NCTS Dark Physics Workshop

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Decays of doubly charmed baryon

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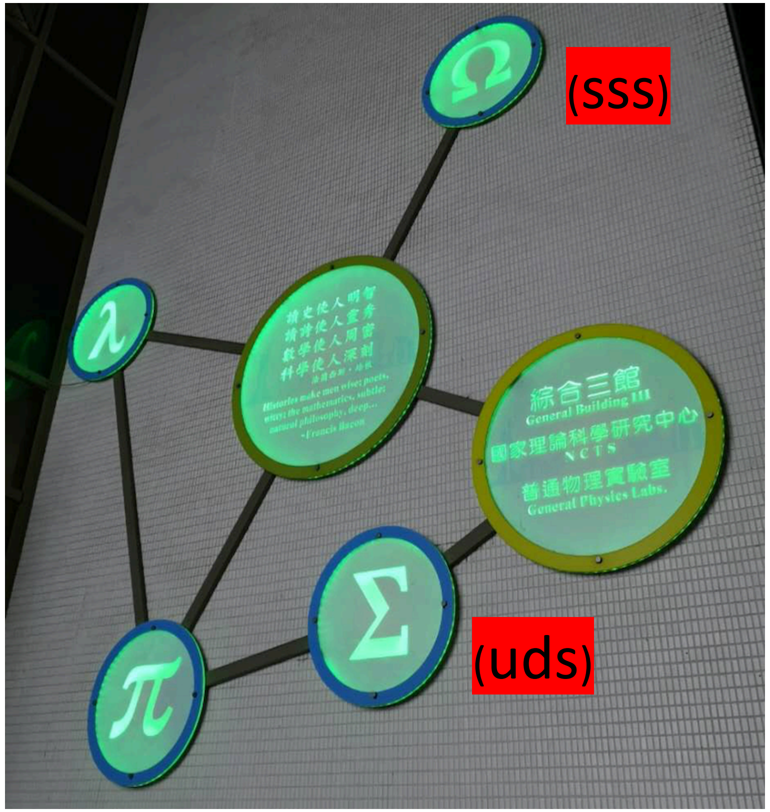
Outline

- Introduction: recent progress
- Theoretical framework
- Results and discussion

Introduction

Why charm?



Life moves on!
Face up to reality: “C”.

Charm meson sector

- Direct CP violation: first CPV in charm has been observed.

$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^- K^+) - A_{CP}(D^0 \to \pi^- \pi^+)$$

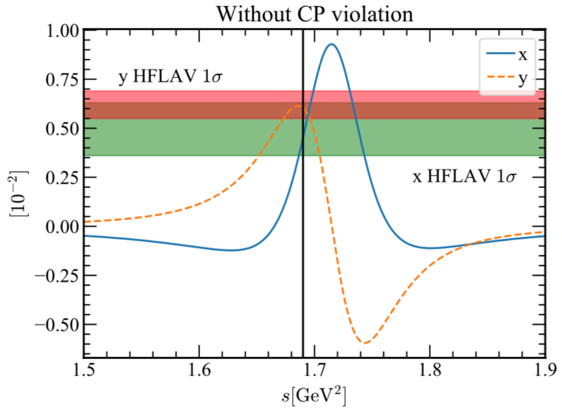
$$\boldsymbol{\Delta A_{CP} = (-15.4 \pm 2.9)\times 10^{-4}}$$

CP violation observed at $\boldsymbol{5.3\sigma}$!!

LHCb, Phys. Rev. Lett. 122, 211803 (2019)

- Indirect CPV in D-Dbar mixing: the first successful quantitative attempt to understand x and y simultaneously.

Parameter	Avg value (HFLAV 2018) [%]
x	$0.36^{+0.21}_{-0.16}$
y	$0.67^{+0.06}_{-0.13}$



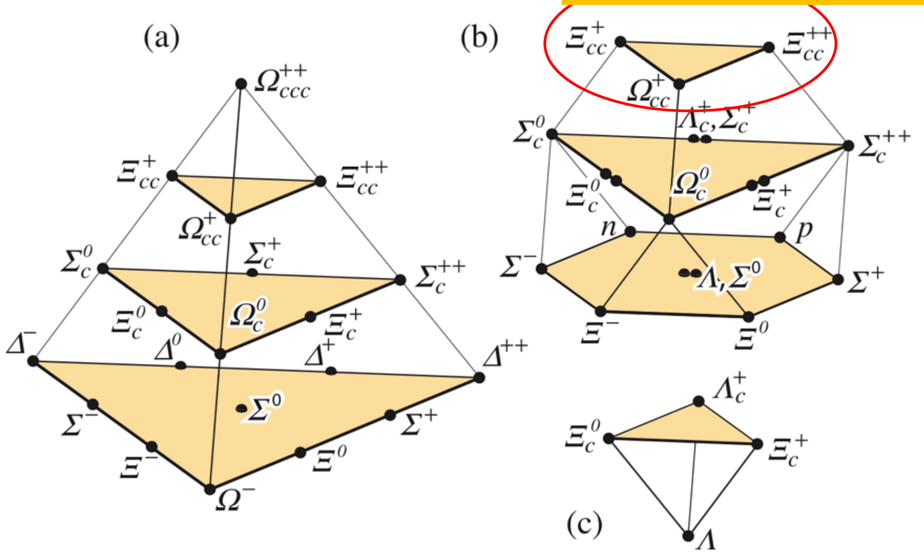
H.Umeeda, FX, F. Yu and H.-n. Li, to appear

Charmed baryons

- Classification of Charmed Baryons

SU(4)

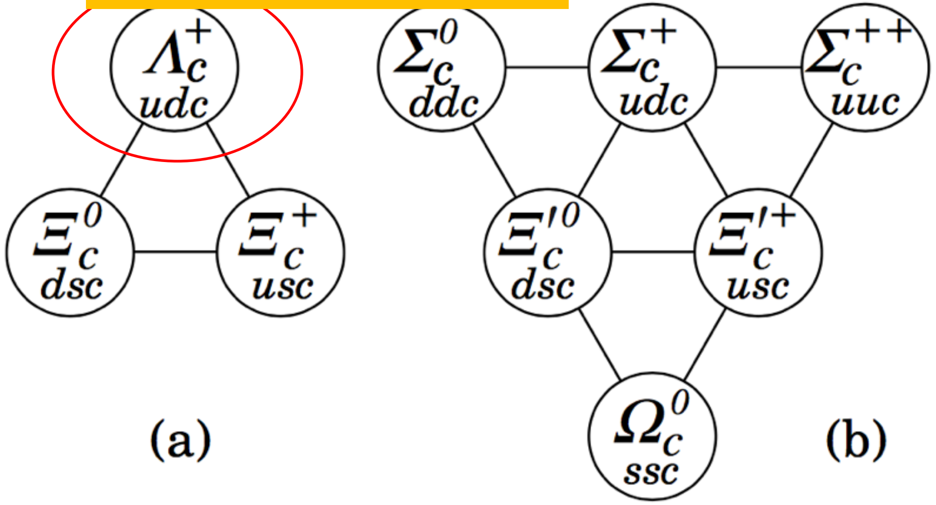
doubly charmed baryon



- Singly charmed baryons

SU(3)

singly charmed baryon



flavor:

$4 \times 4 \times 4 = 20_s + 20_{M_A} + 20_{M_S} + \bar{4}_A$

$3 \times 3 \times 3 = 10_s + 8_{M_A} + 8_{M_S} + 1_A$

$3 \times 3 = \bar{3}_A + 6_S$

- Observation
- (Weak) Decays
- Lifetimes
- CPV

Progress in Λ_c^+: BESIII

- Based on 35 days' data collecting at **BESIII**, 16 papers including 7 PRLs on Λ_c^+ have been published so far.
- About 20 channels have been measured, relevant PDG values has been revised.

  - Absolute branching fraction of Golden mode: $\Lambda_c^+ \to pK\pi$.
  - new technique to measure neutron final state.
  - Single Cabibbo suppressed processes have been touched.
  - Reach the sensitivity of decay asymmetry.

PDG2014

$\Gamma(p\overline{K}^0\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_7/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.66±0.05±0.07	774	ALAM	98	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(p\overline{K}^0\eta)/\Gamma(pK^-\pi^+)$ — Γ_8/Γ_2

Unseen decay modes of the η are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.25±0.04±0.04	57	AMMAR	95	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(p\overline{K}^0\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_9/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.51±0.06 OUR AVERAGE					
0.52±0.04±0.05	985	ALAM	98	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.43±0.12±0.04	83	AVERY	91	CLEO	e^+e^- 10.5 GeV
0.98±0.36±0.08	12	BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(pK^-\pi^+\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{10}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.67±0.04±0.11	2606	ALAM	98	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(pK^*(892)^-\pi^+)/\Gamma(p\overline{K}^0\pi^+\pi^-)$ — Γ_{11}/Γ_9

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.44±0.14	17	ALEEV	94	BIS2	nN 20–70 GeV

$\Gamma(p(K^-\pi^+)_{\text{nonresonant}}\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{12}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.73±0.12±0.05	67	BOZEK	93	NA32	π^- Cu 230 GeV

PDG2019

$\Gamma(pK_S^0\pi^0)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.96±0.13 OUR FIT Error includes scale factor of 1.1.					
1.87±0.13±0.05	558	ABLIKIM	16	BES3	$e^+e^- \to \Lambda_c\overline{\Lambda}_c$, 4.599 GeV

$\Gamma(pK_S^0\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_7/Γ_2

Measurements given as a $\overline{K}^0$ ratio have been divided by 2 to convert to a K_S^0 ratio.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.314±0.018 OUR FIT					
0.33 ±0.03 ±0.04	774	ALAM	98	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(nK_S^0\pi^+)/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.82±0.23±0.11	83	ABLIKIM	17H	BES3	e^+e^- at 4.6 GeV

$\Gamma(p\overline{K}^0\eta)/\Gamma(pK^-\pi^+)$ — Γ_9/Γ_2

Unseen decay modes of the η are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.25±0.04±0.04	57	AMMAR	95	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(pK_S^0\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.59±0.12 OUR FIT Error includes scale factor of 1.2.					
1.53±0.11±0.09	485	ABLIKIM	16	BES3	$e^+e^- \to \Lambda_c\overline{\Lambda}_c$, 4.599 GeV

$\Gamma(pK_S^0\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_{10}/Γ_2

Measurements given as a $\overline{K}^0$ ratio have been divided by 2 to convert to a K_S^0 ratio.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.255±0.015 OUR FIT Error includes scale factor of 1.1.					
0.257±0.031 OUR AVERAGE					
0.26 ±0.02 ±0.03	985	ALAM	98	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.22 ±0.06 ±0.02	83	AVERY	91	CLEO	e^+e^- 10.5 GeV
0.49 ±0.18 ±0.04	12	BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(pK^-\pi^+\pi^0)/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
4.42±0.31 OUR FIT Error includes scale factor of 1.5.					
4.53±0.23±0.30	1849	ABLIKIM	16	BES3	$e^+e^- \to \Lambda_c\overline{\Lambda}_c$, 4.599 GeV

$\Gamma(pK^-\pi^+\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{11}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT

Progress in Λ_c^+: BESIII

- Based on 35 days' data collecting at **BESIII**, 16 papers including 7 PRLs on Λ_c^+ have been published so far.
- Now new data collecting is being operated…

Prof. Haibo Li's WeChat Friend's Circle

Progress in Ξ_c

(772±11) ×10^6 $B\bar{B}$pair

- First measurement of $\Xi_c^0 \to \Xi^- \pi^+$

$$\mathcal{B}(B^- \to \bar{\Lambda}_c^- \Xi_c^0) = [9.51 \pm 2.10(\text{stat.}) \pm 0.88(\text{syst.})] \times 10^{-4}$$

$$\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+) = [1.80 \pm 0.50(\text{stat.}) \pm 0.14(\text{syst.})]\%$$

Belle, PRL 122 (2019) 082001

- The branching fraction of $\Xi_c^+ \to \Xi^0 \pi^+$

$$\mathcal{B}(\bar{B}^0 \to \bar{\Lambda}_c^- \Xi_c^+) = [1.16 \pm 0.42(\text{stat.}) \pm 0.15(\text{syst.})] \times 10^{-3}$$

$$\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+) = (2.86 \pm 1.21 \pm 0.38) \times 10^{-2}$$

Belle, 1904.12093

$$\Gamma(\Xi_c^+ \to \Xi^0 \pi^+)/\Gamma(\Xi_c^+ \to \Xi^- \pi^+ \pi^+) = (0.55 \pm 0.13 \pm 0.09)$$

CLEO, PLB373(1996)261

$$\mathcal{B}(\Xi_c^+ \to \Xi^0 \pi^+) = (1.57 \pm 0.83)\%$$

Doubly charmed baryon

- First doubly charmed baryon is observed via

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

LHCb, PRL 119, 112001 (2017)

- First observation of two body decay

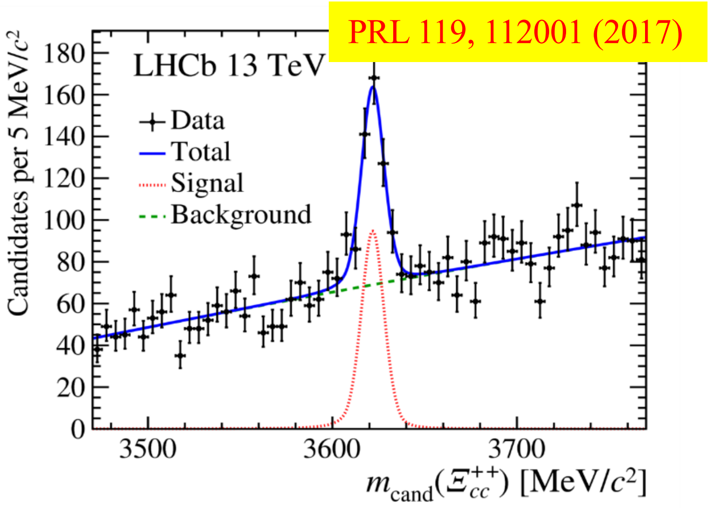
$$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$$

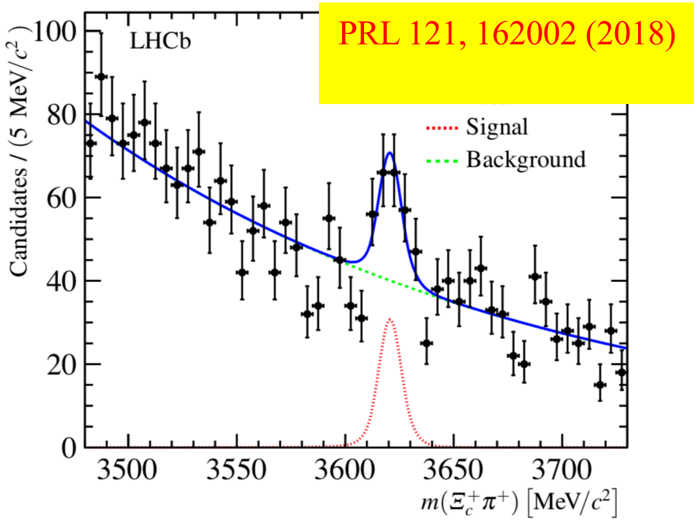
LHCb, PRL 121, 162002 (2018)

- Lifetime and precise mass of Ξ_{cc}^{++} have been measured.

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

$$m_{\Xi_{cc}^{++}} = 3621.55 \pm 0.23 \pm 0.30\ \text{MeV}$$





LHCb, PRL 121, 052002 (2018)

LHCb, 1911.08594 [hep-ex]

Recent study in theory

- SU(3) approach

  - C.Q. Geng, Y.K. Hsiao, Y.H. Lin and L.L. Liu, *“Non-leptonic two-body weak decays of $\Lambda_c(2286)$”*, Phys. Lett. B776, 265 (2017).
  - C.Q. Geng, Y. K. Hsiao, C.W. Liu and T. H. Tsai, *“Charmed baryon weak decays with SU(3) flavor symmetry”*, JHEP 1711, 147 (2017).
  - C.Q. Geng, Y. K. Hsiao, C.W. Liu and T. H. Tsai, *“Anti-triplet charmed baryon decays with SU(3) flavor symmetry”*, Phys. Rev. D97,073006 (2018).
  - C.Q. Geng, Y. K. Hsiao, C.W. Liu and T. H. Tsai, *“SU(3) symmetry breaking in charmed baryon decays”*, Euro. Phys. J. C 78, 593 (2018).
  - C.Q. Geng, Y. K. Hsiao, C.W. Liu, T.H. Tsai, *“Three-body charmed baryon decays with SU(3) flavor symmetry”*, Phys. Rev. D99, 073003 (2019).
  - C.Q. Geng , C.W. Liu, T.H. Tsai, *“Singly Cabibbo suppressed decays of Λ_c with SU(3) flavor symmetry”*, Phys. Lett. B790, 225 (2019).
  - C.Q. Geng , C.W. Liu, T.H. Tsai, *“Semileptonic Decays of Anti-triplet Charmed baryons”*, Phys. Lett. B792, 214 (2019).
  - C.Q. Geng , C.W. Liu, T.H. Tsai, *“Asymmetries of anti-triplet charmed baryon decays”*, Phys. Lett. B794, 19 (2019).
  - C.Q. Geng , C.W. Liu, T.H. Tsai, *“Charmed baryon weak decays with decuplet baryon and SU(3) flavor symmetry”*, Phys. Rev. D99, 114022(2019).
  - J.Y. Cen, C.Q. Geng, C.W. Liu and T.H. Tsai, *“Up-down asymmetries in charmed baryon three-body decays”*, Eur. Phys. J. C79, 946 (2019).

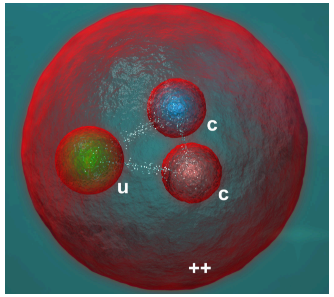
  - H.J. Zhao, Yan-Li Wang, Y.-K. Hsiao, Y. Yu, *“A diagrammatic analysis of two-body charmed baryon decays with flavor symmetry”*, 1811.07265

Recent study in theory

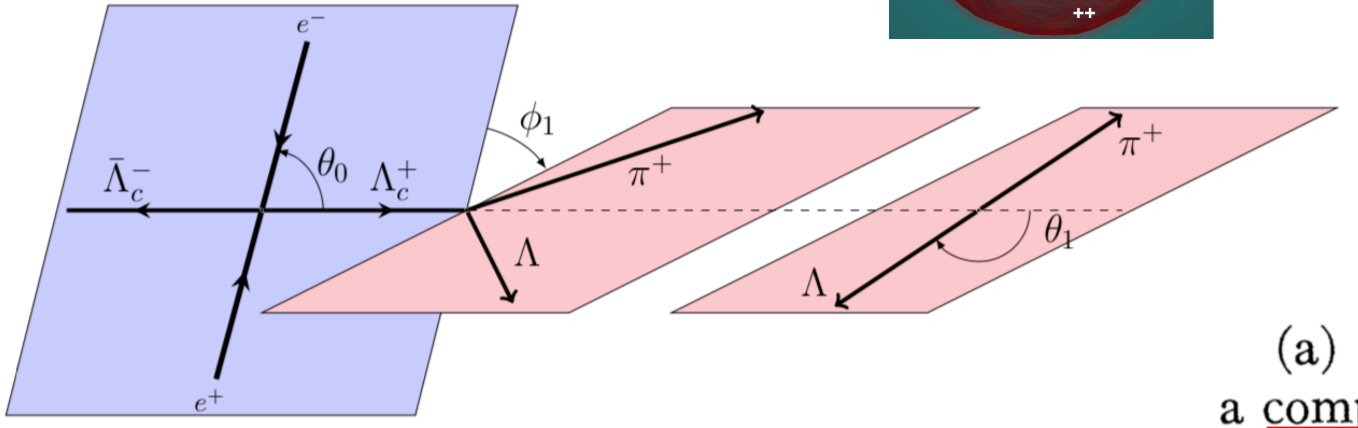
- Calculation concerning factorizable contribution:
  - a series of work by C.D. Lu, W. Wang, F.S. Yu, Z.X. Zhao…
- Rescattering approach
  - L.-J. Jiang, B. He, R.-H. Li, *“Weak decays of doubly heavy baryons”*, Eur. Phys. J. C78(2018),961
- Dynamic calculation based on pole model
  - H.-Y. Cheng, X.-W. Kang, FX, *“Singly Cabibbo-suppressed hadronic decays of Λ_c^+”*, Phys. Rev. D97, 074028 (2018)
  - J. Zou, FX, G. Meng, H.-Y. Cheng, *“Two-body hadronic weak decays of antitriplet charmed baryons”*, 1910.13626, accepted by Phys. Rev. D
  - H.-Y. Cheng, G. Meng, FX, J. Zou, *“Two-body weak decays of doubly charmed baryons”*, to appear

Theoretical working frame

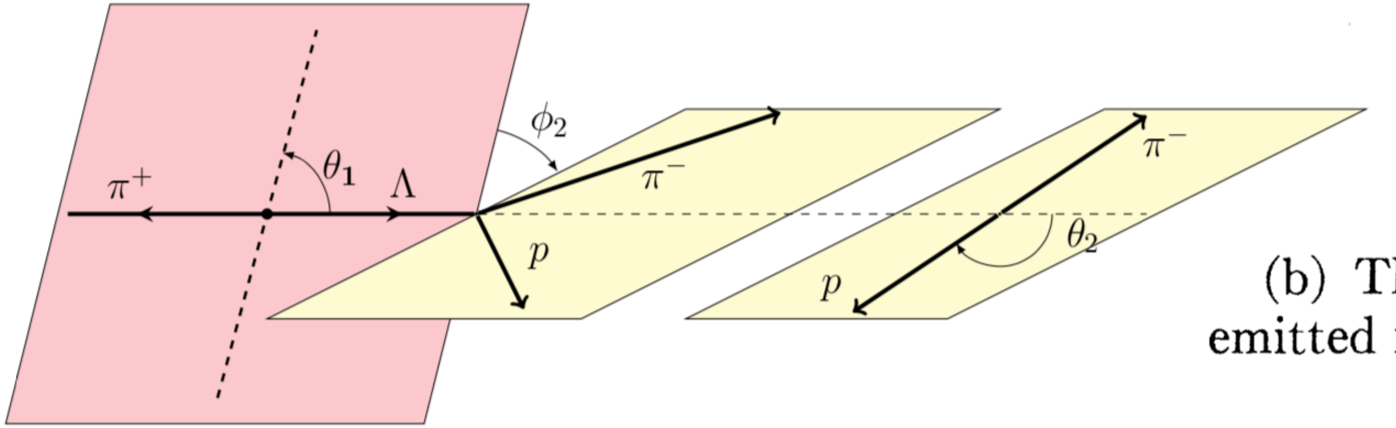
New platform



Traditional observables



CM frame Λ_c^+ rest frame



Λ_c^+ rest frame Λ rest frame

Branching fraction

Polarization

(a) The angular distribution of the decay pion from a completely polarized hyperon at rest.

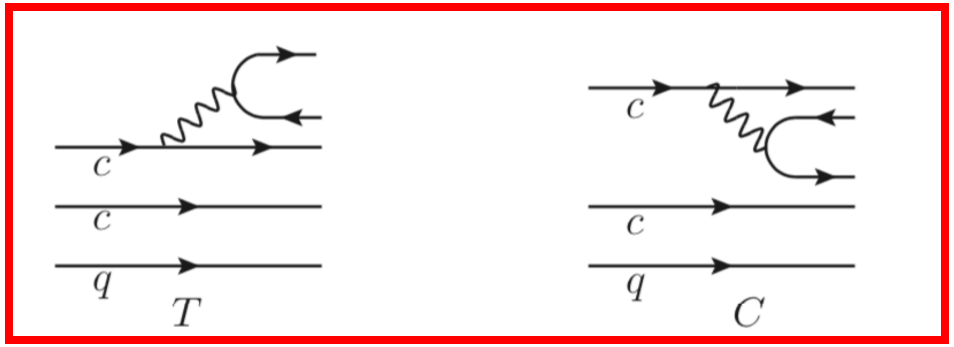
It has been pointed out before[1] that the distribution is proportional to

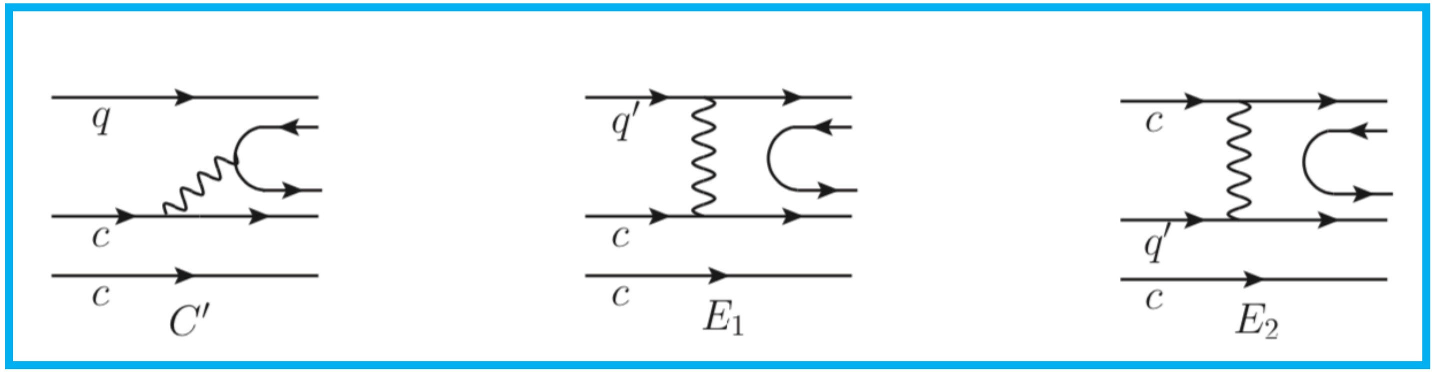
$$[1+\alpha\cos\chi]d\Omega, \quad (1)$$

(b) The longitudinal polarization of the nucleon emitted in the decay of unpolarized hyperons at rest.

Lee-Yang, 1957

Topological diagram approach





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

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

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

Ξ_{cc}^{++}	Contributions	Ξ_{cc}^{+}	Contributions	Ω_{cc}^{+}	Contributions
$\Xi_{cc}^{++} \to \Sigma_c^{++}\overline{K}^0$	C	$\Xi_{cc}^{+} \to \Xi_c^{0}\pi^+$	T, E_1	$\Omega_{cc}^{+} \to \Omega_c^{0}\pi^+$	T
$\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+$	T, C'	$\Xi_{cc}^{+} \to \Xi_c^{\prime 0}\pi^+$	T, E_1	$\Omega_{cc}^{+} \to \Xi_c^{+}\overline{K}^0$	C, C'
$\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+$	T, C'	$\Xi_{cc}^{+} \to \Lambda_c^{+}\overline{K}^0$	C, E_2	$\Omega_{cc}^{+} \to \Xi_c^{\prime +}\overline{K}^0$	C, C'
		$\Xi_{cc}^{+} \to \Sigma_c^{+}\overline{K}^0$	C, E_2		
		$\Xi_{cc}^{+} \to \Xi_c^{+}\pi^0$	C', E_1		
		$\Xi_{cc}^{+} \to \Xi_c^{\prime +}\pi^0$	C', E_1		
		$\Xi_{cc}^{+} \to \Xi_c^{+}\eta$	C', E_1, E_2		
		$\Xi_{cc}^{+} \to \Xi_c^{\prime +}\eta$	C', E_1, E_2		
		$\Xi_{cc}^{+} \to \Sigma_c^{++}K^-$	E_2		
		$\Xi_{cc}^{+} \to \Omega_c^{0}K^+$	E_1		

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

Factorizable contribution

- Naïve factorization

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

$$A^{\rm fac} = \frac{G_F}{\sqrt{2}} a_{1,2} V^*_{ud} V_{cs} f_P (m_{\mathcal{B}_{cc}} - m_{\mathcal{B}_c}) f_1(q^2),$$

$$B^{\rm fac} = -\frac{G_F}{\sqrt{2}} a_{1,2} V^*_{ud} V_{cs} f_P (m_{\mathcal{B}_{cc}} + m_{\mathcal{B}_c}) g_1(q^2).$$

Factorizable contribution

- Wilson coefficient

$$a_1 = c_1 + \frac{c_2}{N_c}, a_2 = c_2 + \frac{c_1}{N_c}$$

- Baryon transition form factor
  - ➢light-front quark model; light-cone sum rules; non-relativistic quark model
  - ➢MIT bag model

$$f_1^{\mathcal{B}_f\mathcal{B}_i}(q^2_{\max}) = \langle \mathcal{B}_f \uparrow | b^\dagger_{q_1} b_{q_2} | \mathcal{B}_i \uparrow \rangle \int d^3\boldsymbol{r}(u_{q_1}(r)u_{q_2}(r) + v_{q_1}(r)v_{q_2}(r)),$$

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

Factorizable contribution: form factor

- Baryon transition form factor: comparison

$\mathcal{B}_{cc} \to \mathcal{B}_c$	$f_1(m_\pi^2)$				$g_1(m_\pi^2)$			
	MIT	LFQM(I)	LFQM(II)	QSR	MIT	LFQM(I)	LFQM(II)	QSR
$\Xi_{cc}^{++} \to \Xi_c^+$	0.577	0.920	0.734	0.664	0.222	0.259	0.172	0.095
$\Xi_{cc}^{++} \to \Xi_c^{\prime +}$	0.386	0.541	0.407	0.360	0.703	0.731	0.496	0.208
$\Xi_{cc}^{+} \to \Xi_c^0$	0.606	0.920	0.734	0.664	0.243	0.259	0.172	0.095
$\Xi_{cc}^{+} \to \Xi_c^{\prime 0}$	0.435	0.541	0.407	0.360	0.758	0.731	0.496	0.208
$\Omega_{cc}^{+} \to \Omega_c^0$	0.505	0.758		0.420	0.947	1.025		0.150

Nonfactorizable: pole model

- **Pole model:** initial baryon decays through a pole,
  - ➢s-wave amplitude: excited state ½⁻ should be taken into account.
  - ➢p-wave amplitude: ground state ½⁺ contributes.

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

requires more effort

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

Current algebra: soft pseudoscalar final state

- Soft-pseudoscalar limit
- Goldberger-Treiman relation

$$A^{\rm com} = -\frac{\sqrt{2}}{f_{P^a}}\langle \mathcal{B}_f|[Q_5^a, H_{\rm eff}^{\rm PV}]|\mathcal{B}_i\rangle = \frac{\sqrt{2}}{f_{P^a}}\underline{\langle \mathcal{B}_f|[Q^a, H_{\rm eff}^{\rm PC}]|\mathcal{B}_i\rangle} \Rightarrow \boxed{a_{\mathcal{B}'\mathcal{B}}}$$

$$B^{\rm ca} = \frac{\sqrt{2}}{f_{P^a}}\sum_{\mathcal{B}_n}\left[g^A_{\mathcal{B}_f\mathcal{B}_n}\frac{m_f+m_n}{m_i-m_n}a_{ni} + a_{fn}\frac{m_i+m_n}{m_f-m_n}g^A_{\mathcal{B}_n\mathcal{B}_i}\right]$$

limitation: only applicable in the decays to soft pseudoscalar modes

Baryon matrix elements & strong coupling

- The two nonperturbative quantities is model dependent.
- In MIT bag model

$$a_{\mathcal{B}'\mathcal{B}} \equiv \langle \mathcal{B}' | \mathcal{H}_{\rm eff}^{\rm PC} | \mathcal{B} \rangle = \frac{G_F}{2\sqrt{2}} V_{cs} V_{ud}^* c_- \langle \mathcal{B}' | O_- | \mathcal{B} \rangle,$$

$$\langle \Xi_c^+ | O_- | \Xi_{cc}^+ \rangle = 4\sqrt{6} X_2 (4\pi), \qquad \langle \Xi_c'^+ | O_- | \Xi_{cc}^+ \rangle = -\frac{4\sqrt{2}}{3} X_1 (4\pi),$$

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

$$g_{\Xi_{cc}^+ \Xi_{cc}^{++}}^{A(\pi^+)} = -\frac{1}{3}(4\pi Z_1), \qquad g_{\Xi_{cc}^+ \Xi_{cc}^+}^{A(\pi^0)} = \frac{1}{6}(4\pi Z_1), \qquad g_{\Xi_{cc}^+ \Xi_{cc}^+}^{A(\eta_8)} = -\frac{1}{6\sqrt{3}}(4\pi Z_1)$$

Results of doubly charmed baryon and discussion

Predictions to Cabibbo-allowed process

Channel	$A^{\rm fac}$	$A^{\rm com}$	$A^{\rm tot}$	$B^{\rm fac}$	$B^{\rm ca}$	$B^{\rm tot}$	$\mathcal{B}_{\rm theo}$	$\alpha_{\rm theo}$
$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$	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
$\Xi_{cc}^{++} \to \Sigma_c^{++} \overline{K}^0$	−2.67	0	−2.67	25.11	0	25.11	1.36	−0.89
$\Xi_{cc}^{+} \to \Xi_c^0 \pi^+$	8.52	10.79	19.31	−16.46	−0.08	−16.54	3.84	−0.31
$\Xi_{cc}^{+} \to \Xi_c^{\prime 0} \pi^+$	5.05	0.04	5.09	−52.31	−17.63	−69.94	1.55	−0.73
$\Xi_{cc}^{+} \to \Xi_c^+ \pi^0$	0	15.26	15.26	0	−10.49	−10.49	2.38	−0.25
$\Xi_{cc}^{+} \to \Xi_c^{\prime +} \pi^0$	0	0.06	0.06	0	−24.97	−24.97	0.17	−0.03
$\Xi_{cc}^{+} \to \Xi_c^+ \eta$	0	21.75	21.75	0	4.86	4.86	4.18	0.07
$\Xi_{cc}^{+} \to \Xi_c^{\prime +} \eta$	0	0.09	0.09	0	−17.87	−17.87	0.05	−0.07
$\Xi_{cc}^{+} \to \Sigma_c^{++} K^-$	0	0.07	0.07	0	22.14	22.14	0.13	0.04
$\Xi_{cc}^{+} \to \Lambda_c^+ \overline{K}^0$	−3.37	8.90	5.53	5.62	−0.07	5.55	0.31	0.40
$\Xi_{cc}^{+} \to \Sigma_c^+ \overline{K}^0$	−2.17	0.04	−2.14	19.37	15.64	35.02	0.38	−0.62
$\Xi_{cc}^{+} \to \Omega_c^0 K^+$	0	0.05	0.05	0	−22.98	−22.98	0.06	−0.03
$\Omega_{cc}^{+} \to \Omega_c^0 \pi^+$	5.71	0	5.71	−67.48	0	−67.48	3.96	−0.83
$\Omega_{cc}^{+} \to \Xi_c^+ \overline{K}^0$	2.62	−8.90	−6.28	−5.29	13.40	8.11	1.15	−0.45
$\Omega_{cc}^{+} \to \Xi_c^{\prime +} \overline{K}^0$	−1.68	−0.04	−1.72	17.44	0.06	17.50	0.29	−0.88

- Lifetime

$$\tau(\Xi_{cc}^+) = 0.45 \times 10^{-13} s$$

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

$$\tau(\Omega_{cc}^+) = 1.28 \times 10^{-13} s$$

H.-Y. Cheng, Y.L. Shi, PRD98(2018) 113005

- Essential role of nonfactorizable contribution

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

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

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

$$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+)_{\text{expt}} \approx (1.83 \pm 1.01)\%$$ vs $$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \approx 0.7\%$$

more promising: $\mathrm{B}(\Xi_{cc}^{++} \to \Xi_c^{\prime +} \pi^+) = 4.65\%$

Ξ_{cc}^{+} and Ω_{cc}^{+} : the undiscovered ones

- The failure of searching Ξ_{cc}^{+} through:

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

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

- The reason can be understood from our prediction:

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

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

- A suggested discovery 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, this work)

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

(J. Zou, FX, G. Meng, H.-Y. Cheng, 1910.13626, accepted by PRD)

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

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

Comparison

Mode	Our	Dhir *et al.* [8, 10]	Gutsche *et al.* [11, 13, 17]	Wang *et al.* [7]	Gerasimov *et al.* [14]	Ke *et al.* [18]	Shi *et al.* [12]
$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$	0.69	6.64 (N)	0.70	6.18	7.01	3.48 ± 0.46	3.1 ± 0.4
		9.19 (H)					
$\Xi_{cc}^{++} \to \Xi_c'^+ \pi^+$	4.65	5.39 (N)	3.03	4.33	5.85	1.96 ± 0.24	0.93 ± 0.19
		7.34 (H)					
$\Xi_{cc}^{++} \to \Sigma_c^{++} \overline{K}^0$	1.36	2.39 (N)	1.25				
		4.69 (H)					

- Our calculation agrees with Gutsche et al.
- For the mode of $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$, Dhir-Shama's result disagrees with ours due to the sign of baryon transition form factor.
- All the nonperturbative quantities are calculated in a consistent model, which guarantees the relative signs at least.

Summary

- All the CF weak decays of doubly charmed baryon has been calculated.
- Receiving large destructive contribution, $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ is predicted to be 0.7%, which is consistent with LHCb experiment in the lower end.
- A discovery mode for Ξ_{cc}^+ is suggested from $\Xi_{cc}^+ \to \Xi_c^0 \pi^+$, due to its large constructive interference in S-wave amplitude.
- The discovery mode for Ω_{cc}^+ is also suggested from $\Omega_{cc}^+ \to \Omega_c^0 \pi^+$, with large pure factorization contribution.