CPV in charmed baryons (theory)

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Outline

- Introduction to CPV of charmed baryons
- Dynamics: final-state-interaction rescattering mechanism
- Observables: T-odd correlations and complimentarity
- Summary

Implications of charm CPV

- LHCb 2019: Observation $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = (-1.54 \pm 0.29) \times 10^{-3}$

→ $|\mathcal{P}/\mathcal{T}|_{\text{charm}} \sim \mathcal{O}(1)$ SM or NP?

✓ **Long-distance contributions**

- LHCb 2022: $A_{CP}(D^0 \to K^+K^-) = (0.77 \pm 0.57) \times 10^{-3}, \quad A_{CP}(D^0 \to \pi^+\pi^-) = (2.31 \pm 0.61) \times 10^{-3}$

→ U-spin anomaly, so NP? See Nierste's and Gisbert's talk

- **Charmed baryon decays** are the next opportunity and challenge of charm physics

Charmed baryon decays

- Charmed baryon decays are the next opportunity and challenge of charm physics
- **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)*
$\Lambda_c^+ \to pK^+K^-$ $\Lambda_c^+ \to p\pi^+\pi^-$	$A_{CP}^{dir}(\Lambda_c^+ \to pK^+K^-) - A_{CP}^{dir}(\Lambda_c^+ \to p\pi^+\pi^-) = (0.30 \pm 0.91 \pm 0.61)\%$	*LHCb, JHEP (2018)*
$\Xi_c^+ \to pK^-\pi^+$	NO CP violation	*LHCb, EPJC (2020)*

most precise to date

Charmed baryon decays

- Charmed baryon decays are the next opportunity and challenge of charm physics
- CP asymmetry sum rules based on SU(3) flavor symmetry are firstly obtained [Grossman and Schacht, PRD (2019)][Di Wang, EPJC (2019)]

$$A_{CP}(\Lambda_c^+ \to pK^-K^+) + A_{CP}(\Xi_c^+ \to \Sigma^+\pi^-\pi^+) = 0,$$

$$A_{CP}(\Lambda_c^+ \to \Sigma^+\pi^-K^+) + A_{CP}(\Xi_c^+ \to pK^-\pi^+) = 0,$$

$$A_{CP}(\Lambda_c^+ \to p\pi^-\pi^+) + A_{CP}(\Xi_c^+ \to \Sigma^+K^-K^+) = 0.$$

- **No any numerical prediction on CPV of charm-baryon decays**

Charmed baryon decays

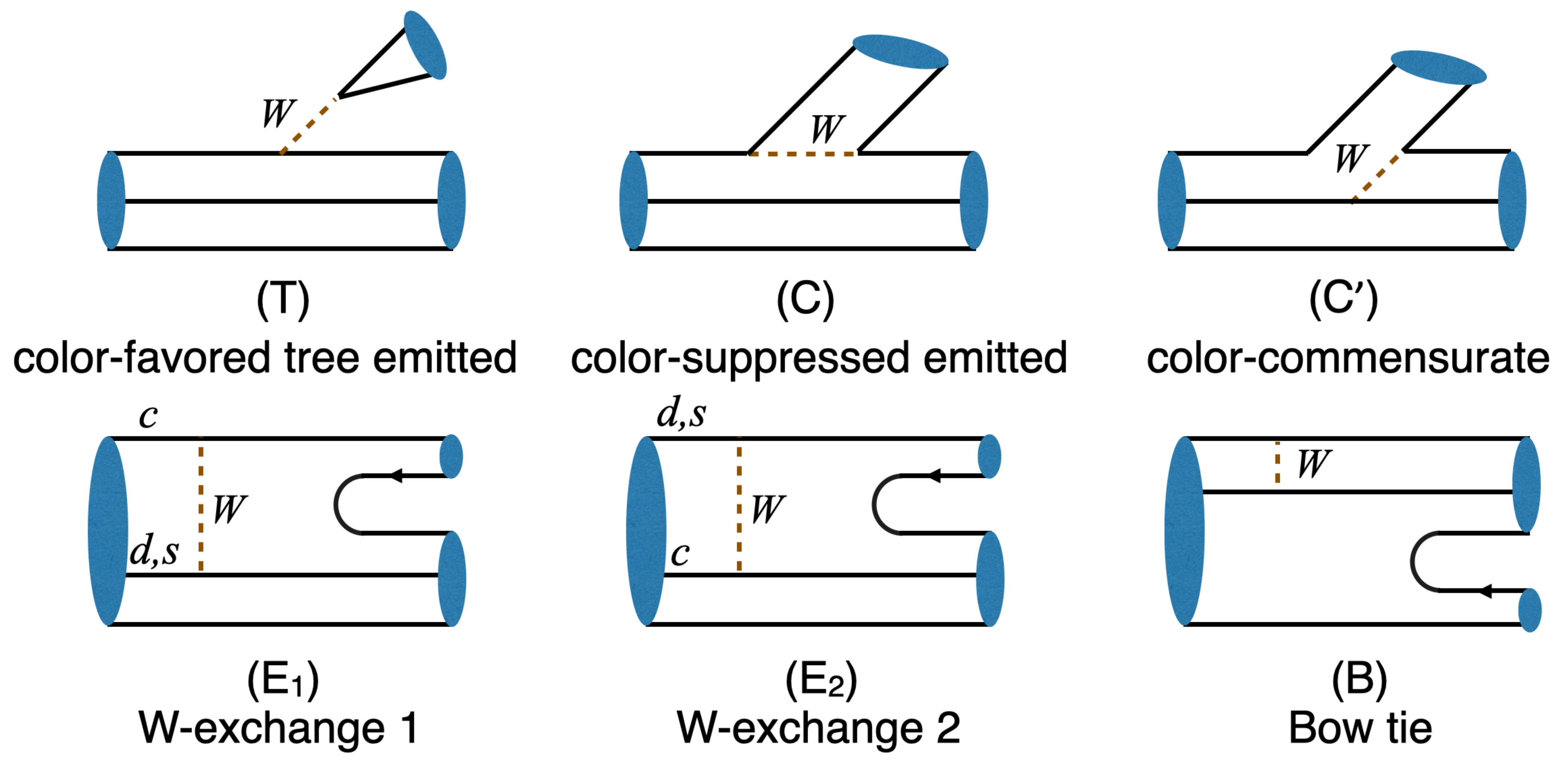
- Two key issues in theory:

1. Dynamics: to predict the decay amplitudes and then CPV

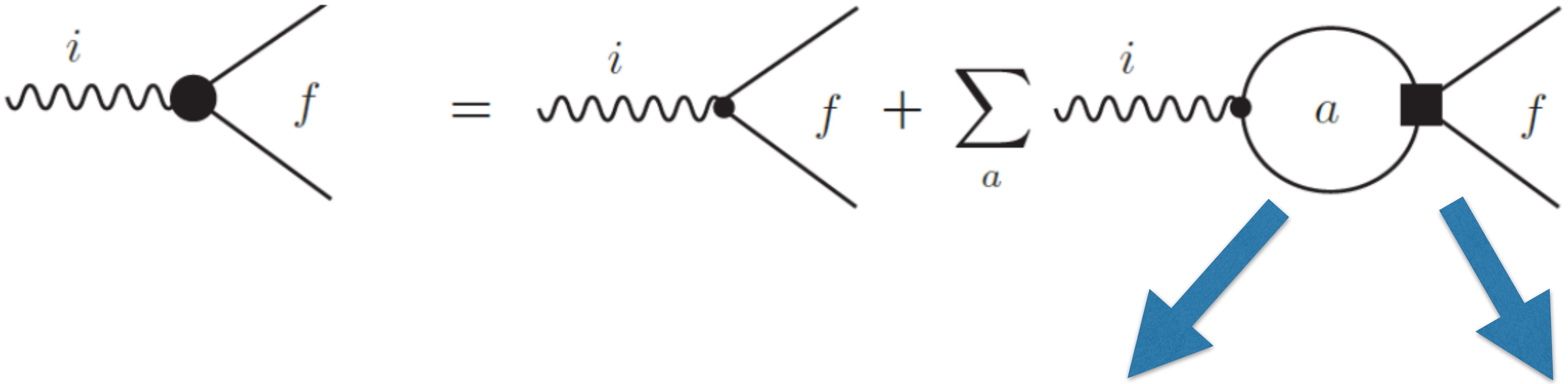
2. Observables: Nonzero spin of baryons may induce fruitful observables

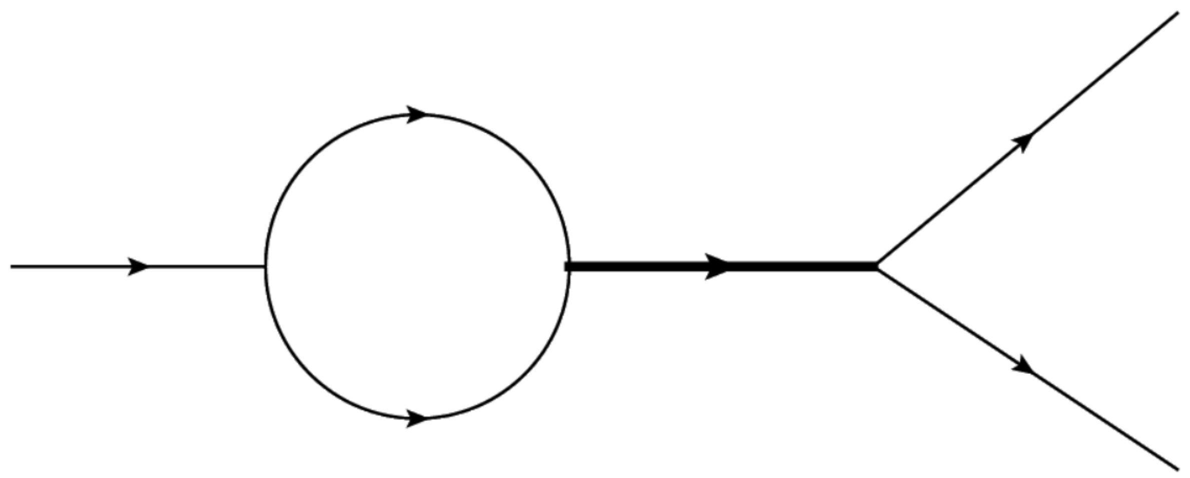
Dynamics of charmed baryon decays

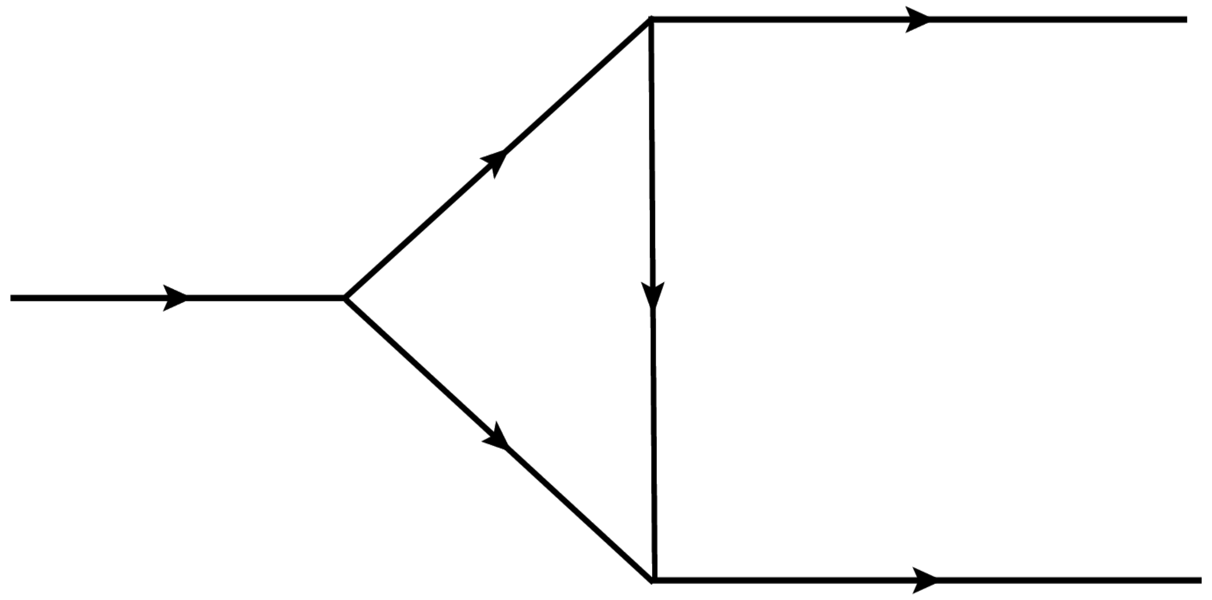
- Dynamics are more complicated in charmed baryon decays
    - Many more topological diagrams + more partial waves
    - SU(3) irreducible representations cannot provide information on penguins
    - Final-state interactions (FSI) are necessary



Final-state interactions



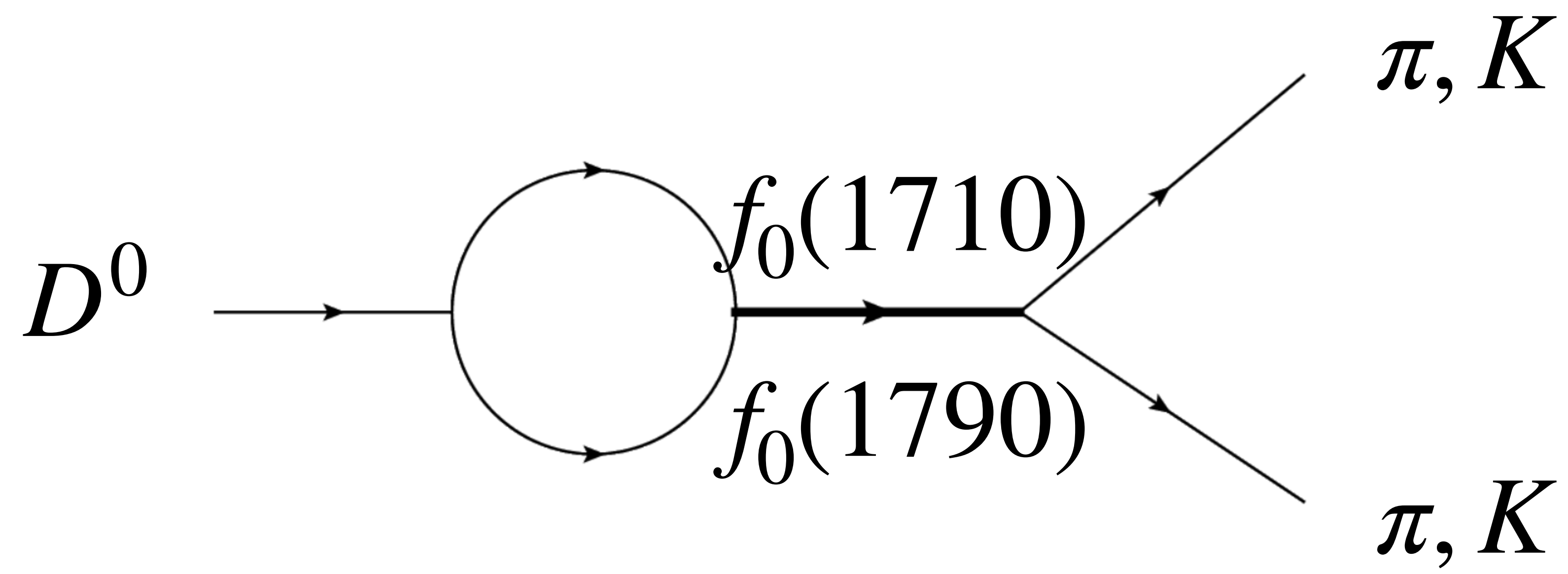




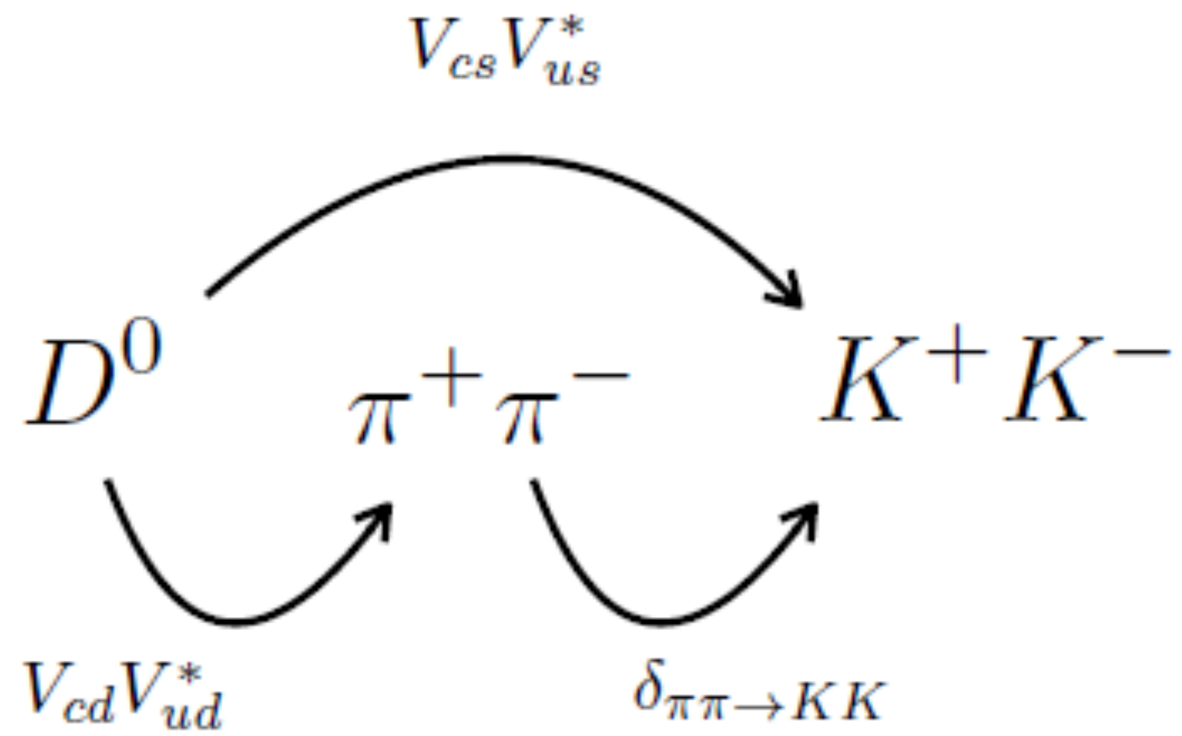
1. s-channel resonant contributions
2. t-channel rescattering mechanism

Final-state interactions

- Resonant contributions for charm CPV [Soni, '19; Schacht, Soni, '22]
  - But lack of enough information on the resonances



- Rescattering mechanism for charm CPV [Bediaga, Frederico, Magalhaes, '23]
  - Data-driven extraction of magnitudes and phases of the $\pi\pi \to KK$ scatterings at the D^0 mass energy
  - Model-independent, not relying on fitting parameters
  - Power of predictions is limited due to only few channels of available data

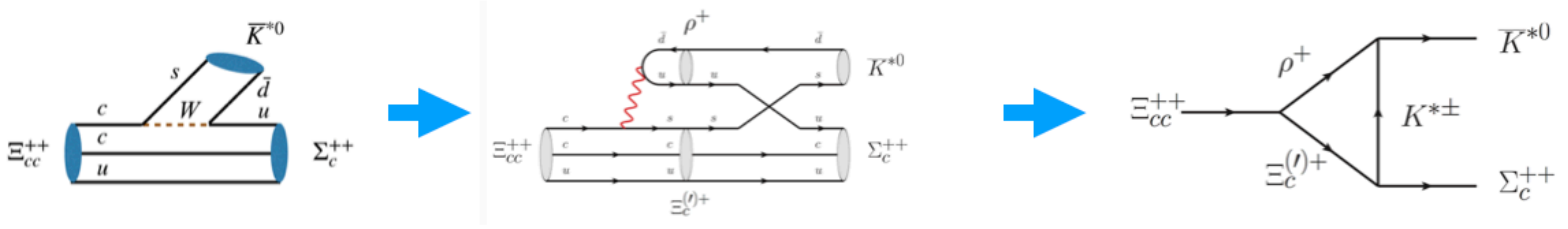


$$\Delta A^{th}_{CP} = -(0.64 \pm 0.18) \times 10^{-3}$$

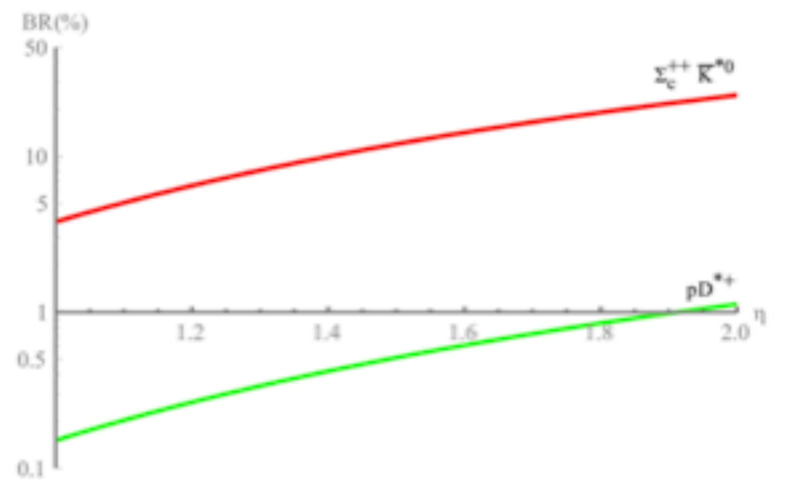
$$\Delta A^{exp}_{CP} = -(1.54 \pm 0.29) \times 10^{-3}$$

Rescattering mechanism

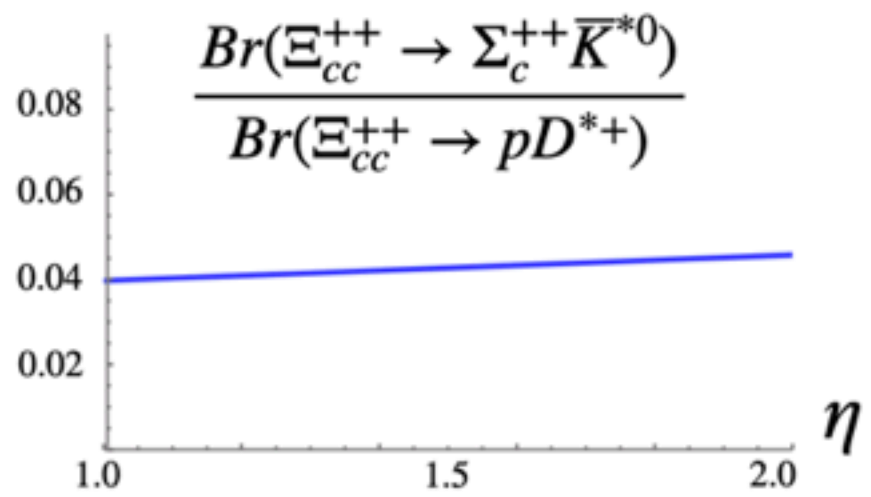
- Rescattering mechanism have been successfully used to predict the discovery channel of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ [FSY, Jiang, Li, Lu, Wang, Zhao, '17]



Topology: C → quark exchange → hadronic triangle



- Theoretical uncertainty is under control in the **ratio** of branching fractions of different processes

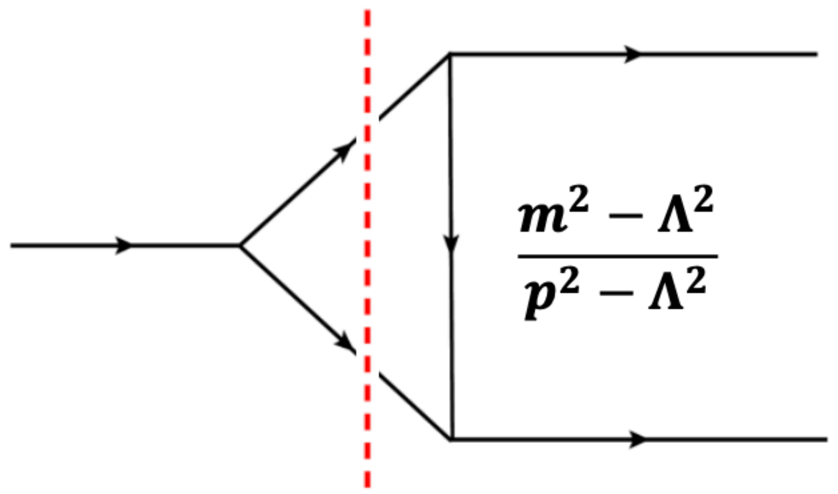


1703.09086
2102.00961

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

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

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



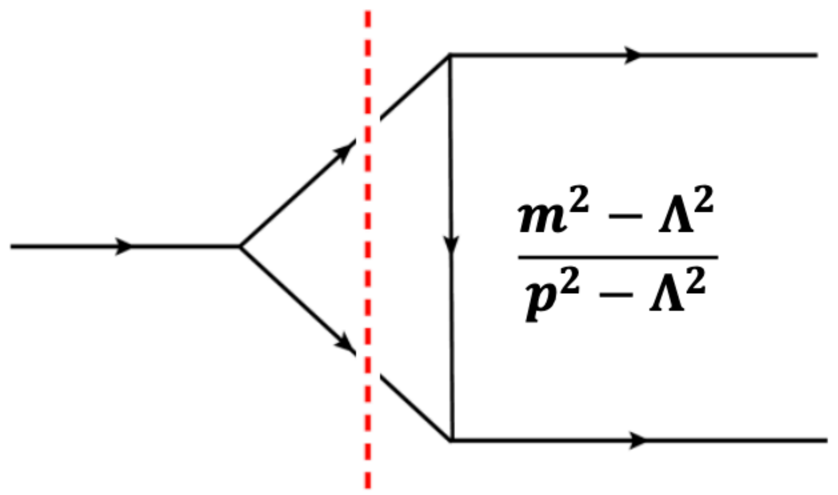
$$\Lambda = m_k + \eta\Lambda_{QCD}$$

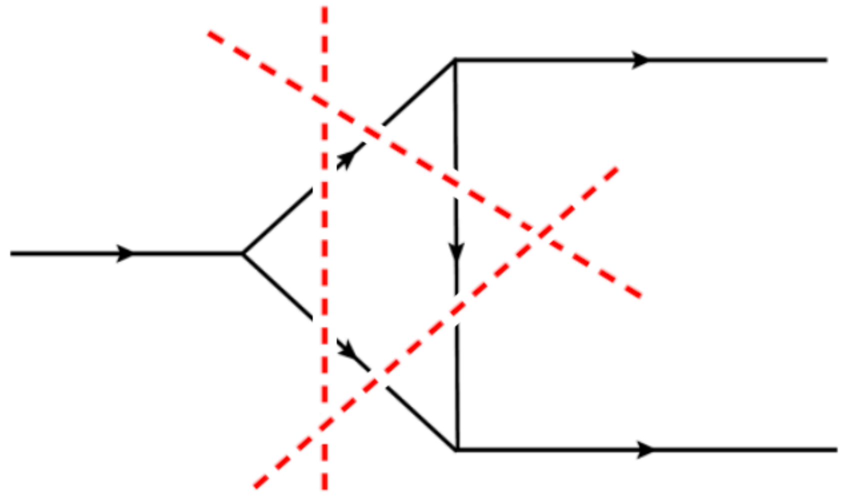
$$\mathcal{A}bs[\mathcal{M}(P_i \to P_3 P_4)] = \frac{1}{2}\sum_{\{P_1P_2\}}\int \frac{d^3p_1}{(2\pi)^3 2E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2}(2\pi)^4\delta^4(p_3+p_4-p_1-p_2) \cdot M(P_i \to \{P_1P_2\}) T^*(P_3P_4 \to \{P_1P_2\}).$$

- **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}	0.65

- **Only a part of the imaginary contribution is included……**

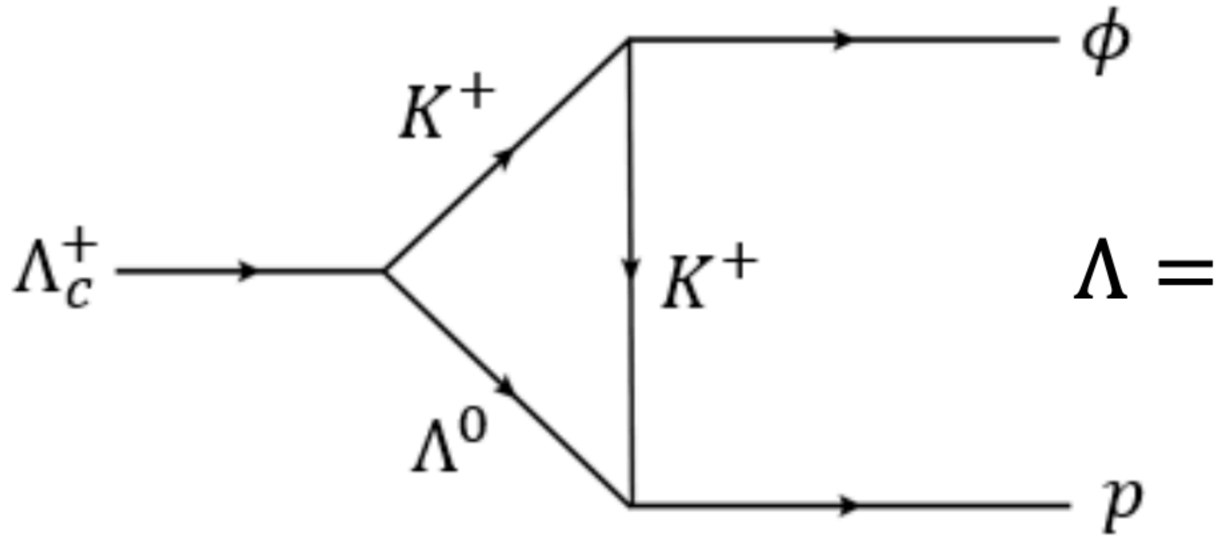




- Off-shell effects
- Lost contribution

- 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



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

$$\mathcal{M}[P,B;V]$$
$$= -i\int \frac{d^4p_1}{(2\pi)^4} g_{BBP}g_{VPP}\bar{u}(p_4,s_4)\gamma_5(\not{p_2}+m_2)(A+B\gamma_5)u(p,s)\epsilon^{\star}_{\mu}(p_3,\lambda_3)(p_1+k)^{\mu}$$
$$\times \frac{1}{(p_1^2-m_1^2+i\epsilon)(p_2^2-m_2^2+i\epsilon)(k^2-m_k^2+i\epsilon)} \boxed{\left(\frac{\Lambda_1^2-m_1^2}{\Lambda_1^2-p_1^2}\right)\left(\frac{\Lambda_2^2-m_2^2}{\Lambda_2^2-p_2^2}\right)\left(\frac{\Lambda_k^2-m_k^2}{\Lambda_k^2-k^2}\right)}$$

- The complete amplitudes with real part and 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 process dependence of the parameters is greatly reduced

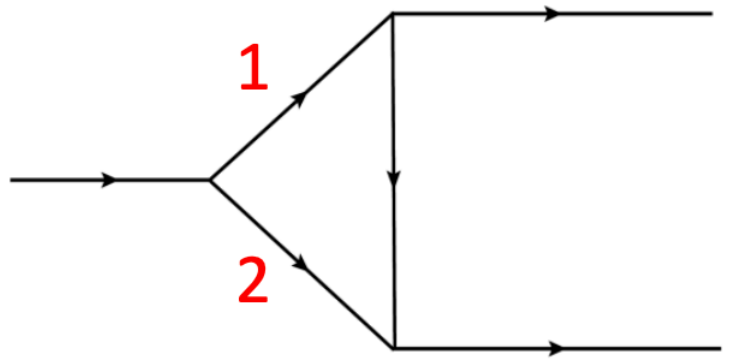
The contribution of the real part is on the same order as the contribution of the imaginary part!

Only one parameter explain all the 8 experimental data!

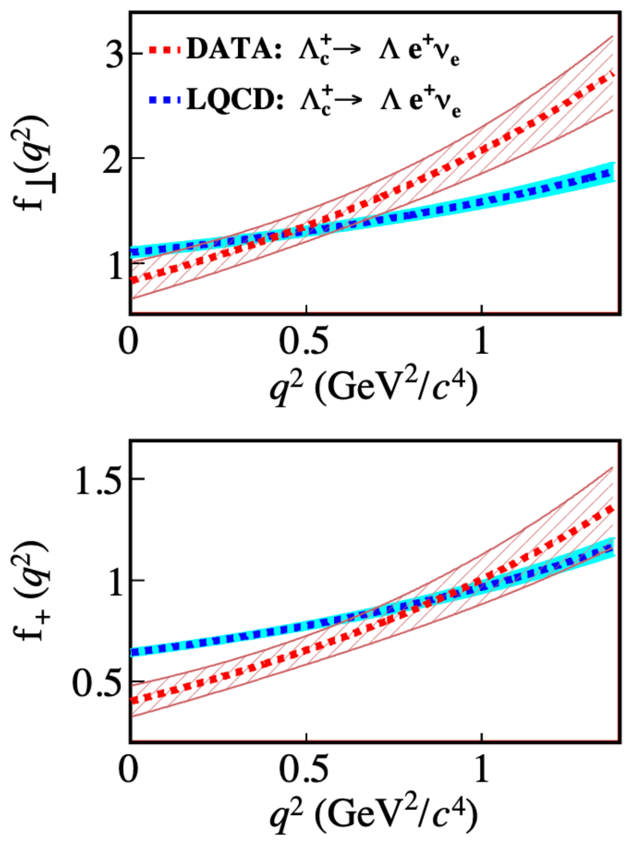
$\Lambda_c \to B_8 V$ for $\Lambda_c \to pK^+K^-$ and $\Lambda_c \to p\pi^+\pi^-$

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

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



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

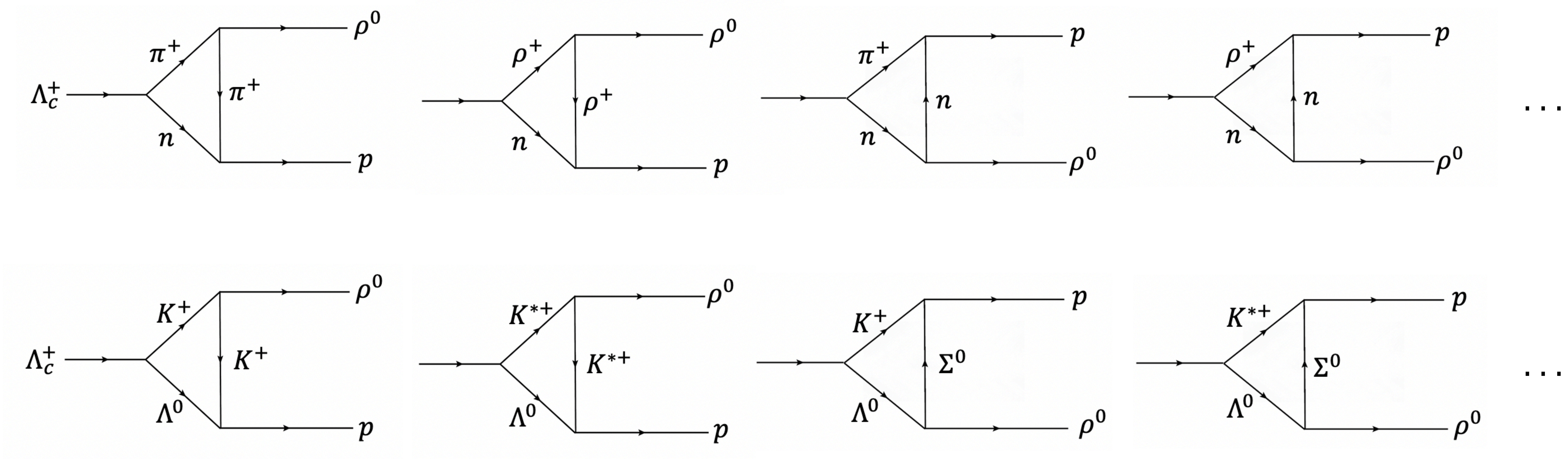


Preliminary results by C.P.Jia, H.Y.Jiang, FSY

Triangle diagrams

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

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



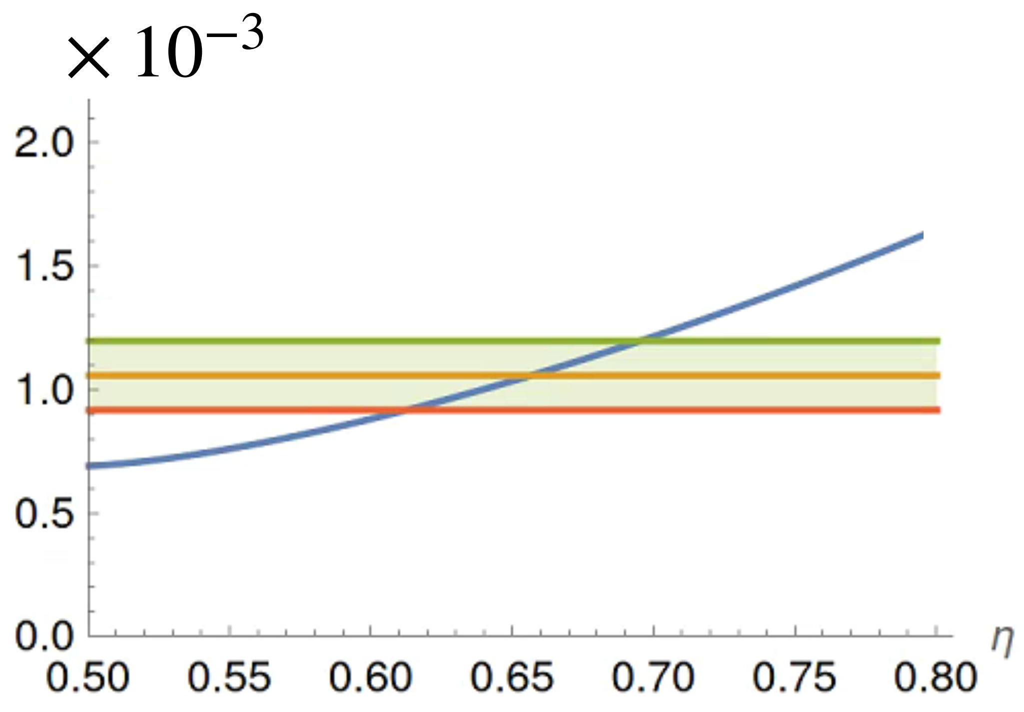
CPV can be easily obtained within the rescattering mechanism

$$\lambda_d\, A_d + \lambda_s\, A_s$$

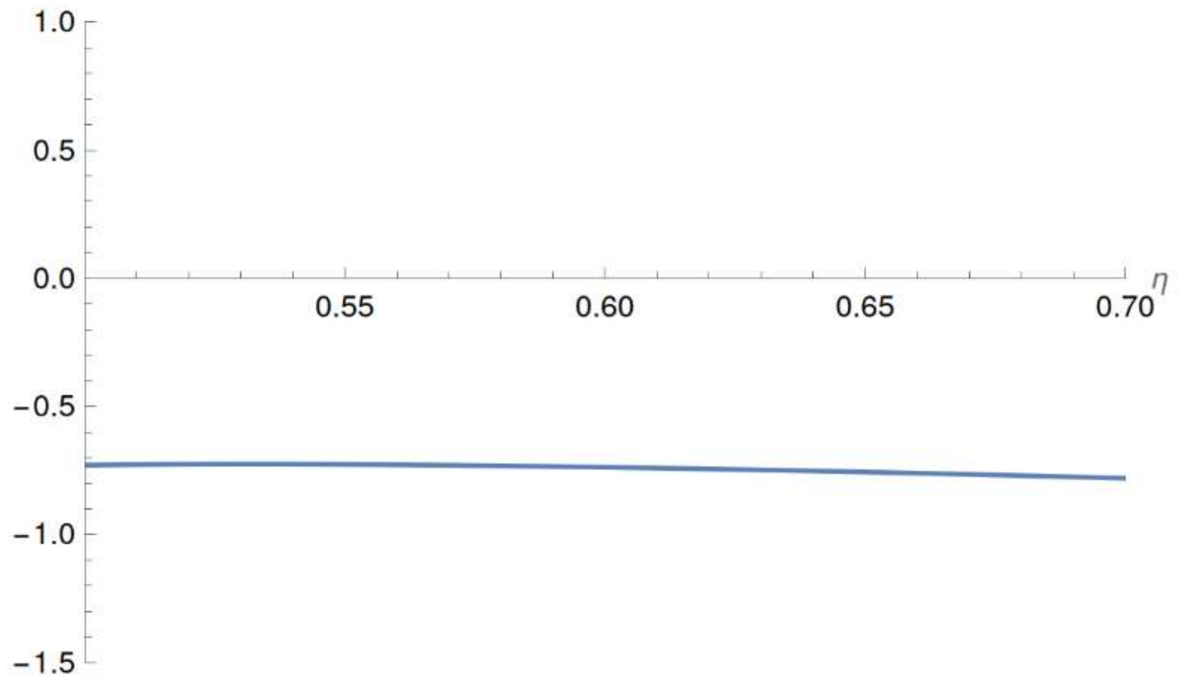
Dependence on η

$\Lambda_c^+ \to p\phi$

Branching fractions



Decay asymmetry α

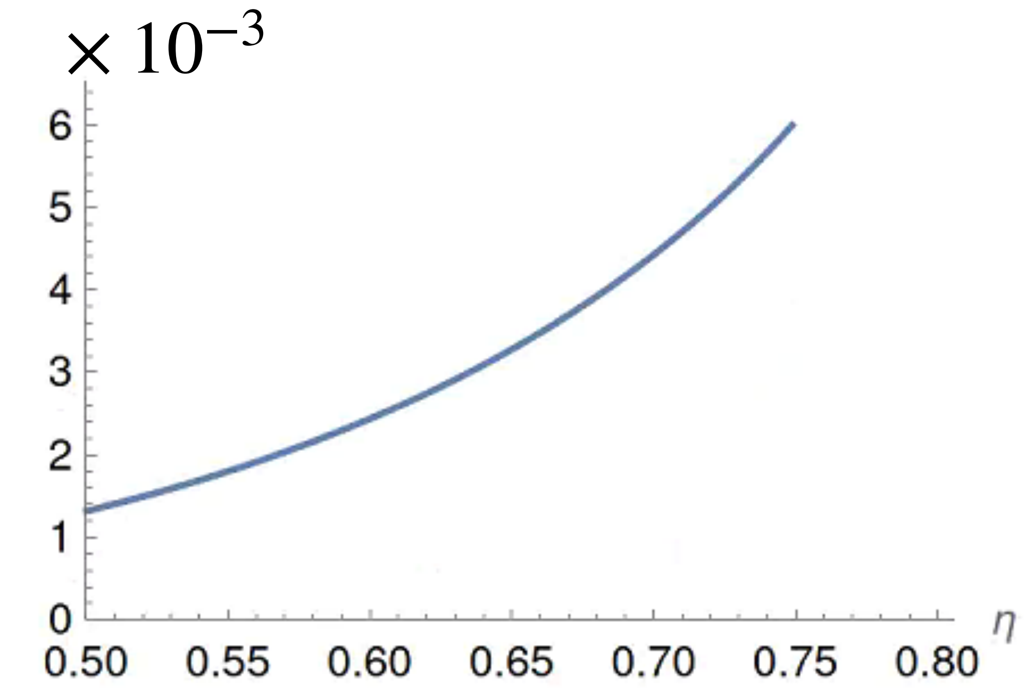


- The decay asymmetries and CPV are insensitive to η, whose dependences are mostly cancelled by the ratios

$$\alpha = \frac{\left|H_{1,\frac{1}{2}}\right|^2 - \left|H_{-1,-\frac{1}{2}}\right|^2}{\left|H_{1,\frac{1}{2}}\right|^2 + \left|H_{-1,-\frac{1}{2}}\right|^2} \qquad A_{CP} = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$$

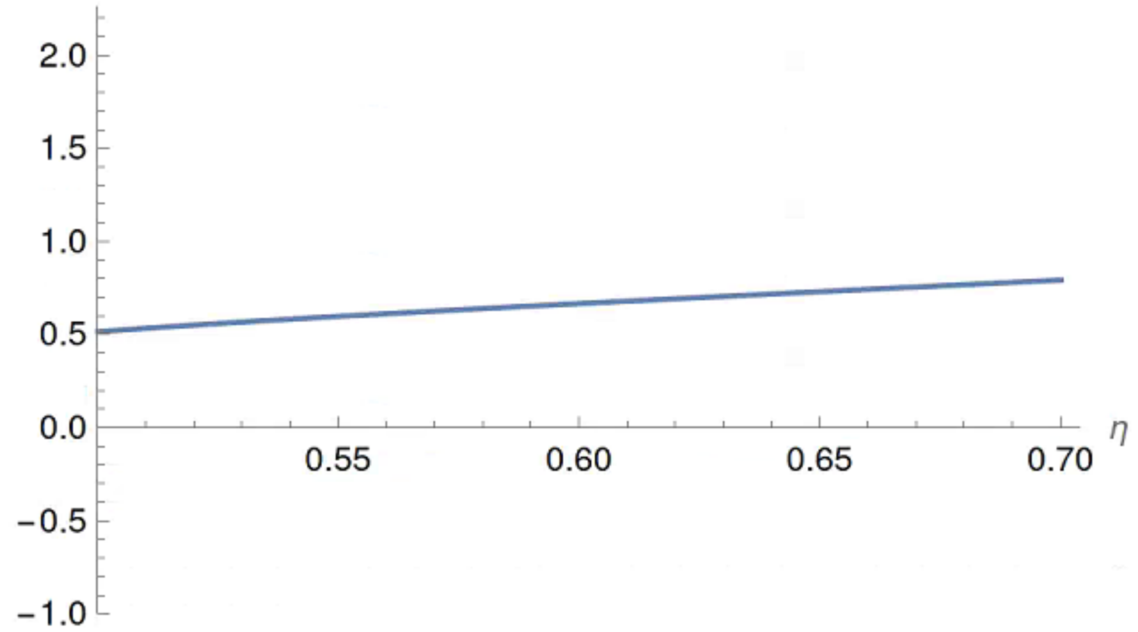
$\Lambda_c^+ \to p\rho^0$

Branching fractions

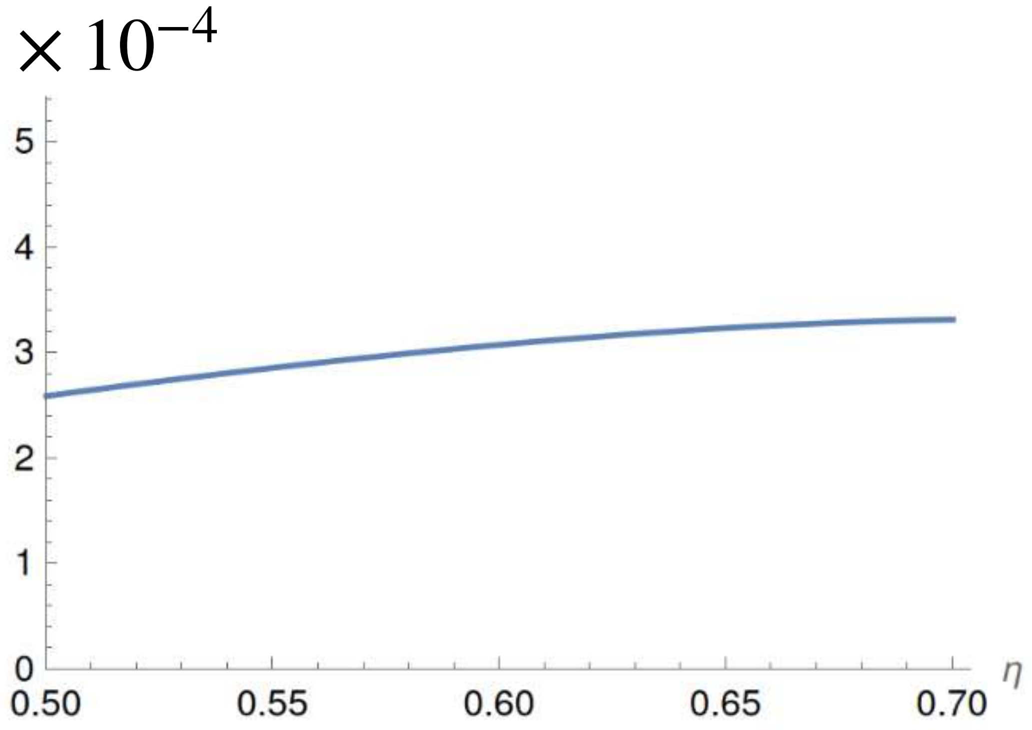


$BR(\Lambda_c^+ \to p\pi^+\pi^-) = (4.60 \pm 0.26) \times 10^{-3}$

Decay asymmetry α



Direct CPV



Preliminary results by C.P.Jia, H.Y.Jiang, FSY

Observables

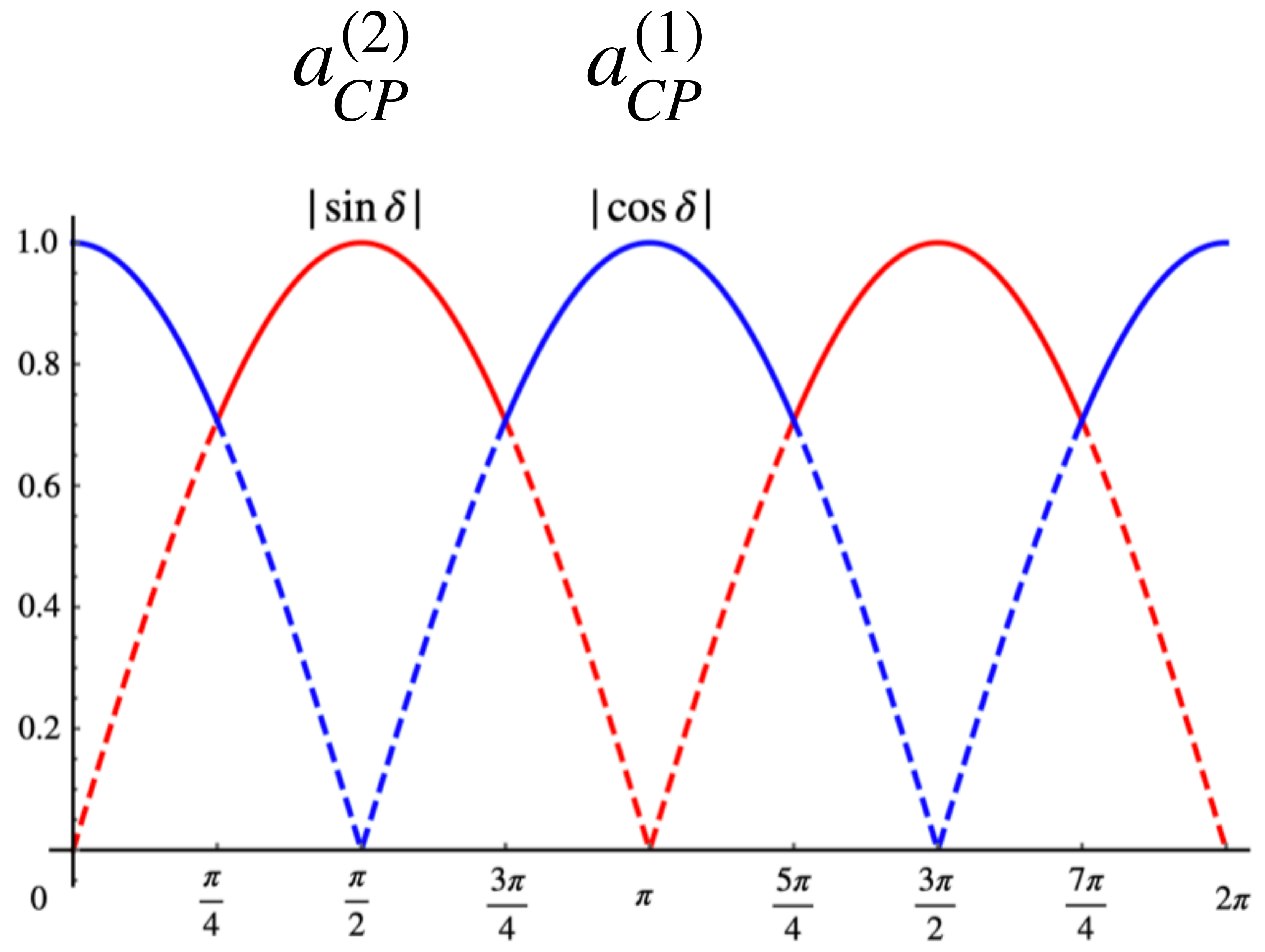
- Baryons have nonzero spins which can construct more observables and thus are helpful to find large CPV for measurements.
- Direct CPV in the decays: $a_{CP}^{\rm dir} \propto \sin\delta_s \sin\phi_w$. Sensitive to the strong phases.
- Momentum $\vec{p}$ and spin $\vec{s}$ are odd under T operation. T-odd triple product: $(\vec{s}_1 \times \vec{s}_2) \cdot \vec{p}$
- Example (1): $\vec{s}_i \times \vec{s}_f \cdot \vec{p}$ measures the β parameter in $\Lambda \to p\pi$ [Lee, Yang, 1957]

  It was found that $a_{CP}^{\beta} \propto \beta + \bar{\beta} \propto \cos\delta_s \sin\phi_w$ [Donoghue, Pakvasa, 1985]
- Example (2): It was proposed to measure $A_B \propto N(\vec{p} \cdot \vec{\epsilon}_1 \times \vec{\epsilon}_2 > 0) - N(\vec{p} \cdot \vec{\epsilon}_1 \times \vec{\epsilon}_2 < 0)$

  in $B \to VV$, whose CPV is $A_B + A_{\overline{B}} \propto \cos\delta_s \sin\phi_w$ [Valencia, 1989]

Complementarity: $\cos\delta_s$ vs $\sin\delta_s$

- Precise prediction on strong phases is far beyond control currently
- Complimentary CPV observables proportional to $\sin\delta$ or $\cos\delta$ cover all the $(0,\ 2\pi)$ region
- Whatever the strong phase is, either $|\sin\delta|$ or $|\cos\delta|$ would be larger than 0.7 which is large enough for measurements



- But keep in mind that not all the CPV observables of $\cos\delta$ and $\sin\delta$ are exactly complementary, since they might have different strong phases.

$$a_{CP}^{(1)} \propto \cos\delta_s \sin\phi_w$$

$$a_{CP}^{(2)} \propto \sin\delta_s \sin\phi_w$$

Why $\cos\delta_s$? What conditions?

- To find the exactly complementary observables, we should know
  - why are some CPV observables proportional to $\cos\delta_s$?
  - what are the conditions to construct such observables?
- **Why $\cos\delta_s$?**
  - T-odd operator Q_-: $TQ_-T^{-1} = -Q_-$
  - T is anti-unitary, $T = UK$ with U a unitary operator and K a complex conjugation
- **Two conditions:**

(1) For a basis of final states and a unitary transformation so that $UT|\psi_n\rangle = e^{i\alpha}|\psi_n\rangle$

(2) Q_- is invariant under this unitary transformation, $UQ_-U^\dagger = Q_-$

[J.P.Wang, Q.Qin, FSY, 2211.07332]

Why $\cos\delta_s$? What conditions?

- **Proof:**

$$\langle f|Q_-|f\rangle = \langle i|S^\dagger Q_- S|i\rangle$$
$$= \sum_{m,n} \langle\psi_i|S^\dagger|\psi_m\rangle\langle\psi_m|Q_-|\psi_n\rangle\langle\psi_n|S|\psi_i\rangle$$
$$= \sum_{m,n} A_m^* A_n \langle\psi_m|Q_-|\psi_n\rangle \ .$$

pure imaginary

$$\langle\psi_m|Q_-|\psi_n\rangle = \langle\psi_m|\mathcal{T}^\dagger\mathcal{T}\, Q_-|\psi_n\rangle^*$$
$$= -\langle\psi_m|\mathcal{T}^\dagger Q_- \mathcal{T}|\psi_n\rangle^*$$
$$= -\langle\psi_m|\mathcal{T}^\dagger\, \mathcal{U}^\dagger\mathcal{U}\, Q_-\, \mathcal{U}^\dagger\mathcal{U}\, \mathcal{T}|\psi_n\rangle^*$$
$$= -\langle\psi_m|\mathcal{T}^\dagger\mathcal{U}^\dagger\, Q_-\, \mathcal{U}\mathcal{T}|\psi_n\rangle^*$$
$$= -\langle\psi_m|Q_-|\psi_n\rangle^* \ ,$$

$$\langle f|Q_-|f\rangle \propto \sum_{m,n} Im(A_m^* A_n)$$

$$A_{\rm CP}^{Q_-} \equiv \frac{\langle f|Q_-|f\rangle - \langle\bar f|\bar Q_-|\bar f\rangle}{\langle f|Q_-|f\rangle + \langle\bar f|\bar Q_-|\bar f\rangle} \propto \sum_{m,n} Im(A_m^* A_n - \bar A_m^* \bar A_n) \propto \cos\delta_s \sin\phi_w$$

Quod erat demonstrandum.

[J.P.Wang, Q.Qin, FSY, 2211.07332]

CPV induced by T-odd and T-even

$$a_{CP}^{\mathrm{T-odd}} \propto \sum_{m,n} Im(A_m^* A_n - \bar{A}_m^* \bar{A}_n) \propto \cos\delta_s \sin\phi_w$$

$$a_{CP}^{\mathrm{T-even}} \propto \sum_{m,n} Re(A_m^* A_n - \bar{A}_m^* \bar{A}_n) \propto \sin\delta_s \sin\phi_w$$

- Example: $\Lambda_c^+ \to \Lambda^0 K^+$, Lee-Yang decay-asymmetry parameter

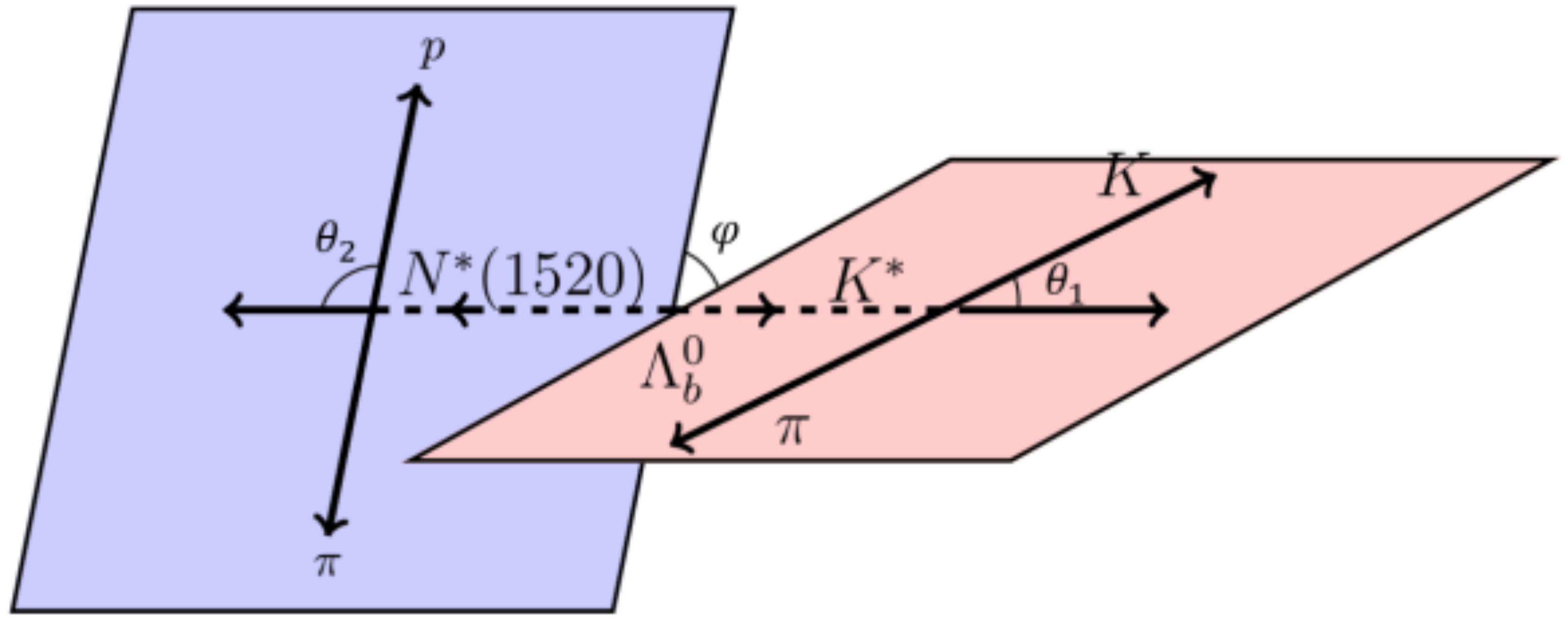
T-even: $\vec{s}_i \cdot \vec{p}$ $\quad$ $\alpha \propto Re[S^* P]$ $\quad$ $a_{CP}^{\alpha} = \dfrac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}} \propto \sin\delta$

T-odd: $(\vec{s}_i \times \vec{s}_f) \cdot \vec{p}$ $\quad$ $\beta \propto Im[S^* P]$ $\quad$ $a_{CP}^{\beta} = \dfrac{\beta + \overline{\beta}}{\beta - \overline{\beta}} \propto \cos\delta$

complimentary

Angular distributions

$$
\begin{aligned}
\frac{d\Gamma}{dc_1\,dc_2\,d\varphi} \propto & -\frac{s_1^2 s_2^2}{\sqrt{3}}\mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}}+\mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin 2\varphi \\
& +\frac{s_1^2 s_2^2}{\sqrt{3}}\mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}}+\mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos 2\varphi \\
& -\frac{4s_1c_1s_2c_2}{\sqrt{6}}\mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}}+\mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin\varphi \\
& +\frac{4s_1c_1s_2c_2}{\sqrt{6}}\mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}}+\mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos\varphi
\end{aligned}
$$



$$\sin\varphi = (\vec{n}_a \times \vec{n}_b)\cdot\hat{p}_b = \vec{n}_a\cdot(\vec{n}_b\times\hat{p}_b) \propto (\vec{p}_1\times\vec{p}_2)\cdot\vec{p}_4$$

$$\sin 2\varphi = 2\sin\varphi\cos\varphi \propto [(\vec{p}_1\times\vec{p}_2)\cdot(\vec{p}_3\times\vec{p}_4)][(\vec{p}_1\times\vec{p}_2)\cdot\vec{p}_4].$$

- Triple-product of momentum, $(\vec{p}_1\times\vec{p}_2)\cdot\vec{p}_3$, is not good. $\sin\varphi$ with $\sin\theta_1\cos\theta_1\sin\theta_2\cos\theta_2$
- Angular distributions of resonant contributions are necessary. It is more clear in theory.

Summary

- CPV of charmed baryons are the next opportunity and challenges of charm physics
- Dynamics are usually difficult. The final-state-interaction rescattering mechanism is developed for charmed baryon decays. CPV is not sensitive to the free parameter.
- CPV induced by T-odd correlations is proportional to $\cos\delta_s$. Prove is given in some general conditions. Complimentary observables are suggested.

Thank you very much!

CP violation in baryons

- Sakharov conditions for **Baryogenesis:**

  1) **baryon** number violation

  2) C and **CP violation**

  3) out of thermal equilibrium

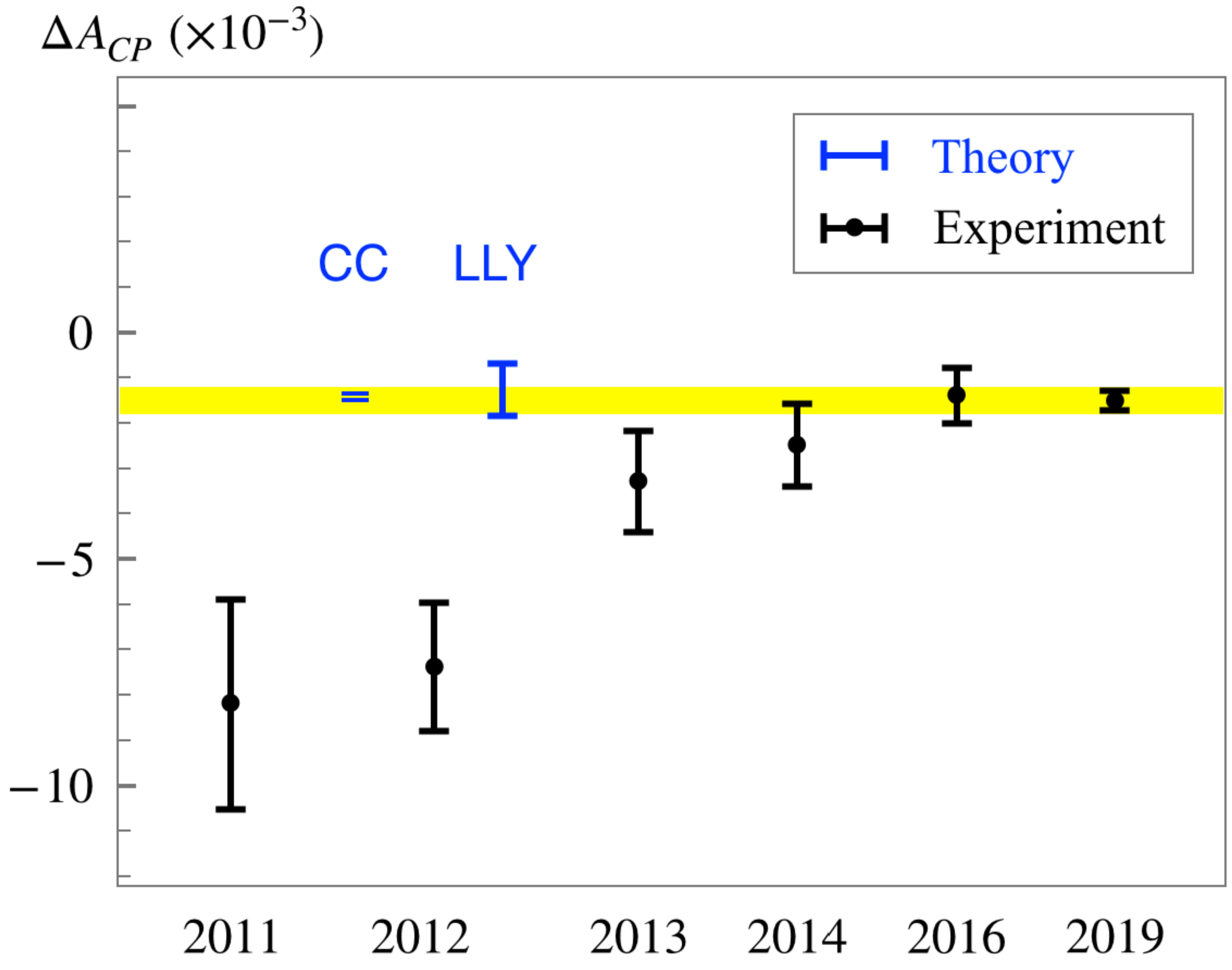
- **CPV: SM < BAU. => new source of CPV, NP**

- CPV well established in K, B and D mesons,

  but CPV never established in any baryon

- **Comparison between precise prediction and measurement is helpful to test the SM and search for NP**

$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$



Saur, **FSY**, Sci.Bull.2020

Th: the only predictions of O(10^{-3})

CC: topological approach + QCDF

Cheng, Chiang, 2012

LLY: factorization-assisted topology (FAT)

Li, Lu, **FSY**, 2012

Exp: LHCb, PRL122, 211803 (2019)

Topological diagrammatic approach successfully predicted the charm CPV !!!