全国第20届重味物理和CP破坏研讨会

Charmed baryon decays with re-scattering mechanism

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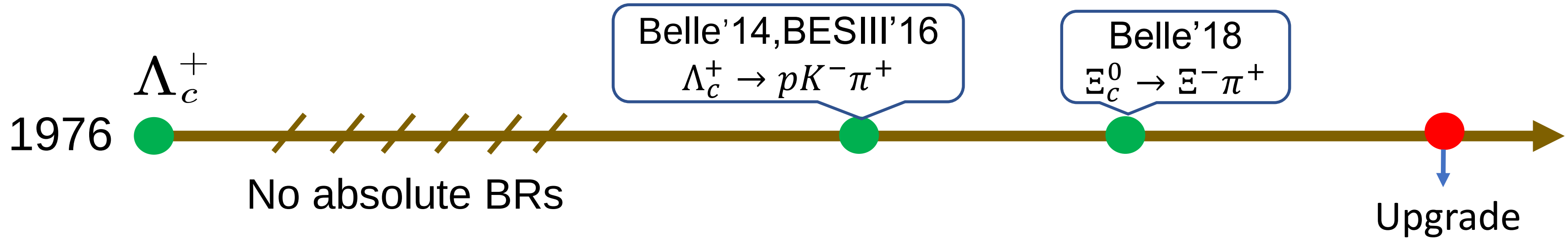
Introduction

- **Experiment：**

Belle,PRL(2014);BESIII,PRL(2016)

Belle,PRL(2019)



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
$\Lambda_c^+ \to \Sigma^+\eta$	$(4.4 \pm 2.0) \times 10^{-3}$	
$\Lambda_c^+ \to \Sigma^+\eta'$	$(1.5 \pm 0.6)\%$	
$\Lambda_c^+ \to \Xi^0K^+$	$(5.5 \pm 0.7) \times 10^{-3}$	
$\Lambda_c^+ \to p\pi^0$	$< 8 \times 10^{-5}$	
$\Lambda_c^+ \to p\eta$	$(1.42 \pm 0.12) \times 10^{-3}$	
$\Lambda_c^+ \to p\eta'$	$(4.73 \pm 0.98) \times 10^{-4}$	
$\Lambda_c^+ \to \Lambda^0K^+$	$(6.1 \pm 1.2) \times 10^{-4}$	
$\Lambda_c^+ \to \Sigma^0K^+$	$(5.2 \pm 0.8) \times 10^{-4}$	
$\Lambda_c^+ \to n\pi^+$	$(0.66 \pm 0.13) \times 10^{-3}$	

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

- BESIII Collaboration……
- Belle II Collaboration……

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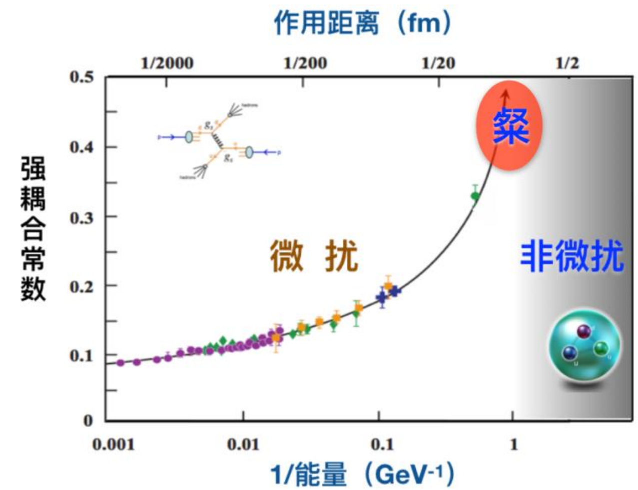
Experiment：

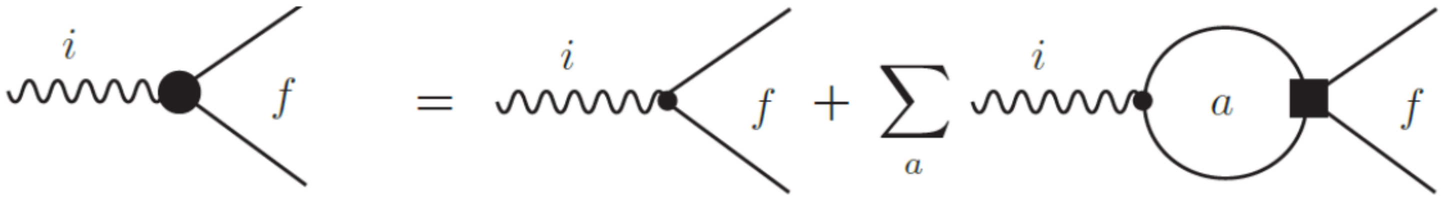
- CP violation is required for the matter-antimatter asymmetry in the Universe [Sakharov, 1967]
- CPV in strange, charm and bottom mesons have been well established.
- No CPV has been yet observed in charmed baryon decays.

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)*
$\Lambda_c^+ \to pK^+K^-$	$A_{CP}^{dir}(\Lambda_c^+ \to pK^+K^-) - A_{CP}^{dir}(\Lambda_c^+ \to p\pi^+\pi^-) = (0.30 \pm 0.91 \pm 0.61)\%$	*LHCb, JHEP (2018)*
$\Lambda_c^+ \to p\pi^+\pi^-$		
$\Xi_c^+ \to pK^-\pi^+$	NO CP violation	*LHCb, EPJC (2020)*

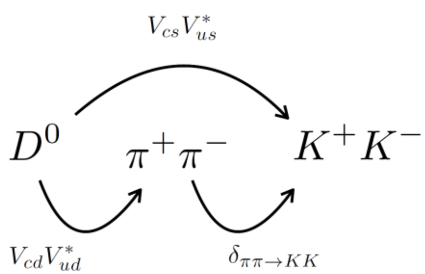
- **Theory：** non-perturbative effects
  - No perturbative calculation based on the first principle
    — $1/m_c$ expansion is not under control
  - Global fit based on the $SU(3)_F$ symmetry:
    — Lots of inspiration when there are no dynamics ①
    - M.J. Savage, R.P. Springer, Phys. Rev. D 42 (1990) 1527.
    - C.D. Lü, W. Wang, F.S. Yu, Phys. Rev. D 93(5) (2016) .
    - C. Q. Geng, Y. K. Hsiao, C. W. Liu and T. H. Tsai, Eur. Phys. J. C 78, no. 7, 593 (2018).
    - C. Q. Geng, C. W. Liu and T. H. Tsai, Phys. Rev. D 101, no.5, 053002 (2020).
  - Dynamical model calculation: theoretical uncertainty ②
    - H. Y. Cheng, X. W. Kang and F. Xu, Phys. Rev. D 97, 074028(2018).
    - J. Zou, F. Xu, G. Meng and H. Y. Cheng, Phys. Rev. D 101, 014011(2020).
    - P. Y. Niu, J. M. Richard, Q. Wang, and Q. Zhao, Phys. Rev. D, 102, 073005(2020).
  - **No any numerical prediction on CPV of charm-baryon decays ③**



➢ Final-state interactions：



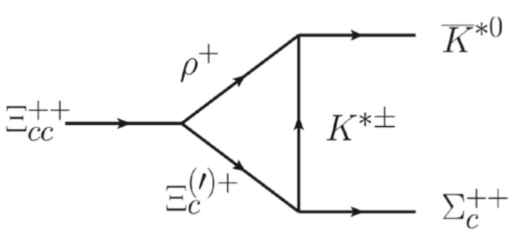
- The natural physical image of the long-distance nonperturbative contribution
  - H. Y. Cheng, C. K. Chua and A. Soni, Phys. Rev. D 71, 014030 (2005). 410 citations
  - H. Y. Cheng and C. W. Chiang, Phys. Rev. D 81, 074021 (2010).
  - Bediaga, Frederico, Magalhaes, PRL2023;Pich, Solomonidi, Silva, PRD2023. data-driven



$$\Delta A_{CP}^{exp} = -(1.54 \pm 0.29) \times 10^{-3}$$

$$\Delta A_{CP}^{th} = -(0.64 \pm 0.18) \times 10^{-3}$$

  - F.-S. Yu, H.-Y. Jiang, R.-H. Li, C.-D. Lv, W. Wang, Z.-X. Zhao, Chin. Phys. C 42 (5) (2018) 051001.

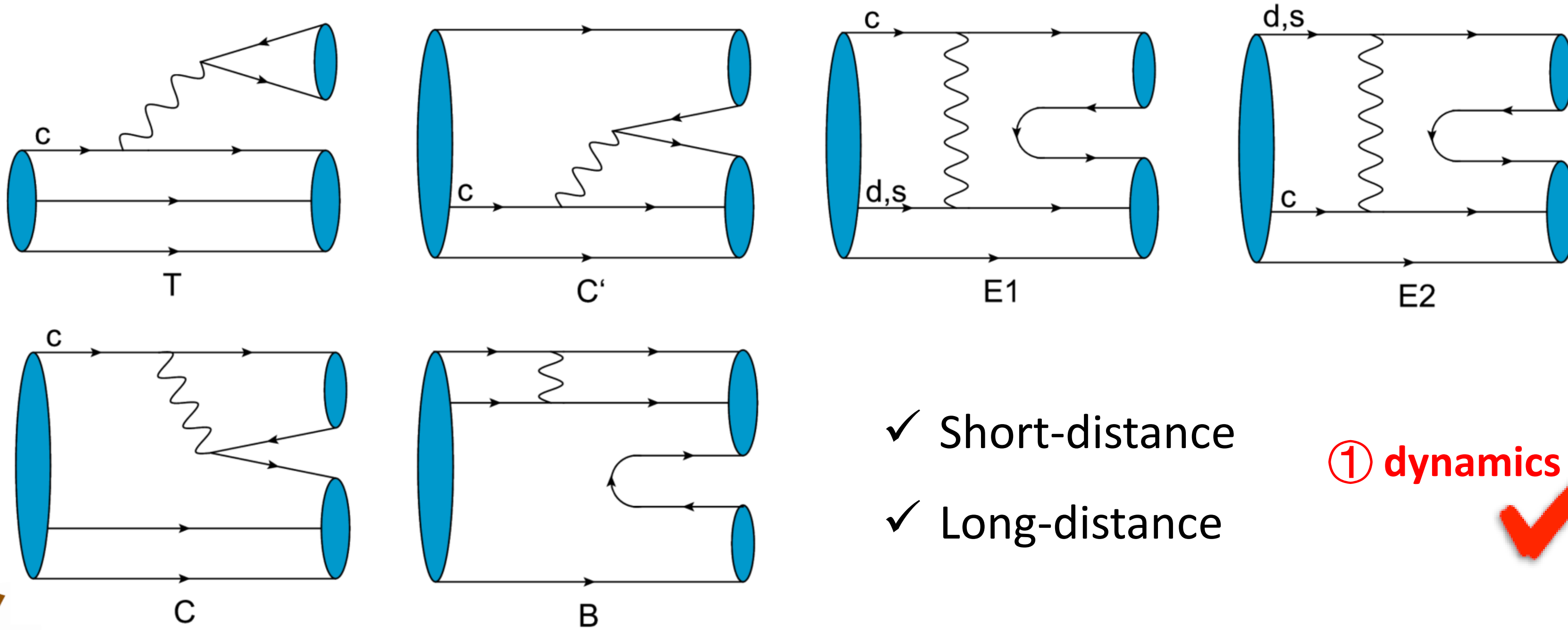


"Discovery Potentials of Doubly Charmed Baryons"

Successfully !

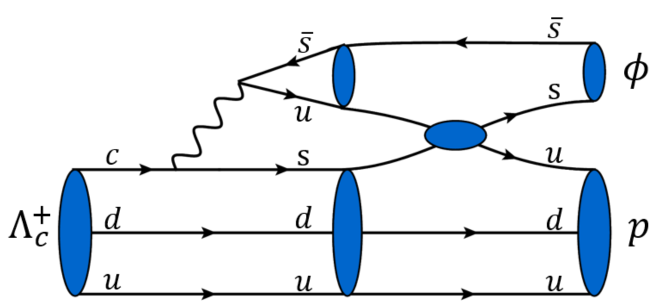
Framework

- Natural physical image of long-distance nonperturbative contribution

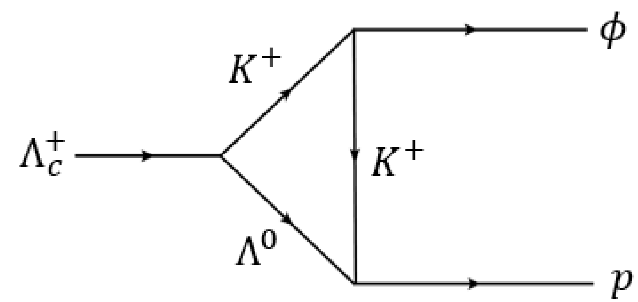


- ✓ Short-distance
- ✓ Long-distance

① **dynamics** ✓



quark exchange



hadronic triangle

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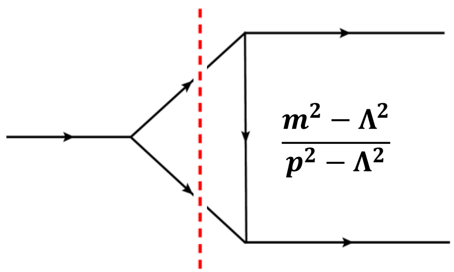
- **Conventional method：** optical theorem + Cutkosky cutting rule

H. Y. Cheng, C. K. Chua and A. Soni, Phys. Rev. D 71, 014030 (2005)……..

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

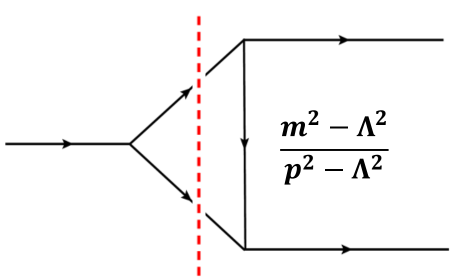


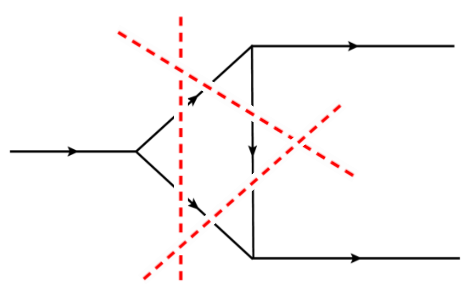
$$Abs[\mathcal{M}(P_i \to P_3 P_4)] = \frac{1}{2} \sum_{\{P_1 P_2\}} \int \frac{d^3 p_1}{(2\pi)^3 2E_1} \int \frac{d^3 p_2}{(2\pi)^3 2E_2} (2\pi)^4 \delta^4(p_3+p_4-p_1-p_2) \cdot M(P_i \to \{P_1 P_2\}) T^*(P_3 P_4 \to \{P_1 P_2\}).$$

- **Strong model-dependent in charmed baryon decay：**

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……**

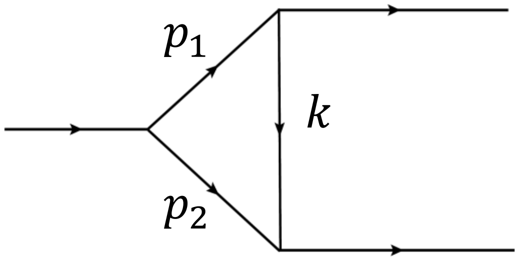




- Off-shell effects
- Lost contribution

J.J. Han, H.Y. Jiang, W. Liu, Z.J. Xiao, and F.S. Yu, ” Chin. Phys. C 45, 053105 (2021).

➤ Improving method： Loop integral



- Integral divergence: Pauli-Villars regularization

$$\frac{1}{k^2-m^2+i\epsilon} \to \frac{1}{k^2-m^2+i\epsilon}+\sum_i \frac{a_i}{k^2-\Lambda_i^2+i\epsilon}$$

$$\Rightarrow \frac{1}{p_1^2-m_1^2+i\epsilon}+\frac{a_1}{p_1^2-\Lambda_1^2+i\epsilon} \sim \frac{1}{p_1^2-m_1^2}\frac{m_1^2-\Lambda_1^2}{p_1^2-\Lambda_1^2} \qquad \Lambda_1 = m_1+\eta\Lambda_{QCD}$$

- Weak vertex:

$$\langle \mathcal{B}_8 M|\mathcal{H}_{eff}|\mathcal{B}_c\rangle^T_{SD} = \frac{G_F}{\sqrt{2}}V^*_{cq'}V_{uq}a_1(\mu)\underbrace{\langle M|\bar{u}\gamma^\mu(1-\gamma_5)q|0\rangle}_{\text{decay constant}}\underbrace{\langle \mathcal{B}_8|\bar{q}'\gamma_\mu(1-\gamma_5)c|\mathcal{B}_c\rangle}_{\text{heavy-to-light form factor}}$$

- Strong scattering:

$$\mathcal{L}_{VPP} = \frac{ig_{VPP}}{\sqrt{2}}Tr[V^\mu[P,\partial_\mu P]]$$

$$\mathcal{L}_{VBB} = f_{1VBB}Tr[\bar{\mathcal{B}}\gamma_\mu V^\mu \mathcal{B}]+\frac{f_{2VBB}}{m_{\mathcal{B}1}+m_{\mathcal{B}2}}Tr[\bar{\mathcal{B}}\sigma_{\mu\nu}\partial^\mu V^\nu \mathcal{B}]$$

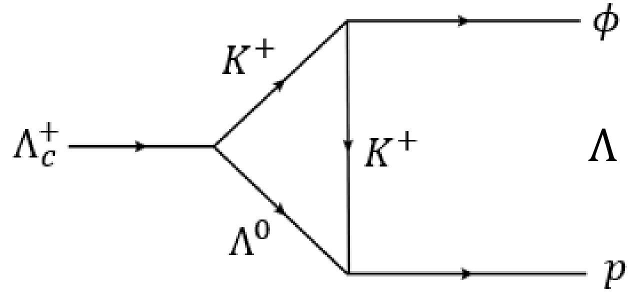
Error sources

- S. Meinel, Phys. Rev. Lett. 118, no.8, 082001 (2017).
- T.M.Aliev, A. Ozpineci, M. Savci and V. S. Zamiralov, Phys. Rev. D80 016010 (2009) .

Framework

➢ Improving method： Loop integral

② **model dependence** ✔



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

$$\mathcal{M}[P,B;V]$$

$$= -i\int \frac{d^4p_1}{(2\pi)^4} g_{BBP}g_{VPP}\bar{u}(p_4,s_4)\gamma_5(\not{p}_2+m_2)(A+B\gamma_5)u(p,s)\epsilon_\mu^\star(p_3,\lambda_3)(p_1+k)^\mu$$

$$\times \frac{1}{(p_1^2-m_1^2+i\epsilon)(p_2^2-m_2^2+i\epsilon)(k^2-m_k^2+i\epsilon)} \boxed{\left(\frac{\Lambda_1^2-m_1^2}{\Lambda_1^2-p_1^2}\right)\left(\frac{\Lambda_2^2-m_2^2}{\Lambda_2^2-p_2^2}\right)\left(\frac{\Lambda_k^2-m_k^2}{\Lambda_k^2-k^2}\right)}$$

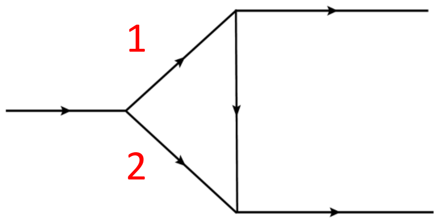
- The complete amplitudes with strong phase

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

- The contribution of the real part is on the same order as the contribution of the imaginary part!
- The process dependence of the parameters is greatly reduced.

- **Branching ratio:** $\eta = 0.6 \pm 0.1$

$$\Gamma(\mathcal{B}_c \to \mathcal{B}_8 V) = \frac{p_c}{8\pi m_i^2} \frac{1}{2} \sum_{\lambda\lambda'\sigma} |\mathcal{A}(\mathcal{B}_c \to \mathcal{B}_8 V)|^2$$



- Only one parameter explains all the 8 experimental data!

decay mode	topology	experiment(%)	Short-distance	prediction(%)
$\Lambda_c^+ \to \Lambda^0 \rho^+$	T, C', E_2, B	4.06 ± 0.52	4.91%	8 ± 0.8
$\Lambda_c^+ \to p\phi$	C	0.106 ± 0.014	1.92×10^{-6}	0.09 ± 0.03
$\Lambda_c^+ \to \Sigma^+\phi$	E_1	0.39 ± 0.06	-	0.49 ± 0.22
$\Lambda_c^+ \to p\omega$	C, C', E_1, E_2, B	0.09 ± 0.04	2.83×10^{-6}	0.08 ± 0.04
$\Lambda_c^+ \to \Sigma^+\rho^0$	C', E_2, B	< 1.7	-	2.0 ± 1.0
$\Lambda_c^+ \to \Sigma^0\rho^+$	C', E_2, B	Isospin	-	Isospin
$\Lambda_c^+ \to \Sigma^+\omega$	C', E_2, B	1.7 ± 0.21	-	1.8 ± 0.7
$\Lambda_c^+ \to p\bar{K}^{*0}$	C, E_1	1.96 ± 0.27	3.47×10^{-5}	2.9 ± 1.2
$\Lambda_c^+ \to \Sigma^+ K^{*0}$	C', E_1	0.35 ± 0.1	-	0.28 ± 0.13

Results and discussion

➢ Decay parameters:

$$\alpha = \frac{\left|H_{1,\frac{1}{2}}\right|^2 - \left|H_{-1,-\frac{1}{2}}\right|^2}{\left|H_{1,\frac{1}{2}}\right|^2 + \left|H_{-1,-\frac{1}{2}}\right|^2}; \quad \beta = \frac{\left|H_{0,\frac{1}{2}}\right|^2 - \left|H_{0,-\frac{1}{2}}\right|^2}{\left|H_{0,\frac{1}{2}}\right|^2 + \left|H_{0,-\frac{1}{2}}\right|^2}; \quad \gamma = \frac{\left|H_{1,\frac{1}{2}}\right|^2 + \left|H_{-1,-\frac{1}{2}}\right|^2}{\left|H_{0,\frac{1}{2}}\right|^2 + \left|H_{0,-\frac{1}{2}}\right|^2}; \quad P_L = \frac{\beta + \alpha \cdot \gamma}{1 + \gamma}$$

decay mode	experiment	α	β	γ	P_L
$\Lambda_c^+ \to \Lambda^0 \rho^+$	-0.76 ± 0.07	-0.80 ± 0.04	-0.98 ± 0.01	0.50 ± 0.1	-0.91 ± 0.03
$\Lambda_c^+ \to \Sigma^+ \phi$	-	-0.012 ± 0.019	0.35 ± 0.09	2.03 ± 0.04	0.11 ± 0.05
$\Lambda_c^+ \to p\omega$	-	0.35 ± 0.04	0.52 ± 0.03	0.46 ± 0.07	0.46 ± 0.03
$\Lambda_c^+ \to p\phi$	-	-0.74 ± 0.03	-0.94 ± 0.04	3.82 ± 1.10	-0.78 ± 0.01
$\Lambda_c^+ \to \Sigma^+ \rho^0$	-	-0.01 ± 0.04	0.18 ± 0.1	1.10 ± 0.11	0.08 ± 0.07
$\Lambda_c^+ \to \Sigma^0 \rho^+$	-	Isospin	Isospin	Isospin	Isospin
$\Lambda_c^+ \to \Sigma^+ \omega$	-	-0.01 ± 0.04	-0.17 ± 0.03	0.49 ± 0.23	-0.12 ± 0.01
$\Lambda_c^+ \to p\bar{K}^{*0}$	-	0.22 ± 0.05	0.60 ± 0.07	1.45 ± 0.20	0.38 ± 0.07
$\Lambda_c^+ \to \Sigma^+ K^{*0}$	-	-0.18 ± 0.11	-0.20 ± 0.03	3.89 ± 1.79	-0.18 ± 0.09

M. Ablikim et al., Phys. Rev. Lett., vol. 129, no. 23, p. 231803, 2022.

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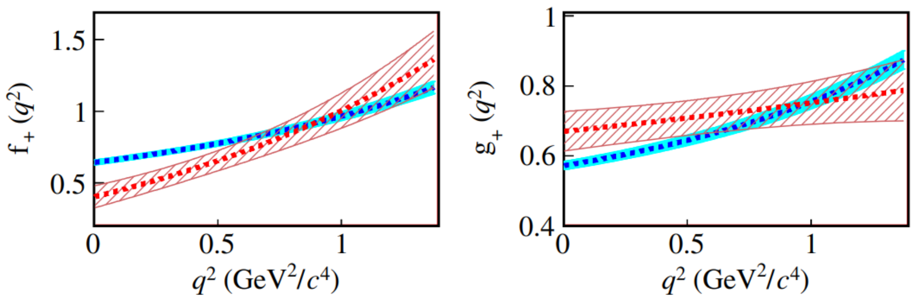
- short-distance dominated:

decay mode	topology	experiment(%)	Short-distance	prediction(%)
$\Lambda_c^+ \to \Lambda^0 \rho^+$	T, C', E_2, B	4.06 ± 0.52	4.91%	8 ± 0.8

$$\langle \mathcal{B}_8 M \left| \mathcal{H}_{eff} \right| \mathcal{B}_c \rangle_{SD}^{T} = \frac{G_F}{\sqrt{2}} V_{cq'}^* V_{uq} a_1(\mu) \langle M \left| \bar{u}\gamma^\mu (1-\gamma_5) q \right| 0 \rangle \langle \mathcal{B}_8 \left| \bar{q}' \gamma_\mu (1-\gamma_5) c \right| \mathcal{B}_c \rangle$$



$$f_1(q^2) = \frac{(m_i + m_f)^2 f_+(q^2) - q^2 f_\perp(q^2)}{s_+},$$

$$g_1(q^2) = \frac{(m_i - m_f)^2 g_+(q^2) - q^2 g_\perp(q^2)}{s_-},$$

FIG. 3. Comparison of form factors with LQCD calculations. The bands show the total uncertainties.

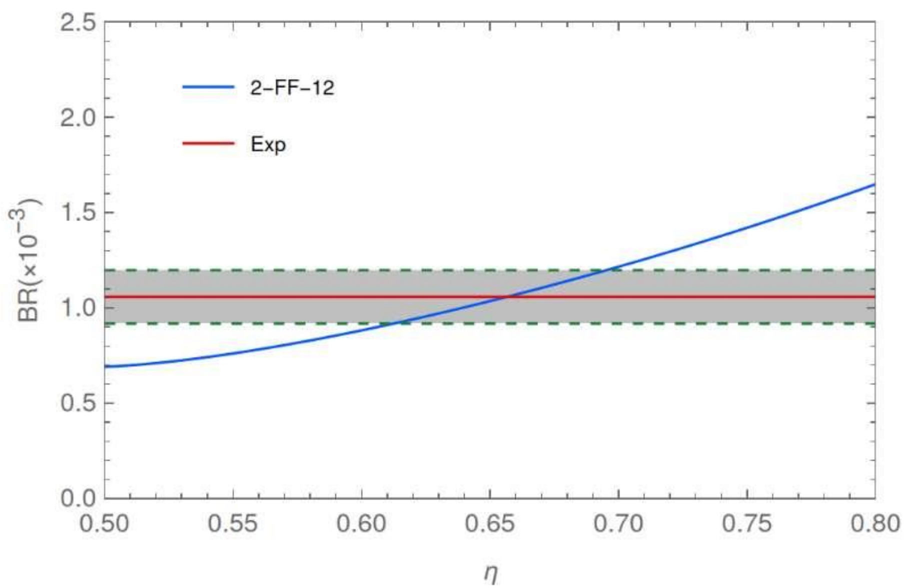
M. Ablikim et al., Phys. Rev. Lett., vol. 129, no. 23, p. 231803, 2022.

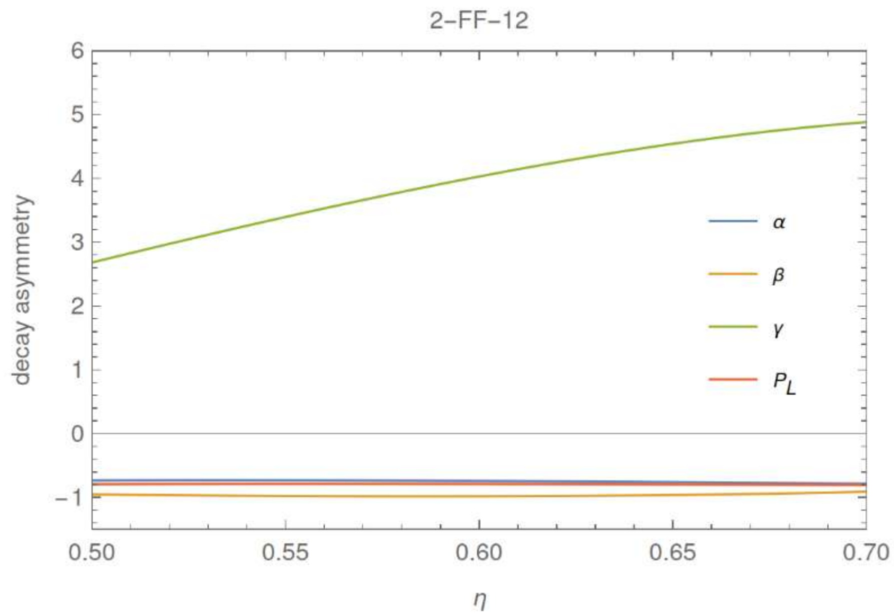
- It is essential to input the much more precise form factors!

- long-distance dominated:

decay mode	topology	experiment(%)	Short-distance	prediction(%)
$\Lambda_c^+ \to p\phi$	C	0.106 ± 0.014	1.92×10^{-6}	0.09 ± 0.03

decay mode	$\boldsymbol{\alpha}$	$\boldsymbol{\beta}$	$\boldsymbol{\gamma}$	$\boldsymbol{P_L}$
$\Lambda_c^+ \to p\phi$	-0.74 ± 0.03	-0.94 ± 0.04	3.82 ± 1.10	-0.78 ± 0.01





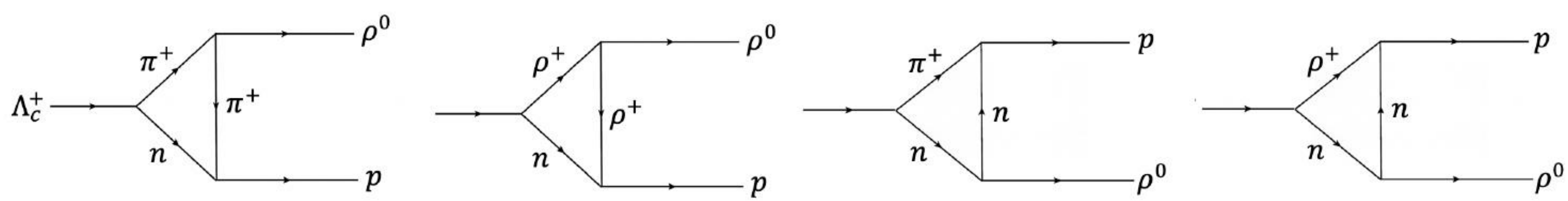
- The branching ratio is dependent on the parameter η;
- The decay parameters are almost independent of the parameter η;

Results and discussion

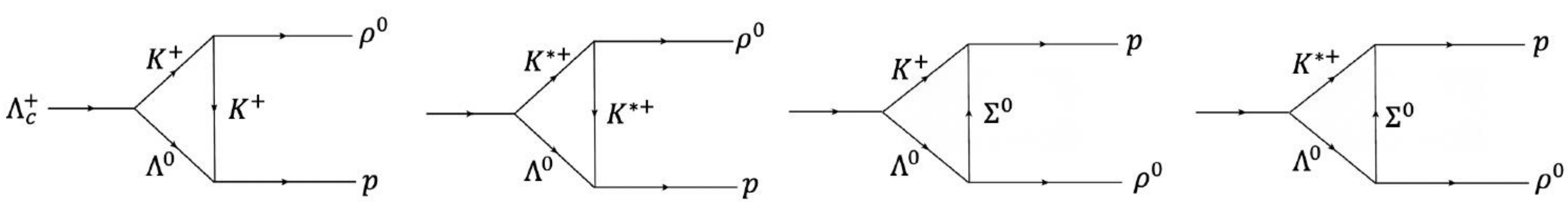
- **CP violation:**
  - key points: phase difference—strong and weak

$$V_{CKM}=\begin{pmatrix} 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+A^2\lambda^5\left(\frac{1}{2}-\rho-i\eta\right) & 1-\frac{\lambda^2}{2}-\lambda^4\left(\frac{1}{8}+\frac{A^2}{2}\right) & A\lambda^2 \\ A\lambda^3(\rho-i\eta)+A\lambda^5(\rho+i\eta) & -A\lambda^2+A\lambda^4\left(\frac{1}{2}-\rho-i\eta\right) & 1-\frac{A^2\lambda^4}{2} \end{pmatrix}$$

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



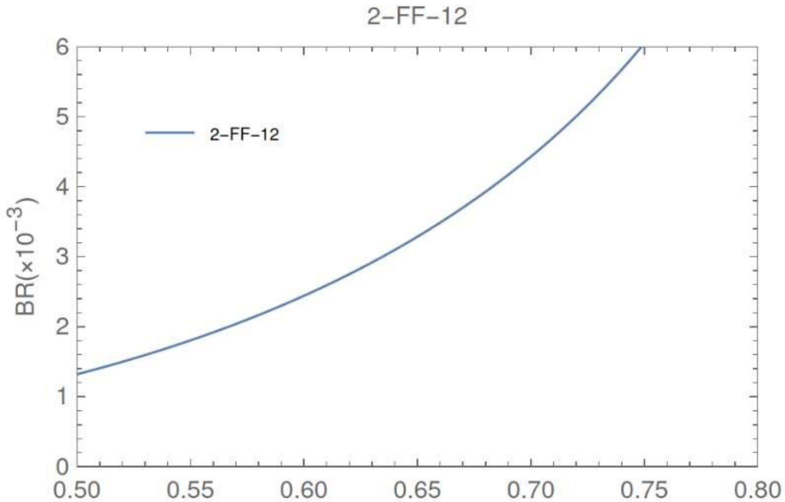
$V_{us}V_{cs}^*$

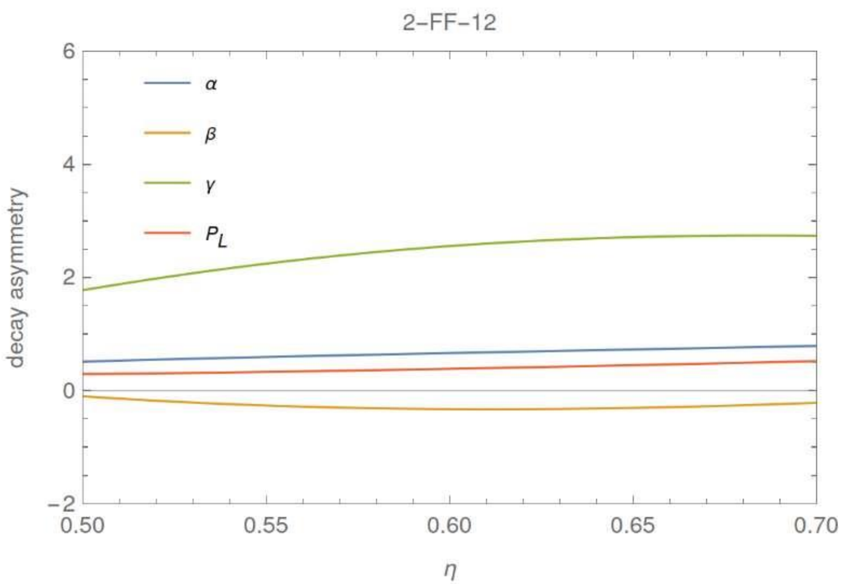


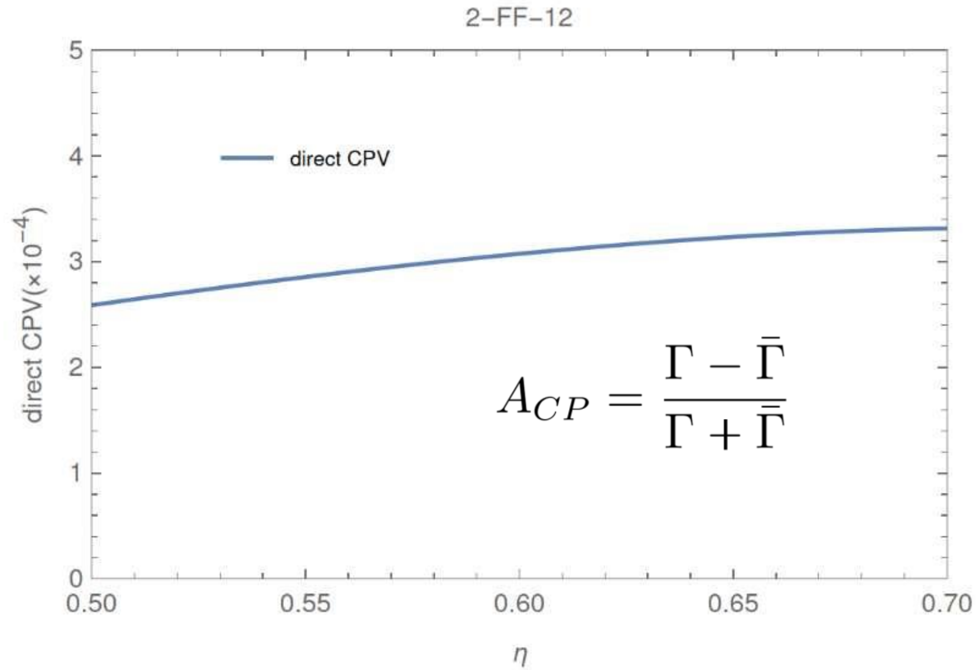
CPV can be easily obtained within the re-scattering mechanism！

- **CP violation:** $\Lambda_c \to p\rho^0$

$$BR(\Lambda_c^+ \to p\pi^+\pi^-) = (4.60 \pm 0.26) \times 10^{-3}$$







$$A_{CP} = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$$

The decay asymmetries and CPV are insensitive to η.

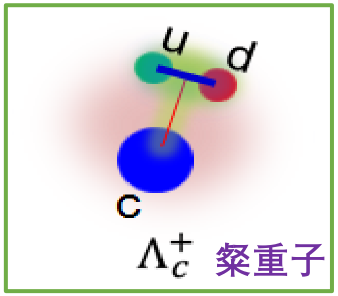
③ **CPV calculation** ✓

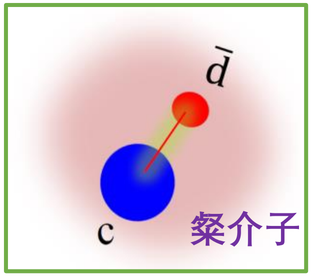
Summary

- Re-scattering mechanism is the natural physical image of the long-distance nonperturbative effects.
- Using only one parameter to explain a class of channels with the re-scattering mechanism, avoids introducing too many parameters and reducing the predictive power of theory.
- Predicting the decay parameters and CP violation of charmed baryon decay naturally.
- Generalizing……

Thank you very much!

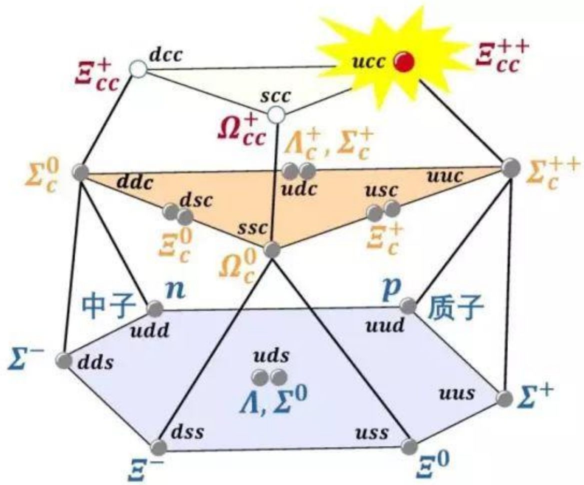
➢ Charmed Hadron：

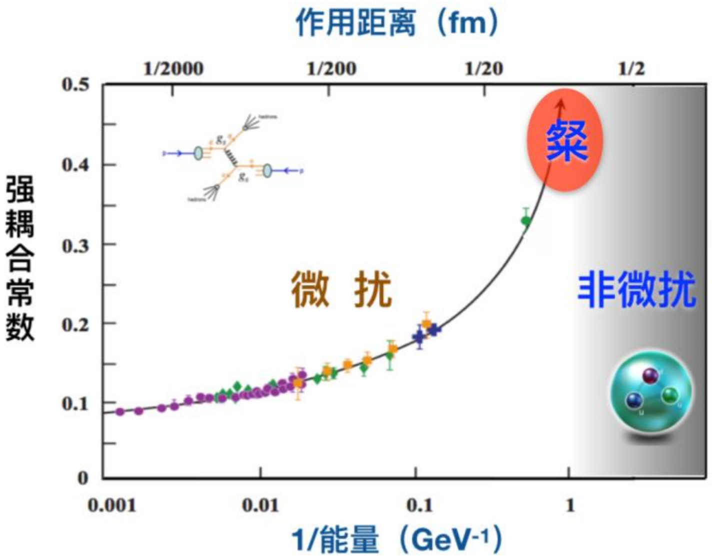




$m_b = 4.18GeV$ perturbation

$m_c = 1.27GeV$





non-perturbative effects

- difficult to calculate
- ideal platform to understand its dynamics