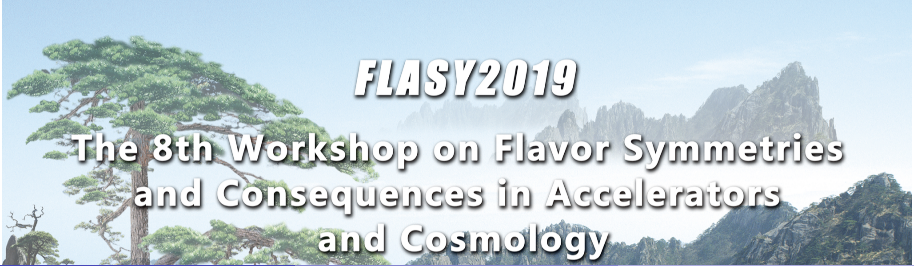
Anti-triplet Charmed Baryon Weak Decays with SU(3) Flavor Symmetry

Chia-Wei Liu

National Tsing-Hua University
Advisor: C. Q. Geng

July 24, 2019



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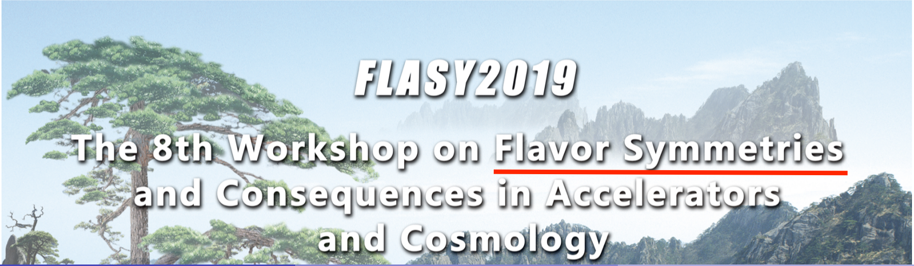

Motivation

- Unknown baryon wave functions
- Failure of the conventional factorization approach

$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+\pi^0)_{EXP} = (1.24 \pm 0.10)\%$$

- Measurements with higher precision in Belle and BESSIII

$$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (6.23 \pm 0.33)\%$$

Decay channels	Absolute branching ratios(%)	Asymmetries
$\Lambda_c^+ \to \Xi(1530)^0 K^+$	$0.502 \pm 0.099 \pm 0.031$	-1.00 ± 0.34[1]
$\Lambda_c^+ \to \Sigma(1385)^+\eta$	$0.91 \pm 0.18 \pm 0.09$[2]	

[1] M. Ablikim *et al.* [BESIII Collaboration], Phys. Lett. B **783**, 200 (2018)

[2] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **99**, no. 3, 032010 (2019)

Motivation

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- C. Q. Geng, Y. K. Hsiao, C. W. Liu and T. H. Tsai, JHEP **1711**, 147 (2017)
- C. Q. Geng, Y. K. Hsiao, C. W. Liu and T. H. Tsai, Eur. Phys. J. C **78**, 593 (2018)
- C. Q. Geng, Y. K. Hsiao, C. W. Liu and T. H. Tsai, Phys. Rev. D **97**, 073006 (2018)
- C. Q. Geng, C. W. Liu and T. H. Tsai, Phys. Lett. B **790**, 225 (2019)
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Outline

Introduction of SU(3) Flavor Symmetry

$$|_1\rangle = |u\rangle \ , |_2\rangle = |d\rangle \ , |_3\rangle = |s\rangle$$
$$|^1\rangle = |\bar{u}\rangle \ , |^2\rangle = |\bar{d}\rangle \ , |^3\rangle = |\bar{s}\rangle$$

$$\pi^+ = |^2_1\rangle = \delta_{i2}\delta^{j1}\,|^i_j\rangle = (\pi^+)^j_i\,|^i_j\rangle$$
$$M = (M)^j_i\,|^i_j\rangle$$

$$(M)^j_i = \begin{pmatrix} \frac{1}{\sqrt{2}}(\pi^0 + c\phi\eta + s\phi\eta') & \pi^- & K^- \\ \pi^+ & \frac{-1}{\sqrt{2}}(\pi^0 - c\phi\eta - s\phi\eta') & \bar{K}^0 \\ K^+ & K^0 & -s\phi\eta + c\phi\eta' \end{pmatrix}_{ij},$$

where $(c\phi, s\phi) = (\cos\phi, \sin\phi)$ and $\phi = (39.3 \pm 1.0)^\circ$.[1]

[1] T. Feldmann, P. Kroll and B. Stech, Phys. Rev. D **58**, 114006 (1998); Phys. Lett. B **449**, 339 (1999).

Introduction of SU(3) Flavor Symmetry

Invariant tensor

$$\epsilon^{ijk}|_{ijk}\rangle \qquad \delta^i_j|^j_i\rangle$$

Introduction of SU(3) Flavor Symmetry

Invariant tensor

$$\epsilon^{ijk}|_{ijk}\rangle \qquad \delta^i_j|^j_i\rangle$$

Antisymmetric tensor gives us singlet

$$\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right) \ ,$$
$$\frac{1}{\sqrt{6}}\left(|rgb\rangle - |rbg\rangle + |gbr\rangle - |grb\rangle + |brg\rangle - |bgr\rangle\right)$$

Same thing happens in color states of mesons

$$\frac{1}{\sqrt{3}}\left(|r\overline{r}\rangle + |g\overline{g}\rangle + |b\overline{b}\rangle\right)$$

Introduction of SU(3) Flavor Symmetry

Anti-triplet charmed baryons

$$\Lambda_c^+ = |udc\rangle - |duc\rangle = |_{12}\rangle_{B_c} - |_{21}\rangle_{B_c} = \epsilon^{ijk}\delta_{k3}\,|_{ij}\rangle_{B_c} \sim \delta_{k3}|^k\rangle$$

$$(\mathbf{B}_c)_i \;=\; (\Xi_c^0, -\Xi_c^+, \Lambda_c^+)_i$$

Octet Baryons

$$\mathbf{B} = \mathbf{B}^{ijk}\,|_{ijk}\rangle = (\mathbf{B}_n)^i_l\epsilon^{ljk}\,|_{ijk}\rangle$$
$$p = |_{112}\rangle - |_{121}\rangle = (\delta^{i1}\delta^{j1}\delta^{k2} - \delta^{i1}\delta^{j2}\delta^{k1})\,|_{ijk}\rangle = (\delta^{i1}\delta_{l3}\epsilon^{ljk})\,|_{ijk}\rangle$$

$$(\mathbf{B}_n)^i_j \;=\; \begin{pmatrix} \frac{1}{\sqrt{6}}\Lambda + \frac{1}{\sqrt{2}}\Sigma^0 & \Sigma^+ & p \\ \Sigma^- & \frac{1}{\sqrt{6}}\Lambda - \frac{1}{\sqrt{2}}\Sigma^0 & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{pmatrix}_{ij}$$

Introduction of SU(3) Flavor Symmetry

Sextet charmed baryons

$$\Sigma_c^+ = |udc\rangle + |duc\rangle = |_{12}\rangle_{B_c} + |_{21}\rangle_{B_c} = (\mathbf{B}'_c)^{ij}|ij\rangle_{B_c}$$

$$(\mathbf{B}'_c)^{ij} = \begin{pmatrix} \Sigma_c^{++} & \frac{1}{\sqrt{2}}\Sigma_c^+ & \frac{1}{\sqrt{2}}\Xi_c'^+ \\ \frac{1}{\sqrt{2}}\Sigma_c^+ & \Sigma_c^0 & \frac{1}{\sqrt{2}}\Xi_c'^0 \\ \frac{1}{\sqrt{2}}\Xi_c'^+ & \frac{1}{\sqrt{2}}\Xi_c'^0 & \Omega_c^0 \end{pmatrix},$$

Decuplet Baryons

$$\psi = \psi(space) \otimes \psi(spin) \otimes \psi(flavor) \otimes \psi(color)$$

$$\mathbf{B}_D = \frac{1}{\sqrt{3}} \left(\begin{pmatrix} \sqrt{3}\Delta^{++} & \Delta^+ & \Sigma'^+ \\ \Delta^+ & \Delta^0 & \frac{\Sigma'^0}{\sqrt{2}} \\ \Sigma'^+ & \frac{\Sigma'^0}{\sqrt{2}} & \Xi'^0 \end{pmatrix}, \begin{pmatrix} \Delta^+ & \Delta^0 & \frac{\Sigma'^0}{\sqrt{2}} \\ \Delta^0 & \sqrt{3}\Delta^- & \Sigma'^- \\ \frac{\Sigma'^0}{\sqrt{2}} & \Sigma'^- & \Xi'^- \end{pmatrix}, \begin{pmatrix} \Sigma'^+ & \frac{\Sigma'^0}{\sqrt{2}} & \Xi'^0 \\ \frac{\Sigma'^0}{\sqrt{2}} & \Sigma'^- & \Xi'^- \\ \Xi'^0 & \Xi'^- & \sqrt{3}\Omega^- \end{pmatrix} \right),$$

Introduction of SU(3) Flavor Symmetry

Sextet charmed baryons

$$\Sigma_c^+ = |udc\rangle + |duc\rangle = |_{12}\rangle_{B_c} + |_{21}\rangle_{B_c} = (\mathbf{B}'_c)^{ij}|ij\rangle_{B_c}$$

$$(\mathbf{B}'_c)^{ij} = \begin{pmatrix} \Sigma_c^{++} & \frac{1}{\sqrt{2}}\Sigma_c^+ & \frac{1}{\sqrt{2}}\Xi_c'^+ \\ \frac{1}{\sqrt{2}}\Sigma_c^+ & \Sigma_c^0 & \frac{1}{\sqrt{2}}\Xi_c'^0 \\ \frac{1}{\sqrt{2}}\Xi_c'^+ & \frac{1}{\sqrt{2}}\Xi_c'^0 & \Omega_c^0 \end{pmatrix},$$

Decuplet Baryons (spin-3/2)

$$\psi = \psi(space) \otimes \psi(spin) \otimes \psi(flavor) \otimes \psi(color)$$

$$\mathbf{B}_D = \frac{1}{\sqrt{3}}\left(\begin{pmatrix} \sqrt{3}\Delta^{++} & \Delta^+ & \Sigma'^+ \\ \Delta^+ & \Delta^0 & \frac{\Sigma'^0}{\sqrt{2}} \\ \Sigma'^+ & \frac{\Sigma'^0}{\sqrt{2}} & \Xi'^0 \end{pmatrix}, \begin{pmatrix} \Delta^+ & \Delta^0 & \frac{\Sigma'^0}{\sqrt{2}} \\ \Delta^0 & \sqrt{3}\Delta^- & \Sigma'^- \\ \frac{\Sigma'^0}{\sqrt{2}} & \Sigma'^- & \Xi'^- \end{pmatrix}, \begin{pmatrix} \Sigma'^+ & \frac{\Sigma'^0}{\sqrt{2}} & \Xi'^0 \\ \frac{\Sigma'^0}{\sqrt{2}} & \Sigma'^- & \Xi'^- \\ \Xi'^0 & \Xi'^- & \sqrt{3}\Omega^- \end{pmatrix} \right),$$

Charmed Baryon Weak Decays

Effective Hamiltonian for c transition

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \left(c_- O_- + c_+ O_+ \right) .$$

$$O_- = \frac{1}{2} \sum_{q,q'=d,s} V_{uq} V^*_{cq'} \left((\bar{u}q)(\bar{q}'c) - (\bar{q}'q)(\bar{u}c) \right) ,$$

$$O_+ = \frac{1}{2} \sum_{q,q'=d,s} V_{uq} V^*_{cq'} \left((\bar{u}q)(\bar{q}'c) + (\bar{q}'q)(\bar{u}c) \right) ,$$

where $(\bar{q}q') \equiv \bar{q}^\alpha \gamma_\mu (1-\gamma_5) q_\alpha$ and $\alpha = r, g, b$.

Charmed Baryon Weak Decays

Effective Hamiltonian for c transition

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}}\left(c_- H(6)_{lk}(\epsilon^{ijl}/2)O^k_{ij} + c_+ H(\overline{15})^{ij}_k O^k_{ij}\right)$$

$$O^k_{ij} = \frac{1}{2}(\bar{q}_i q_k)_{V-A}(\bar{q}_j c)_{V-A} \qquad s_c \equiv V_{cd}$$

$$H(6)_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 2 & -2s_c \\ 0 & -2s_c & 2s_c^2 \end{pmatrix}_{ij},$$

$$H(\overline{15})^{ij}_k = \left(\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}_{ij}, \begin{pmatrix} 0 & s_c & 1 \\ s_c & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}_{ij}, \begin{pmatrix} 0 & -s_c^2 & -s_c \\ -s_c^2 & 0 & 0 \\ -s_c & 0 & 0 \end{pmatrix}_{ij} \right)_k$$

Charmed Baryon Weak Decays

The process $B_c \to B_D(\text{spin-3/2})\ M$

$$\mathbf{M} = \langle \mathbf{B}_D M | \mathcal{H}_{eff} | \mathbf{B}_c \rangle = i q_\mu \overline{w}^\mu_{\mathbf{B}_D} (P - D\gamma_5) u_{\mathbf{B}_c} ,$$

$$\langle \mathbf{B}_D M | \, \mathcal{H}_{eff} \, | \mathbf{B}_c \rangle_{L=1} = (\overline{\mathbf{B}_D})_{ijk} \overline{M}^m_l H^{no}_p (\mathbf{B}_c)_q \langle ({}_{ijk})_{\mathbf{B}_D} ({}^m_l)_M | \, O^p_{no} \, | ({}^q)_{\mathbf{B}_c} \rangle_{L=1}$$

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$$\langle ({}_{ijk})_{\mathbf{B}_D} ({}^m_l)_M | \, O^p_{no} \, | ({}^q)_{\mathbf{B}_c} \rangle_{L=1} \sim P_1 \delta^i_m \delta^j_n \delta^q_o \epsilon^{klp}$$

$$\begin{aligned} P(\mathcal{O}_{\overline{15}}) &= P_1 (\mathbf{B}'_n)_{ijk} (M)^i_l H(\overline{15})^{jn}_m (\mathbf{B}_c)_n \epsilon^{klm} + P_2 (\mathbf{B}'_n)_{ijk} (M)^i_l H(\overline{15})^{jk}_m (\mathbf{B}_c)_n \epsilon^{lmn} \\ &\quad + P_3 (\mathbf{B}'_n)_{ijk} (M)^l_m H(\overline{15})^{ij}_l (\mathbf{B}_c)_n \epsilon^{kmn} \, , \\ P(\mathcal{O}_6) &= P_0 (\mathbf{B}'_n)_{ijk} (\mathbf{B}_c)_l H_{nm}(6) (M)^i_o \epsilon^{jln} \epsilon^{kmo} \, . \end{aligned}$$

Example

$$P(\Lambda_c^+ \to \Delta^{++} K^-) = -2P_0 - P_1$$

Charmed Baryon Weak Decays

We omit O_+ for two reasons

- Factorizable part
  $\langle \mathbf{B}_D | j^{\mu}_{(A)} | \mathbf{B}_c \rangle = 0$
  flavor symmetry

- Nonfactorizable part:
  $\langle \mathbf{B}_2 | O_+ | \mathbf{B}_p \rangle = 0$
  color symmetry

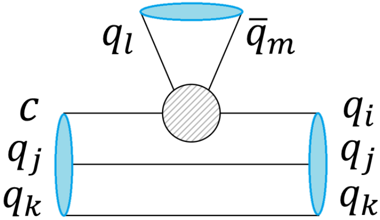

Figure: Factorizable diagram

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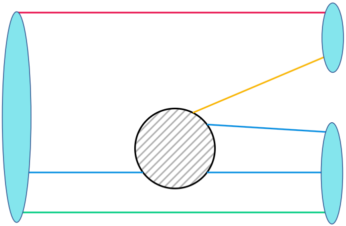

Figure: Nonfactorizable diagram

Charmed Baryon Weak Decays

The process $B_c \to B_D(\text{spin-3/2})\ M$

$$\mathbf{M} = \langle \mathbf{B}_D M | \mathcal{H}_{eff} | \mathbf{B}_c \rangle = i q_\mu \overline{w}^{\mu}_{\mathbf{B}_D} (P - D\gamma_5) u_{\mathbf{B}_c} \,,$$

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$$\langle ({}_{ijk})_{\mathbf{B}_D} ({}^{m}_{l})_M | \, O^{p}_{no} \, | ({}^{q})_{\mathbf{B}_c} \rangle_{L=1} \sim P_1 \delta^{i}_{m} \delta^{j}_{n} \delta^{q}_{o} \epsilon^{klp}$$

$$\begin{aligned} P(\mathcal{O}_{\overline{15}}) &= P_1 (\mathbf{B}'_n)_{ijk} (M)^{i}_{l} H(\overline{15})^{jn}_{m} (\mathbf{B}_c)_n \epsilon^{klm} + P_2 (\mathbf{B}'_n)_{ijk} (M)^{i}_{l} H(\overline{15})^{jk}_{m} (\mathbf{B}_c)_n \epsilon^{lmn} \\ &\quad + P_3 (\mathbf{B}'_n)_{ijk} (M)^{l}_{m} H(\overline{15})^{ij}_{l} (\mathbf{B}_c)_n \epsilon^{kmn} \,, \\ P(\mathcal{O}_6) &= P_0 (\mathbf{B}'_n)_{ijk} (\mathbf{B}_c)_l H_{nm}(6) (M)^{i}_{o} \epsilon^{jln} \epsilon^{kmo} \equiv P_0 f_{\mathbf{B}_c \mathbf{B}_D M} \,. \end{aligned}$$

Example

$$P(\Lambda_c^+ \to \Delta^{++} K^-) = -2P_0 - P_1$$

Numerical Results

Decay width and up-down asymmetry

$$\Gamma\left(B_i \to B_f + P\right) = \frac{|p_c|^3 m_i (m_f + E_f)}{6\pi m_f^2}\left\{|P|^2 + |\overline{D}|^2\right\}$$

$$\alpha \equiv \frac{d\Gamma\left(\vec{P}_{\mathrm{B}_n}\cdot\hat{p}_{\mathrm{B}_n}=+1\right) - d\Gamma\left(\vec{P}_{\mathrm{B}_n}\cdot\hat{p}_{\mathrm{B}_n}=-1\right)}{d\Gamma\left(\vec{P}_{\mathrm{B}_n}\cdot\hat{p}_{\mathrm{B}_n}=+1\right) + d\Gamma\left(\vec{P}_{\mathrm{B}_n}\cdot\hat{p}_{\mathrm{B}_n}=-1\right)} = \frac{2\,\mathrm{Re}\left(P\overline{D}^*\right)}{\left(|P|^2 + |\overline{D}|^2\right)}$$

Table: Experimental data of the up-down asymmetries and branching ratios.

channel	$10^3\mathcal{B}_{exp}$	α_{exp}
$\Lambda_c^+ \to \Delta^{++}K^-$	10.7 ± 2.5	
$\Lambda_c^+ \to \Sigma'^+\eta$	9.1 ± 2.0	
$\Lambda_c^+ \to \Xi'^0 K^+$	5.02 ± 1.04	-1.00 ± 0.34
$\Xi_c^0 \to \Omega^- K^+$	4.2 ± 1.0	
$\Xi_c^+ \to \Sigma'^+\overline{K}^0$	1.0 ± 0.5[1][2]	
$\Xi_c^+ \to \Xi'^0\pi^+$	< 0.1[1][2]	

[1] J. M. Link *et al.* [FOCUS Collaboration], Phys. Lett. B **571**, 139 (2003)

[2] measured relative to $\mathcal{B}(\Xi_c^+ \to \Xi^- 2\pi^+)$

Numerical Results

Fitting Results

$P = P_0 f_{\mathbf{B}_c\mathbf{B}_D M}\,, \qquad D = D_0 f_{\mathbf{B}_c\mathbf{B}_D M}$

$(P_0, D_0)_{pm} = (3.2 \pm 0.4, -5.1 \pm 2.5)10^{-2} G_F\,\mathrm{GeV}\,, \quad R_{P_0 D_0} = 0.70$

Table: Our results of the up-down asymmetries and branching ratios.

channel	$10^3\mathcal{B}_{exp}$	α_{exp}	$10^3\mathcal{B}_{SU(3)}$	$\alpha_{SU(3)}$
$\Lambda_c^+ \to \Delta^{++} K^-$	10.7 ± 2.5		15.3 ± 2.4	$-0.86^{+0.44}_{-0.14}$
$\Lambda_c^+ \to \Sigma'^+ \eta$	9.1 ± 2.0		3.1 ± 0.6	$-0.97^{+0.43}_{-0.03}$
$\Lambda_c^+ \to \Xi'^0 K^+$	5.02 ± 1.04	-1.00 ± 0.34	1.0 ± 0.2	$-1.00^{+0.34}_{-0.00}$
$\Xi_c^0 \to \Omega^- K^+$	4.2 ± 1.0		3.2 ± 0.7	$-1.00^{+0.34}_{-0.00}$
$\Xi_c^+ \to \Sigma'^+ \overline{K}^0$	1.0 ± 0.5[1,2]		0	-
$\Xi_c^+ \to \Xi'^0 \pi^+$	< 0.1[1,2]		0	-

[1] J. M. Link *et al.* [FOCUS Collaboration], Phys. Lett. B **571**, 139 (2003)

[2] measured relative to $\mathcal{B}(\Xi_c^+ \to \Xi^- 2\pi^+)$

channel	$f_{\mathbf{B}_c\mathbf{B}_D M}$	α_{pm}	$10^3\mathcal{B}_{pm}$	$10^3\mathcal{B}_{em}$	$10^3\mathcal{B}$	$10^3\mathcal{B}$	$10^3\mathcal{B}$	$10^3\mathcal{B}_{ex}(\alpha_{ex})$
		our result			[15]	[16]	[34]	data
$\Lambda_c^+ \to \Delta^{++}K^-$	-2	$-0.86^{+0.44}_{-0.14}$	15.3 ± 2.4	12.4 ± 1.0	9.5	27.0	7.0 ± 4.0	10.7 ± 2.5 [2]
$\Lambda_c^+ \to \Delta^+\bar{K}^0$	$-\frac{2\sqrt{3}}{3}$	$-0.86^{+0.44}_{-0.14}$	5.1 ± 0.8	4.1 ± 0.3	3.1	9.0	2.3 ± 1.3	
$\Lambda_c^+ \to \Sigma'^+\pi^0$	$\frac{\sqrt{6}}{3}$	$-0.91^{+0.45}_{-0.10}$	2.2 ± 0.4	2.1 ± 0.2	2.1	5.0	4.6 ± 1.8	
$\Lambda_c^+ \to \Sigma'^+\eta$	$\sqrt{2}$	$-0.97^{+0.43}_{-0.03}$	3.1 ± 0.6	6.2 ± 0.5	-	10.4	2.1 ± 1.1	9.1 ± 2.0 [13]
$\Lambda_c^+ \to \Sigma'^0\pi^+$	$\frac{\sqrt{6}}{3}$	$-0.90^{+0.45}_{-0.10}$	2.2 ± 0.4	2.1 ± 0.2	2.1	5.0	4.6 ± 1.8	
$\Lambda_c^+ \to \Xi'^0K^+$	$\frac{2\sqrt{3}}{3}$	$-1.00^{+0.34}_{-0.00}$	1.0 ± 0.2	4.1 ± 0.3	0.7	5.0	2.3 ± 0.9	5.02 ± 1.04 [11]
								(-1.00 ± 0.34) [11]
$\Xi_c^0 \to \Sigma'^+K^-$	$\frac{2\sqrt{3}}{3}$	$-0.88^{+0.45}_{-0.12}$	3.1 ± 0.5	2.3 ± 0.2	1.3	4.9	1.3 ± 0.7	
$\Xi_c^0 \to \Sigma'^0\bar{K}^0$	$\frac{\sqrt{6}}{3}$	$-0.88^{+0.45}_{-0.12}$	1.6 ± 0.2	1.2 ± 0.1	0.7	2.6	0.6 ± 0.4	
$\Xi_c^0 \to \Xi'^0\pi^0$	$-\frac{\sqrt{6}}{3}$	$-0.91^{+0.45}_{-0.09}$	1.4 ± 0.2	1.2 ± 0.1	0.9	2.8	2.6 ± 1.0	
$\Xi_c^0 \to \Xi'^0\eta$	$-\sqrt{2}$	$-0.97^{+0.42}_{-0.03}$	2.1 ± 0.4	3.5 ± 0.3	-	0.2	1.3 ± 0.6	
$\Xi_c^0 \to \Xi'^-\pi^+$	$-\frac{2\sqrt{3}}{3}$	$-0.91^{+0.45}_{-0.09}$	2.8 ± 0.5	2.3 ± 0.2	1.9	5.6	5.0 ± 2.0	
$\Xi_c^0 \to \Omega^-K^+$	-2	$-1.00^{+0.34}_{-0.00}$	2.3 ± 0.5	7.0 ± 0.6	1.1	3.4	4.5 ± 1.8	5.4 ± 1.6 [2, 14]
$\Xi_c^+ \to \Sigma'^+\bar{K}^0$	0	-	0	0	0	0	0	1.0 ± 0.5 [a b] [2]
$\Xi_c^+ \to \Xi'^0\pi^+$	0	-	0	0	0	0	0	< 0.10[b] [2]

Summary

- There is only two parameters in $\mathbf{B}_c \to \mathbf{B}_D M$.
- We find out

$$\alpha(\Lambda_c^+ \to \Delta^{++} K^-) = -0.86^{+0.44}_{-0.14}\,,$$

which could be tested by the future experiment in BESSIII and Belle.

- Through the experimental data, we predict the non-leptonic decays branching ratios.

THANK YOU