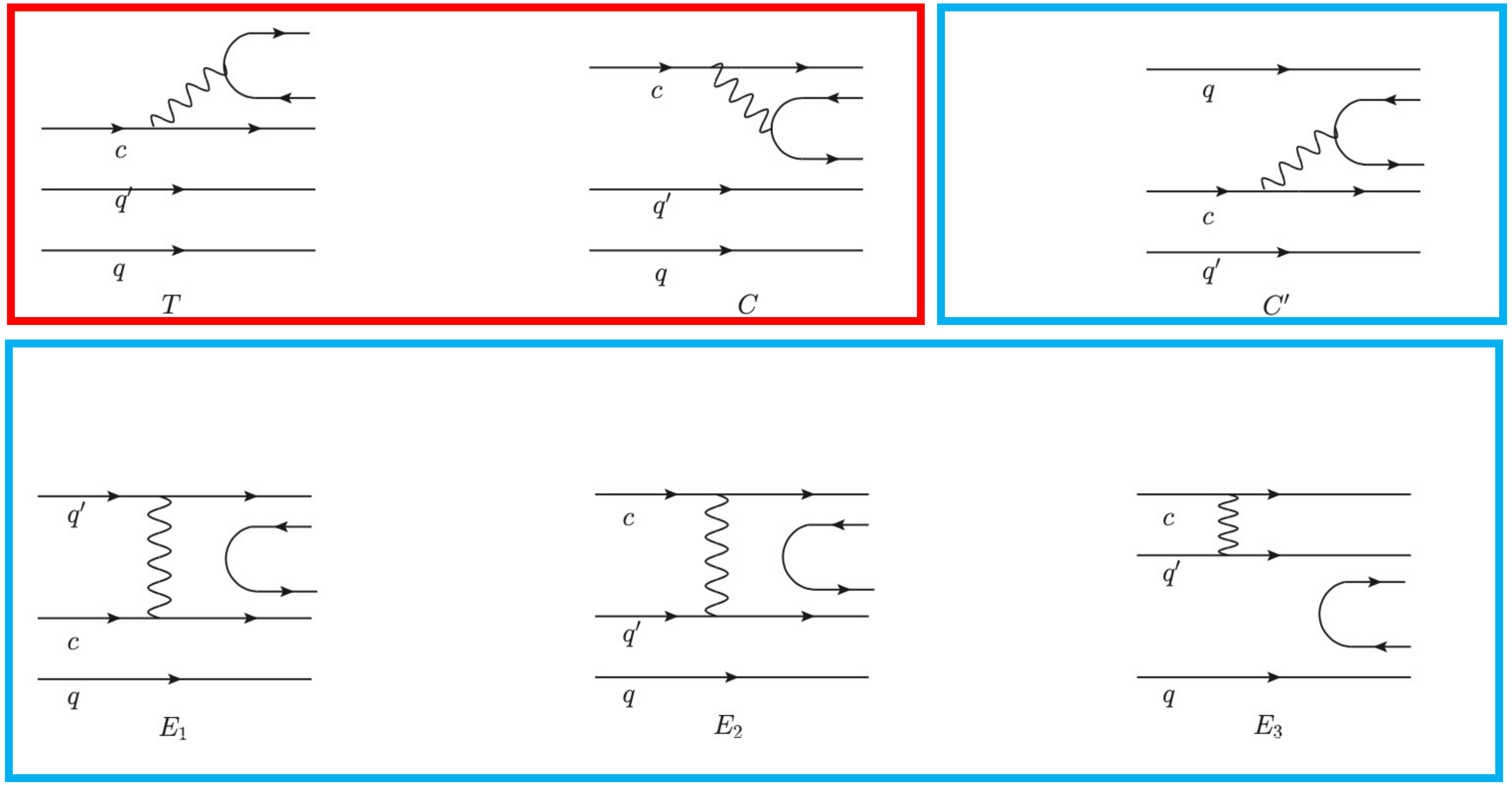
The situation we confront with:

- ❑ more and more modes of charmed baryon decays are being measured,
- ❑ explore the dynamics at charm scale,
- ❑ be a good helper to the experimentalist.

The requirement of **<u>a universal tool</u>** :

- ✓ can identify all types of contributions,
- ✓ can give instructions to further estimations.

The application of topological-diagram in charmed baryons



L.-L. Chau, H.-Y. Cheng and B. Tseng, Phys. Rev. D 54(1996)2132

$$M(\mathcal{B}_i \to \mathcal{B}_f P) = i\bar{u}_f(A - B\gamma_5)u_i$$

$$A = A^{\rm fac} + A^{\rm nf}$$
$$B = B^{\rm fac} + B^{\rm nf}$$

- fac. and nonfac. contribution can be identified
- the estimation of two types of contribution resort to different methods

Factorizable part: naive factorization

$$M = \langle P\mathcal{B}|\mathcal{H}_{\rm eff}|\mathcal{B}_c\rangle = \begin{cases} \frac{G_F}{\sqrt{2}} V_{cd}V_{us}^* a_1 \langle P|(\bar{u}s)|0\rangle\langle\mathcal{B}|(\bar{d}c)|\mathcal{B}_c\rangle, \; P = K^+, \\ \frac{G_F}{\sqrt{2}} V_{cd}V_{us}^* a_2 \langle P|(\bar{s}d)|0\rangle\langle\mathcal{B}|(\bar{u}c)|\mathcal{B}_c\rangle, \; P = K^0, \end{cases}$$

$$\langle K(q)|\bar{s}\gamma_\mu(1-\gamma_5)d|0\rangle = i f_K q_\mu$$

$$\langle\mathcal{B}(p_2)|\bar{c}\gamma_\mu(1-\gamma_5)u|\mathcal{B}_c(p_1)\rangle = \bar{u}_2\left[f_1(q^2)\gamma_\mu - f_2(q^2)i\sigma_{\mu\nu}\frac{q^\nu}{M} + f_3(q^2)\frac{q_\mu}{M} - \left(g_1(q^2)\gamma_\mu - g_2(q^2)i\sigma_{\mu\nu}\frac{q^\nu}{M} + g_3(q^2)\frac{q_\mu}{M}\right)\gamma_5\right]u_1$$

Lattice results of FFs

- ❑ Stefen Meinel, $\Lambda_c \to \Lambda$, PRL 2017; $\Lambda_c \to N$, PRD 2018

Tue 08/06 | **Wed 09/06** | Thu 10/06 | All days

11:00 **Xi_c Semileptonic decays from lattice QCD** *Prof. Wei WANG*

东方绿舟宾馆合欢厅, Shanghai 11:00 - 11:15

Factorizable part: form factor

- MIT bag model estimation

Static limit

$$f_1^{B_f B_i}(q^2_{\rm max}) = \langle B_f \uparrow | b^\dagger_{q_1} b_{q_2} | B_i \uparrow \rangle \int d^3\boldsymbol{r}(u_{q_1}u_{q_2} + v_{q_1}v_{q_2})$$

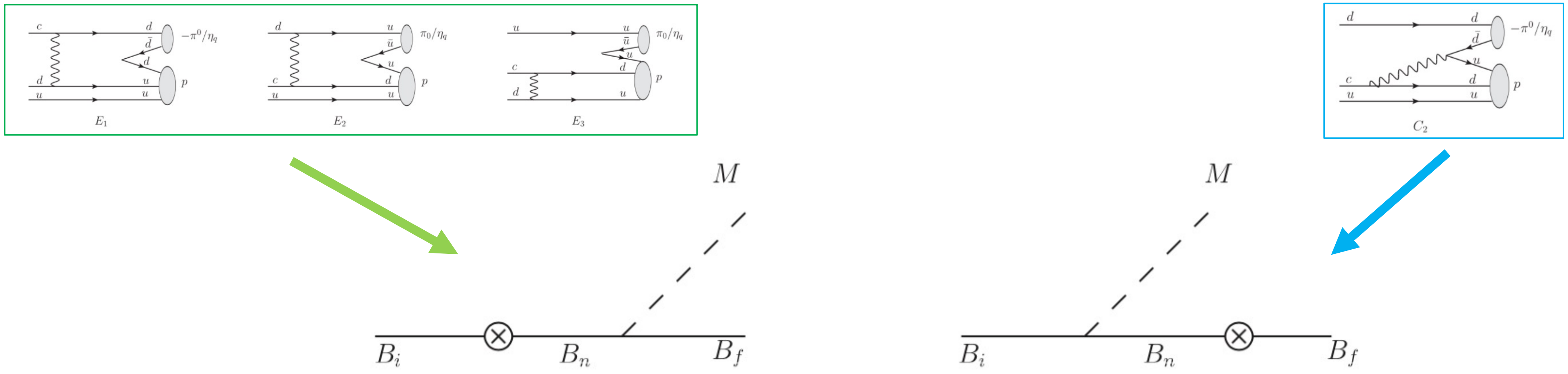
$$g_1^{B_f B_i}(q^2_{\rm max}) = \langle B_f \uparrow | b^\dagger_{q_1} b_{q_2}\sigma_z | B_i \uparrow \rangle \int d^3\boldsymbol{r}(u_{q_1}u_{q_2} - \frac{1}{3}v_{q_1}v_{q_2})$$

Run

$$f_i(q^2) = \frac{f_i(0)}{(1-q^2/m_V^2)^2}, \qquad g_i(q^2) = \frac{g_i(0)}{(1-q^2/m_A^2)^2}$$

modes	$(c\bar q)$	$f_1(q^2_{\rm max})$	$f_1(m_P^2)/f_1(q^2_{\rm max})$	$g_1(q^2_{\rm max})$	$g_1(m_P^2)/g_1(q^2_{\rm max})$
$\Xi_c^+ \to \Sigma^+ \overline{K}^0$	$(c\bar s)$	$-\frac{\sqrt6}{2}Y_1$	0.44907	$-\frac{\sqrt6}{2}Y_2$	0.60286
$\Xi_c^+ \to \Xi^0\pi^+$	$(c\bar s)$	$-\frac{\sqrt6}{2}Y_1^s$	0.49628	$-\frac{\sqrt6}{2}Y_2^s$	0.63416
$\Xi_c^0 \to \Lambda \overline{K}^0$	$(c\bar s)$	$\frac12 Y_1$	0.38700	$\frac12 Y_2$	0.55337
$\Xi_c^0 \to \Sigma^0 \overline{K}^0$	$(c\bar s)$	$\frac{\sqrt3}{2}Y_1$	0.44929	$\frac{\sqrt3}{2}Y_2$	0.60304
$\Xi_c^0 \to \Xi^-\pi^+$	$(c\bar s)$	$-\frac{\sqrt6}{2}Y_1^s$	0.49911	$-\frac{\sqrt6}{2}Y_2^s$	0.63636
$\Xi_c^+ \to \Sigma^0\pi^+$	$(c\bar d)$	$\frac{\sqrt3}{2}Y_1$	0.36045	$\frac{\sqrt3}{2}Y_2$	0.52523
$\Xi_c^+ \to \Lambda\pi^+$	$(c\bar d)$	$-\frac12 Y_1$	0.30260	$-\frac12 Y_2$	0.47622
$\Xi_c^+ \to \Sigma^+\pi^0$	$(c\bar d)$	$-\frac{\sqrt6}{2}Y_1$	0.35774	$-\frac{\sqrt6}{2}Y_2$	0.52294
$\Xi_c^+ \to \Sigma^+\eta_8$	$(c\bar d)$	$-\frac{\sqrt6}{2}Y_1$	0.41371	$-\frac{\sqrt6}{2}Y_2$	0.57735
$\Xi_c^+ \to \Xi^0 K^+$	$(c\bar s)$	$-\frac{\sqrt6}{2}Y_1^s$	0.55058	$-\frac{\sqrt6}{2}Y_2^s$	0.68080
$\Xi_c^0 \to \Lambda\eta_8$	$(c\bar s)$, $(c\bar d)$	$\frac12 Y_1$	0.39685, 0.34715	$\frac12 Y_2$	0.56286, 0.52343
$\Xi_c^0 \to \Sigma^0\eta_8$	$(c\bar s)$, $(c\bar d)$	$\frac{\sqrt3}{2}Y_1$	0.46073, 0.41395	$\frac{\sqrt3}{2}Y_2$	0.61338, 0.57754
$\Xi_c^0 \to \Lambda\pi^0$	$(c\bar d)$	$\frac12 Y_1$	0.30019	$\frac12 Y_2$	0.47410
$\Xi_c^0 \to \Sigma^0\pi^0$	$(c\bar d)$	$\frac{\sqrt3}{2}Y_1$	0.35795	$\frac{\sqrt3}{2}Y_2$	0.52311
$\Xi_c^0 \to \Sigma^-\pi^+$	$(c\bar d)$	$\frac{\sqrt6}{2}Y_1$	0.36183	$\frac{\sqrt6}{2}Y_2$	0.52638
$\Xi_c^0 \to \Xi^- K^+$	$(c\bar s)$	$-\frac{\sqrt6}{2}Y_1^s$	0.55371	$-\frac{\sqrt6}{2}Y_2^s$	0.68316

Non-factorizable part: pole model



S-wave: ½⁻:

$$A^{\text{pole}} = -\sum_{B_n^*(1/2^-)} \left[\frac{g_{B_f B_n^* P} b_{n^* i}}{m_i - m_{n^*}} + \frac{b_{f n^*} g_{B_n^* B_i P}}{m_f - m_{n^*}} \right]$$

P-wave: ½⁺:

$$B^{\text{pole}} = \sum_{B_n} \left[\frac{g_{B_f B_n P} a_{ni}}{m_i - m_n} + \frac{a_{fn} g_{B_n B_i P}}{m_f - m_n} \right].$$

$$\langle \mathcal{B}_i | H_{\text{eff}} | \mathcal{B}_j \rangle = \bar{u}_i (a_{ij} - b_{ij}\gamma_5) u_j, \qquad \langle \mathcal{B}_i^*(1/2^-) | H_{\text{eff}}^{\text{PV}} | \mathcal{B}_j \rangle = i b_{i^* j} \bar{u}_i u_j.$$

Current algebra

- Advantage: avoid ½⁻

$$A^{\rm com} = -\frac{\sqrt{2}}{f_{P^a}}\langle B_f|[Q_5^a, H_{\rm eff}^{PV}]|B_i\rangle = \frac{\sqrt{2}}{f_{P^a}}\langle B_f|[Q^a, H_{\rm eff}^{PC}]|B_i\rangle$$

$$B^{\rm pole} = \frac{\sqrt{2}}{f_{P^a}}\sum_{B_n}\left[g^A_{B_f B_n}\frac{m_f+m_n}{m_i-m_n}a_{ni} + a_{fn}\frac{m_i+m_n}{m_f-m_n}g^A_{B_n B_i}\right]$$

- S-wave: commutator

$$A^{\rm com}(B_i \to B_f K^\pm) = \frac{1}{f_K}\langle B_f|[V_\mp, H_{\rm eff}^{PC}]|B_i\rangle$$

$$V_+\Lambda = -\frac{\sqrt{6}}{2}p$$

$$V_+\Sigma^0 = -\frac{\sqrt{2}}{2}p$$

$$V_+\Xi^- = -\frac{\sqrt{2}}{2}\Sigma^0 - \frac{\sqrt{6}}{2}\Lambda$$

- P-wave: generalized Goldberg-Treiman relation

$$g_{\mathcal{B}'\mathcal{B}P^a} = \frac{\sqrt{2}}{f_{P^a}}(m_{\mathcal{B}'} + m_{\mathcal{B}})g^A_{\mathcal{B}'\mathcal{B}},$$

Baryon matrix elements & axial form factors

- MIT bag model estimation

$$a_{B'B} \equiv \langle B'|\mathcal{H}_{\text{eff}}^{\text{PC}}|B\rangle = \frac{G_F}{2\sqrt{2}} \sum_{q=d,s} V_{cq}V_{uq}^{*} c_{-} \langle B'|O_{-}^{q}|B\rangle$$

$$O_{\pm}^{q} = O_1^q \pm O_2^q = (\bar{q}c)(\bar{u}q) \pm (\bar{q}q)(\bar{u}c)$$

$$c_{-} = c_1 - c_2$$

$$g_{\mathcal{B}'\mathcal{B}}^{A(P)} = \langle \mathcal{B}' \uparrow | b_{q_1}^{\dagger} b_{q_2} \sigma_z | \mathcal{B} \uparrow \rangle \int d^3\boldsymbol{r} \left(u_{q_1} u_{q_2} - \frac{1}{3} v_{q_1} v_{q_2} \right)$$

Selected results

Modes	This work	Geng *et al.* [14, 46]	Expt.
$\Lambda_c^+ \to \Lambda\pi^+$	1.30 (−0.93)	1.27 ± 0.07 (-0.77 ± 0.07)	1.30 ± 0.07 (-0.84 ± 0.09)
$\Lambda_c^+ \to \Sigma^0\pi^+$	2.24 (−0.76)	1.26 ± 0.06 (-0.58 ± 0.10)	1.29 ± 0.07 (-0.73 ± 0.18)
$\Lambda_c^+ \to \Sigma^+\pi^0$	2.24 (−0.76)	1.26 ± 0.06 (-0.58 ± 0.10)	1.25 ± 0.10 (-0.55 ± 0.11)
$\Lambda_c^+ \to \Sigma^+\eta$	0.74 (−0.95)	0.29 ± 0.12 $(-0.70^{+0.59}_{-0.30})$	0.53 ± 0.15
$\Lambda_c^+ \to p\overline{K}^0$	2.11 (−0.75)	3.14 ± 0.15 $(-0.99^{+0.09}_{-0.01})$	3.18 ± 0.16 (0.18 ± 0.45)
$\Lambda_c^+ \to \Xi^0 K^+$	0.73 (0.90)	0.57 ± 0.09 $(1.00^{+0.00}_{-0.02})$	0.55 ± 0.07
$\Lambda_c^+ \to p\pi^0$	0.13 (−0.97)	$0.11^{+0.13}_{-0.11}$ (0.24 ± 0.68)	< 0.27 (BESIII'17); < 0.08 (Belle'21)
$\Lambda_c^+ \to p\eta$	1.28 (−0.55)	1.12 ± 0.28 $(-1.00^{+0.06}_{-0.00})$	1.24 ± 0.29 (BESIII'17); 1.42 ± 0.12 (Belle'21)
$\Lambda_c^+ \to n\pi^+$	0.09 (−0.73)	0.76 ± 0.11 (0.27 ± 0.11)	
$\Lambda_c^+ \to \Lambda K^+$	1.07 (−0.96)	0.66 ± 0.09 (0.09 ± 0.26)	0.61 ± 0.12
$\Lambda_c^+ \to \Sigma^0 K^+$	0.72 (−0.73)	0.52 ± 0.07 $(-0.98^{+0.05}_{-0.02})$	0.52 ± 0.08
$\Lambda_c^+ \to \Sigma^+ K^0$	1.44 (−0.73)	1.05 ± 0.14 $(-0.98^{+0.05}_{-0.02})$	

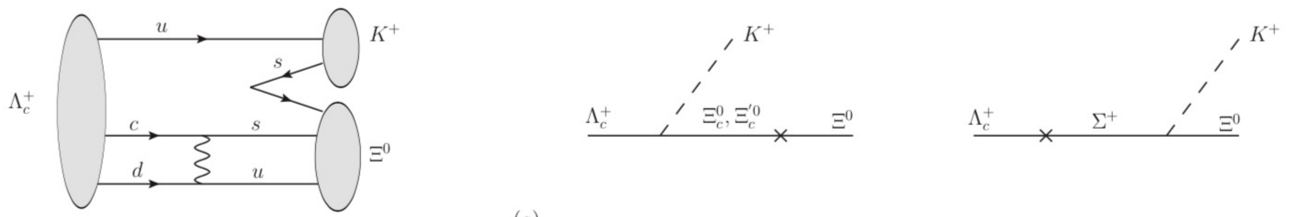
- Some modes are consistent well with experimental results.
- Most predictions for branching fraction and decay asymmetry are consistent with fitting results based on SU(3) symmetry.

Discussion

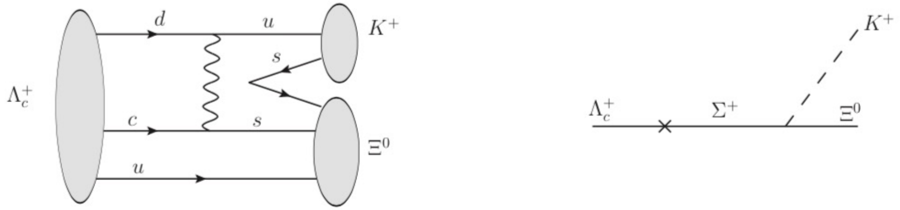
1. Resolve the branching ratio of $\Lambda_c^+ \to \Xi^0 K^+$
2. $\Xi_c^+ \to \Xi^0 \pi^+$ & $\Xi_c^0 \to \Xi^- \pi^+$ tension
3. Promising modes to discover Ξ_{cc}^+ & Ω_{cc}^+

$\Lambda_c^+ \to \Xi^0 K^+$: diagrams

Type-III
W-exchange



(a)



(b)

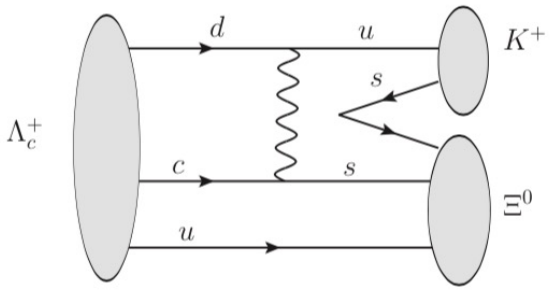
$$A^{\rm com}(\Lambda_c^+ \to \Xi^0 K^+) = \frac{1}{f_K}\left(a_{\Sigma^+\Lambda_c^+} - a_{\Xi^0\Xi_c^0}\right),$$

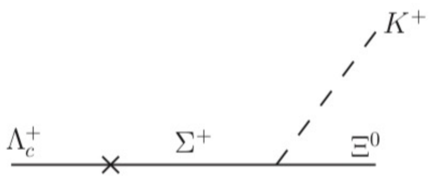
identical under SU(3) → vanishing S-wave → zero alpha

$$B^{\rm ca}(\Lambda_c^+ \to \Xi^0 K^+) = \frac{1}{f_K}\left(g^{A(K^+)}_{\Xi^0\Sigma^+}\frac{m_{\Xi^0}+m_{\Sigma^+}}{m_{\Lambda_c^+}-m_{\Sigma^+}}a_{\Sigma^+\Lambda_c^+} + a_{\Xi^0\Xi_c^0}\frac{m_{\Xi_c^0}+m_{\Lambda_c^+}}{m_{\Xi^0}-m_{\Xi_c^0}}g^{A(K^+)}_{\Xi_c^0\Lambda_c^+} + a_{\Xi^0\Xi_c'^0}\frac{m_{\Xi_c'^0}+m_{\Lambda_c^+}}{m_{\Xi^0}-m_{\Xi_c'^0}}g^{A(K^+)}_{\Xi_c'^0\Lambda_c^+}\right).$$

cancellation

Prediction for $\Lambda_c^+ \to \Xi^0 K^+$





(b)

J.G. Korner, M. Kramer ‘92
P. Zenczykowski ‘94

$$A^{\rm com}(\Lambda_c^+ \to \Xi^0 K^+) = \frac{1}{f_K} a_{\Sigma^+\Lambda_c^+},$$

different from Korner-Kramer: SU(4)

$$B^{\rm ca}(\Lambda_c^+ \to \Xi^0 K^+) = \frac{1}{f_K}\left(g^{A(K^+)}_{\Xi^0\Sigma^+} \frac{m_{\Xi^0} + m_{\Sigma^+}}{m_{\Lambda_c^+} - m_{\Sigma^+}} a_{\Sigma^+\Lambda_c^+} \right)$$

similar

big and positive alpha

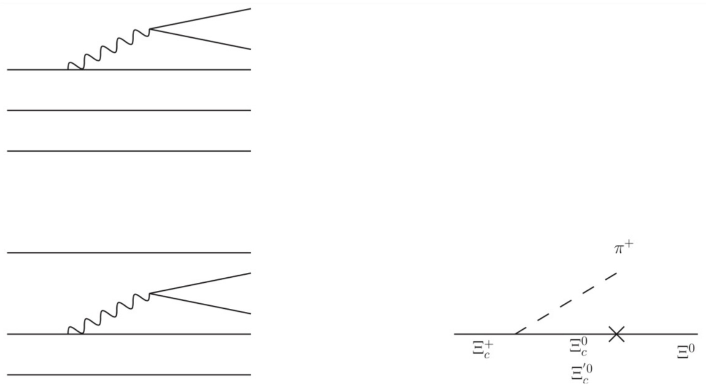
Channel	$A^{\rm fac}$	$A^{\rm com}$	$A^{\rm tot}$	$B^{\rm fac}$	$B^{\rm ca}$	$B^{\rm tot}$	$\mathcal{B}_{\rm theo}$	$\mathcal{B}_{\rm exp}$ [7]	$\alpha_{\rm theo}$	$\alpha_{\rm exp}$
$\Lambda_c^+ \to \Xi^0 K^+$	0	−4.48	−4.48	0	−12.10	−12.10	0.73×10^{-2}	$(0.55 \pm 0.07)10^{-2}$	0.90	

$\Xi_c^0 \to \Sigma^+ K^-$

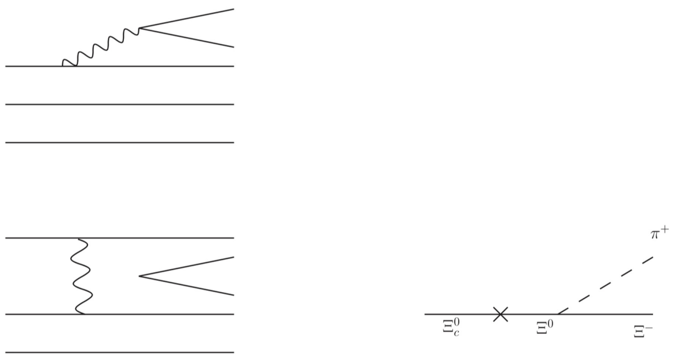
$\Xi_c^0 \to p K^-, \Sigma^+ \pi^-$

$\Xi_c^+ \to \Xi^0\pi^+$ & $\Xi_c^0 \to \Xi^-\pi^+$

$\Xi_c^+ \to \Xi^0\pi^+$



$\Xi_c^0 \to \Xi^-\pi^+$



$$A^{\rm com}(\Xi_c^+ \to \Xi^0\pi^+) = -\frac{1}{f_\pi} a_{\Xi^0\Xi_c^0}$$

$$B^{\rm ca}(\Xi_c^+ \to \Xi^0\pi^+) = \frac{1}{f_\pi}\left(a_{\Xi^0\Xi_c^0}\frac{m_{\Xi_c^+}+m_{\Xi_c^0}}{m_{\Xi^0}-m_{\Xi_c^0}} g^{A(\pi^+)}_{\Xi_c^0\Xi_c^+} + a_{\Xi^0\Xi_c'^0}\frac{m_{\Xi_c^+}+m_{\Xi_c'^0}}{m_{\Xi^0}-m_{\Xi_c'^0}} g^{A(\pi^+)}_{\Xi_c'^0\Xi_c^+}\right)$$

$$A^{\rm com}(\Xi_c^0 \to \Xi^-\pi^+) = \frac{1}{f_\pi} a_{\Xi^0\Xi_c^0}$$

$$B^{\rm ca}(\Xi_c^0 \to \Xi^-\pi^+) = \frac{1}{f_\pi}\left(g^{A(\pi^+)}_{\Xi^-\Xi^0}\frac{m_{\Xi^-}+m_{\Xi^0}}{m_{\Xi_c^0}-m_{\Xi^0}} a_{\Xi^0\Xi_c^0}\right)$$

Channel	$A^{\rm fac}$	$A^{\rm com}$	$A^{\rm tot}$	$B^{\rm fac}$	$B^{\rm ca}$	$B^{\rm tot}$	$\mathcal{B}_{\rm theo}$	$\mathcal{B}_{\rm exp}$	$\alpha_{\rm theo}$	$\alpha_{\rm exp}$
$\Xi_c^0 \to \Xi^-\pi^+$	-7.42	-5.36	-12.78	28.24	2.65	30.89	6.47	1.80 ± 0.52	-0.95	-0.6 ± 0.4
$\Xi_c^+ \to \Xi^0\pi^+$	-7.41	5.36	-2.05	28.07	-14.03	14.04	1.72	1.57 ± 0.83	-0.78	$-$

constructive

destructive

$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$: the examining channel

- Our prediction

$$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \approx 0.7\%$$

- Experimental hint

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \times \mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+) \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.035 \pm 0.009(\text{stat.}) \pm 0.003(\text{syst.})$$

LHCb, PRL 121 (2018) 162002

$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (6.28 \pm 0.32)\%$ PDG2018 ← BESIII

$\mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = (0.45 \pm 0.21 \pm 0.07)\%$ Belle, PRD100(2019) 031101

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+)} = 0.49 \pm 0.27$$

$\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+) \approx \frac{2}{3}\mathcal{B}(\Xi_{cc}^{++} \to \Sigma_c^{++}\overline{K}^{*0})$ assumption

$\mathcal{B}(\Xi_{cc}^{++} \to \Sigma_c^{++}\overline{K}^{*0}) = 5.61\%$ T. Gutsche, et. al. PRD100(2019) 114037

$$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+)_{\text{expt}} \approx (1.83 \pm 1.01)\%$$

- Comparison

Mode	Our	Dhir *et al.* [8, 10]	Gutsche *et al.* [11, 13, 17]	Wang *et al.* [7]	Gerasimov *et al.* [14]
$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$	0.69	6.64 (N)	0.70	6.18	7.01
		9.19 (H)			
$\Xi_{cc}^{++} \to \Xi_c^{\prime +} \pi^+$	4.65	5.39 (N)	3.03	4.33	5.85
		7.34 (H)			
$\Xi_{cc}^{++} \to \Sigma_c^{++}\overline{K}^0$	1.36	2.39 (N)	1.25		
		4.69 (H)			

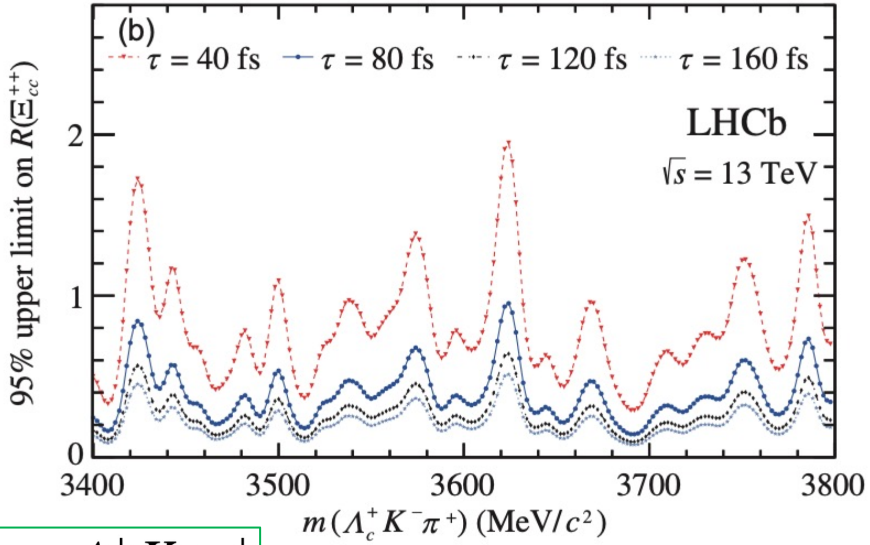
- Promising channels

Channel	A^{fac}	A^{com}	A^{tot}	B^{fac}	B^{ca}	B^{tot}	$\mathcal{B}_{\text{theo}}$	α_{theo}
$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$	7.40	−10.79	−3.38	−15.06	18.91	3.85	0.69	−0.41
$\Xi_{cc}^{++} \to \Xi_c^{\prime +} \pi^+$	4.49	−0.04	4.45	−48.50	0.06	−48.44	4.65	−0.84
$\Xi_{cc}^{+} \to \Xi_c^0 \pi^+$	8.52	10.79	19.31	−16.46	−0.08	−16.54	3.84	−0.31

$$\mathrm{B}(\Xi_{cc}^{++} \to \Xi_c'^{+} \pi^+) = 4.65\%$$

Ξ_{cc}^{+} and Ω_{cc}^{+} : present situation

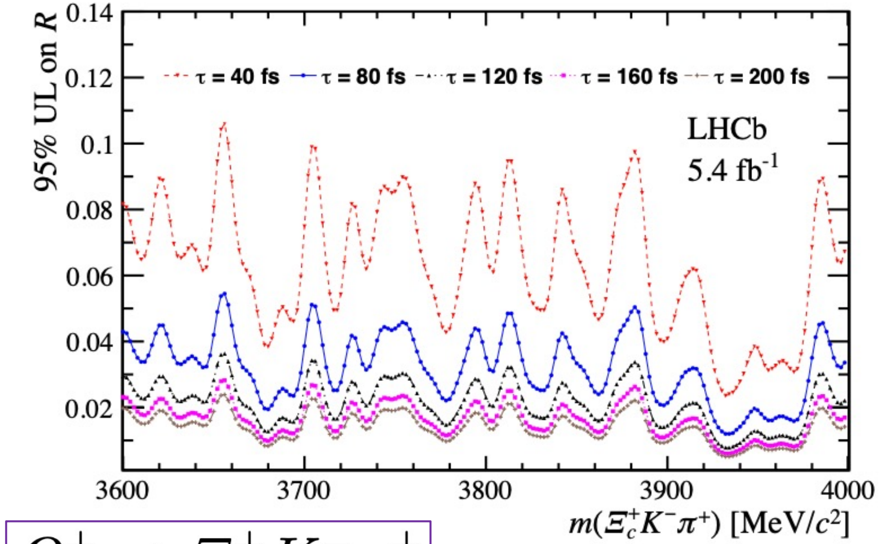
$$\mathcal{R}(\Xi_{cc}^{++}) \equiv \frac{\sigma(\Xi_{cc}^{+}) \times \mathcal{B}(\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}$$



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

LHCb, Sci. China Phys. Mech. Astron. 63 221062 (2020)

$$R \equiv \frac{\sigma(\Omega_{cc}^{+}) \times \mathcal{B}(\Omega_{cc}^{+} \to \Xi_c^+ K^- \pi^+) \times \mathcal{B}(\Xi_c^+ \to p K^- \pi^+)}{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) \times \mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)}$$



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

LHCb, 2105.06841

❑ Explanation

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

$B(\Xi_{cc}^{+} \to \Sigma_c^{++} K^-) = 0.13\%$

H.-Y. Cheng, G. Meng, FX, J. Zou, Phys. Rev. D 101 (2020), 034034

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

$B(\Xi_{cc}^{+} \to \Lambda_c^+ \overline{K}^{0*}) = 0.48\%$

L.J. Jiang, B. He, R.H. Li, EPJC 78(2018)no.11,961

Ξ_{cc}^{+} and Ω_{cc}^{+} : the suggested discovering mode

- A suggested discovering channel for Ξ_{cc}^{+} :

$$\Xi_{cc}^{+} \to \Xi_c^0\pi^+ \to \Xi^-\pi^+\pi^+ \to \Lambda\pi^-\pi^+\pi^+ \to p\pi^-\pi^-\pi^+\pi^+$$

$B(\Xi_{cc}^{+} \to \Xi_c^0\pi^+)$= 3.84% (large Br)

H.-Y. Cheng, G. Meng, FX, J. Zou, Phys. Rev. D 101 (2020), 034034

$B(\Xi_c^0 \to \Xi^-\pi^+)$= 6.47% (the largest channel)

J. Zou, FX, G. Meng and H.-Y. Cheng, PRD101(2020), 014011

- A similar suggested discovering channel for Ω_{cc}^{+} :

$$\Omega_{cc}^{+} \to \Xi^0\overline{K}^0\pi^+ \to \Lambda\pi^0\overline{K}^0\pi^+ \to p\pi^-\pi^0\overline{K}^0\pi^+$$

$B(\Omega_{cc}^{+} \to \Omega_c^0\pi^+)$= 3.96% (large Br)

H.-Y. Cheng, G. Meng, FX, J. Zou, Phys. Rev. D 101 (2020), 034034

$B(\Omega_c^0 \to \Xi^0\overline{K}^0)$= 3.78% (CF, the largest channel)

S. Hu, G. Meng , FX, PRD101 (2020), 094101

Summary (II)

- Weak decays of singly & doubly charmed baryons are predicted.
- Branching fraction of $\Lambda_c^+ \to \Xi^0 K^+$ is resolved.
- A tension exists in $\Xi_c^+ \to \Xi^0 \pi^+$ and $\Xi_c^0 \to \Xi^- \pi^+$.
- Promising modes to discovery the remaining 2 doubly charmed baryons are proposed.