Weak Decays and CP Violation For Charmed Baryons

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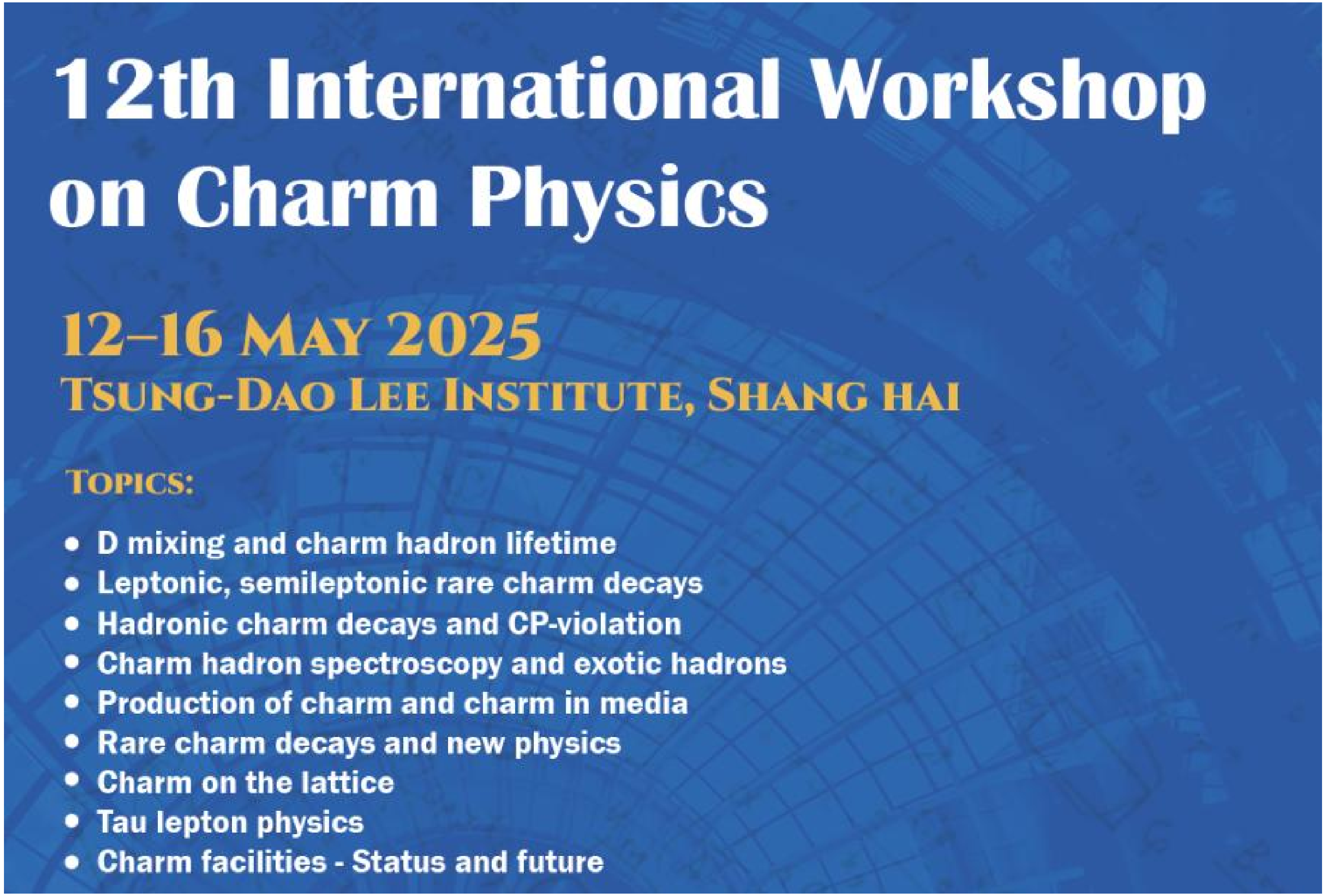

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1. Charmed Baryon Two Body Weak Decays

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1. Charmed Baryon Two Body Weak Decays

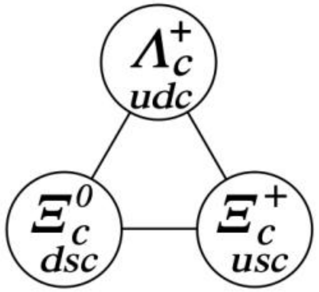
Charmed baryons with a single charm quark are baryon made of a charm quark c and two of the light quarks out of u, d or s.

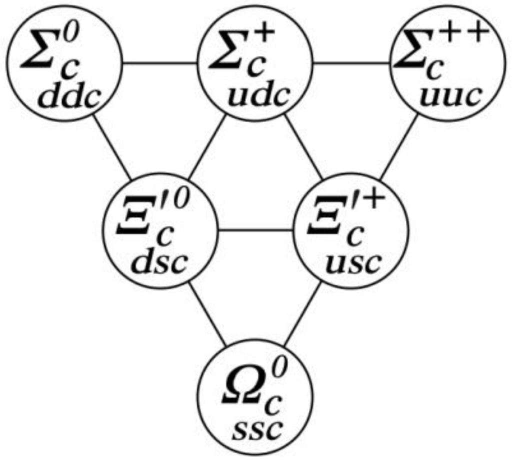
They can be grouped into SU(3) flavor symmetry of light quarks.

The low-lying ones are anti-triplet and symetric-sextet representations,

For two light quarks to be antisymmetric and symmetric respectively.

$$(T^{ij}_{\mathbf{c\bar{3}}}) = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix}$$





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

$$T_{\bar{3},i} = \epsilon_{ijk} T_{\bar{3}}^{jk} = \left(\Xi_c^0 \; -\Xi_c^+ \; \Lambda_c^+ \right)$$

Sextet decays are mainly strong interaction, but anti-triplet decays are weak ones. In this talk I will be concerned with CP violation in anti-triplet charmed two body decays.

The process we will study are T_{c3} -> B P . Here B, P (which include a singlet η_1)are

$$B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & \frac{\Lambda}{\sqrt{6}} - \frac{\Sigma^0}{\sqrt{2}} & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{pmatrix}, \qquad P_8 = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta_8 \end{pmatrix}$$

physical states $\eta = \eta_8 \cos\phi - \eta_1 \sin\phi, \eta' = \eta_8 \sin\phi + \eta_1 \cos\phi,$

The observables are the branching ratios *B* and polarization parameters

$$\mathcal{M} = \langle \mathbf{B}_f P | \mathcal{H}_{\rm eff} | \mathbf{B}_i \rangle = i\overline{u}_f \left(F - G\gamma_5\right) u_i$$

$$\Gamma = \frac{p_f}{8\pi} \frac{(M_i + M_f)^2 - M_P^2}{M_i^2} \left(|F|^2 + \kappa^2 |G|^2\right),$$

$$\alpha = \frac{2\kappa {\rm Re}(F^* G)}{|F|^2 + \kappa^2 |G|^2}, \qquad \beta = \frac{2\kappa {\rm Im}(F^* G)}{|F|^2 + \kappa^2 |G|^2},$$

$$\gamma = \frac{|F|^2 - \kappa^2 |G|^2}{|F|^2 + \kappa^2 |G|^2}, \qquad F^* G = |F^* G| e^{i(\delta_P - \delta_S)}$$

$$\kappa = p_f/(E_f + M_f),$$

$$B = \frac{1}{\sqrt{2}} \sum_a B_a \lambda_a, \quad P = \frac{1}{\sqrt{2}} \sum_a P_a \lambda_a$$

$$B_1 = \frac{\Sigma^+ + \Sigma^-}{\sqrt{2}}, \quad B_2 = \frac{i(\Sigma^+ - \Sigma^-)}{\sqrt{2}}, \quad B_3 = \Sigma^0, \quad B_4 = \frac{p + \Xi^-}{\sqrt{2}},$$

$$B_5 = \frac{i(p - \Xi^-)}{\sqrt{2}}, \quad B_6 = \frac{n + \Xi^0}{\sqrt{2}}, \quad B_7 = \frac{i(n - \Xi^0)}{\sqrt{2}}, \quad B_8 = \Lambda,$$

$$P_1 = \frac{\pi^+ + \pi^-}{\sqrt{2}}, \quad P_2 = \frac{i(\pi^+ - \pi^-)}{\sqrt{2}}, \quad P_3 = \pi^0, \quad P_4 = \frac{K^+ + K^-}{\sqrt{2}},$$

$$P_5 = \frac{i(K^+ - K^-)}{\sqrt{2}}, \quad P_6 = \frac{K^0 + \bar{K}^0}{\sqrt{2}}, \quad P_7 = \frac{i(K^0 - \bar{K}^0)}{\sqrt{2}}, \quad B_8 = \eta_8.$$

$$A_{CP} = \frac{\mathcal{B} - \overline{\mathcal{B}}}{\mathcal{B} + \overline{\mathcal{B}}}, \quad A_{CP}^{\alpha} = \frac{\alpha + \overline{\alpha}}{2}$$

Also the CP violating observables

Similar for $A_{CP}^{\beta,\gamma}$

Experimental data for anti-trplet charmed baryon two body weak decays

from LHCb, Belle, Belle II, BESIII (PDG)...

Channels	$\mathcal{B}_{\rm exp}(\%)$	$\alpha_{\rm exp}$	$\mathcal{B}(\%)$	α	β	γ
$\Lambda_c^+ \to pK_S$	1.59(7)	−0.754(10)	1.66(4)	−0.754(25)	−0.35(40)	0.56(23)
$\Lambda_c^+ \to pK_L$	1.67(7)		1.56(4)	−0.76(2)	−0.33(38)	0.56(21)
$\Lambda_c^+ \to \Lambda^0\pi^+$	1.29(5)	−0.768(5)	1.28(5)	−0.771(16)	0.39(2)	0.50(4)
$\Lambda_c^+ \to \Sigma^0\pi^+$	1.27(6)	−0.466(18)	1.23(5)	−0.469(15)	0.05(16)	0.88(1)
$\Lambda_c^+ \to \Sigma^+\pi^0$	1.24(9)	−0.48(3)	1.23(5)	−0.47(2)	0.05(16)	0.88(1)
$\Lambda_c^+ \to \Xi^0 K^+$	0.55(7)	0.01(16)	0.41(3)	−0.32(5)	0.51(4)	0.80(4)
$\Lambda_c^+ \to \Lambda^0 K^+$	0.064(3)	−0.546(34)	0.064(3)	−0.534(47)	0.26(7)	0.80(3)
$\Lambda_c^+ \to \Sigma^0 K^+$	0.0371(31)	−0.54(20)	0.0398(21)	−0.69(5)	−0.02(17)	0.73(6)
$\Lambda_c^+ \to n\pi^+$	0.066(13)		0.069(8)	−0.54(10)	0.75(4)	0.39(11)
$\Lambda_c^+ \to \Sigma^+ K_S$	0.048(14)		0.040(2)	−0.69(5)	−0.02(17)	0.73(6)
$\Lambda_c^+ \to p\pi^0$	0.0179(41)		0.0191(33)	−0.93(33)	0.12(24)	−0.34(97)
$\Lambda_c^+ \to p\eta$	0.158(11)		0.163(8)	−0.71(8)	−0.03(50)	0.71(9)
$\Lambda_c^+ \to \Sigma^+\eta$	0.32(5)	−0.99(6)	0.33(4)	−0.97(4)	−0.24(17)	0.07(18)
$\Lambda_c^+ \to p\eta'$	0.0484(91)		0.0443(76)	−0.10(26)	−0.18(22)	−0.98(6)
$\Lambda_c^+ \to \Sigma^+\eta'$	0.41(8)	−0.46(7)	0.23(4)	−0.45(7)	0.86(8)	−0.23(26)
$\Xi_c^+ \to \Xi^0\pi^+$	1.6(80)		0.99(14)	−0.53(18)	0.55(13)	0.64(8)
$\Xi_c^+ \to pK_S$	0.072(32)		0.116(7)	−0.88(4)	−0.03(22)	0.47(9)
$\Xi_c^+ \to \Lambda^0\pi^+$	0.0452(203)		0.0201(64)	−1.00(1)	0.05(30)	−0.04(42)
$\Xi_c^+ \to \Sigma^0\pi^+$	0.12(5)		0.28(1)	−0.64(3)	0.17(7)	0.75(2)
$\Xi_c^0 \to \Xi^-\pi^+$	1.80(52)	−0.64(5)	2.97(7)	−0.71(3)	0.18(6)	0.68(3)
$\Xi_c^0 \to \Xi^0\pi^0$	0.69(14)	−0.9(27)	0.70(1)	−0.72(5)	−0.02(18)	0.69(6)
Channels	$\mathcal{R}_X^{\rm exp}$	$\alpha_{\rm exp}$	$\mathcal{R}_X$	α	β	γ
$\Xi_c^0 \to \Lambda^0 K_S$	0.229(14)		0.223(7)	−0.63(2)	−0.19(27)	0.76(8)
$\Xi_c^0 \to \Sigma^0 K_S$	0.038(7)		0.038(8)	−1.00(8)	0.01(31)	−0.08(105)
$\Xi_c^0 \to \Sigma^+ K^-$	0.123(12)		0.132(10)	−0.41(6)	0.64(5)	0.65(7)
$\Xi_c^0 \to \Xi^0\eta$	0.11(1)		0.11(1)	0.22(17)	−0.31(14)	0.92(5)
$\Xi_c^0 \to \Xi^0\eta'$	0.08(2)		0.11(1)	−0.66(7)	0.74(9)	−0.12(22)

2023: Measurements of strong phases in $\Lambda_c^+ \to \Xi^0 K^+$

PRL **132**, 031801 (2024)

$$\delta_P - \delta_S = -1.55 \pm 0.27(+\pi)\,, \quad \alpha = 0.01 \pm 0.16$$

* CP even and Cabibbo-favored, but very important to studies of CP violation!

The main decay amplitudes can be determined with SU(3) symmetry.

Theoretically, large CP violation effects are predicted which may be detected by experiments and test the SM in the near future.

Charmed baryon weak decays in the SM at quark level

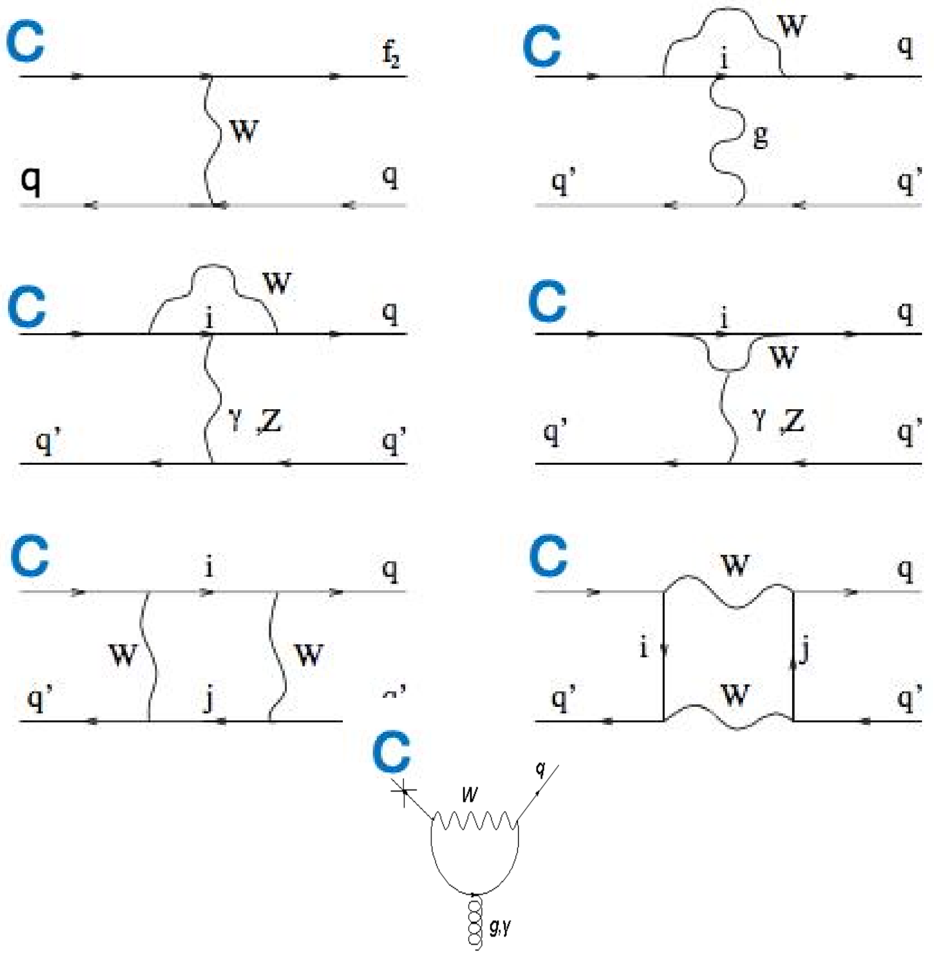
$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \left[\sum_{q,q'=d,s} V^*_{cq} V_{uq'} \left(C_1 Q_1^{qq'} + C_2 Q_2^{qq'} \right) + \lambda_b \sum_{i=3\sim6} C_i Q_i \right] + (H.c.)\,,$$

$$Q_1^{qq'} = (\overline{u}\gamma_\mu(1-\gamma_5)q')(\overline{q}\gamma^\mu(1-\gamma_5)c), \quad Q_2^{qq'} = (\overline{q}\gamma_\mu(1-\gamma_5)q')(\overline{u}\gamma^\mu(1-\gamma_5)c)$$

$\lambda_q = V^*_{cq} V_{uq}.$ $C_{3\sim6}$ are suppressed by an order of $\mathcal{O}(10^{-1})$

$$C_\pm = (C_1 \pm C_1)/2, \qquad O_\pm = \sum V^*_{cq} V_{uq'} \left(Q_1^{qq'} \pm Q_2^{qq'} \right)$$

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} (C_- O_- \pm C_+ O_+)$$



Using CKM unitarity $\lambda_d + \lambda_s + \lambda_b = 0$, we can write B_c to B P for Cabibbo Faviored (CF), Singlely Cabibbo surpressed (SCS) and doublely suppressed and penguin (CP) decay amplitudes as

$$\mathcal{M} = V^*_{cs} V_{ud} \mathcal{M}^{\rm CF} + \frac{\lambda_s - \lambda_d}{2} \mathcal{M}^{\rm SCS} + \lambda_b \mathcal{M}^{\rm CP} + V^*_{cd} V_{us} \mathcal{M}^{\rm DCS}$$

$M^i = \langle B\,P | - L^i | B_c \rangle = B(F - G\,\gamma_5)\, B_c\, P$

Tree and penguin contributions
The first one should include gluon exchange at different legs

2. SU(3) Symmetry and Decay Amplitudes

The calculation for M is extremely difficuty due to strong interaction at low energy. We will use SU(3) flavor symmetry to reduce the numbers of the amplitudes and try to fit from data. Because there 3 light quarks, the LagrangiaWe decompose the Lagrangian accordingly to have:

$$\underbrace{3 \otimes 3 \otimes \bar{3}}_{\mathcal{H}_{eff}} = \underbrace{(15_+ \oplus 3_+)}_{O_+} \oplus \underbrace{(\bar{6} \oplus 3_-)}_{O_-}$$

We decompose the Lagrangian accordingly to have:

$$\mathcal{L}^{\rm CF}_{eff} = -\frac{G_F}{\sqrt{2}} V^*_{cs} V_{ud} \{C_+[(\bar{u}d)_{V-A}(\bar{s}c)_{V-A} + (\bar{s}d)_{V-A}(\bar{u}c)_{V-A}]_{\mathbf{15}} + C_-[(\bar{u}d)_{V-A}(\bar{s}c)_{V-A} - (\bar{s}d)_{V-A}(\bar{u}c)_{V-A}]_{\bar{\mathbf{6}}}\},$$

$$\mathcal{L}^{\rm SCS}_{eff} = -\frac{G_F}{\sqrt{2}} \frac{\lambda_s - \lambda_d}{2} \{C_+[(\bar{u}s)_{V-A}(\bar{s}c)_{V-A} + (\bar{s}s)_{V-A}(\bar{u}c)_{V-A} - (\bar{d}d)_{V-A}(\bar{u}c)_{V-A} - (\bar{u}d)_{V-A}(\bar{d}c)_{V-A}]_{\mathbf{15}}$$
$$+C_-[(\bar{u}s)_{V-A}(\bar{s}c)_{V-A} - (\bar{s}s)_{V-A}(\bar{u}c)_{V-A} + (\bar{d}d)_{V-A}(\bar{u}c)_{V-A} - (\bar{u}d)_{V-A}(\bar{d}c)_{V-A}]_{\bar{\mathbf{6}}}\},$$

$$\mathcal{L}^{\rm CP}_{eff} = \frac{G_F}{\sqrt{2}} \frac{\lambda_b}{4} \{C_+[(\bar{u}d)_{V-A}(\bar{d}c)_{V-A} + (\bar{d}d)_{V-A}(\bar{u}c)_{V-A} + (\bar{s}s)_{V-A}(\bar{u}c)_{V-A} + (\bar{u}s)_{V-A}(\bar{s}c)_{V-A} - 2(\bar{u}u)_{V-A}(\bar{u}c)_{V-A}]_{\mathbf{15}}$$
$$+C_+ \sum_{q=u,d,s} [(\bar{u}q)_{V-A}(\bar{q}c)_{V-A} + (\bar{q}q)_{V-A}(\bar{u}c)_{V-A}]_{\mathbf{3}_+} + 2C_- \sum_{q=d,s} [(\bar{u}q)_{V-A}(\bar{q}c)_{V-A} - (\bar{q}q)_{V-A}(\bar{u}c)_{V-A}]_{\mathbf{3}_-}\} \quad (9)$$

$$\mathcal{L}^{\rm DCS}_{eff} = -\frac{G_F}{\sqrt{2}} V^*_{cs} V_{ud} \{C_+[(\bar{u}s)_{V-A}(\bar{d}c)_{V-A} + (\bar{d}s)_{V-A}(\bar{u}c)_{V-A}]_{\mathbf{15}} + C_-[(\bar{u}s)_{V-A}(\bar{d}c)_{V-A} - (\bar{d}s)_{V-A}(\bar{u}c)_{V-A}]_{\bar{\mathbf{6}}}\}. \quad (10)$$

L^{CP} should also include penguon 3 contributions. All 3 amplitudes are proportional to λ_b which can be neglected if not consider CP violation.

Can write the effective Hamiltonian according SU(3) representations as

$$\mathcal{H}(\mathbf{R})^{ij}_k = V^*_{cs}V_{ud}\mathcal{H}(\mathbf{R}^{\rm CF})^{ij}_k + \frac{\lambda_s-\lambda_d}{2}\mathcal{H}(\mathbf{R}^{\rm SCS})^{ij}_k + \lambda_b\mathcal{H}(\mathbf{R}^{\rm CP})^{ij}_k + V^*_{cd}V_{us}\mathcal{H}(\mathbf{R}^{\rm DCS})^{ij}_k$$

$$\mathbf{R}\in\{\mathbf{15},\overline{\mathbf{6}},\mathbf{3}_\pm\}$$

$$\mathcal{H}(\mathbf{15})^{ij}_k = \mathcal{H}(\mathbf{15})^{ji}_k \text{ and } \mathcal{H}(\overline{\mathbf{6}})_{ij} = \mathcal{H}(\overline{\mathbf{6}})_{ji}$$

$$\mathcal{H}(\mathbf{15}^{\rm CF})^{ij}_k(\overline{q}_iq^k)(\overline{q}_jc) = [(\bar ud)_{V-A}(\bar sc)_{V-A} + (\bar sd)_{V-A}(\bar uc)_{V-A}]_{\mathbf{15}}$$

$$\mathcal{H}(\overline{\mathbf{6}}^{\rm CF})_{kl}\epsilon^{lij}(\overline{q}_iq^k)(\overline{q}_jc) = [(\bar ud)_{V-A}(\bar sc)_{V-A} - (\bar sd)_{V-A}(\bar uc)_{V-A}]_{\overline{\mathbf{6}}},$$

If terms proportional to λ_b is neglected, $\lambda_s - \lambda_d$ is approximated to be $2\lambda_s$

Non-zero entris in H

$$\mathcal{H}(\mathbf{15}^{\rm CF})^{13}_2 = \mathcal{H}(\mathbf{15}^{\rm CF})^{31}_2 = \mathcal{H}(\overline{\mathbf{6}})_{22} = 1.$$

$$\mathcal{H}(\overline{\mathbf{6}}^{\rm DCS})_{33} = \mathcal{H}(\mathbf{15}^{\rm DCS})^{12}_3 = 1,\quad \mathcal{H}(\overline{\mathbf{6}}^{\rm SCS}))_{23} = \mathcal{H}(\mathbf{15}^{\rm SCS}))^{12}_2 = -\mathcal{H}(\mathbf{15}^{\rm SCS}))^{13}_3 = -1,$$

$$\mathcal{H}(\mathbf{15}^{\rm CP})^{11}_1 = -2\mathcal{H}(\mathbf{15}^{\rm CP})^{12}_2 = -2\mathcal{H}(\mathbf{15}^{\rm CP})^{13}_3 = -\mathcal{H}(\mathbf{3}^{\rm CP}_-) = -2\mathcal{H}(\mathbf{3}^b_+) = \frac{1}{2},$$

Hadronizing quark into hadrons, we have

$$\begin{aligned} M \;=\; & f^a(P)^l_l(\bar B)^j_k H(\bar 6)_{ij}(B_c)^{ik} + f^b(P)^l_k(\bar B)^k_j H(\bar 6)_{il}(B_c)^{ij} + f^c(P)^l_j(\bar B)^k_l H(\bar 6)_{ik}(B_c)^{ij} + f^d(P)^l_j(\bar B)^k_i H(\bar 6)_{kl}(B_c)^{ij} \\ & + f^e(P)^l_k(\bar B)^i_j H(15)^{jk}_l(B_c)_i + f^{e1}(P)^l_l(\bar B)^j_k H(15)^{ik}_j(B_c)_i + f^{e2}(P)^j_l(\bar B)^l_k H(15)^{ik}_j(B_c)_i + f^{e3}(P)^l_k(\bar B)^j_l H(15)^{ik}_j(B_c)_i \\ & + f^{e4}(P)^i_k(\bar B)^l_j H(15)^{jk}_l(B_c)_i + f^a_3(P)^k_k(\bar B)^j_i H(3)^i(B_c)_j + f^b_3(P)^i_k(\bar B)^k_m H(3)^m(B_c)_i + f^c_3(P)^m_k(\bar B)^k_m H(3)^i(B_c)_i \\ & + f^d_3(P)^m_n(\bar B)^k_m H(3)^n(B_c)_k \end{aligned}$$

For CF, SCS, DCS processes, one should multiply $V^*_{cs}V_{ud}$, $(\lambda_s - \lambda_d)/2$ and $V^*_{cd}V_{us}$, respectively.

Reduce the number of amplitude using Koner-Pati-Woo Therorem

The 15 is from O_+ which is total symmetric by exchanging color indices, while the initial baryon and final baryons are total antisymmetric in color, so if there are two quark in a baryon are connected to the 15, that amplitude must be zero because ising match in colors.

For this reason, out of the five amplitudes related to 15, only f^e survives. We have then the following terms

$$\begin{aligned} M \;=\; & f^a(P)^l_l(\bar{B})^j_k H(\bar{6})_{ij}(B_c)^{ik} + f^b(P)^l_k(\bar{B})^k_j H(\bar{6})_{il}(B_c)^{ij} + f^c(P)^l_j(\bar{B})^k_l H(\bar{6})_{ik}(B_c)^{ij} + f^d(P)^l_j(\bar{B})^k_i H(\bar{6})_{kl}(B_c)^{ij} \\ + \; & f^e(P)^l_n(\bar{B})^k_m H(15)^{mn}_l(B_c)_k + f^a_3(P)^k_k(\bar{B})^j_i H(3)^i(B_c)_j + f^b_3(P)^i_k(\bar{B})^k_m H(3)^m(B_c)_i + f^c_3(P)^m_k(\bar{B})^k_m H(3)^i(B_c)_i \\ + \; & +f^d_3(P)^m_n(\bar{B})^k_m H(3)^n(B_c)_k \qquad (17) \end{aligned}$$

If just want to obtain CP conserving branching ratios, terms proportional to λ_b can be neglected, the H(3) terms are always proportional to λ_b and therefore can be dropped.

Therefore the amplitudes reduce to total of 5 complex f^i terms. Since each f^i contains the F^i and G^i terms, normalizing one of them to be real, there are total 19 real paramerters to account for Tc3 -> B P decays. There are more than 19 data points, it is possible to determine all 19 paramters for the decays.

For determing 15, 6 amplitudes, the 19 parameters will be used to fit data!

Amplitudes from Data Fitting

TABLE I. The fitting results of parameters by CP conserved experimental quantities and adopt Branching ratio ($Rr = \Xi_c^0 \to \Xi^0\pi^0$ and Ξ_c^+) with $\chi^2 = 2.53$

f^b	f^c	f^d	f^e	g^b	g^c	g^d	g^e
-0.068 ± 0.014	-0.026 ± 0.002	-0.014 ± 0.014	-0.015 ± 0.014	0.189 ± 0.051	-0.030 ± 0.012	0.071 ± 0.033	-0.007 ± 0.033
0	-0.0076 ± 0.0037	-0.0002 ± 0.00061	-0.0005 ± 0.0089	-0.139 ± 0.036	0.0956 ± 0.0072	0.071 ± 0.033	-0.017 ± 0.018

Looks a reasonably good fit, but f^i_3 are missing.

For CP concerving studies, this is good approximation, but for CP violation studies, this is problematic.

Without f^i_3, when λ_b is neglected, $\lambda_s - \lambda_d = 0$, there is no CP violation in direct decays.

If λ_b is not zero, $\lambda_s - \lambda_d = 2\lambda_s - \lambda_b$, there is CP violation because the appearance λ_b, asymmetries are of order 10^{-4}.

But if λ_b is kept to have CP violation, one should also include f^i_3 terms because they are proportioinal to λ_b !!

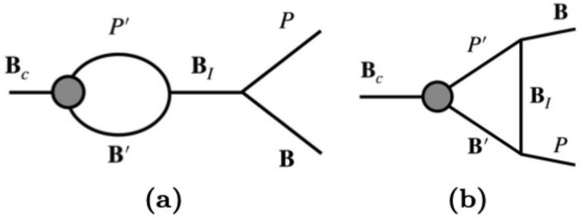
3. CP Violation in Charmed Baryon Decays

Need to include f^{i}_{3} for a better anaylsis. How to include them in?

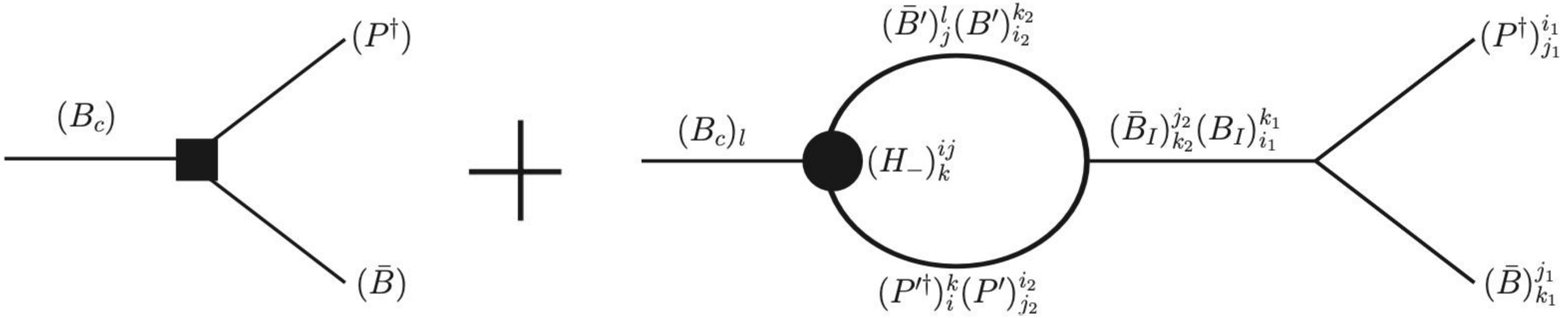
Through re-scattering effects

The total amplitude should be the sum of

Tree amplitudes + Re-scattering ones



$$\mathcal{L}_{\mathbf{B_c B}P} = \mathcal{L}^{\rm Tree}_{\mathbf{B_c B}P} + \mathcal{L}^{\rm FSR\text{-}s}_{\mathbf{B_c B}P} + \mathcal{L}^{\rm FSR\text{-}t}_{\mathbf{B_c B}P}.$$



$$\mathcal{L}^{\rm Tree}_{\mathbf{B_c B}P} = \sum_{P,\mathbf{B},\mathbf{B_c}} F^{\rm Tree}_{\mathbf{B_c B}P} P^\dagger \bar{\mathbf{B}}\mathbf{B}_c = (P^\dagger)^k_i (\bar{\mathbf{B}})^l_j [\tilde{F}^+_V (H_+)^{ij}_k + \tilde{F}^-_V (H_-)^{ij}_k](\mathbf{B_c})_l$$

$$\mathcal{L}^{\rm Strong}_{\mathbf{BB'}P} = \sum_{\mathbf{B}',P}\left(\sum_{\mathbf{B}_+} g_{\mathbf{B}_+\mathbf{B}'P} P^\dagger \bar{\mathbf{B}}'\gamma_5 \mathbf{B}_+ + \sum_{\mathbf{B}_-} g_{\mathbf{B}_-\mathbf{B}P} P^\dagger \bar{\mathbf{B}}'\mathbf{B}_-\right)$$
$$= g_+ \left[(P^\dagger)^i_j (\bar{\mathbf{B}}')^j_k \gamma_5 + (P^\dagger)^j_k (\bar{\mathbf{B}}')^i_j \gamma_5\right](\mathbf{B}_+)^k_i + g_- \left[(P^\dagger)^i_j (\bar{\mathbf{B}}')^j_k + r_-(P^\dagger)^j_k (\bar{\mathbf{B}}')^i_j\right](\mathbf{B}_+)^k_i$$

$$
\begin{aligned}
\langle \mathcal{L}^{\text{FRS-s}}_{\mathbf{B_c BP}} \rangle &= \sum_{\mathbf{B_I},\mathbf{B'},\mathbf{P'}} \langle \mathcal{L}^{\text{strong}}_{\mathbf{B_I BP}} \mathcal{L}^{\text{strong}}_{\mathbf{B_I B' P'}} \mathcal{L}^{\text{Tree}}_{\mathbf{B_c B' P'}} \rangle_{\text{FRS-s}} \\
&= \langle g_- \left[\left(P^\dagger\right)^{i_1}_{j_1} \left(\overline{\mathbf{B}}\right)^{j_1}_{k_1} \left(\mathbf{B}_I\right)^{k_1}_{i_1} + r_- \left(P^\dagger\right)^{j_1}_{k_1} \left(\overline{\mathbf{B}}\right)^{i_1}_{j_1} \left(\mathbf{B}_I\right)^{k_1}_{i_1} \right] g_- \left[\left(P'\right)^{i_2}_{j_2} \left(\overline{\mathbf{B}}_I\right)^{j_2}_{k_2} \left(\mathbf{B}'\right)^{k_2}_{i_2} + r_- \left(P'\right)^{j_2}_{k_2} \left(\overline{\mathbf{B}}_I\right)^{i_2}_{j_2} \left(\mathbf{B}'\right)^{k_2}_{i_2} \right] \\
&\quad \left[\left(P'^\dagger\right)^{k}_{i} \left(\overline{\mathbf{B}'}\right)^{l}_{j} \tilde{F}^-_V \left(\mathcal{H}_-\right)^{ij}_{k} \left(\mathbf{B}_c\right)_l \right] \rangle_{\text{FRS-s}} \\
&= \sum_{a,b,c=1}^{8} \langle \frac{g_-^2 \tilde{F}^-_V}{8} (P^\dagger)^{i_1}_{j_1} (\overline{\mathbf{B}})^{j_1}_{k_1} (\mathbf{B}^-_{\mathbf{I}})_a (\lambda_a)^{k_1}_{i_1} (P'_c)(\lambda_c)^{i_2}_{j_2} (\overline{\mathbf{B}}^-_{\mathbf{I}})_a (\lambda^\dagger_a)^{j_2}_{k_2} (\mathbf{B}')_b (\lambda_b)^{k_2}_{i_2} (P'^\dagger_c)(\lambda^\dagger_c)^{k}_{i} (\overline{\mathbf{B}'})_b (\lambda^\dagger_b)^{l}_{j} (\mathcal{H}_-)^{ij}_{k} (\mathbf{B}_c)_l \rangle \\
&+ r_- \begin{pmatrix} i_1 \leftrightarrow j_1 \\ j_1 \leftrightarrow k_1 \end{pmatrix} + r_- \begin{pmatrix} i_2 \leftrightarrow j_2 \\ j_2 \leftrightarrow k_2 \end{pmatrix} + r_-^2 \begin{pmatrix} i_1 \leftrightarrow j_1, i_2 \leftrightarrow j_2 \\ j_1 \leftrightarrow k_1, j_2 \leftrightarrow k_2 \end{pmatrix}
\end{aligned}
$$

$$
\begin{aligned}
\langle \mathcal{L}^{\text{FRS-s}}_{\mathbf{B_c BP}} \rangle &= \frac{1}{8} \left(\int \frac{d^4 q}{(2\pi)^4} \frac{\not{P}_{\mathbf{B_I}} + m_I}{P^2_{\mathbf{B_I}} - m_I^2} \cdot \frac{\not{P}_{\mathbf{B'}} + m_{\mathbf{B'}}}{P^2_{\mathbf{B'}} - m^2_{\mathbf{B'}}} \cdot \frac{g_-^2 \tilde{F}^-_V}{(q - P_{B'})^2 - m^2_{P'}} \right) \\
&\quad \sum_{a,b,c=1}^{8} \langle (P^\dagger)^{i_1}_{j_1} (\overline{\mathbf{B}})^{j_1}_{k_1} (\lambda_a)^{k_1}_{i_1} (\lambda_c)^{i_2}_{j_2} (\lambda^\dagger_a)^{j_2}_{k_2} (\lambda_b)^{k_2}_{i_2} (\lambda^\dagger_c)^{k}_{i} (\lambda^\dagger_b)^{l}_{j} (\mathcal{H}_-)^{ij}_{k} (\mathbf{B}_c)_l \rangle + \ldots \\
&= \frac{3 \tilde{S}^-_V}{8} \sum_{a,b,c=1}^{8} \langle (P^\dagger)^{i_1}_{j_1} (\overline{\mathbf{B}})^{j_1}_{k_1} (\lambda_a)^{k_1}_{i_1} (\lambda_c)^{i_2}_{j_2} (\lambda^\dagger_a)^{j_2}_{k_2} (\lambda_b)^{k_2}_{i_2} (\lambda^\dagger_c)^{k}_{i} (\lambda^\dagger_c)^{l}_{j} (\mathcal{H}_-)^{ij}_{k} (\mathbf{B}_c)_l \rangle + \ldots
\end{aligned}
$$

$$\langle \mathcal{L}^{\text{FSR-s}}_{\mathbf{B}_c\mathbf{B}P}\rangle \propto \quad \tilde{S}^-_V \left[(P^\dagger)^{i_1}_{j_1}(\overline{\mathbf{B}})^{j_1}_{k_1} \quad (\delta^{k_1}_{k_2}\delta^{j_2}_{i_1} - \tfrac{1}{3}\delta^{k_1}_{i_1}\delta^{j_2}_{k_2})(\delta^{i_2}_{i}\delta^{k}_{j_2} - \tfrac{1}{3}\delta^{i_2}_{j_2}\delta^{k}_{i})(\delta^{k_2}_{j}\delta^{l}_{i_2} - \tfrac{1}{3}\delta^{k_2}_{i_2}\delta^{l}_{j}) \quad (\mathcal{H}_-)^{ij}_{k}(\mathbf{B}_c)_l\right] +$$
$$r_-\tilde{S}^-_V \left[(P^\dagger)^{j_1}_{k_1}(\overline{\mathbf{B}})^{i_1}_{j_1} \quad (\delta^{k_1}_{k_2}\delta^{j_2}_{i_1} - \tfrac{1}{3}\delta^{k_1}_{i_1}\delta^{j_2}_{k_2})(\delta^{i_2}_{i}\delta^{k}_{j_2} - \tfrac{1}{3}\delta^{i_2}_{j_2}\delta^{k}_{i})(\delta^{k_2}_{j}\delta^{l}_{i_2} - \tfrac{1}{3}\delta^{k_2}_{i_2}\delta^{l}_{j}) \quad (\mathcal{H}_-)^{ij}_{k}(\mathbf{B}_c)_l\right] +$$
$$r_-\tilde{S}^-_V \left[(P^\dagger)^{i_1}_{j_1}(\overline{\mathbf{B}})^{j_1}_{k_1} \quad (\delta^{k_1}_{j_2}\delta^{i_2}_{i_1} - \tfrac{1}{3}\delta^{k_1}_{i_1}\delta^{i_2}_{j_2})(\delta^{j_2}_{i}\delta^{k}_{k_2} - \tfrac{1}{3}\delta^{j_2}_{k_2}\delta^{k}_{i})(\delta^{k_2}_{j}\delta^{l}_{i_2} - \tfrac{1}{3}\delta^{k_2}_{i_2}\delta^{l}_{j}) \quad (\mathcal{H}_-)^{ij}_{k}(\mathbf{B}_c)_l\right] +$$
$$r^2_-\tilde{S}^-_V \left[(P^\dagger)^{j_1}_{k_1}(\overline{\mathbf{B}})^{i_1}_{j_1} \quad (\delta^{k_1}_{j_2}\delta^{i_2}_{i_1} - \tfrac{1}{3}\delta^{k_1}_{i_1}\delta^{i_2}_{j_2})(\delta^{j_2}_{i}\delta^{k}_{k_2} - \tfrac{1}{3}\delta^{j_2}_{k_2}\delta^{k}_{i})(\delta^{k_2}_{j}\delta^{l}_{i_2} - \tfrac{1}{3}\delta^{k_2}_{i_2}\delta^{l}_{j}) \quad (\mathcal{H}_-)^{ij}_{k}(\mathbf{B}_c)_l\right]$$

$$\tilde{f}^b = \tilde{F}^-_V - (r_- + 4)\tilde{S}^- + \sum_{\lambda=\pm}(2r^2_\lambda - r_\lambda)\tilde{T}^-_\lambda\,,$$
$$\tilde{f}^c = -r_-(r_- + 4)\tilde{S}^- + \sum_{\lambda=\pm}(r^2_\lambda - 2r_\lambda + 3)\tilde{T}^-_\lambda\,,$$
$$\tilde{f}^d = \tilde{F}^-_V + \sum_{\lambda=\pm}(2r^2_\lambda - 2r_\lambda - 4)\tilde{T}^-_\lambda\,, \quad \tilde{f}^e = \tilde{F}^+_V\,,$$
$$\tilde{f}^b_3 = (1 - \frac{7r_-}{2})\tilde{S}^- - \sum_{\lambda=\pm}(r^2_\lambda - 5r_\lambda/2 + 1)\tilde{T}^-_\lambda\,,$$
$$\tilde{f}^c_3 = \frac{(r_- + 1)(7r_- - 2)}{6}\tilde{S}^- + \sum_{\lambda=\pm}\frac{1}{6}(r^2_\lambda + 11r_\lambda + 1)\tilde{T}^-_\lambda\,,$$
$$\tilde{f}^d_3 = \frac{2r_- - 7r^2_-}{2}\tilde{S}^- - \sum_{\lambda=\pm}\frac{(r_\lambda + 1)^2}{2}\tilde{T}^-_\lambda - \frac{1}{4}\left(\tilde{F}^+_V + 2\tilde{F}^-_V\right).$$

Fi from tree
Si s-channel res-ecattering
Ti t-channel re-scattering

Si and Ti appear in f^i_3 , using the 4 determined from amplitude fit previously, and then intert into f^i_3
Therfore f^i_3 are determined.

Where $\tilde{T}^-$ represent the overall unknown constants in the t-channel S-wave FSR with the subscript denoting the B_I parity. we have determined $r_+ \approx 2.47$ and $r_- \approx 2.56$[26]. We take $r_- = r_+$ to combine the summations and redefine$\tilde{T}_\pm = (\tilde{T}^\pm_+ + \tilde{T}^\pm_-)$. The left unknown $(\tilde{F}^\pm_V, \tilde{S}^-, \tilde{T}^-)$ can be got through solve the equations of $\tilde{f}^{b,c,d,e}$ whose values from fit job. The predictions A_{CP} and $A^{\alpha,\beta,\gamma}_{CP}$ within the framework of FRS are collected in the Table.V.

4. Results and Conclusions

Channels	$A^{\alpha}_{CP}(10^{-3})$	$A^{\beta}_{CP}(10^{-3})$	$A^{\gamma}_{CP}(10^{-3})$	$A_{CP}(10^{-3})$
$\Lambda_c^+ \to \Sigma^+ K_S$	0.02(1)	0.11(3)	0.01(2)	0.34(2)
$\Lambda_c^+ \to \Sigma^0 K^+$	0.02(1)	0.11(3)	0.01(2)	0.34(2)
$\Lambda_c^+ \to p\pi^0$	0.14(69)	−0.23(79)	−0.48(29)	−0.98(39)
$\Lambda_c^+ \to n\pi^+$	0.08(20)	0.16(25)	−0.20(16)	−0.77(12)
$\Lambda_c^+ \to \Lambda^0 K^+$	0.02(18)	−0.11(7)	0.05(13)	−0.41(15)
$\Xi_c^+ \to \Sigma^+ \pi^0$	0.0(12)	0.10(3)	0.02(10)	0.15(10)
$\Xi_c^+ \to \Sigma^0 \pi^+$	0.01(11)	0.05(5)	0.0(10)	0.13(8)
$\Xi_c^+ \to \Xi^0 K^+$	−0.03(15)	−0.17(22)	0.13(9)	0.83(9)
$\Xi_c^+ \to p K_S$	−0.02(2)	−0.14(4)	−0.02(3)	−0.33(2)
$\Xi_c^+ \to \Lambda^0 \pi^+$	0.01(12)	0.25(32)	−0.41(23)	0.03(13)
$\Xi_c^0 \to \Sigma^+ \pi^-$	−0.53(17)	−0.45(15)	0.14(8)	1.83(9)
$\Xi_c^0 \to \Sigma^0 \pi^0$	−0.03(10)	0.18(17)	−0.03(6)	0.31(6)
$\Xi_c^0 \to \Sigma^- \pi^+$	0.05(5)	0.0(7)	0.06(10)	0.03(5)
$\Xi_c^0 \to \Xi^0 K_S$	−0.07(3)	0.11(3)	−0.04(0)	0.41(3)
$\Xi_c^0 \to \Xi^- K^+$	−0.05(6)	0.0(7)	−0.05(7)	−0.05(7)
$\Xi_c^0 \to p K^-$	0.61(20)	0.48(15)	−0.18(10)	−1.80(10)
$\Xi_c^0 \to n K_S$	0.08(5)	−0.16(5)	0.09(1)	−0.44(3)
$\Xi_c^0 \to \Lambda^0 \pi^0$	0.01(5)	−0.13(22)	0.24(10)	−0.02(6)

Did not include η and η’ in the fit because this involves singlet η_1 which need inclusion of new amplitudes. In progress to include all them in.

CP violation effects are enhanced by re-scattering .

CP violating decay rate asymmetries can be as large a $1.8\text{x}10^{-3}$.

A_{CP} (Ξ_C^0-> p K^-) - A_{CP} (Ξ_C^0-> Σ^+ π^-) ~ - 3.63 $\text{x}10^{-3}$

Similar to enhanced observed

$A_{CP}(D^0 \to K^+K^-)$ - $A_{CP}(D^0 \to \pi^+\pi^-)$ ~$-1.54\text{x}10^{-3}$

Experiments go for CP violation in charm Baryon Decays

Thank you for your attentions!