The 6th International Workshop on Future Tau Charm Facilities

Theoretical studies on CP violation in charmed baryon decays

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Based on: arxiv: 2408.14959 [hep-ph]

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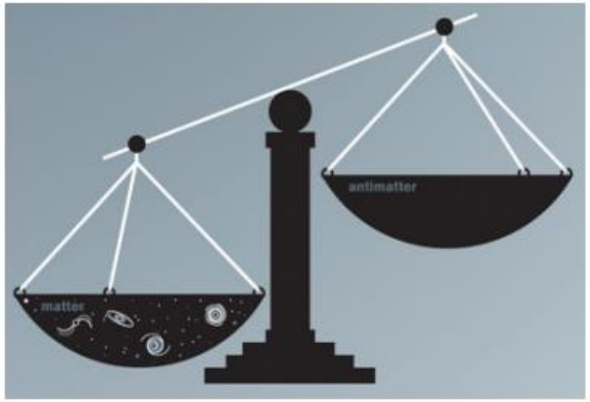
November 19, 2024

Introductions and Motivations

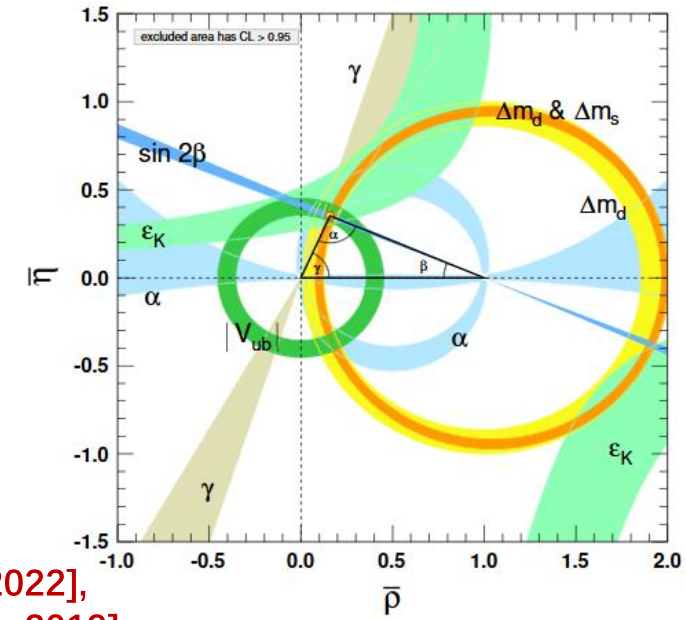
Sakharov conditions for Baryogenesis:

- Baryon number violation
- C and CP violation
- Out of thermal equilibrium



CPV is also important in:

- Test SM and understanding of strong dynamics
- Search for new physics



Test the unitarity of CKM

CPV was well established in the meson system, so what about for baryon system?

However, CPV never established in baryon decays:

- For b-baryon decays: PQCD, QCDF?
- For charm baryon?

[Lu, Wang, Zou, Ali, Kramer, 2009], [Zhou...2022], [Yu,Han,Li,FSY,HnLi...2024]，[Hong-Wei Ke...,2019]

- $m_b \approx 4.2$ GeV
- $m_c \approx 1.3$ GeV

Introductions and Motivations

Experimental side:

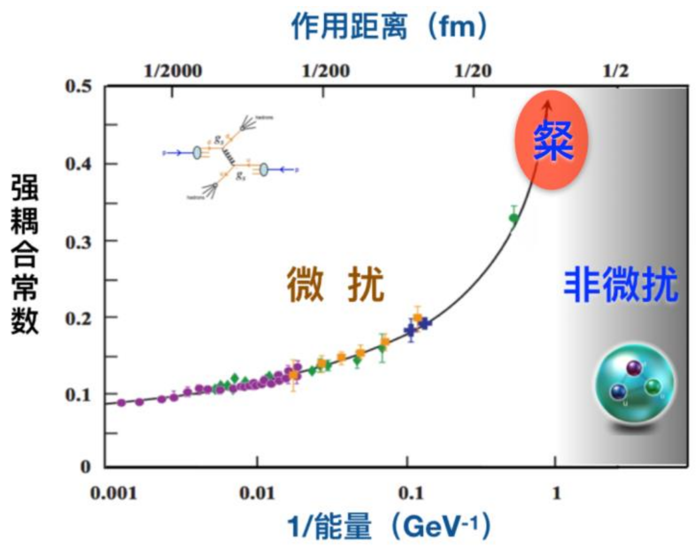
Processes	Branching Ratio	Decay Parameter α
$\Lambda_c^+ \to \Lambda^0\pi^+$	$(1.30 \pm 0.07)\%$	-0.84 ± 0.09
$\Lambda_c^+ \to \Sigma^+\pi^0$	$(1.25 \pm 0.10)\%$	-0.55 ± 0.11
$\Lambda_c^+ \to \Sigma^0\pi^+$	$(1.29 \pm 0.07)\%$	-0.73 ± 0.18
$\Lambda_c^+ \to pK_S^0$	$(1.59 \pm 0.08)\%$	0.2 ± 0.5
$\Lambda_c^+ \to \Sigma^+\eta$	$(4.4 \pm 2.0) \times 10^{-3}$	
$\Lambda_c^+ \to \Sigma^+\eta'$	$(1.5 \pm 0.6)\%$	
$\Lambda_c^+ \to \Xi^0 K^+$	$(5.5 \pm 0.7) \times 10^{-3}$	
$\Lambda_c^+ \to p\pi^0$	$< 8 \times 10^{-5}$	
$\Lambda_c^+ \to p\eta$	$(1.42 \pm 0.12) \times 10^{-3}$	
$\Lambda_c^+ \to p\eta'$	$(4.73 \pm 0.98) \times 10^{-4}$	
$\Lambda_c^+ \to \Lambda^0 K^+$	$(6.1 \pm 1.2) \times 10^{-4}$	
$\Lambda_c^+ \to \Sigma^0 K^+$	$(5.2 \pm 0.8) \times 10^{-4}$	
$\Lambda_c^+ \to n\pi^+$	$(0.66 \pm 0.13) \times 10^{-3}$	

- BESIII,Belle II and LHCb

Processes	Branching Ratio	Decay Parameter α
$\Lambda_c^+ \to \Lambda^0\rho^+$	$(4.06 \pm 0.52)\%$	-0.763 ± 0.070
$\Lambda_c^+ \to \Sigma^+\rho^0$	$< 1.7\%$	
$\Lambda_c^+ \to p\bar{K}^{*0}$	$(1.96 \pm 0.27)\%$	
$\Lambda_c^+ \to \Sigma^+\omega$	$(1.70 \pm 0.21)\%$	
$\Lambda_c^+ \to \Sigma^+\phi$	$(3.9 \pm 0.6) \times 10^{-3}$	
$\Lambda_c^+ \to \Sigma^+ K^{*0}$	$(3.5 \pm 1.0) \times 10^{-3}$	
$\Lambda_c^+ \to p\phi$	$(1.06 \pm 0.14) \times 10^{-3}$	
$\Lambda_c^+ \to p\omega$	$(8.3 \pm 1.1) \times 10^{-4}$	

process	CPV observables	
$\Lambda_c^+ \to \Lambda\pi^+$	$A_{CP}^{\alpha} = -0.07 \pm 0.19 \pm 0.24$	*FOCUS,PLB (2006)*
$\Lambda_c^+ \to \Lambda K^+$	$A_{CP}^{dir} = 0.021 \pm 0.026 \pm 0.001$	*Belle, Sci.Bull. (2023)*
	$A_{CP}^{\alpha} = -0.023 \pm 0.086 \pm 0.071$	
$\Lambda_c^+ \to \Sigma^0 K^+$	$A_{CP}^{dir} = 0.025 \pm 0.054 \pm 0.004$	
	$A_{CP}^{\alpha} = 0.08 \pm 0.35 \pm 0.14$	
$\Xi_c^0 \to \Xi^-\pi^+$	$A_{CP}^{\alpha} = 0.024 \pm 0.052 \pm 0.014$	*Belle, PRL (2021)*
$\Lambda_c^+ \to pK^+K^-$ $\Lambda_c^+ \to p\pi^+\pi^-$	$A_{CP}^{dir}(\Lambda_c^+ \to pK^+K^-) - A_{CP}^{dir}(\Lambda_c^+ \to p\pi^+\pi^-) = (0.30 \pm 0.91 \pm 0.61)\%$	*LHCb, JHEP (2018)*
$\Xi_c^+ \to pK^-\pi^+$	NO CP violation	*LHCb, EPJC (2020)*

Introductions and Motivations



Theoretical side: non-perturbative effects

- No theoretical calculation based on the first principle
- $1/m_c$ expansion is not well under control: D mixing, lifetimes...

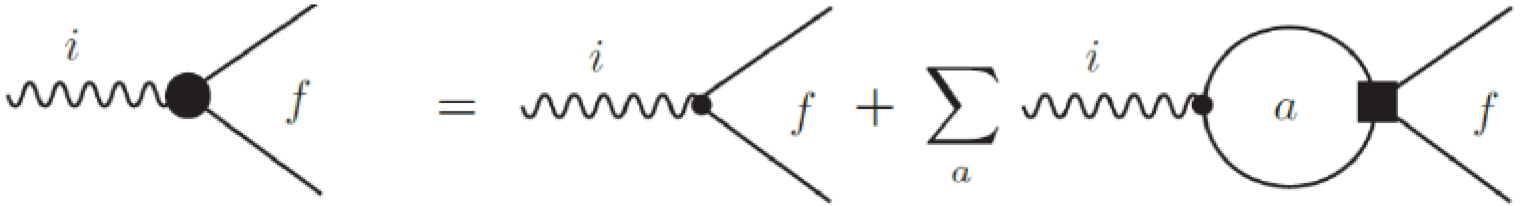
Some theoretical studies:

- Global analysis based on $SU(3)$ flavor symmetry
  - Lots of inspiration when there are no dynamics
  - The CP asymmetries is difficult to predict since no information on penguins
  - Refs: [Lu, Wang, Yu 2009],[Geng,Liu...2018,2020,2024],[Xu, Cheng...2024],[Wang..2024]..
- Dynamical model calculation
  - Pole model, current algebra, quark model...
  - Refs: [Xu,Cheng...2018,2020],[Zeng,Xu..2024]...

No any numerical prediction on CPV of charm-baryon decays

- Final state interactions may provide a picture
- Clear strong phase sources

Final state interactions



$$\mathcal{A}(i \to f) = \sum_j \langle f|U(+\infty,0)|j\rangle\langle j|\mathcal{H}_w|i\rangle$$

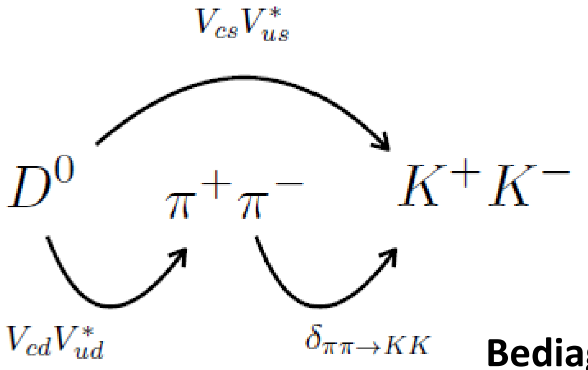
Hai Yang Cheng… 2005,2010

The natural physical picture of the long-distance nonperturbative contribution

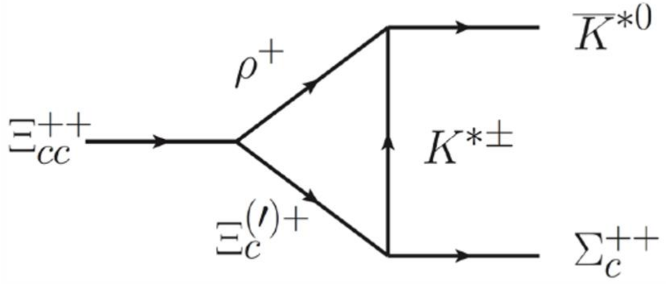
Some successful applications:

- Data-driven prediction for $D \to \pi^+\pi^-/K^+K^-$ meson CPV
- Discovery Potentials of Doubly Charmed Baryons

It deserves to develop the rescattering mechanism to study CPV of charmed baryons



Bediaga, Frederico, Magalhaes, PRL2023



Yu, Jiang, Li, Lu, Wang, Zhao,2016

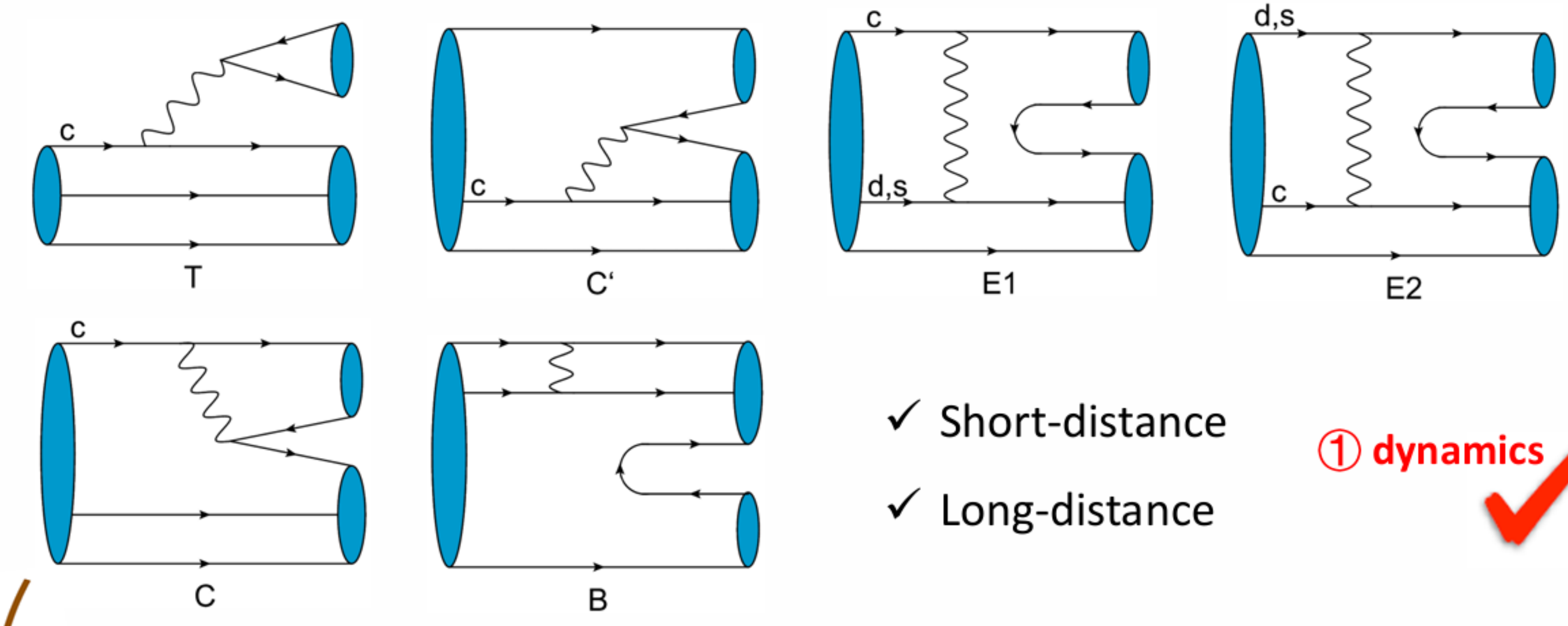
Final state interactions

Topological diagrams:

- T diagram is naive factorized
- The other diagrams receive large non-factorizable contribution
  - Large branching ratios for some channel without T diagrams
  - Power rules from SCET with $\frac{|C|}{|T|} \sim \frac{|E|}{|C|} \sim \frac{\Lambda_{QCD}}{m_c}$

decay mode	topology	experiment(%)	Short-distance
$\Lambda_c^+ \to p\phi$	C	0.106 ± 0.014	1.92×10^{-6}

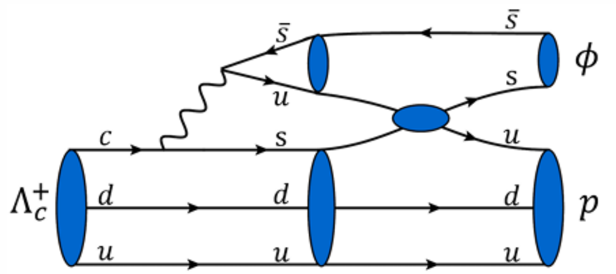
- Exp: $BR(\Lambda_c^+ \to p\phi) = (1.06 \pm 0.14) \times 10^{-3}$



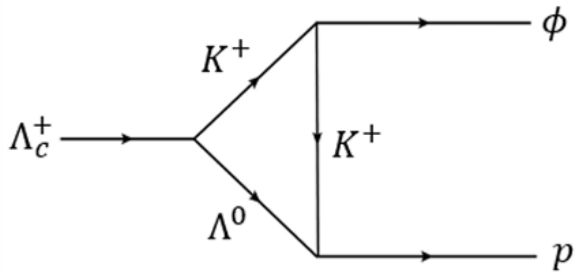
✓ Short-distance

✓ Long-distance

① dynamics



quark exchange



hadronic triangle

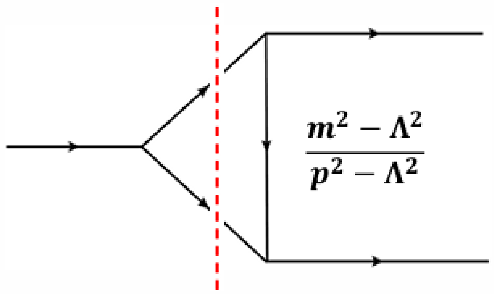
Hence, these non-factorization parts must be included in order to predict BR and CPV of charm baryon decays. FSIs can be useful!

Final state interactions

Calculating long distance contributions:

- Conventional method: optical theorem + Cutkosky cutting rule

H. Y. Cheng, C. K. Chua and A. Soni, Phys. Rev. D 71, 014030 (2005)........ $\Lambda = m_k + \eta\Lambda_{QCD}$

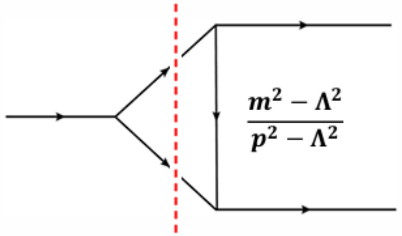


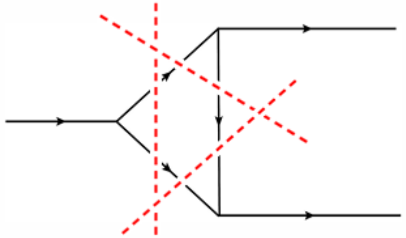
$$\mathcal{A}bs[\mathcal{M}(P_i \to P_3 P_4)]$$
$$= \frac{1}{2}\sum_{\{P_1P_2\}}\int \frac{d^3 p_1}{(2\pi)^3 2E_1}\int \frac{d^3 p_2}{(2\pi)^3 2E_2}(2\pi)^4\delta^4(p_3+p_4-p_1-p_2)$$
$$\cdot M(P_i \to \{P_1P_2\}) T^*(P_3P_4 \to \{P_1P_2\}).$$

- It is not successful since strong parameter dependence

decay mode	Topology diagram	Experiment(%)	Short-distance	η
$\Lambda_c^+ \to \Sigma^+\phi$	E_1	0.39 ± 0.06	-	6.5
$\Lambda_c^+ \to p\omega$	C, C', E_1, E_2, B	0.09 ± 0.04	2.83×10^{-6}	0.60

- Only a part of the imaginary contribution is included, and the real part might be remarkable



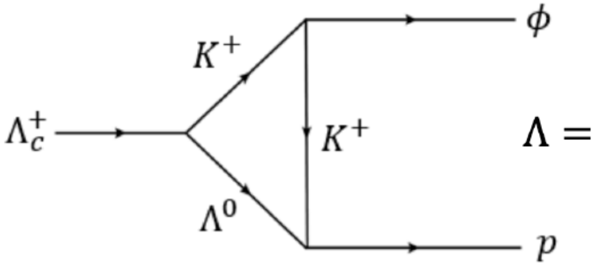


- Off-shell effects
- Lost contribution

Final state interactions

Calculating long distance contributions by complete loop integral:

$$\mathcal{M}[P,\mathcal{B}_8;P] = -i\int \frac{d^4k}{(2\pi)^4} g_{BBP}\cdot g_{VPP}\bar{u}(p_4,s_4)\gamma_5(\not{p}_2+m_2)(A+B\gamma_5)u(p,s) \times \varepsilon^*_\mu(p_3,\lambda_3)(p_1+k)^\mu \frac{\mathcal{F}}{(p_1^2-m_1^2+i\epsilon)(p_2^2-m_2^2+i\epsilon)(k^2-m_k^2+i\epsilon)},$$



$$\Lambda = m_k + \eta\Lambda_{QCD}$$

$$\mathcal{F} = \left(\frac{\Lambda_1^2-m_1^2}{\Lambda_1^2-p_1^2}\right)\left(\frac{\Lambda_2^2-m_2^2}{\Lambda_2^2-p_2^2}\right),$$

- To regulate possible divergence introducing a parameter

- Weak vertex is treated under naive factorization
- Only T topological contribution is considered for short distance contribution
- Strong scatterings are treated through effective interaction at hadron level
- The s-channel re-scattering contributions are ignored in our calculation

We obtained the complete amplitude with real and imaginary parts

$$\begin{pmatrix} \{0.,\ 0.,\ -1.57956\times10^{-7}+6.40596\times10^{-8}\,i\} & \{4.65132\times10^{-7}+1.10998\times10^{-6}\,i,\ 0.,\ 0.\} \\ \{0.,\ \underline{-1.00635\times10^{-6}+1.46048\times10^{-7}\,i},\ 0.\} & \{0.,\ 0.,\ 4.56956\times10^{-7}-2.83047\times10^{-7}\,i\} \end{pmatrix}$$

[C.P.Jia, H.Y.Jiang, **JPWang**, F.S.Yu, 2408.14959]

- Large branching ratios is given $(0.9\pm0.3)\times10^{-3}$ for $\Lambda_c^+ \to p\phi$ which is consistent with exp.
- Remarkable real part of amplitudes, hence more reasonable strong phases are achieved

Our results for $\Lambda_c^+ \to B_8 V$

Branching ratios with model parameter $\eta = 0.6 \pm 0.1$:

- Only pseudo-scalar meson octet, vector meson octet, baryon octet and decuplet are included in the re-scattering amplitudes.
- Only one parameter explains all the 8 experimental data!
- Prediction power is significant once parameter η is fitted.
- The successful applications for BRs largely boost our confidence to predict CP asymmetries

[C.P.Jia, H.Y.Jiang, **JPWang**, F.S.Yu, 2408.14959]

表 I: The branching ratio of $\Lambda_c^+ \to \mathcal{B}_8 V$ processes with $\eta = 0.6 \pm 0.1$.

Decay modes	Topology	$\mathcal{B}R_{\rm SD}(\%)$	$\mathcal{B}R_{\rm LD}(\%)$	$\mathcal{B}R_{\rm tot}(\%)$	$\mathcal{B}R_{\rm exp}(\%)$
$\Lambda_c^+ \to \Lambda^0 \rho^+$	T, C', E_2, B	6.12	$2.30^{+1.18}_{-1.94}$	$6.26^{+2.44}_{-1.39}$	4.06 ± 0.52
$\Lambda_c^+ \to \Sigma^+ \rho^0$	C', E_2, B	–	–	$0.77^{+1.38}_{-0.53}$	< 1.7
$\Lambda_c^+ \to \Sigma^+ \omega$	C', E_2, B	–	–	$2.06^{+0.40}_{-1.78}$	1.7 ± 0.21
$\Lambda_c^+ \to \Sigma^+ \phi$	E_1	–	–	$0.33^{+0.08}_{-0.29}$	0.39 ± 0.06
$\Lambda_c^+ \to p \bar{K}^{*0}$	C, E_1	3.26×10^{-3}	$3.76^{+1.37}_{-3.43}$	$3.70^{+1.29}_{-3.39}$	1.96 ± 0.27
$\Lambda_c^+ \to \Xi^0 K^{*+}$	E_2, B	–	–	$1.94^{+0.40}_{-1.68}$	–
Decay modes	Topology	$\mathcal{B}R_{\rm SD}(\times 10^{-3})$	$\mathcal{B}R_{\rm LD}(\times 10^{-3})$	$\mathcal{B}R_{\rm tot}(\times 10^{-3})$	$\mathcal{B}R_{\rm exp}(\times 10^{-3})$
$\Lambda_c^+ \to \Lambda^0 K^{*+}$	T, C', E_2, B	2.92	$2.78^{+1.28}_{-1.02}$	$4.71^{+0.48}_{-0.20}$	–
$\Lambda_c^+ \to \Sigma^0 K^{*+}$	C', E_2, B	–	–	$1.60^{+0.89}_{-0.62}$	–
$\Lambda_c^+ \to \Sigma^+ K^{*0}$	C', E_1	–	–	$2.10^{+1.37}_{-0.86}$	3.5 ± 1.0
$\Lambda_c^+ \to p\phi$	C	1.78×10^{-3}	$1.44^{+1.14}_{-0.66}$	$1.37^{+1.13}_{-0.65}$	1.06 ± 0.14
$\Lambda_c^+ \to p\omega$	C, C', E_1, E_2, B	1.48×10^{-3}	$1.28^{+0.46}_{-0.37}$	$1.26^{+0.45}_{-0.37}$	0.83 ± 0.11
$\Lambda_c^+ \to p\rho^0$	C, C', E_1, E_2, B	1.81×10^{-3}	$2.79^{+1.89}_{-1.29}$	$2.72^{+1.87}_{-1.27}$	–
$\Lambda_c^+ \to n\rho^+$	T, C', E_2, B	7.14	$8.50^{+9.57}_{-4.72}$	$26.39^{+13.71}_{-8.86}$	–
Decay modes	Topology	$\mathcal{B}R_{\rm SD}(\times 10^{-4})$	$\mathcal{B}R_{\rm LD}(\times 10^{-4})$	$\mathcal{B}R_{\rm tot}(\times 10^{-4})$	$\mathcal{B}R_{\rm exp}$
$\Lambda_c^+ \to p K^{*0}$	C, C'	9.28×10^{-4}	$0.53^{+3.67}_{-0.38}$	$0.55^{+3.71}_{-0.39}$	–
$\Lambda_c^+ \to n K^{*+}$	T, C'	3.66	$0.44^{+1.64}_{-0.30}$	$5.08^{+1.95}_{-0.66}$	–

Our results for $\Lambda_c^+ \to B_8 V$

Asymmetry parameters with model parameter $\eta = 0.6 \pm 0.1$:

- Asymmetry parameters are sensitive to strong phases, and therefore are powerful to test different dynamical models.

$$\alpha = \frac{|H_{1,\frac{1}{2}}|^2 - |H_{-1,-\frac{1}{2}}|^2}{|H_{1,\frac{1}{2}}|^2 + |H_{-1,-\frac{1}{2}}|^2}, \quad \beta = \frac{|H_{0,\frac{1}{2}}|^2 - |H_{0,-\frac{1}{2}}|^2}{|H_{0,\frac{1}{2}}|^2 + |H_{0,-\frac{1}{2}}|^2}, \quad \gamma = \frac{|H_{1,\frac{1}{2}}|^2 + |H_{-1,-\frac{1}{2}}|^2}{|H_{0,\frac{1}{2}}|^2 + |H_{0,-\frac{1}{2}}|^2},$$

$$P_L = \frac{|H_{1,\frac{1}{2}}|^2 - |H_{-1,-\frac{1}{2}}|^2 + |H_{0,\frac{1}{2}}|^2 - |H_{0,-\frac{1}{2}}|^2}{|H_{1,\frac{1}{2}}|^2 + |H_{-1,-\frac{1}{2}}|^2 + |H_{0,\frac{1}{2}}|^2 + |H_{0,-\frac{1}{2}}|^2}.$$

[P.C.Hong *et al Chinese Phys. C* **47** 053101]

- Experimental data for $\Lambda_c^+ \to \Lambda\rho^+$ are well consistent with our results

$\alpha = -0.58;$

$\beta = -0.88;$

$\gamma = 0.63;$

$P_L = -0.76 \pm 0.07;$

BSEIII,2022,JHEP

表 II: The decay asymmetry parameters of $\Lambda_c^+ \to \mathcal{B}_8 V$ processes with $\eta = 0.6 \pm 0.1$.

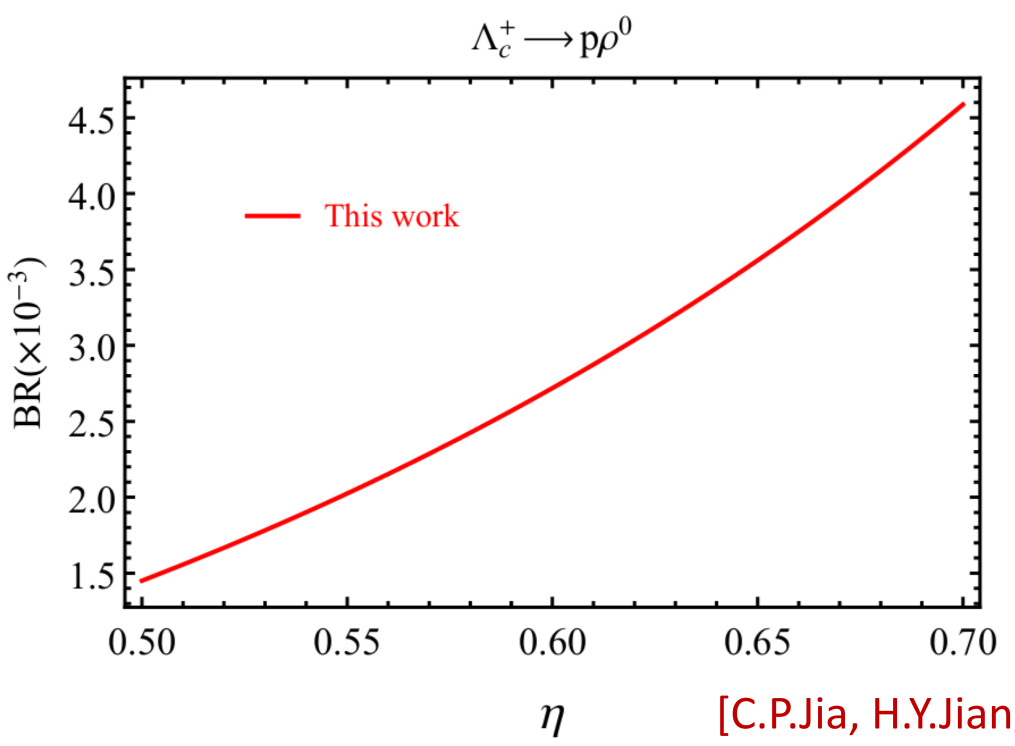
Decay modes	α	β	γ	P_L
$\Lambda_c^+ \to \Lambda^0\rho^+$	$-0.30^{+0.45}_{-0.40}$	$-0.67^{+0.06}_{-0.28}$	$0.30^{-0.20}_{+0.19}$	$-0.58^{+0.06}_{-0.28}$
$\Lambda_c^+ \to \Sigma^+\rho^0$	$-0.82^{-0.17}_{+0.04}$	$-0.54^{-0.08}_{+0.02}$	$0.74^{+0.95}_{-0.14}$	$-0.66^{+0.05}_{-0.16}$
$\Lambda_c^+ \to \Sigma^+\omega$	$0.85^{+0.002}_{-0.07}$	$0.58^{+0.12}_{-0.001}$	$3.27^{+1.17}_{-1.17}$	$0.81^{+0.02}_{-0.07}$
$\Lambda_c^+ \to \Sigma^+\phi$	$-0.11^{+0.002}_{-0.03}$	$0.47^{+0.11}_{-0.10}$	$2.12^{+0.08}_{-0.06}$	$0.08^{+0.04}_{-0.05}$
$\Lambda_c^+ \to p\bar{K}^{*0}$	$0.15^{+0.01}_{-0.15}$	$0.73^{+0.21}_{-0.52}$	$3.15^{+1.35}_{-0.02}$	$0.29^{+0.19}_{-0.12}$
$\Lambda_c^+ \to \Xi^0 K^{*+}$	$-0.12^{+0.06}_{-0.15}$	$-0.03^{+0.03}_{-0.005}$	$1.56^{+0.14}_{-0.03}$	$-0.08^{+0.05}_{-0.10}$
$\Lambda_c^+ \to \Lambda^0 K^{*+}$	$-0.77^{+0.14}_{-0.08}$	$-0.39^{+0.25}_{-0.22}$	$1.54^{+0.21}_{-0.27}$	$-0.62^{+0.17}_{-0.13}$
$\Lambda_c^+ \to \Sigma^0 K^{*+}$	$-0.03^{+0.02}_{-0.01}$	$0.31^{+0.04}_{-0.07}$	$2.21^{+0.48}_{-0.33}$	$0.08^{+0.04}_{-0.03}$
$\Lambda_c^+ \to \Sigma^+ K^{*0}$	$0.07^{+0.06}_{-0.004}$	$0.40^{+0.02}_{-0.03}$	$1.52^{+0.08}_{-0.07}$	$0.20^{+0.02}_{-0.01}$
$\Lambda_c^+ \to p\phi$	$-0.11^{+0.06}_{-0.004}$	$-0.16^{+0.12}_{-0.07}$	$5.98^{+1.07}_{-0.76}$	$-0.12^{+0.07}_{-0.01}$
$\Lambda_c^+ \to p\omega$	$0.31^{+0.14}_{-1.02}$	$0.08^{+0.04}_{-0.05}$	$0.12^{+0.17}_{-0.06}$	$0.11^{+0.02}_{-0.11}$
$\Lambda_c^+ \to p\rho^0$	$-0.29^{+0.15}_{-0.05}$	$-0.54^{+0.01}_{-0.04}$	$2.12^{+0.14}_{-0.17}$	$-0.37^{+0.10}_{-0.05}$
$\Lambda_c^+ \to n\rho^+$	$-0.95^{+0.003}_{-0.004}$	$-0.61^{+0.14}_{-0.11}$	$0.36^{+0.01}_{-0.01}$	$-0.70^{+0.10}_{-0.08}$
$\Lambda_c^+ \to pK^{*0}$	$0.45^{+0.07}_{-0.14}$	$-0.27^{+0.48}_{-0.16}$	$9.87^{+3.61}_{-3.64}$	$0.39^{+0.09}_{-0.18}$
$\Lambda_c^+ \to nK^{*+}$	$-0.89^{+0.29}_{-0.05}$	$-0.83^{+0.37}_{-0.10}$	$1.04^{+0.34}_{-0.14}$	$-0.86^{+0.32}_{-0.07}$

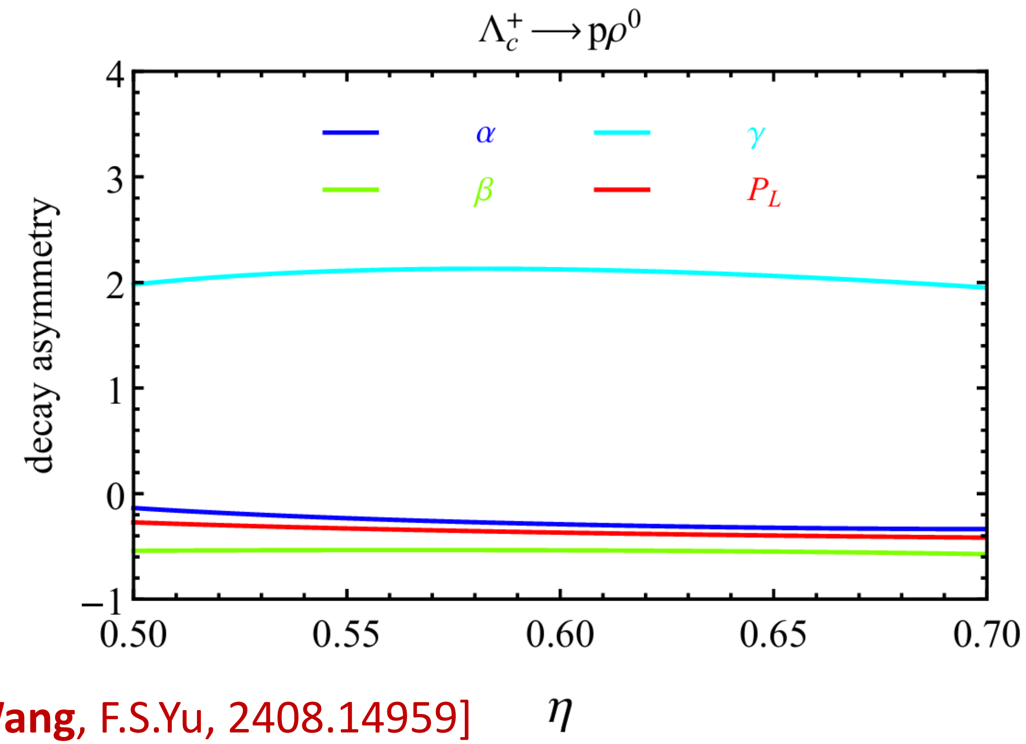
[C.P.Jia, H.Y.Jiang, **JPWang**, F.S.Yu, 2408.14959]

Our results for $\Lambda_c^+ \to B_8 V$

Asymmetry parameters with model parameter $\eta = 0.6 \pm 0.1$:

- The parameters dependence is largely suppressed for asymmetry parameters since they are defined by ratios, which can be seen directly from the comparison of BR and $\alpha, \beta, \gamma, P_L$





[C.P.Jia, H.Y.Jiang, **JPWang**, F.S.Yu, 2408.14959]

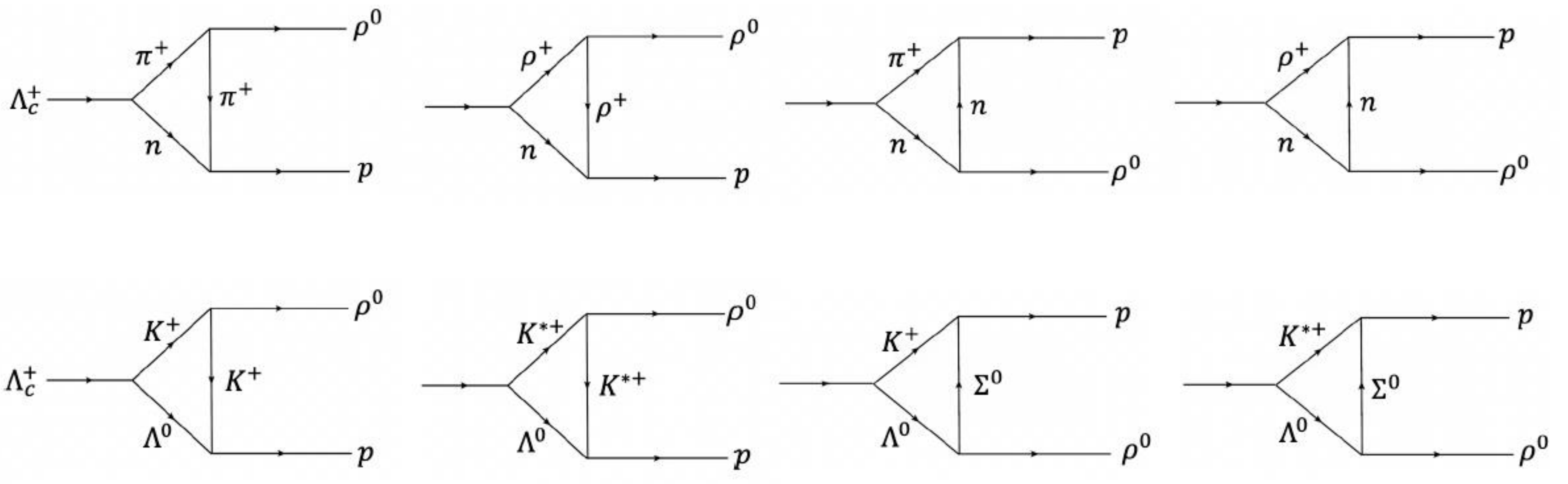
- The stable CP asymmetries predictions are expected since they are also defined by some ratios

CP violation

Key point: strong and weak phases difference

$V_{ud}V_{cd}^{*}$

$V_{us}V_{cs}^{*}$



CPV can be easily obtained within the rescattering mechanism

$$\lambda_d A_d + \lambda_s A_s$$

[C.P.Jia, H.Y.Jiang, **JPWang**, F.S.Yu, 2408.14959]

- Strong phases are obtained through re-scattering mechanism easily
- Weak phases are obtained by CKM matrix

Our results for $\Lambda_c^+ \to B_8 V$

CP asymmetries with model parameter $\eta = 0.6 \pm 0.1$:

$$A_{CP}^{dir} = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}, \qquad \alpha_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}, \qquad \beta_{CP} = \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}}, \qquad \gamma_{CP} = \frac{\gamma - \bar{\gamma}}{\gamma + \bar{\gamma}}, \qquad P_{L,CP} = \frac{P_L - \bar{P}_L}{P_L + \bar{P}_L}.$$

TABLE V: The CP asymmetries($\times 10^{-4}$) of $\Lambda_c^+ \to \mathcal{B}_8 V$ processes with $\eta = 0.6 \pm 0.1$.

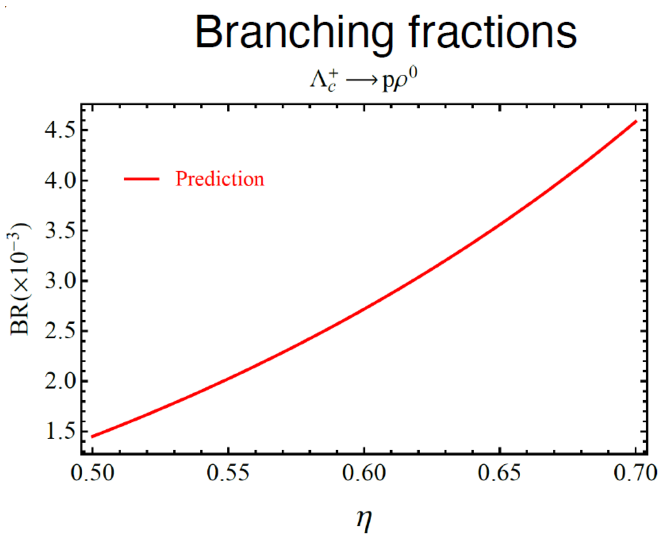
Decay modes	A_{CP}^{dir}	α_{CP}	β_{CP}	γ_{CP}	$P_{L,CP}$
$\Lambda_c^+ \to \Lambda^0 K^{*+}$	$0.89^{+0.91}_{-0.61}$	$-0.84^{+0.62}_{-0.97}$	$-2.12^{+1.60}_{-8.07}$	$0.61^{+0.40}_{-0.31}$	$-1.07^{+0.77}_{-1.43}$
$\Lambda_c^+ \to \Sigma^0 K^{*+}$	$2.28^{+0.92}_{-0.85}$	$13.75^{+18.22}_{-2.24}$	$2.55^{+2.02}_{-0.76}$	$-1.00^{+0.18}_{-0.50}$	$0.69^{+2.28}_{-0.89}$
$\Lambda_c^+ \to \Sigma^+ K^{*0}$	$-1.99^{+0.80}_{-0.74}$	$5.51^{+0.06}_{-1.11}$	$0.95^{+0.02}_{-0.20}$	$0.64^{+0.08}_{-0.05}$	$1.64^{+0.26}_{-0.18}$
$\Lambda_c^+ \to p\omega$	$4.55^{+0.36}_{-0.81}$	$19.61^{+8.95}_{-9.35}$	$-14.80^{-0.30}_{-1.99}$	$8.32^{+0.28}_{-8.17}$	$-2.16^{+0.01}_{-2.21}$
$\Lambda_c^+ \to p\rho^0$	$3.73^{+0.95}_{-1.16}$	$0.48^{+0.54}_{-0.98}$	$2.88^{+0.09}_{-0.71}$	$-1.23^{+0.90}_{-0.42}$	$1.77^{+0.20}_{-0.05}$
$\Lambda_c^+ \to n\rho^+$	$-1.45^{+0.29}_{-0.52}$	$0.01^{+0.32}_{-0.07}$	$1.86^{+1.34}_{-1.00}$	$-1.21^{+0.40}_{-0.01}$	$1.08^{+0.71}_{-0.59}$

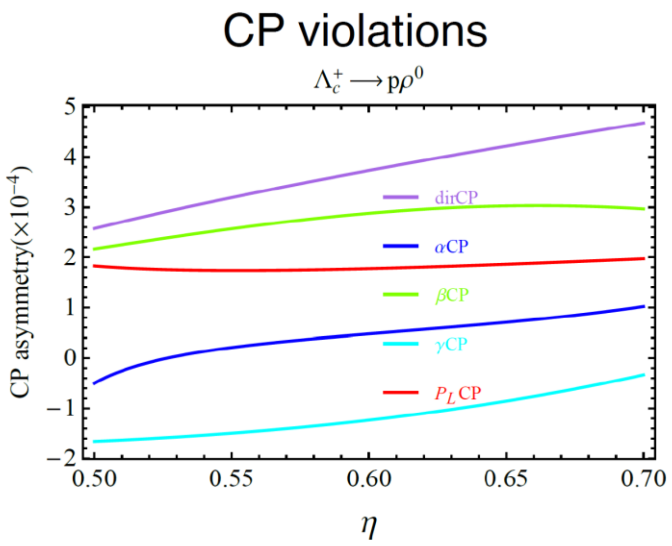
CP asymmetry is propotional to sine of weak phase [C.P.Jia, H.Y.Jiang, **JPWang**, F.S.Yu, 2408.14959]

$$A_{CP}^{dir} \approx -2\frac{\text{Im}(\lambda_d^* \lambda_s)}{|\lambda_d|^2}\frac{\text{Im}(\mathcal{A}_d^* \mathcal{A}_s)}{|\mathcal{A}_d - \mathcal{A}_s|^2}. \qquad \Delta\phi = \arctan\left[\frac{\text{Im}(V_{cd})}{\text{Re}(V_{cd})}\right] \sim 6 \times 10^{-4}.$$

Our results for $\Lambda_c^+ \to B_8 V$

CP asymmetries with model parameter $\eta = 0.6 \pm 0.1$:





- The decay asymmetries and CPV are insensitive to η, whose dependences are mostly cancelled by the ratios

Summary

- Final-State-Interaction (FSI) is a physical picture of long-distance effect.
- Improved FSI method is develop to successfully study charm-baryon decays
- Using only one parameter, it could explain almost all the experimental data.
- It has reasonable strong phases, thus can predict CP violation.
- Theoretical uncertainties can be lowered down in the decay asymmetries and CPV by the ratios.
- The applications for b-baryon CP violation are promised and on going

Thank you very much!

Back up

- Weak vertex and amplitude

$$\langle \mathcal{B}_8 M \,|\mathcal{H}_{eff}|\, \mathcal{B}_c\rangle^T_{SD} = \frac{G_F}{\sqrt{2}} V^*_{cq'} V_{uq} a_1(\mu) \langle M\,|\bar{u}\gamma^\mu(1-\gamma_5)q|\,0\rangle \left\langle \mathcal{B}_8 \left|\bar{q}'\gamma_\mu(1-\gamma_5)c\right| \mathcal{B}_c\right\rangle ,$$

$$\langle \mathcal{B}_8 M \,|\mathcal{H}_{eff}|\, \mathcal{B}_c\rangle^C_{SD} = \frac{G_F}{\sqrt{2}} V^*_{cq'} V_{uq} a_2(\mu) \langle M\,|\bar{u}\gamma^\mu(1-\gamma_5)q|\,0\rangle \left\langle \mathcal{B}_8 \left|\bar{q}'\gamma_\mu(1-\gamma_5)c\right| \mathcal{B}_c\right\rangle ,$$

- Strong effective Lagrangian

$$\mathcal{L}_{VPP} = \frac{i g_{\rho\pi\pi}}{\sqrt{2}} Tr\left[V^\mu \left[P, \partial_\mu P\right]\right]$$

$$\mathcal{L}_{VVV} = \frac{i g_{\rho\rho\rho}}{\sqrt{2}} Tr\left[\left(\partial_\nu V_\mu V^\mu - V_\mu \partial_\nu V^\mu\right) V^\nu\right]$$

$$\mathcal{L}_{VVP} = \frac{4 g_{VVP}}{f_P} \epsilon^{\mu\nu\alpha\beta} Tr\left[\partial_\mu V_\nu \partial_\alpha V_\beta P\right]$$

$$\mathcal{L}_{\mathcal{B}_8\mathcal{B}_8 P} = \sqrt{2} D Tr\left[\bar{\mathcal{B}}_8 i\gamma_5 \left\{P, \mathcal{B}_8\right\}\right] + \sqrt{2} F Tr\left[\bar{\mathcal{B}}_8 i\gamma_5 \left[P, \mathcal{B}_8\right]\right]$$

$$\mathcal{L}_{\mathcal{B}_8\mathcal{B}_8 V} = \sqrt{2} D' Tr\left[\bar{\mathcal{B}}_8 \gamma_\mu \left\{V^\mu, \mathcal{B}_8\right\}\right] + \sqrt{2} F' Tr\left[\bar{\mathcal{B}}_8 \gamma_\mu \left[V^\mu, \mathcal{B}_8\right]\right] - \sqrt{2}(D' - F') Tr(\bar{\mathcal{B}}_8 \gamma_\mu \mathcal{B}_8) Tr V^\mu$$

$$\mathcal{L}_{\mathcal{B}_{10}\mathcal{B}_8 P} = \frac{g_{\Delta N\pi}}{m_\pi} \epsilon_{ijk} (\bar{\mathcal{B}}_8)^j_l (\mathcal{B}_{10})^{mkl}_\mu \partial^\mu P^i_m$$

$$\mathcal{L}_{\mathcal{B}_{10}\mathcal{B}_8 V} = -i \frac{g_{\rho N\Delta}}{m_\rho} \left[(\bar{\mathcal{B}}_{10})^\mu \gamma^5 \gamma^\nu \mathcal{B}_8 + \bar{\mathcal{B}}_8 \gamma^5 \gamma^\nu (\mathcal{B}_{10})^\mu\right] \left(\partial_\mu \rho_\nu - \partial_\nu \rho_\mu\right)$$