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

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The 2nd Asian-European-Institute workshop for BSM

Outline

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- 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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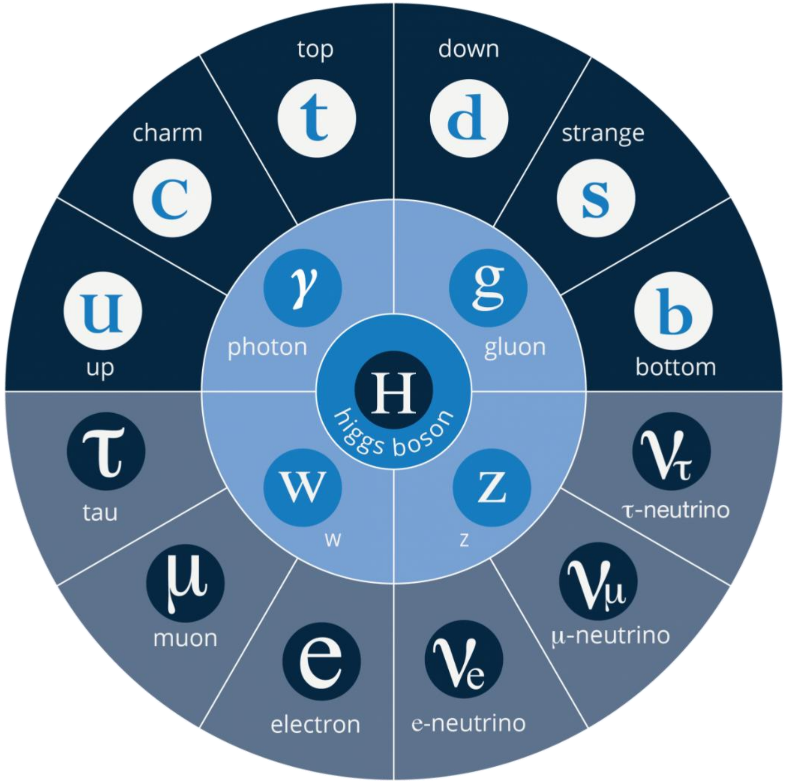
The Standard Model

- 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

Experiments that start collecting results recently

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 **(LHCb)**

First observation of $\Lambda_c \to n\pi^+$ **PRL128(2022)142001**
First observation of $\Lambda_c \to pK^-e^+\nu$ **arXiv:2207.11483**

Belle Collaboration

LHCb

BESIII

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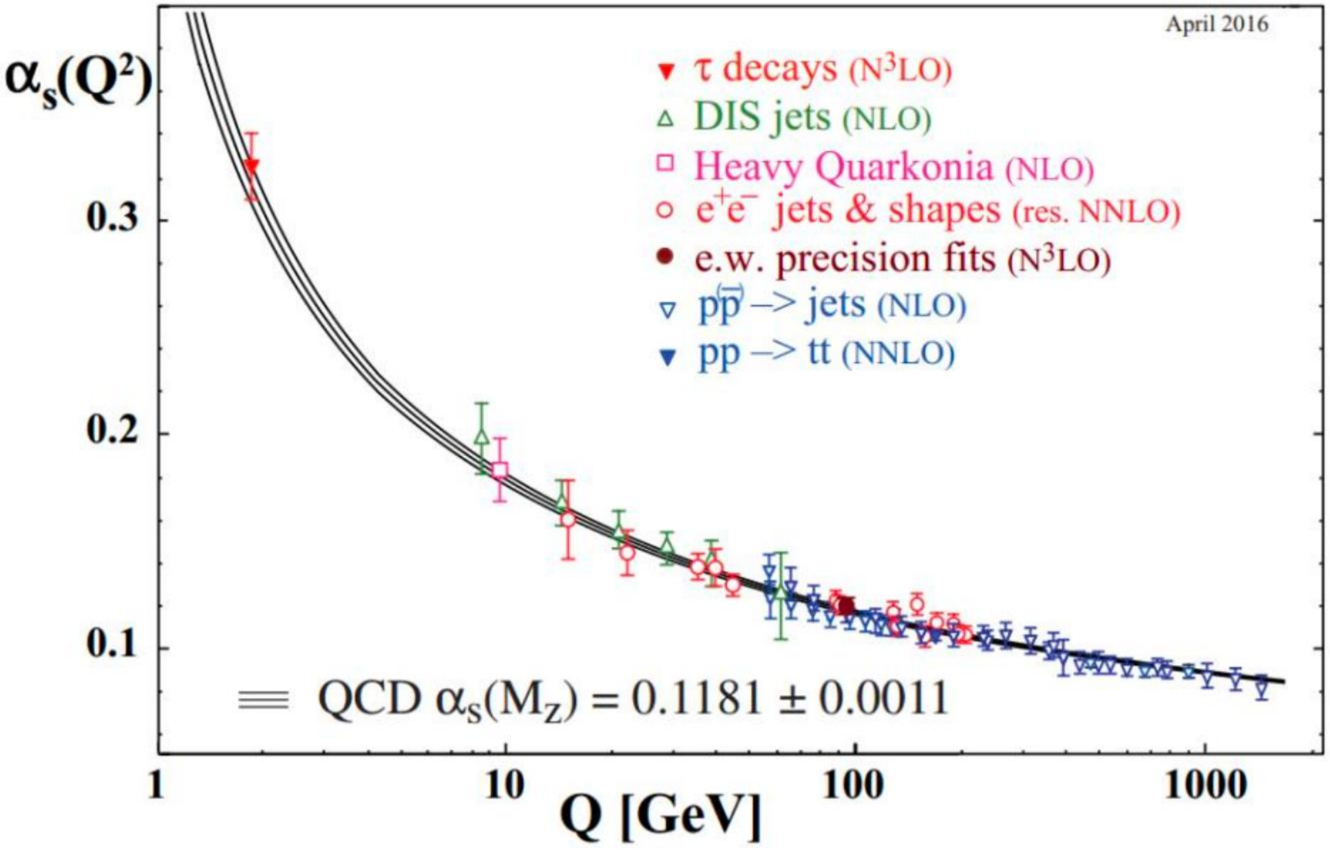
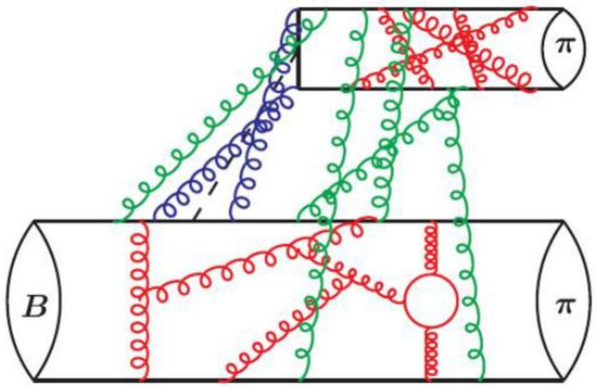
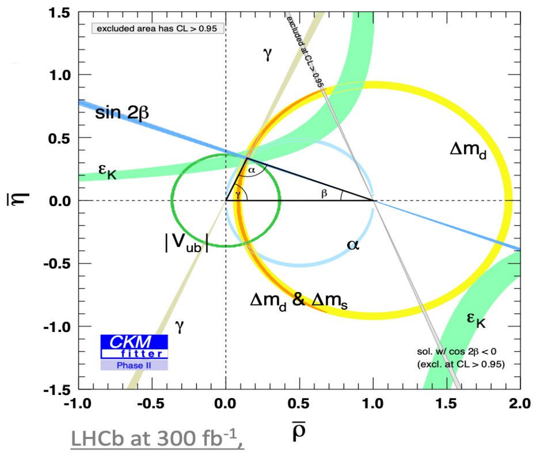
Quantum Chromodynamics in SM







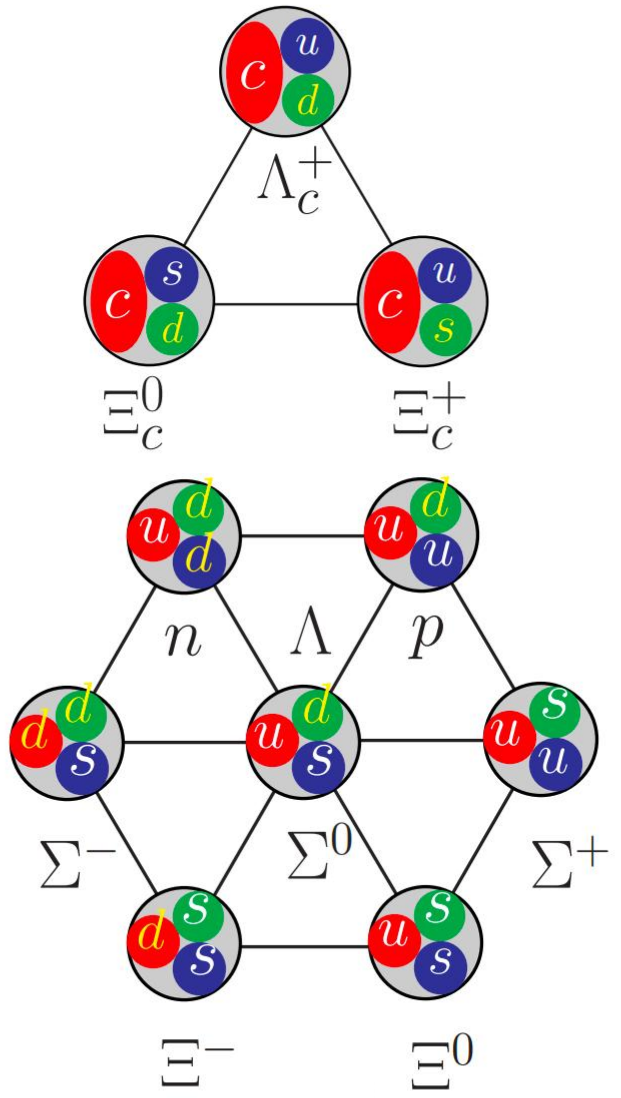
LHCb at 300 fb^{-1},
CMS/ATLAS at 3000 fb^{-1}, Belle II at 50 ab^{-1}.

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.

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



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SU(3) symmetry in QCD

- The SU(3) symmetry analysis is an important non-perturbative method.
- The SU(3) symmetry can greatly simplify the complexity and results of calculation.
- The SU(3) symmetry method has been sucessfully applied in meson and baryon decay processes.

The SU(3) amplitude in semi-leptonic decays

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

PART 02

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

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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(%)
$\Lambda_c \to \Lambda e^+ \nu_e$	$3.6 \pm 0.4[1]$	3.6 ± 0.4
$\Lambda_c \to \Lambda \mu^+ \nu_\mu$	$3.5 \pm 0.5[1]$	3.5 ± 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 charm baryon decays

SU(3) symmetry analysis method

Anti-triplet:

$$
\begin{array}{cc}
 & \begin{array}{ccc} \mathbf{u} & \mathbf{d} & \mathbf{s} \end{array} \\
T_{c\bar{3}} = & \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix} \begin{array}{c} \mathbf{u} \\ \mathbf{d} \\ \mathbf{s} \end{array}
\end{array}
$$

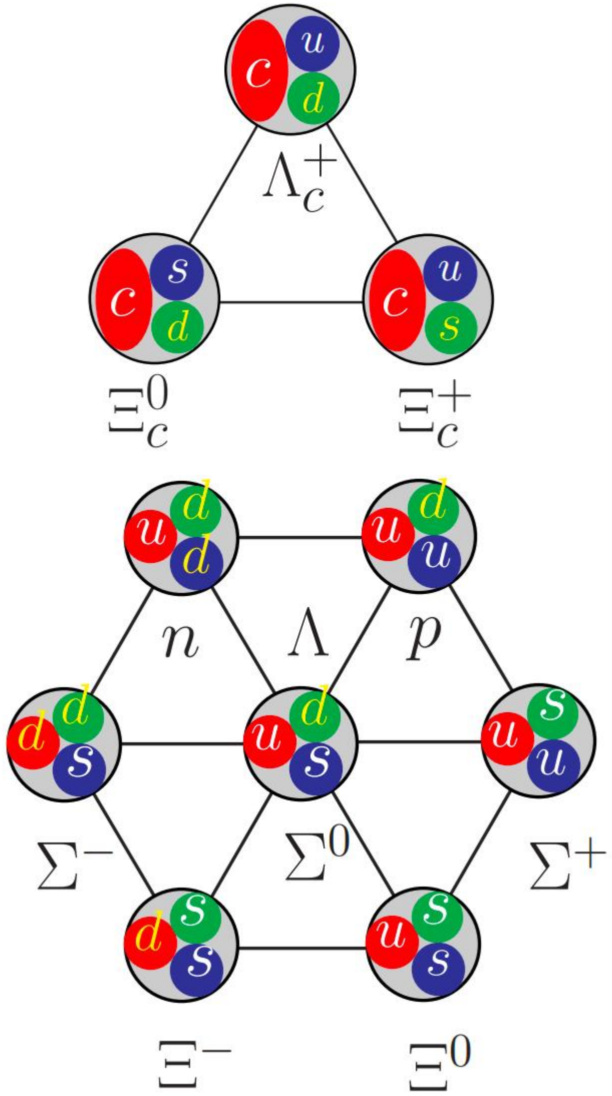
Octet:

$$T^{ijk} = \epsilon_{ikm}(T_8)^m_j,$$

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

Hamiltonian: $\mathcal{H}_{c\to d/s} = \frac{G_F}{\sqrt{2}}\left[V^*_{cq}\bar{q}\gamma^\mu(1-\gamma_5)c\,\bar{\nu}_\ell\gamma_\mu(1-\gamma_5)\ell\right] + h.c.$

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



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SU(3) symmetry in semi-leptonic decays

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

$$g_{\mu\nu} = -\sum_{\lambda=0,\pm 1} \epsilon_\mu^*(\lambda)\epsilon_\nu(\lambda) + \epsilon_\mu^*(t)\epsilon_\nu(t)$$

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

$$\mathcal{A}(B_c \to B_q \ell^+ \nu) = \frac{G_F}{\sqrt{2}} V_{cq}^* \left(-\sum_{\lambda_w=0,\pm 1} H_{\lambda,\lambda_w} L_{\lambda_w} + H_{\lambda,t} L_t \right)$$

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

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

SU(3) matrix

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

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

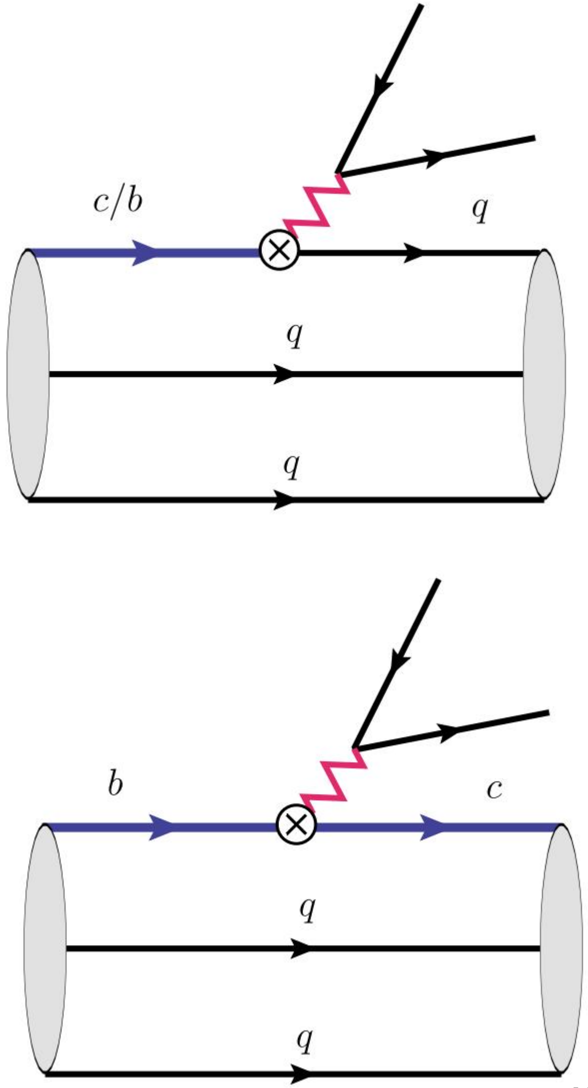
$$a_1^{\lambda,\lambda_W} = \bar{u}(\lambda)\left[\boxed{f_1\gamma^\mu} \boxed{+ f_2\frac{i\sigma^{\nu\mu}}{M_i}q^\nu + f_3\frac{q^\mu}{M_i}}\right]u(\lambda_i)\epsilon_\mu^*(\lambda_W) - \bar{u}(\lambda)\left[\boxed{f_1'\gamma^\mu} \boxed{+ f_2'\frac{i\sigma^{\nu\mu}}{M_i}q^\nu + f_3'\frac{q^\mu}{M_i}}\right]\gamma_5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

dominant **suppressed by 1/mb**

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

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

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



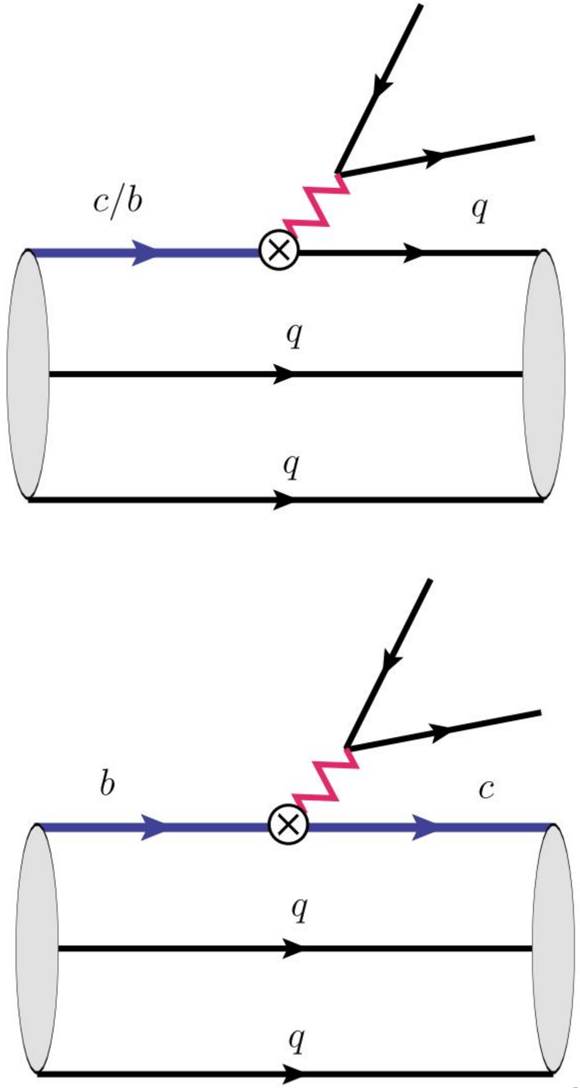
SU(3) symmetry in semi-leptonic charm baryon decays

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
$\boxed{\chi^2/d.o.f = 14.3}$	$f_1 = 1.05 \pm 0.30$	$f_1' = 0.11 \pm 0.95$

Need to consider the SU(3) symmetry breaking effect



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

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:

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

global fit

Helicity amplitude:

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

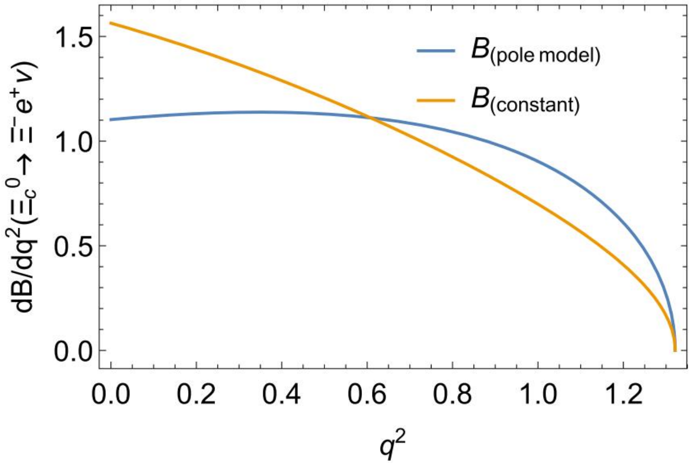
$$f_i(q^2)=\frac{f_i}{1-\frac{q^2}{m_p^2}},\qquad f_i(q^2)=f_i$$

Pole model

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	$f_1=1.01\pm0.87,\ \delta f_1=-0.51\pm0.92$		$\chi^2/d.o.f=1.6$
(Pole model)	$f_1'=0.60\pm0.49,\ \delta f_1'=-0.23\pm0.41$		
Fit parameter	$f_1=0.86\pm0.92,\ \delta f_1=-0.25\pm0.88$		$\chi^2/d.o.f=1.9$
(Constant)	$f_1'=0.85\pm0.36,\ \delta f_1'=-0.43\pm0.50$		

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

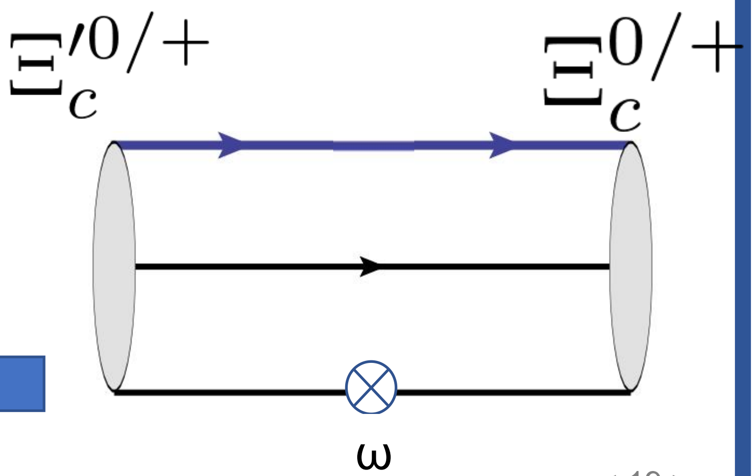
Amplitude:

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

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

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

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



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

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

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

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

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

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

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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:

Belle:

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

BESIII:

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

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

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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:

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

$$O_1^{q_1\bar{q}_2 q_3} = (\bar{q}_{1\alpha} c_\beta)_{V-A} (\bar{q}_{3\beta} q_{2\alpha})_{V-A}, \quad O_2^{q_1\bar{q}_2 q_3} = (\bar{q}_{1\alpha} c_\alpha)_{V-A} (\bar{q}_{3\beta} q_{2\beta})_{V-A}.$$

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

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

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

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

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

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The SU(3) analyse

$$
\begin{aligned}
\mathcal{M} = {}& a_{15}(T_{c\bar{3}})_i(H_{\overline{15}})_j^{\{ik\}}(\overline{T_8})_k^j P_l^l + b_{15}(T_{c\bar{3}})_i(H_{\overline{15}})_j^{\{ik\}}(\overline{T_8})_k^l P_l^j \\
&+c_{15}(T_{c\bar{3}})_i(H_{\overline{15}})_j^{\{ik\}}(\overline{T_8})_l^j P_k^l + d_{15}(T_{c\bar{3}})_i(H_{\overline{15}})_l^{\{jk\}}(\overline{T_8})_j^l P_k^i \\
&+e_{15}(T_{c\bar{3}})_i(H_{\overline{15}})_l^{\{jk\}}(\overline{T_8})_j^i P_k^l + a_6(T_{c\bar{3}})^{[ik]}(H_{\bar{6}})_{\{ij\}}(\overline{T_8})_k^j P_l^l \\
&+b_6(T_{c\bar{3}})^{[ik]}(H_{\bar{6}})_{\{ij\}}(\overline{T_8})_k^l P_l^j + c_6(T_{c\bar{3}})^{[ik]}(H_{\bar{6}})_{\{ij\}}(\overline{T_8})_l^j P_k^l \\
&+d_6(T_{c\bar{3}})^{[kl]}(H_{\bar{6}})_{\{ij\}}(\overline{T_8})_k^i P_l^j.
\end{aligned}
$$

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) analyse

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

Experiment data

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

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

(input) $\mathcal{B}(\Xi_c^0 \to \Sigma^+K^-) = (2.21 \pm 0.13 \pm 0.19 \pm 0.64) \times 10^{-3}$.

$$\mathcal{B}(\Xi_c^0 \to p\pi^-) = (5.817 \pm 1.79) \times 10^{-6}$$

$$\mathcal{B}(\Xi_c^0 \to pK^-) = \mathcal{B}(\Xi_c^0 \to \Sigma^+\pi^-) = (1.113 \pm 0.349) \times 10^{-4}.$$

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

3σ standard deviation

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

We need further analysis

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

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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:

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

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

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

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:

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

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

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

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

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The new experiment data in 2022

BesIII

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

Belle

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

Belle Collaboration

Tsung-Dao Lee Institute

The SU(3) symmetry breaking

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

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

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

arXiv:2210.07211

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

$$A' = u_1(\boldsymbol{B}_c)_i H(\overline{3})^i(\boldsymbol{B}_n)^j_k(M)^k_j + u_2(\boldsymbol{B}_c)_i H(\overline{3})^j(\boldsymbol{B}_n)^i_k(M)^k_j + u_3(\boldsymbol{B}_c)_i H(\overline{3})^j(\boldsymbol{B}_n)^k_j(M)^i_k$$

$$B' = A'\Big|_{u_i \to v_i}$$

arXiv:2210.12728

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.

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
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$\alpha(\Lambda_c^+ \to pK_S^0)$	0.18 ± 0.45
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$\alpha(\Lambda_c \to \Sigma^+\eta)$	-0.99 ± 0.0583
$\alpha(\Lambda_c \to \Sigma^+\eta')$	-0.46 ± 0.07

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

The fit results can be good when we exclude two experiment data.

channel		$\chi^2/d.o.f$
$\Lambda_c^+ \to p\eta$	$\alpha(\Lambda_c \to \Sigma^0 K^+)$	1.02
$\Lambda_c^+ \to pK_s^0$	$\alpha(\Lambda_c \to \Sigma^0 K^+)$	1.01

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!