SU(3) symmetry and its breaking effective in charm baryon decays

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Outline

- Introduction
- SU(3) symmetry in semi-leptonic charm baryon decays
- SU(3) symmetry in non-leptonic charm baryon decays
- Recent progress in the charm baryon decays
- Conclusion and outlook

PART 01

Introduction

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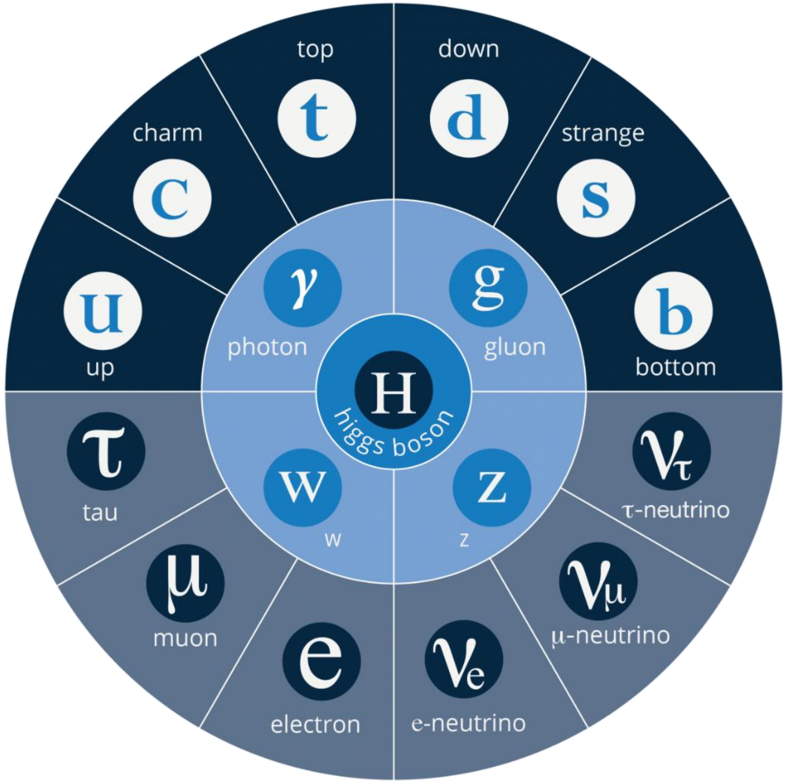
The Standard Model

- The Standard Medel has shown the grest success in the past decades.
- The particle physics has entered the era of high precision.
- The precise test of Standard Model (SM) will help us find new physics or new particles indirectly



Precision test Standard Model

- **Anomaly in B physics:**

$$R_K \equiv \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)} = 0.846^{+0.042+0.013}_{-0.039-0.012},$$

$$R_{K^*} \equiv \frac{\mathcal{B}(B \to K^*\mu^+\mu^-)}{\mathcal{B}(B \to K^*e^+e^-)} = 0.69^{+0.11}_{-0.07} \pm 0.05,$$

- **Precision test in electroweak model**

$$M_W = 80,433.5 \pm 9.4MeV$$

- **Precision test of CKM matrix**

Experiments that start from 2008

LHCb

Experiments that start collecting results recently

Belle II

Fermilab

Introduction

charm baryon in experiment

Measurement of $\Lambda_c \to pK^-\pi^+$ decay **PRD 103, 072004(2021)**

First observation of $\Lambda_c \to p\eta'$ **JHEP 03 (2022) 090**

First search for the weak radiative decays **arXiv:2206.12517**

$$\Lambda_c \to \Sigma^+\gamma \qquad \Xi_c^0 \to \Xi^0\gamma$$

R(Λ_c)=0.242 ± 0.026 ± 0.040 ± 0.059 **PRL 128 (2022)191803**

First observation of $\Lambda_c \to n\pi^+$ **PRL128(2022)142001**

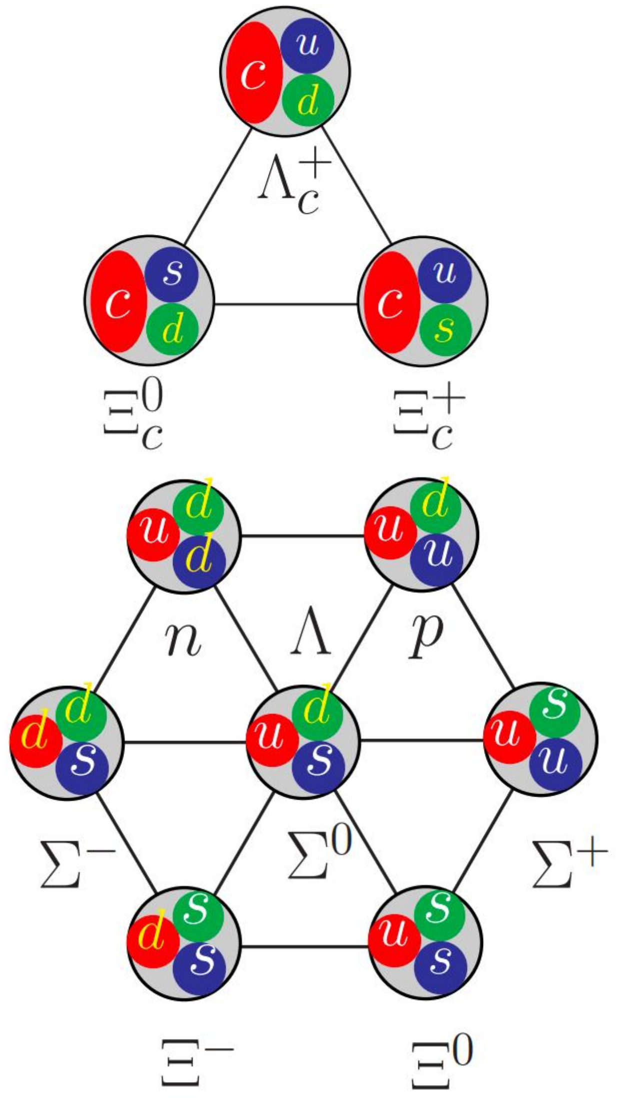
First observation of $\Lambda_c \to pK^-e^+\nu$ **arXiv:2207.11483**

SU(3) symmetry in QCD

- **The SU(3) symmetry is the symmetry of three light quarks (u,d,s) in hadron states.**

- **Using this symmetry we can easily avoide the non-perturbative parts and complicated parts in QCD.**

$$\Gamma(\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell) = \Gamma(\Xi_c^+ \to \Xi^0 \ell^+ \nu_\ell) = \frac{3}{2}\Gamma(\Lambda_c^+ \to \Lambda^0 \ell^+ \nu_\ell)$$



PART 02

SU(3) symmetry in semi-leptonic charm baryon decays

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SU(3) symmetry in semi-leptonic charm baryon decays

SU(3) relations

Amplitude: $H_{\lambda,\lambda_w} = a_1^{\lambda,\lambda_w} \times (T_{c\bar{3}})^{[ij]}(H_3)^k \epsilon_{ikm}(T_8)^m_j,$

expand

$\Lambda_c^+ \to \Lambda^0 \ell^+ \nu_\ell$	$-\sqrt{\frac{2}{3}} a_1^{\lambda,\lambda_w} V_{cs}^*$	$\Xi_c^+ \to \Xi^0 \ell^+ \nu_\ell$	$-a_1^{\lambda,\lambda_w} V_{cs}^*$
$\Lambda_c^+ \to n \ell^+ \nu_\ell$	$a_1^{\lambda,\lambda_w} V_{cd}^*$	$\Xi_c^0 \to \Sigma^- \ell^+ \nu_\ell$	$a_1^{\lambda,\lambda_w} V_{cd}^*$
$\Xi_c^+ \to \Sigma^0 \ell^+ \nu_\ell$	$\frac{a_1^{\lambda,\lambda_w} V_{cd}^*}{\sqrt{2}}$	$\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell$	$a_1^{\lambda,\lambda_w} V_{cs}^*$
$\Xi_c^+ \to \Lambda^0 \ell^+ \nu_\ell$	$-\frac{a_1^{\lambda,\lambda_w} V_{cd}^*}{\sqrt{6}}$		

$$\Gamma(\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell) = \Gamma(\Xi_c^+ \to \Xi^0 \ell^+ \nu_\ell) = \frac{3}{2}\Gamma(\Lambda_c^+ \to \Lambda^0 \ell^+ \nu_\ell)$$

Hamiltonian, initial state and final state in SU(3) matrix

$$T_{c\bar{3}} = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix},$$

$$T_8 = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda^0}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda^0}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\frac{2\Lambda^0}{\sqrt{6}} \end{pmatrix}$$

$$(H_3)^1 = 0, \quad (H_3)^2 = V_{cd}^*, \quad (H_3)^3 = V_{cs}^*$$

SU(3) symmetry in semi-leptonic charm baryon decays

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SU(3) relations

Channel	experiment data(%)	SU(3) symmetry(%)
$\Lambda_c \to \Lambda e^+ \nu_e$	$3.6 \pm 0.4[1]$	$\boxed{3.6 \pm 0.4}$
$\Lambda_c \to \Lambda \mu^+ \nu_\mu$	$3.5 \pm 0.5[1]$	$\boxed{3.5 \pm 0.5}$
$\Xi_c^+ \to \Xi^0 e^+ \nu_e$	$7 \pm 4[1]$	12.7 ± 1.35
$\Xi_c^0 \to \Xi^- e^+ \nu_e$	$1.54 \pm 0.35[2,3]$	4.10 ± 0.46
$\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu$	$1.27 \pm 0.44[3]$	3.98 ± 0.57

input data

2σ standard deviation
6σ standard deviation
5σ standard deviation

Very large SU(3) symmetry breaking effect

New Physics？

SU(3) symmetry in semi-leptonic decays

$$\mathcal{A}(B_c \to B_q \ell^+ \nu_\ell) = \frac{G_F}{\sqrt{2}} V_{cq}^* \langle B_q | \bar{q} \gamma^\mu (1-\gamma_5) c | B_c \rangle \langle \ell^+ \nu_\ell | \bar{\nu}_\ell \gamma^\nu (1-\gamma_5) \ell | 0 \rangle g_{\mu\nu},$$

$$g_{\mu\nu} = -\sum_{\lambda=0,\pm1} \epsilon_\mu^*(\lambda)\epsilon_\nu(\lambda) + \epsilon_\mu^*(t)\epsilon_\nu(t)$$

$$\epsilon_\mu(t) = \frac{q^\mu}{\sqrt{q^2}},$$

$$\mathcal{A}(B_c \to B_q \ell^+ \nu) = \frac{G_F}{\sqrt{2}} V_{cq}^* \left(-\sum_{\lambda_W=0,\pm1} H_{\lambda,\lambda_W} L_{\lambda_W} + H_{\lambda,t} L_t \right)$$

$$H_{\lambda,\lambda_W} = \langle B_q | \bar{q} \gamma^\mu (1-\gamma_5) c | B_c \rangle \epsilon_\mu^*(\lambda_W),$$

$$L_{\lambda_W} = \langle \ell^+ \nu_\ell | \bar{\nu}_\ell \gamma^\nu (1-\gamma_5) \ell | 0 \rangle \epsilon_\nu(\lambda_W),$$

SU(3) matrix

$$H_{\lambda,\lambda_W} = a_1^{\lambda,\lambda_W} \times (T_{c\bar{3}})^{[ij]} (H_3)^k \epsilon_{ikm} (T_8)^m_j$$

The SU(3) amplitude in semi-leptonic decays

Channel	Amplitude
$\Lambda_c^+ \to \Lambda^0 \ell^+ \nu_\ell$	$-\sqrt{\frac{2}{3}} a_1^{\lambda,\lambda_W} V_{cs}^*$
$\Lambda_c^+ \to n \ell^+ \nu_\ell$	$a_1^{\lambda,\lambda_W} V_{cd}^*$
$\Xi_c^+ \to \Sigma^0 \ell^+ \nu_\ell$	$\frac{a_1^{\lambda,\lambda_W} V_{cd}^*}{\sqrt{2}}$
$\Xi_c^+ \to \Lambda^0 \ell^+ \nu_\ell$	$-\frac{a_1^{\lambda,\lambda_W} V_{cd}^*}{\sqrt{6}}$
$\Xi_c^+ \to \Xi^0 \ell^+ \nu_\ell$	$-a_1^{\lambda,\lambda_W} V_{cs}^*$
$\Xi_c^0 \to \Sigma^- \ell^+ \nu_\ell$	$a_1^{\lambda,\lambda_W} V_{cd}^*$
$\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell$	$a_1^{\lambda,\lambda_W} V_{cs}^*$

SU(3) symmetry in semi-leptonic decays

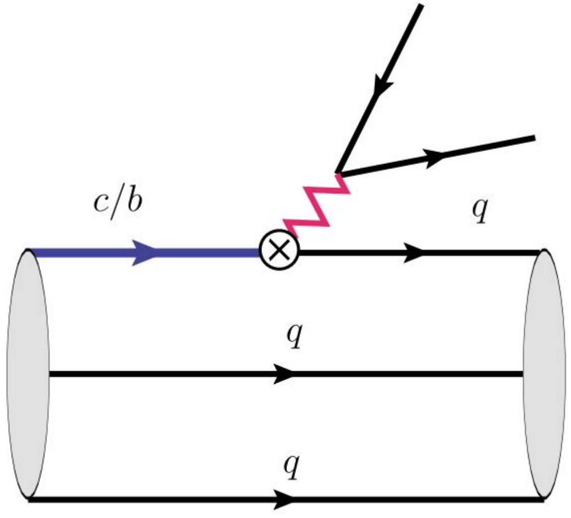
$$a_1^{\lambda,\lambda_W} = \bar{u}(\lambda)\left[\boxed{f_1\gamma^\mu}\boxed{+ f_2\frac{i\sigma^{\nu\mu}}{M_i}q^\nu + f_3\frac{q^\mu}{M_i}}\right]u(\lambda_i)\epsilon^*_\mu(\lambda_W) - \bar{u}(\lambda)\left[\boxed{f_1'\gamma^\mu}\boxed{+ f_2'\frac{i\sigma^{\nu\mu}}{M_i}q^\nu + f_3'\frac{q^\mu}{M_i}}\right]\gamma_5 u(\lambda_i)\epsilon^*_\mu(\lambda_W).$$

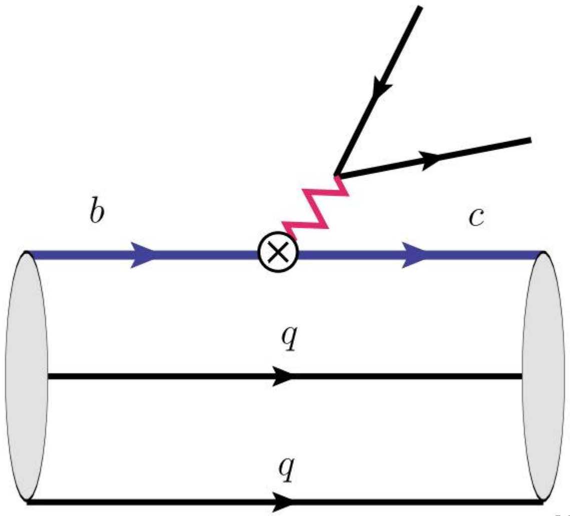
dominant suppressed by 1/mb

$$f_i(q^2) = \frac{f_i}{1-\frac{q^2}{m_p^2}},$$

$$\frac{d\Gamma}{dq^2} = \frac{(m_\ell^2-q^2)^2\sqrt{\lambda}G_F^2V_{SU(3)}^2}{284\pi^3M^3(q^2)^3}\Big[(f_1(q^2))^2\times(3s_+m_\ell^2\left(q^2+s_-\right)+s_-\left(3q^2+s_+\right)\left(m_\ell^2+2q^2\right)) +(f_1'(q^2))^2\times(3s_-m_\ell^2\left(q^2+s_+\right)+s_+\left(3q^2+s_-\right)\left(m_\ell^2+2q^2\right))\Big].$$

$s_- = (M-M')^2-q^2,\ s_+ = (M+M')^2-q^2$ $\sqrt{\lambda} = \sqrt{s_-s_+}$





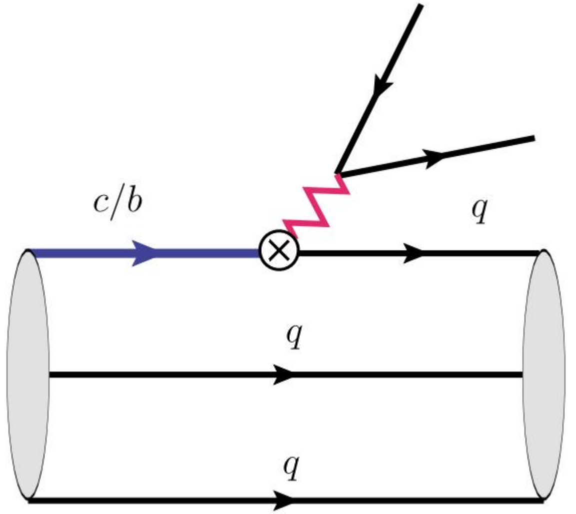
SU(3) symmetry in semi-leptonic charm baryon decays

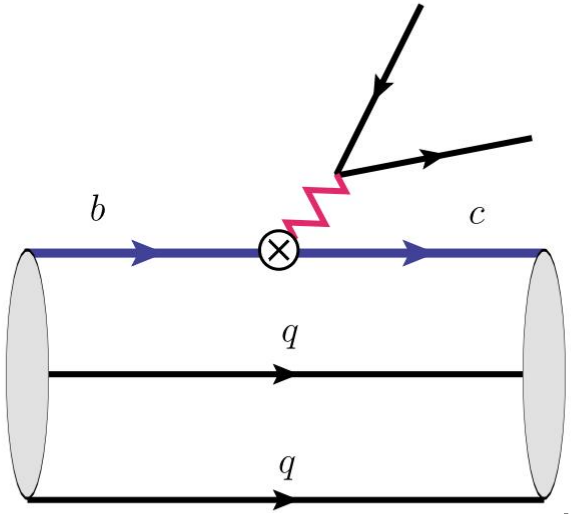
SU(3) symmetry in semi-leptonic decays

Table 3
Experimental and fit data of anti-triplet charmed baryons decays.

Channel	Branching ratio (%)	
	Experimental data	Fit data
$\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$	3.60 ± 0.40	1.94 ± 0.18
$\Lambda_c^+ \to \Lambda^0 \mu^+ \nu_\mu$	3.5 ± 0.5	1.87 ± 0.176
$\Xi_c^+ \to \Xi^0 e^+ \nu_e$	2.3 ± 1.5	6.53 ± 0.60
$\Xi_c^0 \to \Xi^- e^+ \nu_e$	1.54 ± 0.35	2.17 ± 0.20
$\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu$	1.27 ± 0.44	2.09 ± 0.19
$\chi^2/d.o.f = 14.3$	$f_1 = 1.05 \pm 0.30$	$f_1' = 0.11 \pm 0.95$

Need to consider the SU(3) symmetry breaking effect





SU(3) symmetry breaking from the quark mass

SU(3) symmetry breaking

$$M=\begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix} \sim m_s \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} = m_s \times \boxed{\omega.}$$

$$\begin{aligned} H_{\lambda,\lambda_W} = \quad & a_1^{\lambda,\lambda_W} \times (T_{c\bar{3}})^{[ij]}(H_3)^k \epsilon_{ikm}(T_8)^m_j + a_2^{\lambda,\lambda_W} \times (T_{c\bar{3}})^{[in]}(H_3)^k \epsilon_{ikm}(T_8)^m_j \omega^j_n \\ & + a_3^{\lambda,\lambda_W} \times (T_{c\bar{3}})^{[in]}(H_3)^k \epsilon_{kjm}(T_8)^m_i \omega^j_n + a_4^{\lambda,\lambda_W} \times (T_{c\bar{3}})^{[in]}(H_3)^k \epsilon_{jim}(T_8)^m_k \omega^j_n \\ & + a_5^{\lambda,\lambda_W} \times (T_{c\bar{3}})^{[ij]}(H_3)^k \epsilon_{inm}(T_8)^m_j \omega^n_k . \end{aligned}$$

Amplitude:

$\Lambda_c^+ \to \Lambda^0 l^+ \nu$	$-\sqrt{\frac{2}{3}}(a_1^{\lambda,\lambda_w} + a_5^{\lambda,\lambda_w})V^*_{\rm cs}$	$\Xi_c^+ \to \Xi^0 \ell^+ \nu_\ell$	$-(a_1^{\lambda,\lambda_w} + a_2^{\prime\lambda,\lambda_w} - a_4^{\prime\lambda,\lambda_w} + a_5^{\lambda,\lambda_w})V^*_{\rm cs}$
$\Lambda_c^+ \to n l^+ \nu$	$a_1 V^*_{\rm cd}$	$\Xi_c^0 \to \Sigma^- \ell^+ \nu_\ell$	$(a_1^{\lambda,\lambda_w} + a_3^{\lambda,\lambda_w} - a_4^{\prime\lambda,\lambda_w})V^*_{\rm cd}$
$\Xi_c^+ \to \Sigma^0 \ell^+ \nu_\ell$	$\frac{(a_1^{\lambda,\lambda_w} + a_3^{\lambda,\lambda_w} - a_4^{\prime\lambda,\lambda_w})V^*_{\rm cd}}{\sqrt{2}}$	$\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell$	$(a_1^{\lambda,\lambda_w} + a_2^{\prime\lambda,\lambda_w} - a_4^{\prime\lambda,\lambda_w} + a_5^{\lambda,\lambda_w})V^*_{\rm cs}$
$\Xi_c^+ \to \Lambda^0 \ell^+ \nu_\ell$	$-\frac{(a_1^{\lambda,\lambda_w} + 2a_2^{\prime\lambda,\lambda_w} - a_3^{\lambda,\lambda_w} - a_4^{\prime\lambda,\lambda_w})V^*_{\rm cd}}{\sqrt{6}}$		

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global fit

Helicity amplitude:

$$a_1^{\lambda,\lambda_W} + a_5^{\lambda,\lambda_W} = f_1(q^2) \times \bar{u}(\lambda)\gamma^\mu u(\lambda_i)\epsilon_\mu^*(\lambda_W) - f_1'(q^2) \times \bar{u}(\lambda)\gamma^\mu\gamma_5 u(\lambda_i)\epsilon_\mu^*(\lambda_W),$$
$$a_2^{\lambda,\lambda_W} - a_4^{\lambda,\lambda_W} = \delta f_1(q^2) \times \bar{u}(\lambda)\gamma^\mu u(\lambda_i)\epsilon_\mu^*(\lambda_W) - \delta f_1'(q^2) \times \bar{u}(\lambda)\gamma^\mu\gamma_5 u(\lambda_i)\epsilon_\mu^*(\lambda_W),$$
$$a_3^{\lambda,\lambda_W} = \Delta f_1(q^2) \times \bar{u}(\lambda)\gamma^\mu u(\lambda_i)\epsilon_\mu^*(\lambda_W) - \Delta f_1'(q^2) \times \bar{u}(\lambda)\gamma^\mu\gamma_5 u(\lambda_i)\epsilon_\mu^*(\lambda_W),$$

$$f_i(q^2) = \frac{f_i}{1-\frac{q^2}{m_p^2}},$$

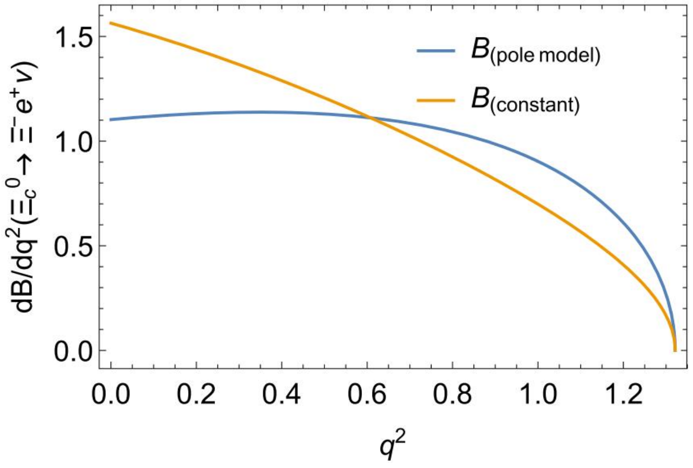
Pole model

$$f_i(q^2) = f_i$$

Constant

	Experimental data	Fit data (pole model)	Fit data (constant).
$\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$	3.6 ± 0.4	3.61 ± 0.32	3.62 ± 0.32
$\Lambda_c^+ \to \Lambda^0 \mu^+ \nu_\mu$	3.5 ± 0.5	3.48 ± 0.30	3.45 ± 0.30
$\Xi_c^+ \to \Xi^0 e^+ \nu_e$	2.3 ± 1.5	3.89 ± 0.73	3.92 ± 0.73
$\Xi_c^0 \to \Xi^- e^+ \nu_e$	1.54 ± 0.35	1.29 ± 0.24	1.31 ± 0.24
$\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu$	1.27 ± 0.44	1.24 ± 0.23	1.24 ± 0.23
Fit parameter	$f_1 = 1.01 \pm 0.87,\ \delta f_1 = -0.51 \pm 0.92$		$\chi^2/d.o.f = 1.6$
(Pole model)	$f_1' = 0.60 \pm 0.49,\ \delta f_1' = -0.23 \pm 0.41$		
Fit parameter	$f_1 = 0.86 \pm 0.92,\ \delta f_1 = -0.25 \pm 0.88$		$\chi^2/d.o.f = 1.9$
(Constant)	$f_1' = 0.85 \pm 0.36,\ \delta f_1' = -0.43 \pm 0.50$		

The differential branching ratio with two different treatments of form factors



SU(3) symmetry in semi-leptonic charm baryon decays

$\Xi_c^{0/+} - \Xi_c^{\prime 0/+}$ mixing effect

Symmetry breaking matrix:

$$\omega = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

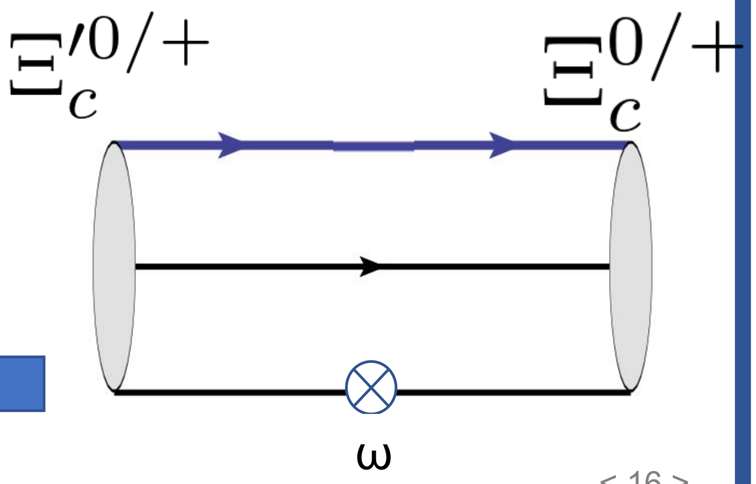
Amplitude:

$$H_{\lambda,\lambda_w}(T_{c\bar{3}}\omega \to T_{c6}) = d^{\lambda,\lambda_w} \times (T_{c\bar{3}})^{[ij]}\omega_j^k (T_{c6})_{\{ki\}}.$$

$$T_{c6} = \begin{pmatrix} \Sigma_c^{++} & \frac{\Sigma_c^{+}}{\sqrt{2}} & \frac{\Xi_c^{+\prime}}{\sqrt{2}} \\ \frac{\Sigma_c^{+}}{\sqrt{2}} & \Sigma_c^{0} & \frac{\Xi_c^{0\prime}}{\sqrt{2}} \\ \frac{\Xi_c^{+\prime}}{\sqrt{2}} & \frac{\Xi_c^{0\prime}}{\sqrt{2}} & \Omega_c^{0} \end{pmatrix}$$

The anti-triplet and sextet and mixing by the SU(3) symmetry breaking effect ω.

$$\Xi_c^{0/+mass} = \cos\theta \times \Xi_c^{0/+} + \sin\theta \times \Xi_c^{0/+\prime}$$



SU(3) symmetry in semi-leptonic charm baryon decays

$\Xi_c^{0/+} - \Xi_c^{\prime 0/+}$ mixing effect

Amplitude of sextet semi-leptonic decays:

$$
\begin{aligned}
H_{\lambda,\lambda_W} = &\boxed{c_1^{\lambda,\lambda_w} \times (T_{c6})^{\{ij\}}(H_3)^k \epsilon_{ikm}(T_8)^m_j} + c_2^{\lambda,\lambda_w} \times (T_{c6})^{\{in\}}(H_3)^k \epsilon_{ikm}(T_8)^m_j \omega^j_n \\
&+ c_3^{\lambda,\lambda_w} \times (T_{c6})^{\{in\}}(H_3)^k \epsilon_{kjm}(T_8)^m_i \omega^j_n + c_4^{\lambda,\lambda_w} \times (T_{c6})^{\{in\}}(H_3)^k \epsilon_{jim}(T_8)^m_k \omega^j_n \\
&+ c_5^{\lambda,\lambda_w} \times (T_{c6})^{\{ij\}}(H_3)^k \epsilon_{inm}(T_8)^m_j \omega^n_k.
\end{aligned}
$$

Amplitude after sextex and anti-triplet mixing: $\Xi_c^{0mass} \to \Xi^- \ell^+ \nu_\ell$

$$
H^{mass}_{\lambda,\lambda_W} \propto V^*_{cs}(a_1^{\lambda,\lambda_w} + a_2^{\lambda,\lambda_w} - a_4^{\lambda,\lambda_w} + a_5^{\lambda,\lambda_w} + \frac{c_1^{\lambda,\lambda_w}}{\sqrt{2}}\theta),
$$

SU(3) amplitude

$\Lambda_c^+ \to \Lambda^0 l^+ \nu$	$-\sqrt{\frac{2}{3}}(a_1^{\lambda,\lambda_w} + a_5^{\lambda,\lambda_w})V^*_{cs}$
$\Lambda_c^+ \to n l^+ \nu$	$a_1 V^*_{cd}$
$\Xi_c^+ \to \Sigma^0 \ell^+ \nu_\ell$	$\frac{(a_1^{\lambda,\lambda_w} + a_3^{\lambda,\lambda_w} - a_4^{\lambda,\lambda_w} - \frac{c_1^{\lambda,\lambda_w}}{\sqrt{2}}\theta)V^*_{cd}}{\sqrt{2}}$
$\Xi_c^+ \to \Lambda^0 \ell^+ \nu_\ell$	$-\frac{(a_1^{\lambda,\lambda_w} + 2a_2^{\lambda,\lambda_w} - a_3^{\lambda,\lambda_w} - a_4^{\lambda,\lambda_w} + \frac{3c_1^{\lambda,\lambda_w}}{\sqrt{2}}\theta)V^*_{cd}}{\sqrt{6}}$
$\Xi_c^+ \to \Xi^0 \ell^+ \nu_\ell$	$-(a_1^{\lambda,\lambda_w} + a_2^{\lambda,\lambda_w} - a_4^{\lambda,\lambda_w} + a_5^{\lambda,\lambda_w} + \frac{c_1^{\lambda,\lambda_w}}{\sqrt{2}}\theta)V^*_{cs}$
$\Xi_c^0 \to \Sigma^- \ell^+ \nu_\ell$	$(a_1^{\lambda,\lambda_w} + a_3^{\lambda,\lambda_w} - a_4^{\lambda,\lambda_w} - \frac{c_1^{\lambda,\lambda_w}}{\sqrt{2}}\theta)V^*_{cd}$
$\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell$	$(a_1^{\lambda,\lambda_w} + a_2^{\lambda,\lambda_w} - a_4^{\lambda,\lambda_w} + a_5^{\lambda,\lambda_w} + \frac{c_1^{\lambda,\lambda_w}}{\sqrt{2}}\theta)V^*_{cs}$

SU(3) symmetry in semi-leptonic charm baryon decays

$\Xi_c^{0/+} - \Xi_c^{\prime 0/+}$ mixing effect

Redefine the helicity amplitude:

$$a_4^{\prime\lambda,\lambda_w} = a_4^{\lambda,\lambda_w} + c_1^{\lambda,\lambda_w}\theta/\sqrt{2} \qquad a_2^{\prime\lambda,\lambda_w} = a_2^{\lambda,\lambda_w} + \sqrt{2}c_1^{\lambda,\lambda_w}\theta$$

Absorb the θ and c_1 into a_2 and a_4

	Experimental data	Fit data (pole model)	Fit data (constant).
$\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$	3.6 ± 0.4	3.61 ± 0.32	3.62 ± 0.32
$\Lambda_c^+ \to \Lambda^0 \mu^+ \nu_\mu$	3.5 ± 0.5	3.48 ± 0.30	3.45 ± 0.30
$\Xi_c^+ \to \Xi^0 e^+ \nu_e$	2.3 ± 1.5	3.89 ± 0.73	3.92 ± 0.73
$\Xi_c^0 \to \Xi^- e^+ \nu_e$	1.54 ± 0.35	1.29 ± 0.24	1.31 ± 0.24
$\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu$	1.27 ± 0.44	1.24 ± 0.23	1.24 ± 0.23
Fit parameter (Pole model)		$f_1 = 1.01 \pm 0.87,\ \delta f_1 = -0.51 \pm 0.92$ $f_1' = 0.60 \pm 0.49,\ \delta f_1' = -0.23 \pm 0.41$	$\chi^2/d.o.f = 1.6$
Fit parameter (Constant)		$f_1 = 0.86 \pm 0.92,\ \delta f_1 = -0.25 \pm 0.88$ $f_1' = 0.85 \pm 0.36,\ \delta f_1' = -0.43 \pm 0.50$	$\chi^2/d.o.f = 1.9$

Δf_1 and $\Delta f_1'$ cannot be constrained due to the lack of experimental data,

SU(3) amplitude

$\Lambda_c^+ \to \Lambda^0 l^+ \nu$	$-\sqrt{\frac{2}{3}}(a_1^{\lambda,\lambda_w} + a_5^{\lambda,\lambda_w})V_{\rm cs}^*$
$\Lambda_c^+ \to n l^+ \nu$	$a_1 V_{\rm cd}^*$
$\Xi_c^+ \to \Sigma^0 \ell^+ \nu_\ell$	$\frac{(a_1^{\lambda,\lambda_w} + a_3^{\lambda,\lambda_w} - a_4^{\lambda,\lambda_w} - \frac{c_1^{\lambda,\lambda_w}}{\sqrt{2}}\theta)V_{\rm cd}^*}{\sqrt{2}}$
$\Xi_c^+ \to \Lambda^0 \ell^+ \nu_\ell$	$-\frac{(a_1^{\lambda,\lambda_w} + 2a_2^{\lambda,\lambda_w} - a_3^{\lambda,\lambda_w} - a_4^{\lambda,\lambda_w} + \frac{3c_1^{\lambda,\lambda_w}}{\sqrt{2}}\theta)V_{\rm cd}^*}{\sqrt{6}}$
$\Xi_c^+ \to \Xi^0 \ell^+ \nu_\ell$	$-(a_1^{\lambda,\lambda_w} + a_2^{\lambda,\lambda_w} - a_4^{\lambda,\lambda_w} + a_5^{\lambda,\lambda_w} + \frac{c_1^{\lambda,\lambda_w}}{\sqrt{2}}\theta)V_{\rm cs}^*$
$\Xi_c^0 \to \Sigma^- \ell^+ \nu_\ell$	$(a_1^{\lambda,\lambda_w} + a_3^{\lambda,\lambda_w} - a_4^{\lambda,\lambda_w} - \frac{c_1^{\lambda,\lambda_w}}{\sqrt{2}}\theta)V_{\rm cd}^*$
$\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell$	$(a_1^{\lambda,\lambda_w} + a_2^{\lambda,\lambda_w} - a_4^{\lambda,\lambda_w} + a_5^{\lambda,\lambda_w} + \frac{c_1^{\lambda,\lambda_w}}{\sqrt{2}}\theta)V_{\rm cs}^*$

More data!

SU(3) symmetry in semi-leptonic charm baryon decays

Prodiction

$$\mathcal{B}(\Lambda_c^+ \to n e^+ \nu_e) = (0.520 \pm 0.046)\%$$
$$\mathcal{B}(\Lambda_c^+ \to n \mu^+ \nu_\mu) = (0.506 \pm 0.045)\%$$

$$\mathcal{B}(\Xi_c^+ \to \Sigma^0 e^+ \nu_e) = (0.496 \pm 0.046)\%,$$
$$\mathcal{B}(\Xi_c^+ \to \Lambda^0 e^+ \nu_e) = (0.067 \pm 0.013)\%,$$
$$\mathcal{B}(\Xi_c^0 \to \Sigma^- e^+ \nu_e) = (0.333 \pm 0.031)\%,$$
$$\mathcal{B}(\Xi_c^+ \to \Sigma^0 \mu^+ \nu_\mu) = (0.481 \pm 0.044)\%,$$
$$\mathcal{B}(\Xi_c^+ \to \Lambda^0 \mu^+ \nu_\mu) = (0.069 \pm 0.0213)\%,$$
$$\mathcal{B}(\Xi_c^0 \to \Sigma^- \mu^+ \nu_\mu) = (0.323 \pm 0.029)\%.$$

Scenarios

Assuming a_5 has no contributions

Assuming a_2 a_3 and a_5 has no contributions

PART 03

• SU(3) symmetry in non-leptonic charm baryon decays

TSUNG-DAO LEE INSTITUTE

The non-leptonic charm baryon two body decays

Belle collaboration | **BESIII collaboration**

2021:

$$\mathcal{B}(\Xi_c^0 \to \Lambda K_S^0) = (4.12 \pm 0.14 \pm 0.21 \pm 1.19) \times 10^{-3},$$
$$\mathcal{B}(\Xi_c^0 \to \Sigma^0 K_S^0) = (0.69 \pm 0.10 \pm 0.08 \pm 0.20) \times 10^{-3},$$
$$\mathcal{B}(\Xi_c^0 \to \Sigma^+ K^-) = (2.21 \pm 0.13 \pm 0.19 \pm 0.64) \times 10^{-3}.$$

2022:

$$\mathcal{B}(\Lambda_c^+ \to p\eta') = (4.73 \pm 0.82 \pm 0.47 \pm 0.24) \times 10^{-4},$$
$$\mathcal{B}(\Lambda_c^+ \to \Lambda^0 K^+) = (6.57 \pm 0.17 \pm 0.11 \pm 0.35) \times 10^{-4},$$
$$\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+) = (3.58 \pm 0.19 \pm 0.06 \pm 0.19) \times 10^{-4},$$
$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ \eta) = (3.14 \pm 0.35 \pm 0.11 \pm 0.25) \times 10^{-3},$$
$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ \eta') = (4.16 \pm 0.75 \pm 0.21 \pm 0.33) \times 10^{-3},$$

$$\mathcal{B}(\Lambda_c^+ \to n\pi^+) = (6.6 \pm 1.2 \pm 0.4) \times 10^{-4},$$
$$\mathcal{B}(\Lambda_c^+ \to p\eta') = (5.62^{+2.46}_{-2.04} \pm 0.26) \times 10^{-4},$$
$$\mathcal{B}(\Lambda_c^+ \to \Lambda^0 K^+) = (6.21 \pm 0.44 \pm 0.26 \pm 0.34) \times 10^{-4},$$
$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0) = (4.8 \pm 1.4 \pm 0.2 \pm 0.3) \times 10^{-4},$$
$$\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+) = (4.7 \pm 0.9 \pm 0.1 \pm 0.3) \times 10^{-4}.$$

The non-leptonic charm baryon two body decays have received a lot of experimental attention

The non-leptonic charm baryon two body decays

Hadron states:

$$T_{c\bar{3}}=\begin{pmatrix}0 & \Lambda_c^+ & \Xi_c^+\\ -\Lambda_c^+ & 0 & \Xi_c^0\\ -\Xi_c^+ & -\Xi_c^0 & 0\end{pmatrix},\quad T_8=\begin{pmatrix}\frac{\Sigma^0}{\sqrt{2}}+\frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p\\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}}+\frac{\Lambda}{\sqrt{6}} & n\\ \Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}}\end{pmatrix},\quad P=\begin{pmatrix}\frac{\pi^0+\eta_q}{\sqrt{2}} & \pi^+ & K^+\\ \pi^- & \frac{-\pi^0+\eta_q}{\sqrt{2}} & K^0\\ K^- & \bar{K}^0 & \eta_s\end{pmatrix}.$$

Hamiltonian:

$$\mathcal{H}_{\rm eff}=\sum_{i=1,2}\frac{G_F}{\sqrt{2}}C_i(V_{cs}V_{ud}^*O_i^{s\bar{d}u}+V_{cq}V_{uq}^*O_i^{q\bar{q}u}+V_{cd}V_{us}^*O_i^{d\bar{s}u})+\text{h.c.},\quad q=s,d,$$

$$O_1^{q_1\bar{q}_2q_3}=(\bar{q}_{1\alpha}c_\beta)_{V-A}(\bar{q}_{3\beta}q_{2\alpha})_{V-A},\quad O_2^{q_1\bar{q}_2q_3}=(\bar{q}_{1\alpha}c_\alpha)_{V-A}(\bar{q}_{3\beta}q_{2\beta})_{V-A}.$$

$$\boxed{3\otimes\bar{3}\otimes 3=3\oplus 3\oplus\bar{6}\oplus 15.}$$

$$\boxed{\begin{aligned}&V_{cs}^*V_{ud}\approx 1\\ &V_{cs}^*V_{us}(-V_{cd}^*V_{ud})\approx\sin\theta=0.2265\pm 0.00048\\ &V_{cd}^*V_{us}\approx\sin^2\theta\end{aligned}}$$

$$(H_{\bar{6}})_2^{31}=-(H_{\bar{6}})_2^{13}=1,\quad (H_{15})_2^{31}=(H_{15})_2^{13}=1$$

$$(H_{\bar{6}})_3^{31}=-(H_{\bar{6}})_3^{13}=(H_{\bar{6}})_2^{12}=-(H_{\bar{6}})_2^{21}=\sin\theta,$$
$$(H_{15})_3^{31}=(H_{15})_3^{13}=-(H_{15})_2^{21}=-(H_{15})_2^{12}=\sin\theta$$

$$(H_{\bar{6}})_3^{21}=-(H_{\bar{6}})_3^{12}=\sin^2\theta,\quad (H_{15})_3^{21}=(H_{15})_3^{12}=\sin^2\theta.$$

The SU(3) analyse

$$
\begin{aligned}
\mathcal{M} = {} & a_{15}(T_{c\bar{3}})_i(H_{\overline{15}})^{\{ik\}}_j(\overline{T_8})^j_k P^l_l + b_{15}(T_{c\bar{3}})_i(H_{\overline{15}})^{\{ik\}}_j(\overline{T_8})^l_k P^j_l \\
& + c_{15}(T_{c\bar{3}})_i(H_{\overline{15}})^{\{ik\}}_j(\overline{T_8})^j_l P^l_k + d_{15}(T_{c\bar{3}})_i(H_{\overline{15}})^{\{jk\}}_l(\overline{T_8})^l_j P^i_k \\
& + e_{15}(T_{c\bar{3}})_i(H_{\overline{15}})^{\{jk\}}_l(\overline{T_8})^i_j P^l_k + a_6(T_{c\bar{3}})^{[ik]}(H_{\overline{6}})_{\{ij\}}(\overline{T_8})^j_k P^l_l \\
& + b_6(T_{c\bar{3}})^{[ik]}(H_{\overline{6}})_{\{ij\}}(\overline{T_8})^l_k P^j_l + c_6(T_{c\bar{3}})^{[ik]}(H_{\overline{6}})_{\{ij\}}(\overline{T_8})^j_l P^l_k \\
& + d_6(T_{c\bar{3}})^{[kl]}(H_{\overline{6}})_{\{ij\}}(\overline{T_8})^i_k P^j_l .
\end{aligned}
$$

SU(3) relations

$$\mathcal{M}(\Lambda_c^+ \to \Sigma^0\pi^+) = -\mathcal{M}(\Lambda_c^+ \to \Sigma^+\pi^0),$$

$$\mathcal{M}(\Lambda_c^+ \to \Sigma^+ K^0) = \mathcal{M}(\Xi_c^+ \to p\bar{K}^0),$$

$$\mathcal{M}(\Lambda_c^+ \to n\pi^+) = \mathcal{M}(\Xi_c^+ \to \Xi^0 K^+),$$

$$\mathcal{M}(\Xi_c^0 \to n\bar{K}^0) = -\mathcal{M}(\Xi_c^0 \to \Xi^0 K^0),$$

$$\mathcal{M}(\Lambda_c^+ \to nK^+) = -\sin^2\theta\,\mathcal{M}(\Xi_c^+ \to \Xi^0\pi^+),$$

$$\mathcal{M}(\Xi_c^+ \to n\pi^+) = -\sin^2\theta\,\mathcal{M}(\Lambda_c^+ \to \Xi^0 K^+),$$

$$\mathcal{M}(\Xi_c^+ \to \Sigma^+ K^0) = -\sin^2\theta\,\mathcal{M}(\Lambda_c^+ \to p\bar{K}^0),$$

$$\mathcal{M}(\Xi_c^+ \to \Sigma^+ \bar{K}^0) = -\frac{1}{\sin^2\theta}\mathcal{M}(\Lambda_c^+ \to pK^0),$$

$$\mathcal{M}(\Xi_c^0 \to \Sigma^- K^+) = -\sin\theta\,\mathcal{M}(\Xi_c^0 \to \Sigma^-\pi^+) = \sin\theta\,\mathcal{M}(\Xi_c^0 \to \Xi^- K^+) = \sin^2\theta\,\mathcal{M}(\Xi_c^0 \to \Xi^-\pi^+),$$

$$\mathcal{M}(\Xi_c^0 \to p\pi^-) = \sin\theta\,\mathcal{M}(\Xi_c^0 \to pK^-) = -\sin\theta\,\mathcal{M}(\Xi_c^0 \to \Sigma^+\pi^-) = \sin^2\theta\,\mathcal{M}(\Xi_c^0 \to \Sigma^+ K^-).$$

The SU(3) analysis

Experiment data(%)

$$\Gamma(\Lambda_c^+ \to \Sigma^0\pi^+) = \Gamma(\Lambda_c^+ \to \Sigma^+\pi^0)$$

$\Lambda_c^+ \to \Sigma^0\pi^+$	1.29 ± 0.07
$\Lambda_c^+ \to \Sigma^+\pi^0$	1.25 ± 0.10

$$\Gamma(\Xi_c^0 \to \Xi^- K^+) = \sin^2\theta\Gamma(\Xi_c^0 \to \Xi^-\pi^+)$$

$\Xi_c^0 \to \Xi^-\pi^+$	1.43 ± 0.32
$\Xi_c^0 \to \Xi^- K^+$	0.039 ± 0.012

prediction: $\mathcal{B}(\Xi_c^0 \to \Xi^- K^+) = (7.3 \pm 1.6) \times 10^{-4}$

3σ standard deviation

We need further analysis

SU(3) analysis

Helicity amplitude:

$$q_6 = G_F \bar{u}(f_6^q - g_6^q \gamma_5)u, \qquad q = a, b, c, d,$$
$$q_{15} = G_F \bar{u}(f_{15}^q - g_{15}^q \gamma_5)u, \quad q = a, b, c, d, e,$$

Observations:

$$\frac{d\Gamma}{d\cos\theta_M} = \frac{G_F^2 |\vec{p}_{B_n}|(E_{B_n} + M_{B_n})}{8\pi M_{B_c}}(|F|^2 + \kappa^2 |G|^2)(1 + \alpha \hat{\omega}_i \cdot \hat{p}_{B_n})$$

$$\alpha = 2\mathrm{Re}(\mathrm{F} * \mathrm{G})\kappa/(|\mathrm{F}|^2 + \kappa^2|\mathrm{G}|^2), \kappa = |\tilde{\mathrm{p}}_{\mathrm{B_n}}|/(\mathrm{E}_{\mathrm{B_n}} + \mathrm{M}_{\mathrm{B_n}}).$$

$$\kappa^2 = \frac{(M_{B_c} - M_{B_n})^2 - M_M^2}{(M_{B_c} + M_{B_n})^2 - M_M^2}$$

9 SU(3) amplitude and 18 form fators!

Depending on the specific processes, the F and G linear functions of f_i and g_i are the scalar and peseudoscalar form factors, respectively.

SU(3) symmetry in non-leptonic charm baryon decays

Experiment data

$\Lambda_c^+ \to pK_S^0$	1.59 ± 0.08
$\Lambda_c^+ \to p\eta$	0.124 ± 0.03
$\Lambda_c^+ \to \Lambda\pi^+$	1.3 ± 0.07
$\Lambda_c^+ \to \Sigma^0\pi^+$	1.29 ± 0.07
$\Lambda_c^+ \to \Sigma^+\pi^0$	1.25 ± 0.10
$\Lambda_c^+ \to \Xi^0 K^+$	0.55 ± 0.07
$\Lambda_c^+ \to \Lambda K^+$	0.061 ± 0.012
$\Lambda_c^+ \to \Sigma^+\eta$	0.44 ± 0.20
$\Lambda_c^+ \to \Sigma^+\eta'$	1.5 ± 0.60
$\Lambda_c^+ \to \Sigma^0 K^+$	0.052 ± 0.008
$\Xi_c^+ \to \Xi^0\pi^+$	1.6 ± 0.8
$\Xi_c^0 \to \Lambda K_S^0$	0.334 ± 0.067
$\Xi_c^0 \to \Xi^-\pi^+$	1.43 ± 0.32
$\Xi_c^0 \to \Xi^- K^+$	0.039 ± 0.012
$\Xi_c^0 \to \Sigma^0 K_S^0$	0.069 ± 0.024
$\Xi_c^0 \to \Sigma^+ K^-$	0.221 ± 0.068

$\alpha(\Lambda_c^+ \to pK_S^0)$	0.18 ± 0.45
$\alpha(\Lambda_c^+ \to \Lambda\pi^+)$	-0.84 ± 0.09
$\alpha(\Lambda_c^+ \to \Sigma^0\pi^+)$	-0.73 ± 0.18
$\alpha(\Lambda_c^+ \to \Sigma^+\pi^0)$	-0.55 ± 0.11
$\alpha(\Xi_c^0 \to \Xi^-\pi^+)$	-0.6 ± 0.4

21 experimental data

SU(3) amplitude for Cabibbo allowed process

$\Lambda_c^+ \to \Sigma^0\pi^+$	$(-b_6 + b_{15} + c_6 - c_{15} + d_6)/\sqrt{2}$
$\Lambda_c^+ \to \Lambda\pi^+$	$-(b_6 - b_{15} + c_6 - c_{15} + d_6 + 2e_{15})/\sqrt{6}$
$\Lambda_c^+ \to \Sigma^+\pi^0$	$(b_6 - b_{15} - c_6 + c_{15} - d_6)/\sqrt{2}$
$\Lambda_c^+ \to pK_S^0$	$(\sin^2\theta\,(-d_6 + d_{15} + e_{15}) + b_6 - b_{15} - e_{15})/\sqrt{2}$
$\Lambda_c^+ \to \Xi^0 K^+$	$-c_6 + c_{15} + d_{15}$
$\Xi_c^+ \to \Sigma^+ K_S^0$	$(\sin^2\theta\,(b_6 - b_{15} - e_{15}) - d_6 + d_{15} + e_{15})/\sqrt{2}$
$\Xi_c^+ \to \Xi^0\pi^+$	$-d_6 - d_{15} - e_{15}$
$\Xi_c^0 \to \Sigma^0 K_S^0$	$(-\sin^2\theta\,(b_6 + b_{15} - e_{15}) + (c_6 + c_{15} + d_6 - e_{15}))/2$
$\Xi_c^0 \to \Lambda K_S^0$	$\sqrt{3}\sin^2\theta\,(b_6 + b_{15} - 2c_6 - 2c_{15} - 2d_6 + e_{15})/6$ $+\sqrt{3}(2b_6 + 2b_{15} - c_6 - c_{15} - d_6 - e_{15})/6$
$\Xi_c^0 \to \Sigma^+ K^-$	$c_6 + c_{15} + d_{15}$
$\Xi_c^0 \to \Xi^-\pi^+$	$b_6 + b_{15} + e_{15}$
$\Xi_c^0 \to \Xi^0\pi^0$	$(-b_6 - b_{15} + d_6 + d_{15})/\sqrt{2}$

Globel fit

parameters	Our work	
	scalar (f)	pseudoscalar (g)
b_6	-0.111 ± 0.0093	0.142 ± 0.026
c_6	-0.010 ± 0.018	-0.106 ± 0.078
d_6	-0.042 ± 0.015	0.02 ± 0.12
b_{15}	0.0448 ± 0.0091	-0.021 ± 0.019
c_{15}	0.063 ± 0.018	0.140 ± 0.052
d_{15}	-0.018 ± 0.014	-0.11 ± 0.12
e_{15}	0.0382 ± 0.0044	0.185 ± 0.024
a	0.121 ± 0.064	0.22 ± 0.77
a'	—	—
χ^2/d.o.f.	0.744	

No SU(3) symmetry breaking!

There are not enough data to deteremine the amplitude a_6 and a_{15}. We define the new amplitude:

$$a = a_6 - a_{15}, \quad a' = a_6 + a_{15}.$$

and form factors:

$$f^a = f_6^a - f_{15}^a, \quad f^{a\prime} = f_6^a + f_{15}^a,$$

$$g^a = g_6^a - g_{15}^a, \quad g^{a\prime} = g_6^a + g_{15}^a,$$

Globel fit

channel	Experimental data (10^{-2})	Our work (10^{-2})
$\Lambda_c^+ \to pK_S^0$	1.59 ± 0.08	1.587 ± 0.077
$\Lambda_c^+ \to p\eta$	0.124 ± 0.03	0.127 ± 0.024
$\Lambda_c^+ \to \Lambda\pi^+$	1.3 ± 0.07	1.307 ± 0.069
$\Lambda_c^+ \to \Sigma^0\pi^+$	1.29 ± 0.07	1.272 ± 0.056
$\Lambda_c^+ \to \Sigma^+\pi^0$	1.25 ± 0.10	1.283 ± 0.057
$\Lambda_c^+ \to \Xi^0 K^+$	0.55 ± 0.07	0.548 ± 0.068
$\Lambda_c^+ \to \Lambda K^+$	0.061 ± 0.012	0.064 ± 0.010
$\Lambda_c^+ \to \Sigma^+\eta$	0.44 ± 0.20	0.45 ± 0.19
$\Lambda_c^+ \to \Sigma^+\eta'$	1.5 ± 0.60	1.5 ± 0.60
$\Lambda_c^+ \to \Sigma^0 K^+$	0.052 ± 0.008	0.0504 ± 0.0056
$\Xi_c^+ \to \Xi^0\pi^+$	1.6 ± 0.8	0.54 ± 0.18
$\Xi_c^0 \to \Lambda K_S^0$	0.334 ± 0.067	0.334 ± 0.065
$\Xi_c^0 \to \Xi^-\pi^+$	1.43 ± 0.32	1.21 ± 0.21
$\Xi_c^0 \to \Xi^- K^+$	0.039 ± 0.012	0.047 ± 0.0083
$\Xi_c^0 \to \Sigma^0 K_S^0$	0.069 ± 0.024	0.069 ± 0.024
$\Xi_c^0 \to \Sigma^+ K^-$	0.221 ± 0.068	0.221 ± 0.068
channel	Experimental data	Our work
$\alpha(\Lambda_c^+ \to pK_S^0)$	0.18 ± 0.45	0.19 ± 0.41
$\alpha(\Lambda_c^+ \to \Lambda\pi^+)$	-0.84 ± 0.09	-0.841 ± 0.083
$\alpha(\Lambda_c^+ \to \Sigma^0\pi^+)$	-0.73 ± 0.18	-0.605 ± 0.088
$\alpha(\Lambda_c^+ \to \Sigma^+\pi^0)$	-0.55 ± 0.11	-0.603 ± 0.088
$\alpha(\Xi_c^0 \to \Xi^-\pi^+)$	-0.6 ± 0.4	-0.56 ± 0.32
$\chi^2/d.o.f.$	—	0.744

Prediction for Cabibbo allowed process

channel	SU(3) amplitude	branching ratio (10^{-2})	α
$\Lambda_c^+ \to \Sigma^0\pi^+$	$(-b_6 + b_{15} + c_6 - c_{15} + d_6)/\sqrt{2}$	1.272 ± 0.056	-0.605 ± 0.088
$\Lambda_c^+ \to \Lambda\pi^+$	$-(b_6 - b_{15} + c_6 - c_{15} + d_6 + 2e_{15})/\sqrt{6}$	1.307 ± 0.069	-0.841 ± 0.083
$\Lambda_c^+ \to \Sigma^+\pi^0$	$(b_6 - b_{15} - c_6 + c_{15} - d_6)/\sqrt{2}$	1.283 ± 0.057	-0.603 ± 0.088
$\Lambda_c^+ \to pK_S^0$	$(\sin^2\theta\,(-d_6 + d_{15} + e_{15}) + b_6 - b_{15} - e_{15})/\sqrt{2}$	1.587 ± 0.077	0.19 ± 0.41
$\Lambda_c^+ \to \Xi^0 K^+$	$-c_6 + c_{15} + d_{15}$	0.548 ± 0.068	0.866 ± 0.090
$\Xi_c^+ \to \Sigma^+ K_S^0$	$(\sin^2\theta\,(b_6 - b_{15} - e_{15}) - d_6 + d_{15} + e_{15})/\sqrt{2}$	0.53 ± 0.70	0.6 ± 2.2
$\Xi_c^+ \to \Xi^0\pi^+$	$-d_6 - d_{15} - e_{15}$	0.54 ± 0.18	-0.94 ± 0.15
$\Xi_c^0 \to \Sigma^0 K_S^0$	$(-\sin^2\theta\,(b_6 + b_{15} - e_{15}) + (c_6 + c_{15} + d_6 - e_{15}))/2$	0.069 ± 0.024	1.00 ± 0.13
$\Xi_c^0 \to \Lambda K_S^0$	$\sqrt{3}\sin^2\theta\,(b_6 + b_{15} - 2c_6 - 2c_{15} - 2d_6 + e_{15})/6$ $+\sqrt{3}(2b_6 + 2b_{15} - c_6 - c_{15} - d_6 - e_{15})/6$	0.334 ± 0.065	-0.04 ± 0.63
$\Xi_c^0 \to \Sigma^+ K^-$	$c_6 + c_{15} + d_{15}$	0.221 ± 0.068	-0.9 ± 1.0
$\Xi_c^0 \to \Xi^-\pi^+$	$b_6 + b_{15} + e_{15}$	1.21 ± 0.21	-0.56 ± 0.32
$\Xi_c^0 \to \Xi^0\pi^0$	$(-b_6 - b_{15} + d_6 + d_{15})/\sqrt{2}$	0.256 ± 0.093	-0.23 ± 0.60
$\Lambda_c^+ \to \Sigma^0 K^+$	$\sin\theta\,(-b_6 + b_{15} + d_6 + d_{15})/\sqrt{2}$	0.0504 ± 0.0056	-0.953 ± 0.040

PART 04

• Recent progress in the charm baryon decays

TSUNG-DAO LEE INSTITUTE

Recent progress in the charm baryon decays

李政道研究所 TSUNG-DAO LEE INSTITUTE

The new experiment data in 2022

BesIII

$$\mathcal{B}(\Lambda_c^+ \to n\pi^+) = (6.6 \pm 1.2 \pm 0.4) \times 10^{-4},$$
$$\mathcal{B}(\Lambda_c^+ \to p\eta') = (5.62^{+2.46}_{-2.04} \pm 0.26) \times 10^{-4},$$
$$\mathcal{B}(\Lambda_c^+ \to \Lambda^0 K^+) = (6.21 \pm 0.44 \pm 0.26 \pm 0.34) \times 10^{-4},$$
$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0) = (4.8 \pm 1.4 \pm 0.2 \pm 0.3) \times 10^{-4},$$
$$\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+) = (4.7 \pm 0.9 \pm 0.1 \pm 0.3) \times 10^{-4}.$$

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$$\mathcal{B}(\Lambda_c^+ \to p\eta') = (4.73 \pm 0.82 \pm 0.47 \pm 0.24) \times 10^{-4},$$
$$\mathcal{B}(\Lambda_c^+ \to \Lambda^0 K^+) = (6.57 \pm 0.17 \pm 0.11 \pm 0.35) \times 10^{-4},$$
$$\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+) = (3.58 \pm 0.19 \pm 0.06 \pm 0.19) \times 10^{-4},$$
$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ \eta) = (3.14 \pm 0.35 \pm 0.11 \pm 0.25) \times 10^{-3},$$
$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ \eta') = (4.16 \pm 0.75 \pm 0.21 \pm 0.33) \times 10^{-3},$$
$$\alpha(\Lambda_c^+ \to \Lambda^0 K^+) = -0.023 \pm 0.086 \pm 0.071,$$
$$\alpha(\Lambda_c^+ \to \Sigma^0 K^+) = 0.08 \pm 0.35 \pm 0.14,$$
$$\alpha(\Lambda_c^+ \to \Sigma^+ \eta) = -0.99 \pm 0.03 \pm 0.05,$$
$$\alpha(\Lambda_c^+ \to \Sigma^+ \eta') = -0.46 \pm 0.06 \pm 0.03.$$

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BELLE Belle Collaboration

Recent progress in the charm baryon decays

The SU(3) symmetry breaking

$\Xi_c^{0/+} - \Xi_c^{\prime 0/+}$ mixing angle (bag model)

$\Xi_c^0 - \Xi_c^{\prime 0} \longrightarrow |\theta_c| = 0.137\pi$

$\Xi_c^+ - \Xi_c^{\prime +} \longrightarrow |\theta_c| = 0.2\pi$

The SU(3) symmetry breaking in non-leptonic decays

$$
\begin{aligned}
A' &= u_1(\boldsymbol{B}_c)_i H(\bar{3})^i(\boldsymbol{B}_n)^j_k(M)^k_j + u_2(\boldsymbol{B}_c)_i H(\bar{3})^j(\boldsymbol{B}_n)^i_k(M)^k_j \\
&\quad + u_3(\boldsymbol{B}_c)_i H(\bar{3})^j(\boldsymbol{B}_n)^k_j(M)^i_k \\
B' &= A'\Big|_{u_i \to v_i}
\end{aligned}
$$

arXiv:2210.07211

(Chao-Qiang Geng, Xiang-Nan Jin, Chia-Wei Liu)

arXiv:2211.12960

(Chia-Wei Liu，Chao-Qiang Geng)

arXiv:2210.12728

(Huiling Zhong, Fanrong Xu, Qiaoyi Wen, Yu Gu)

Tsung-Dao Lee Institute

The SU(3) symmetry breaking

channel	Experimental data(10^{-2})
$\Lambda_c^+ \to pK_S^0$	1.59 ± 0.08
$\Lambda_c^+ \to p\eta$	0.124 ± 0.03
$\Lambda_c^+ \to \Lambda\pi^+$	1.3 ± 0.07
$\Lambda_c^+ \to \Sigma^0\pi^+$	3.61 ± 0.73
$\Lambda_c^+ \to \Sigma^+\pi^0$	1.25 ± 0.10
$\Lambda_c^+ \to \Xi^0 K^+$	0.55 ± 0.07
$\Lambda_c^+ \to \Lambda K^+$	0.0657 ± 0.0040
$\Lambda_c^+ \to \Sigma^+ K_s^0$	0.048 ± 0.014
$\Lambda_c^+ \to \Sigma^+\eta$	0.314 ± 0.044
$\Lambda_c^+ \to \Sigma^+\eta'$	0.416 ± 0.085
$\Lambda_c^+ \to \Sigma^0 K^+$	0.0358 ± 0.0028
$\Xi_c^+ \to \Xi^0\pi^+$	1.6 ± 0.8
$\Xi_c^0 \to \Lambda K_S^0$	0.334 ± 0.067
$\Xi_c^0 \to \Xi^-\pi^+$	1.43 ± 0.32
$\Xi_c^0 \to \Xi^- K^+$	0.039 ± 0.012
$\Xi_c^0 \to \Sigma^0 K_S^0$	0.069 ± 0.024
$\Xi_c^0 \to \Sigma^+ K^-$	0.221 ± 0.068

$\alpha(\Lambda_c^+ \to pK_S^0)$	0.18 ± 0.45
$\alpha(\Lambda_c^+ \to \Lambda\pi^+)$	-0.775 ± 0.006
$\alpha(\Lambda_c^+ \to \Sigma^0\pi^+)$	-0.463 ± 0.018
$\alpha(\Lambda_c^+ \to \Sigma^+\pi^0)$	-0.48 ± 0.028
$\alpha(\Xi_c^0 \to \Xi^-\pi^+)$	-0.6 ± 0.4
$\alpha(\Lambda_c^+ \to \Lambda K^+)$	-0.585 ± 0.052
$\alpha(\Lambda_c \to \Sigma^0 K^+)$	-0.55 ± 0.201
$\alpha(\Lambda_c \to \Sigma^+\eta)$	-0.99 ± 0.0583
$\alpha(\Lambda_c \to \Sigma^+\eta')$	-0.46 ± 0.07

$$\chi^2/d.o.f = 2.82$$

The experiment data in not enough for us to consider the SU(3) symmetry breaking effect in glabel fit.

Expecting more data!

PART 05

• Conclusion and outlook

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Conclusion and outlook

- There are an obvious evidence which show that the charm baryon semi-leptonic and non-leptonic two body decay processes have SU(3) symmetry breaking effect.

- The SU(3) symmetry breaking effect can be explained by the anti-triplet and sextet charm baryon mixing effect.

- The charm baryon decay processes may be a new platform for search new physics.

- We eagerly waiting for data from future experimental facilities.

Thanks！