粲强子CP破坏的理论研究

于福升

兰州大学

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Outline

- Introduction of CPV of charmed hadrons
- Final-State-Interaction (FSI)
- FSI triangle diagrams
- FSI $N\pi$ rescatterings
- Summary

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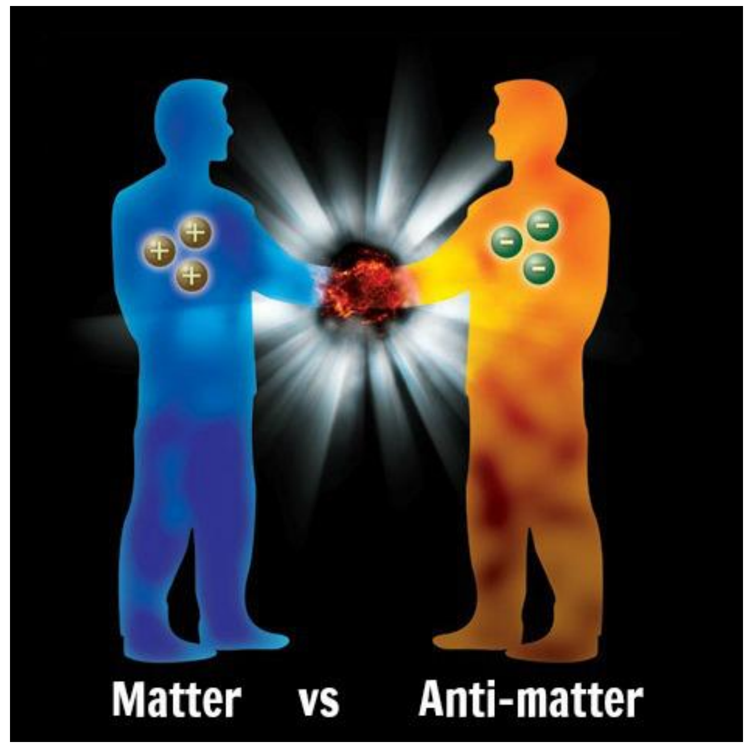
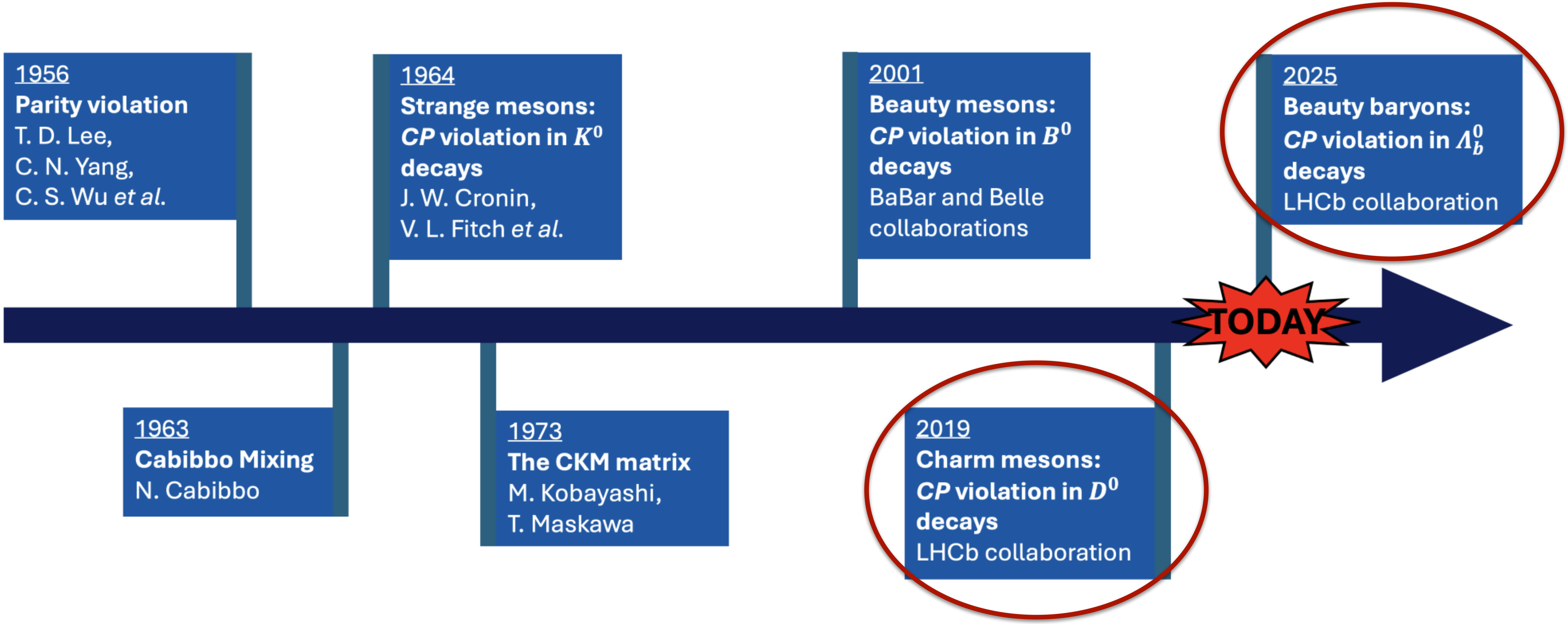
CP violation

- **CP violation** is a necessary condition for **matter-antimatter asymmetry of the Universe**
  - CPV: SM < matter-antimatter asymmetry.
    => new source of CPV, new physics
- **CPV in baryons**
  - The visible universe is mainly made of **baryons**.



Fu-Sheng Yu

First observations of CPV in charm and baryon systems



Next card to be turned: CPV of charmed baryon?

K meson

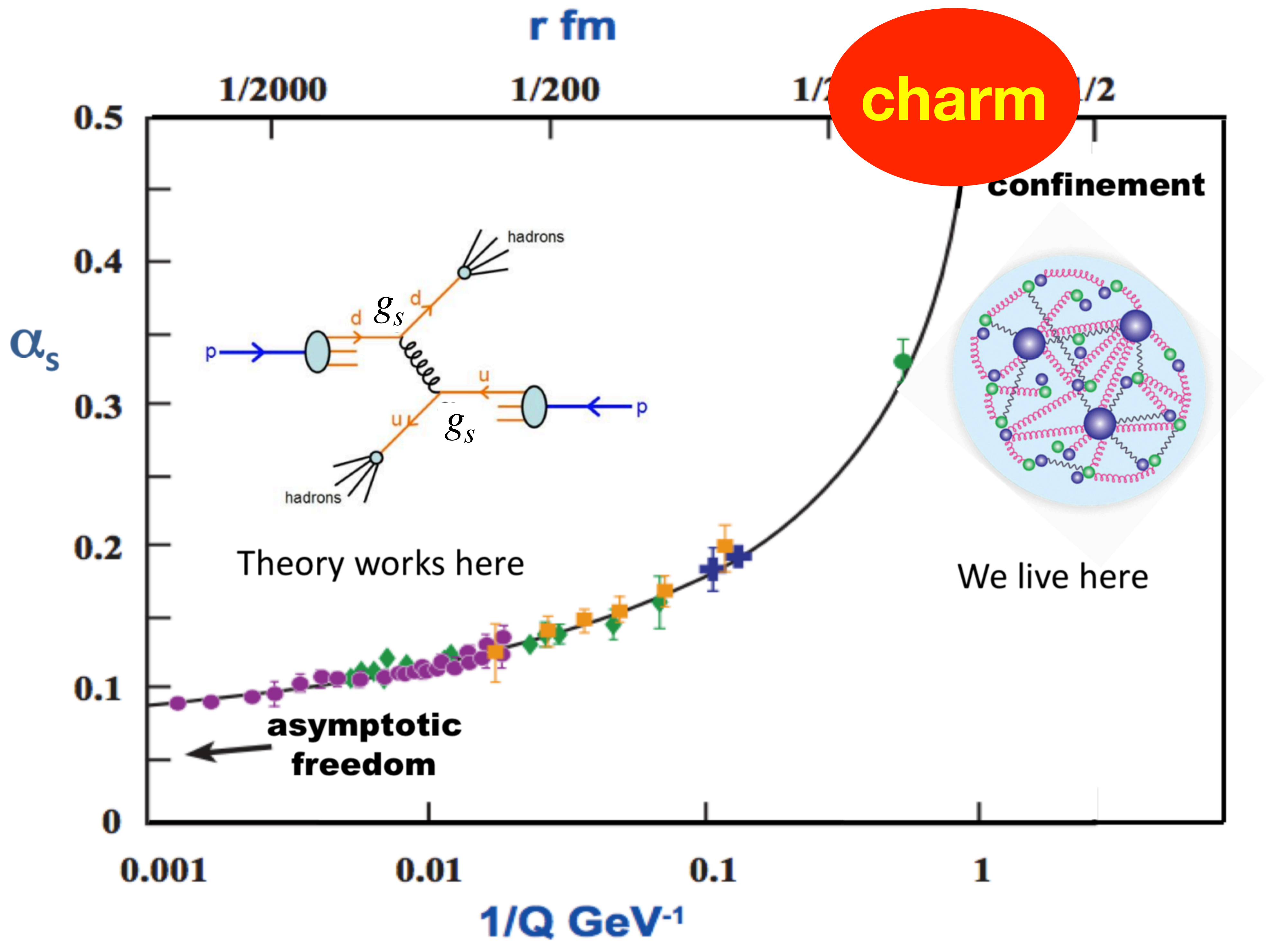
B meson

D meson

Λ_b^0 baryon

Charmed baryon?

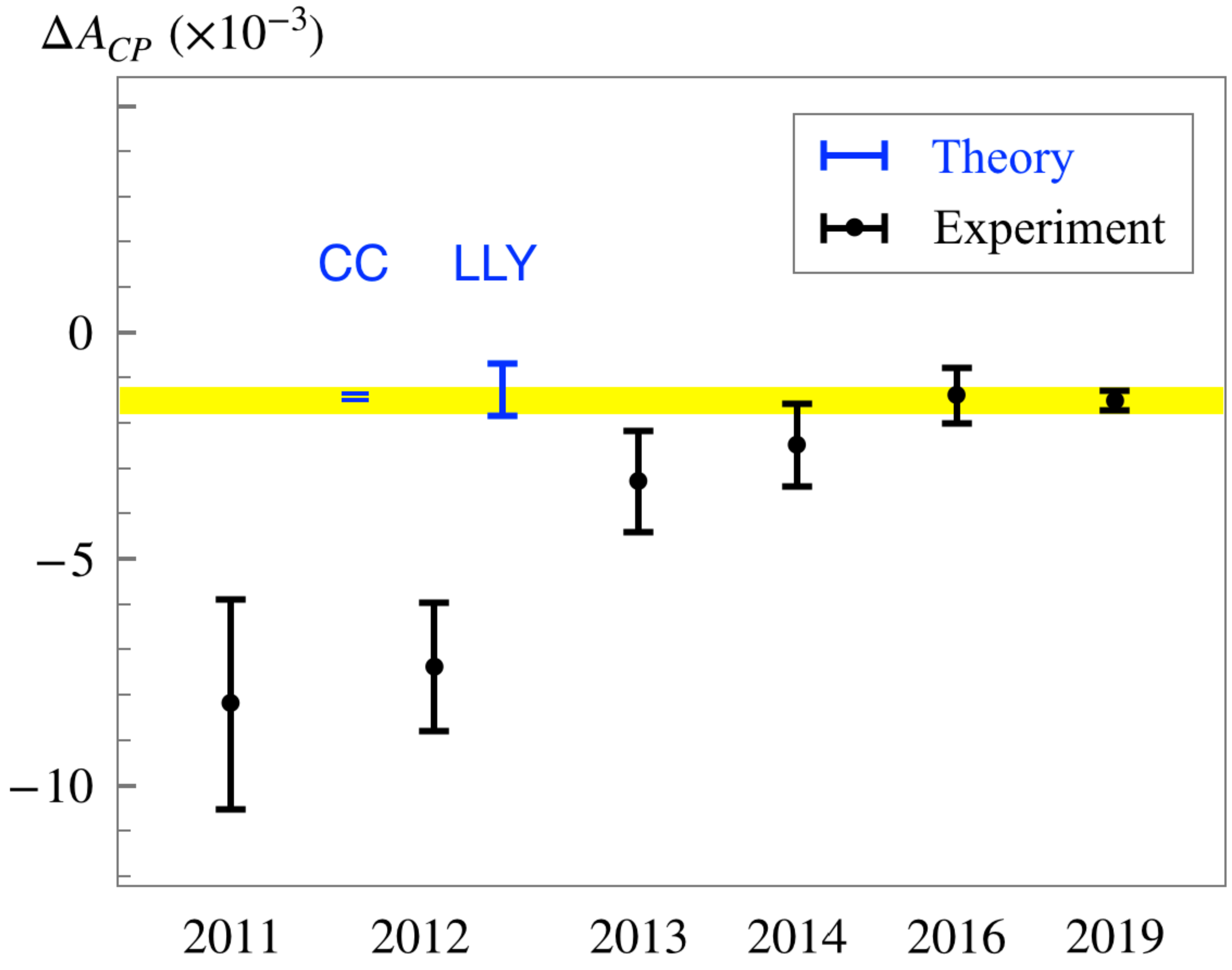
Dynamics @ charm scale



from S.Olsen

- ✓ **Large non-perturbative / long-distance contributions in charmed hadron decays**
- ✓ **It is usually challenging in theory**

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



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)

Long-distance dynamics are included in topological diagrams

Implications of ΔA_{CP}

$$\mathcal{A}(D^0 \to K^+K^-) = \lambda_s \mathcal{T}^{KK} + \lambda_b \mathcal{P}^{KK}, \qquad \mathcal{A}(D^0 \to \pi^+\pi^-) = \lambda_d \mathcal{T}^{\pi\pi} + \lambda_b \mathcal{P}^{\pi\pi},$$

$$\Delta A_{CP} = -2r\sin\gamma\left(\frac{|\mathcal{P}^{KK}|}{|\mathcal{T}^{KK}|}\sin\delta^{KK} + \frac{|\mathcal{P}^{\pi\pi}|}{|\mathcal{T}^{\pi\pi}|}\sin\delta^{\pi\pi}\right) \qquad r = |\lambda_b/\lambda_{d,s}|$$

$$2r\sin\gamma = 1.5\times 10^{-3}$$

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

→

$$\left(\frac{|\mathcal{P}^{KK}|}{|\mathcal{T}^{KK}|}\sin\delta^{KK} + \frac{|\mathcal{P}^{\pi\pi}|}{|\mathcal{T}^{\pi\pi}|}\sin\delta^{\pi\pi}\right) \approx 1$$

✓ **Charm is different from bottom**

See H.Y.Cheng's talk

$$|\mathcal{P}/\mathcal{T}|_{\rm charm} \sim \mathcal{O}(1) \quad v.s. \quad |\mathcal{P}/\mathcal{T}|_{\rm bottom} \sim \mathcal{O}(0.1)$$

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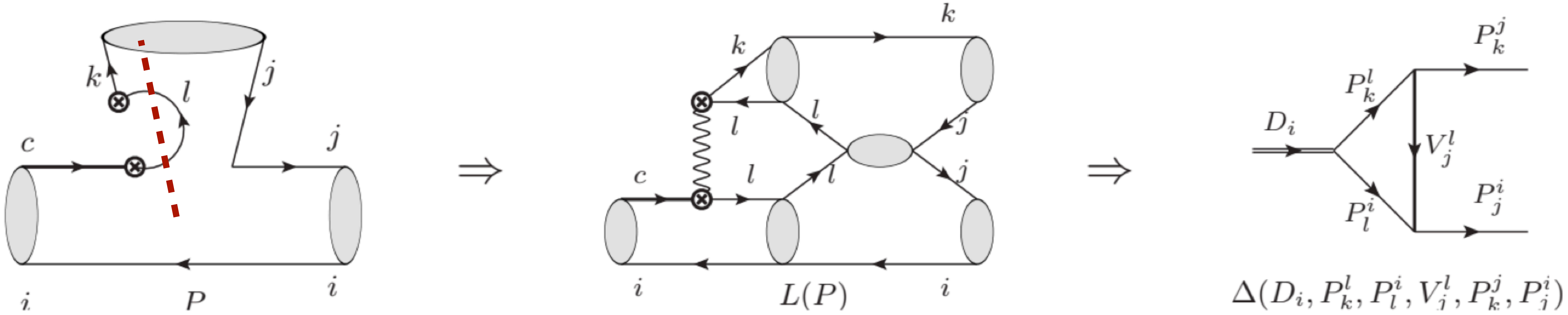
Final-state interactions (FSI)

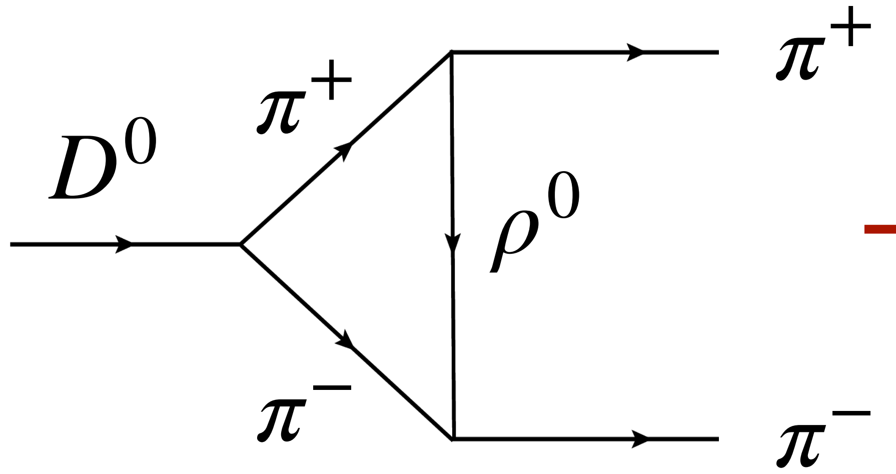
- Quark loops: d & s quark in the loops by tree operators
- They can be generated by the long-distance final-state interactions
- They are larger than contributions from penguin operators, $a_1 \sim 1 \ \gg \ a_{4,6} \sim 0.1$



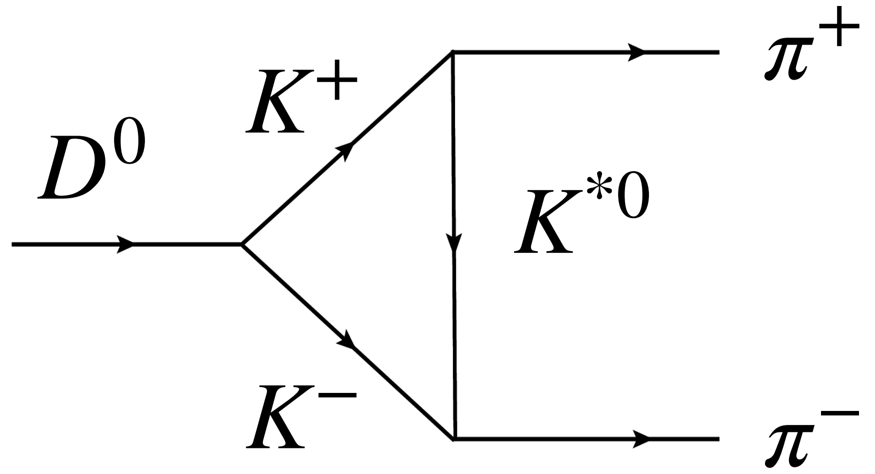
D.Wang, 2111.11201

- CPV generated by interference between d-quark loop and s-quark loop

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



$+$ $V^*_{cs}V_{us}$



$|P/T| \sim 1$

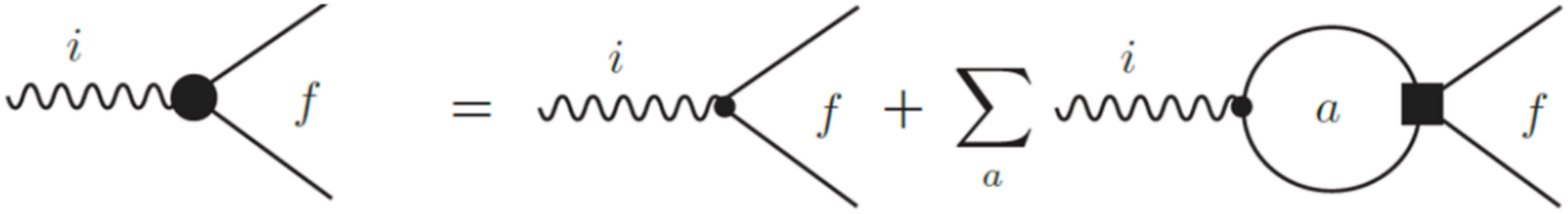
Final-state interactions (FSI)

$$\mathcal{A} = \mathcal{S}^{1/2} \mathcal{A}_0$$

Long-time long-distance strong interaction

Short-time short-distance weak interaction

$$\langle f | \mathcal{H}_W | i \rangle = \sum_a \langle f | a \rangle \langle a | \mathcal{H}_W | i \rangle$$

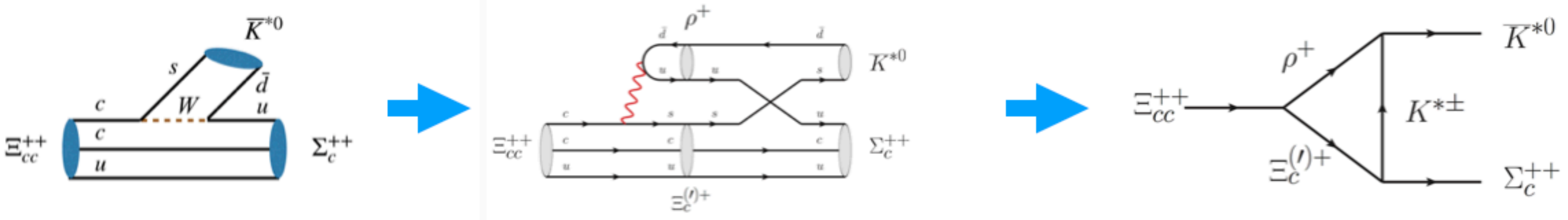


L. Wolfenstein, Phys. Rev. D 43, 151 (1991).

- Extensively studied in heavy flavor physics

FSI for prediction on discovery of Ξ_{cc}^{++}

- FSI mechanism have been successfully used to predict the discovery channel of $\Xi_{cc}^{++} \to (\Sigma_c^{++}\overline{K}^{*0} \to)\ \Lambda_c^+ K^- \pi^+ \pi^+$ [FSY, Jiang, Li, Lu, Wang, Zhao, '17]



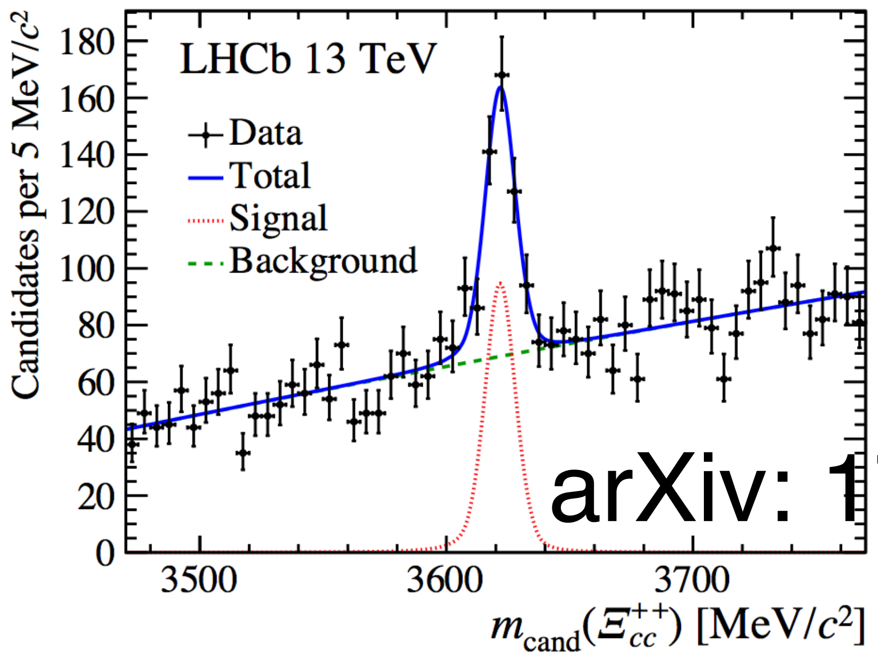
Topology: C — quark exchange — hadronic triangle

Discovery Potentials of Doubly Charmed Baryons

Fu-Sheng Yu[1,2,*] Hua-Yu Jiang[1,2], Run-Hui Li[3], Cai-Dian Lü[4,5,†] Wei Wang[6,‡] and Zhen-Xing Zhao[6]

arXiv: 1703.09086

$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ are the most favorable decay modes



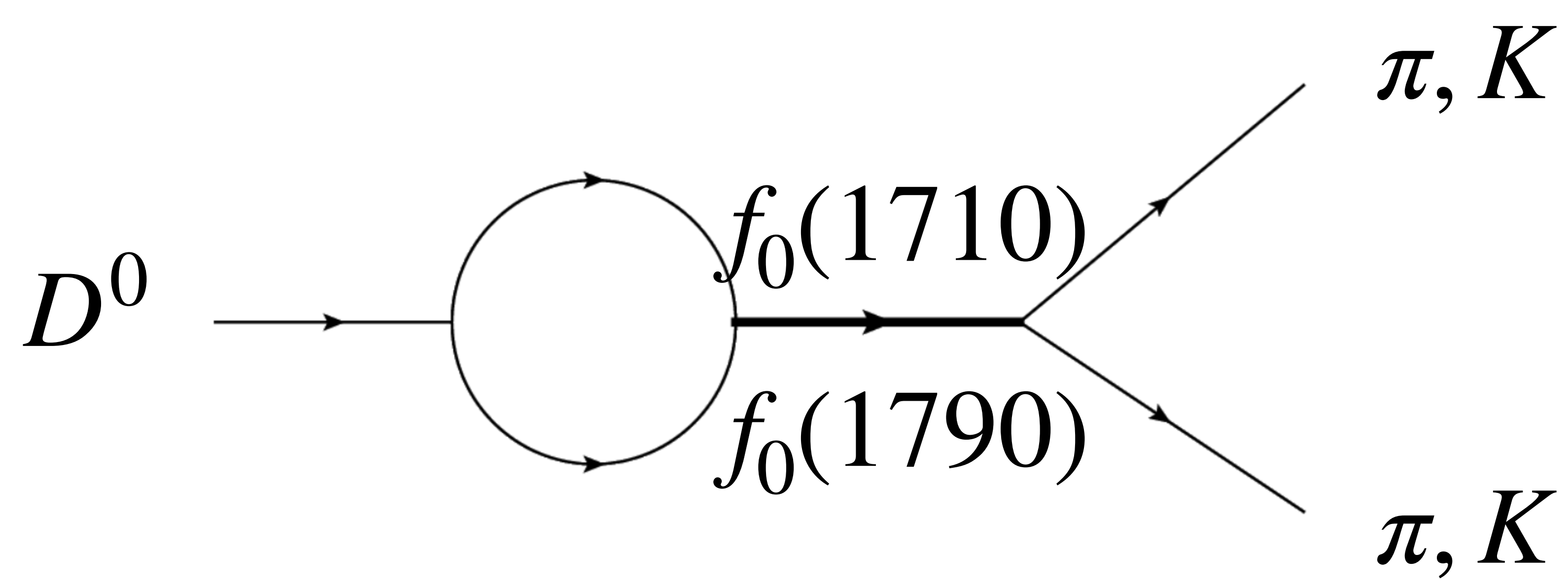
arXiv: 1707.01621

$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

FSI for CPV of charmed meson

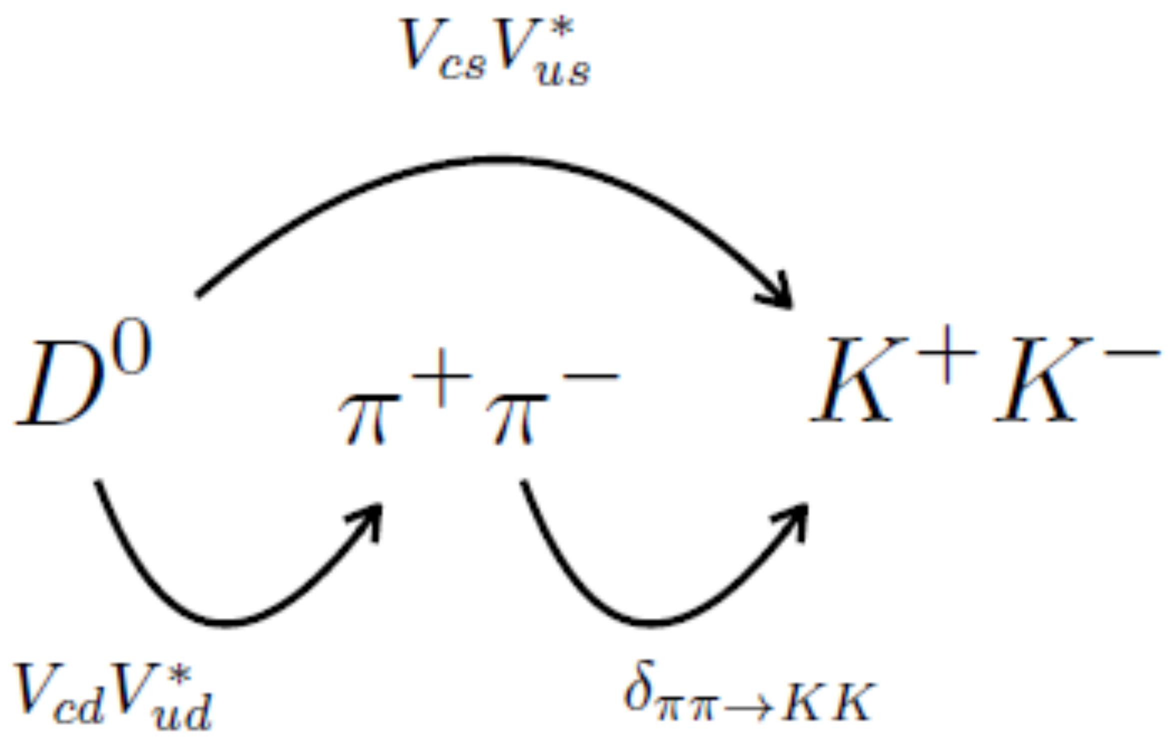
- Resonant contributions for charm CPV
  - But lack of enough information on the resonances

  Soni, '19; Schacht, Soni, '22



- Rescattering mechanism for charm CPV
  - Data-driven extraction of magnitudes and phases of the $\pi\pi \to KK$ scatterings at the D^0 mass energy

  Bediaga, Frederico, Magalhaes, '23; Pich, Solomonidi, Silva, '23



FSI for CPV of charmed baryon

- Global fit for the long-distance penguin topological diagrams

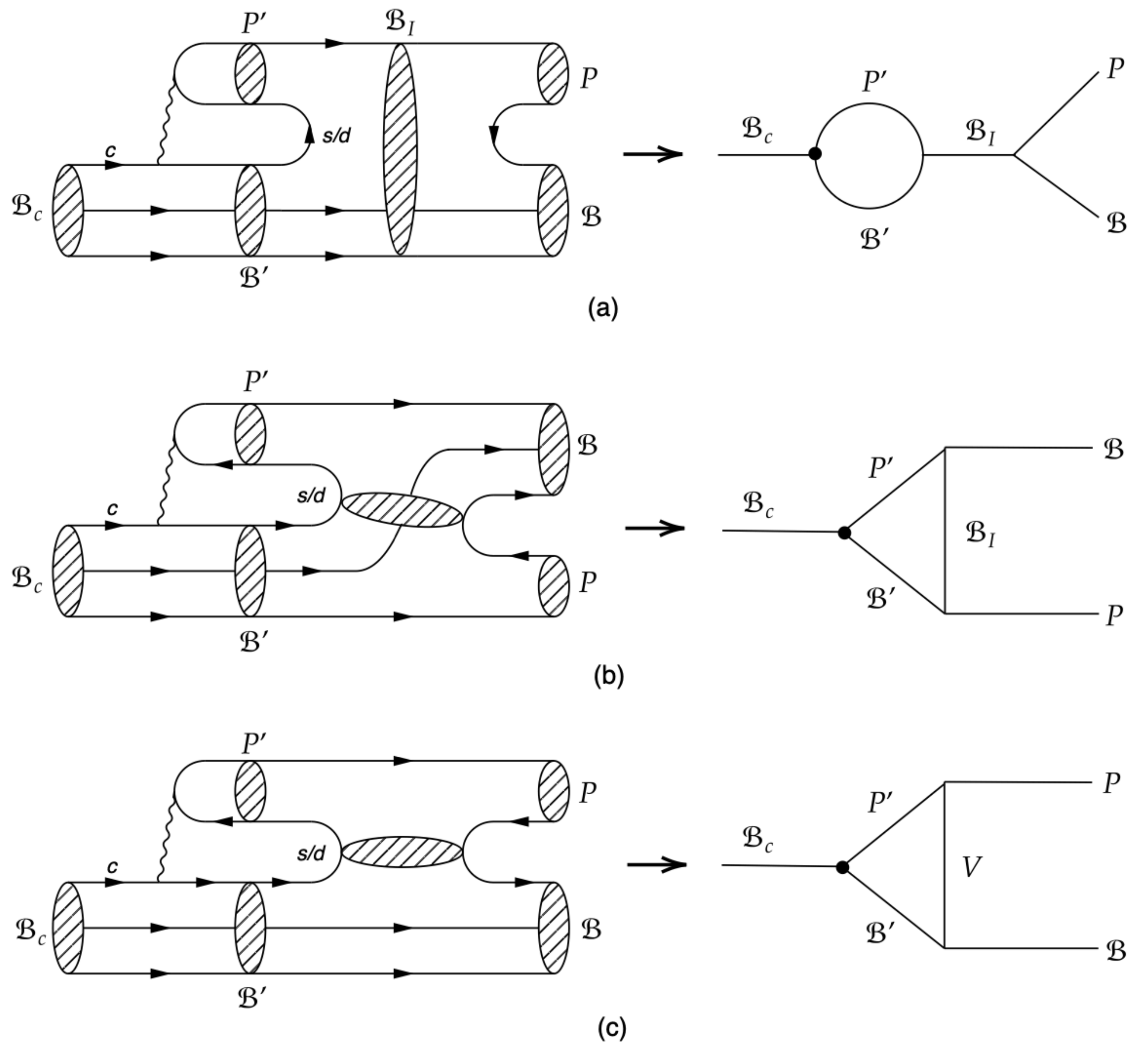
$$A_{CP}(\Xi_c^0 \to pK^-) = -(1.48 \pm 0.25 \pm 0.12) \times 10^{-3}$$

$$A_{CP}(\Xi_c^0 \to \Sigma^+\pi^-) = (1.77 \pm 0.25 \pm 0.14) \times 10^{-3}$$

X.G.He, C.W.Liu, 2404.19166, 2506.19005

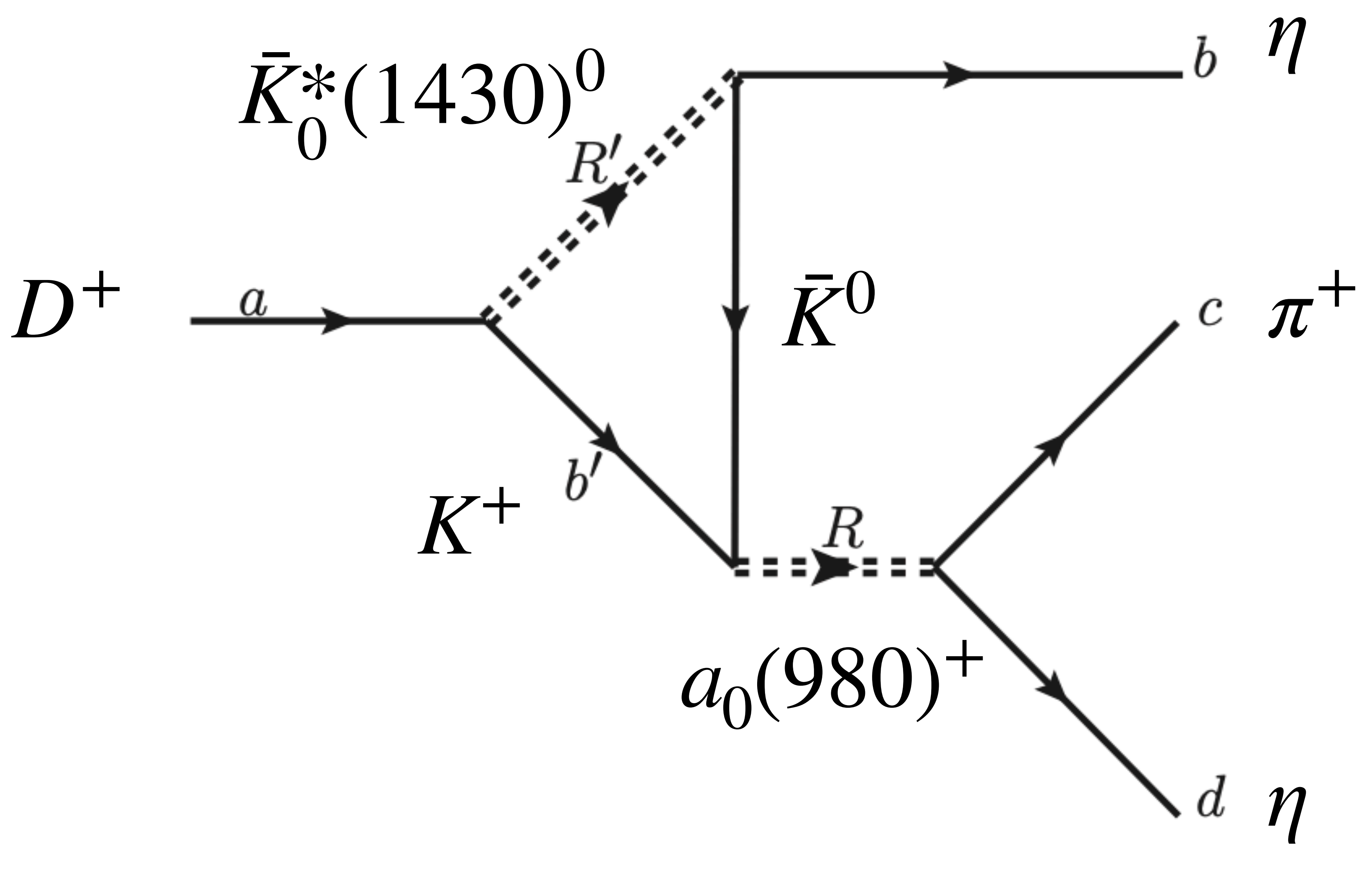
$$\mathcal{A}_{CP}(\Lambda_c \to p\pi^0) = -(0.8 \pm 0.3) \times 10^{-3}, \quad \mathcal{A}_{CP}(\Lambda_c \to p\eta') = (1.4 \pm 0.1) \times 10^{-3},$$
$$\mathcal{A}_{CP}(\Xi_c^0 \to \Sigma^0\eta) = (1.2 \pm 0.2) \times 10^{-3}, \quad \mathcal{A}_{CP}(\Xi_c^+ \to \Sigma^+\eta) = (1.2 \pm 0.2) \times 10^{-3}.$$

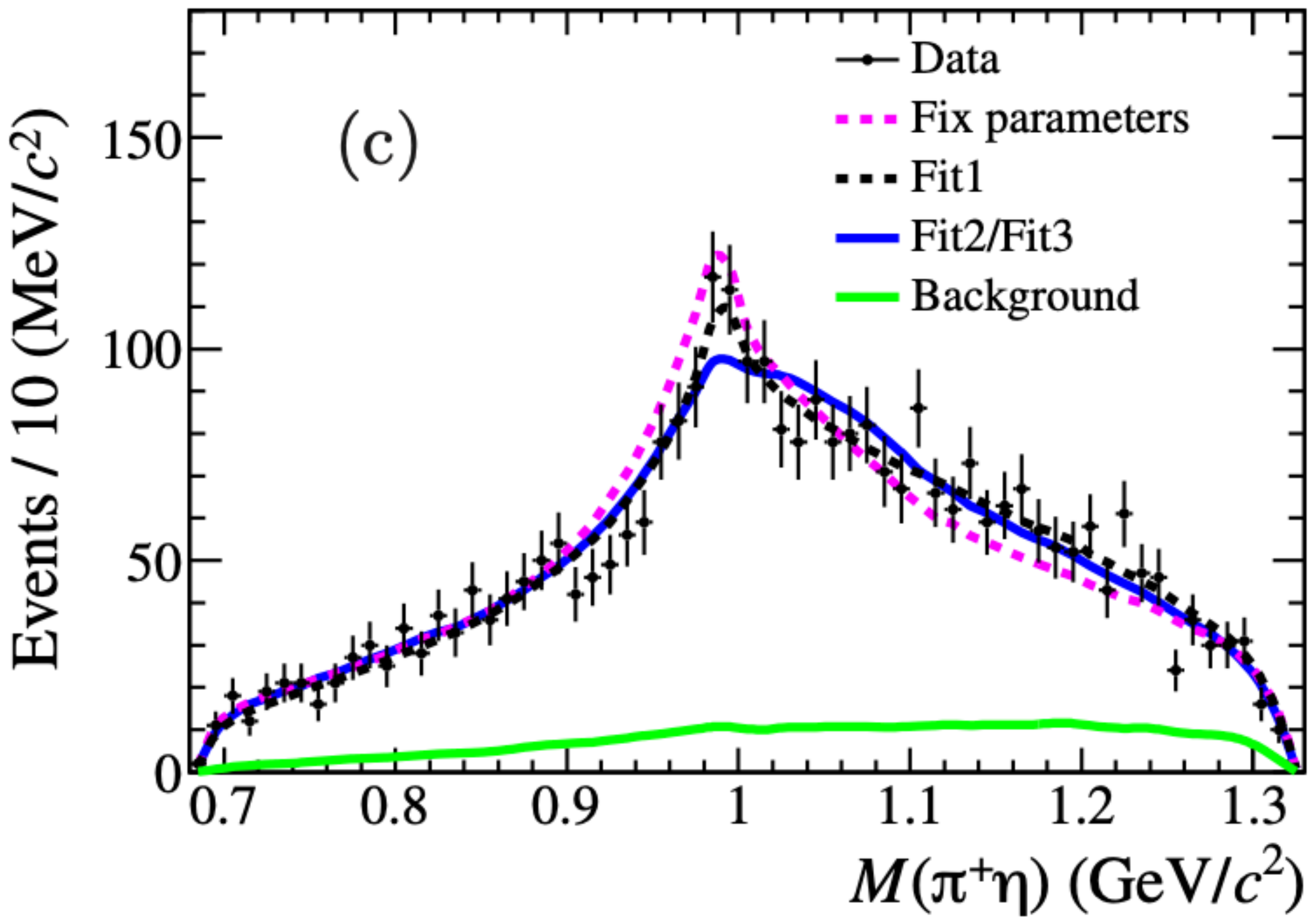
H.Y.Cheng, F.Xu, H.Zhong, 2505.0750



See H.Y.Cheng’s and C.W.Liu’s talks

First experimental confirmation of FSI





$$A_\alpha = (1 + C A_{\rm loop}) P_\alpha$$

$$|C| = 0.113 \pm 0.015_{\rm stat.} \pm 0.048_{\rm syst.}$$

BESIII, 2505.12086

See L.Y.Dong's talk

Fit1: pole position of the a0(980) is 107MeV higher than KK threshold

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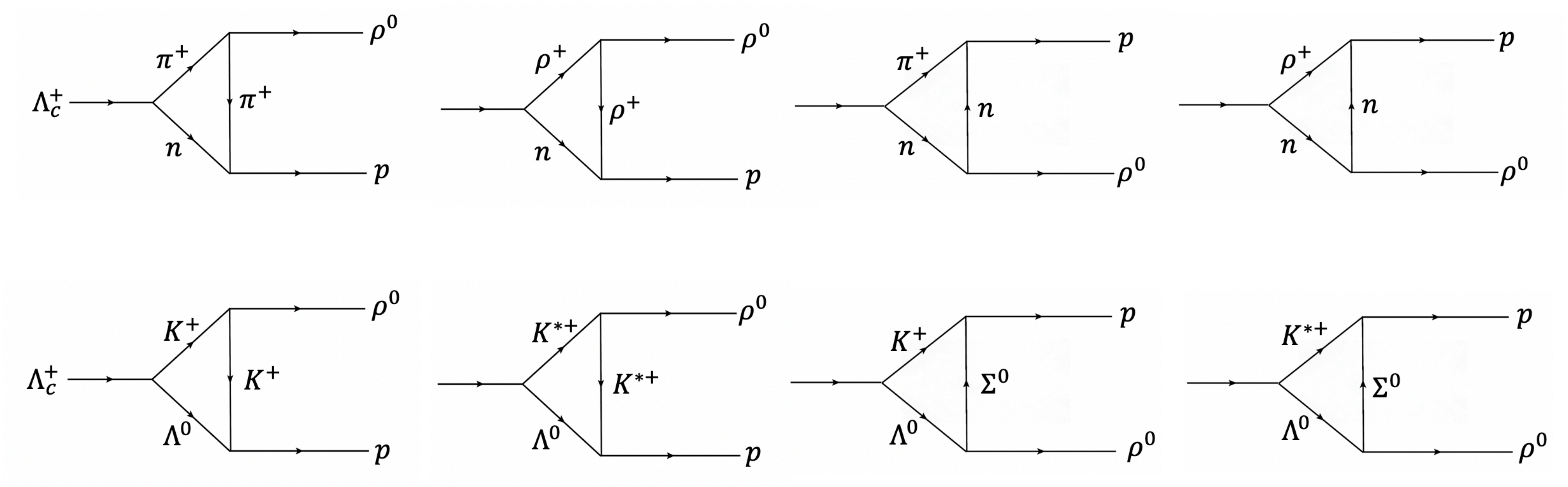
Our work on FSI triangle diagrams

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

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



…

…

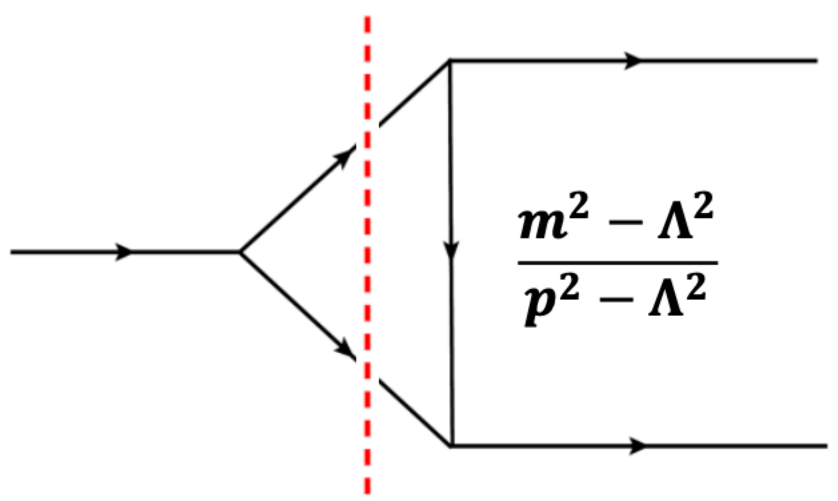
$$\lambda_d\, A_d + \lambda_s\, A_s$$

Dynamical predictions on CPV for modes without much data, such as $\Lambda_c^+ \to \mathscr{B}_8 V$

Loop integrals of triangle diagrams

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

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

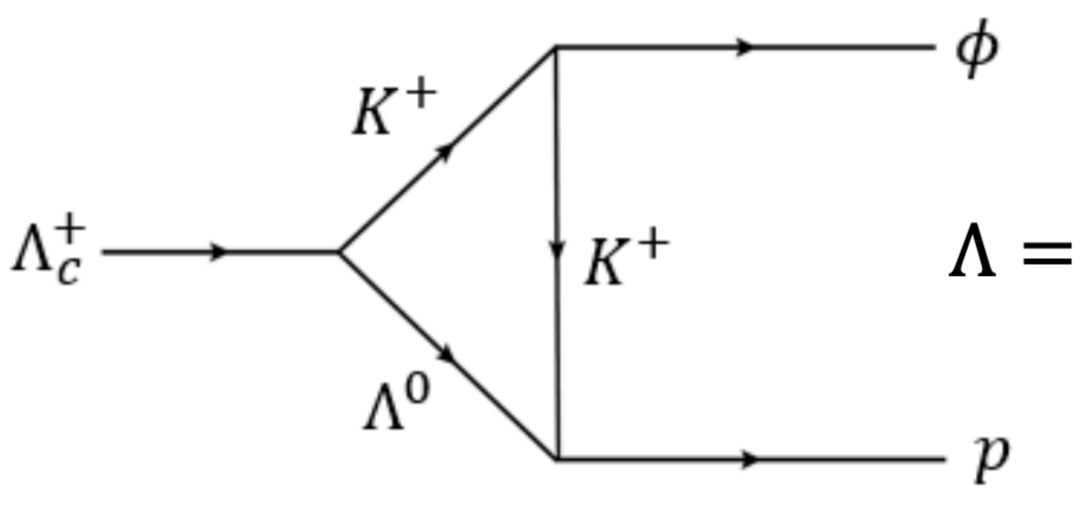


$\Lambda = m_k + \eta\Lambda_{QCD}$

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

- Only imaginary part, hard for CPV

➢ **Improving method： Loop integral**



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

- Complete amplitudes with both real and imaginary parts
- Non-trivial strong phases
- Suitable for CPV and decay asymmetries

Branching Fractions

Only one parameter explains all the 9 experimental data!

TABLE III: 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}	$2.79^{+1.89}_{-1.29}$	$2.72^{+1.87}_{-1.27}$	1.52 ± 0.44
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	$0.44^{+1.64}_{-0.30}$	$5.08^{+1.95}_{-0.66}$	–

C.P.Jia, H.Y.Jiang, J.P.Wang, FSY, 2408.14959

Dependence on parameter η

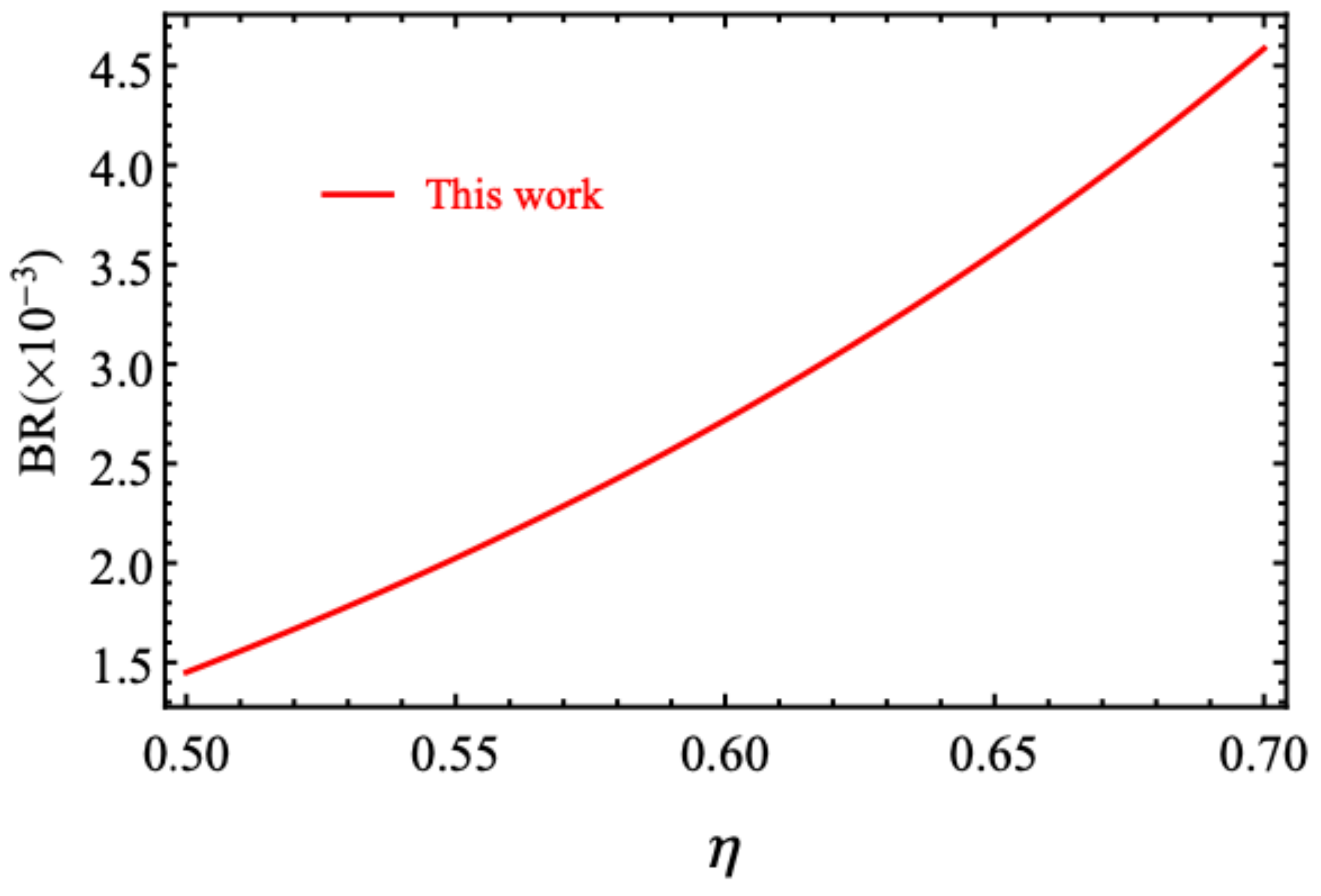
- The decay asymmetries and CPV are insensitive to η, whose dependences are mostly cancelled by the ratios

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

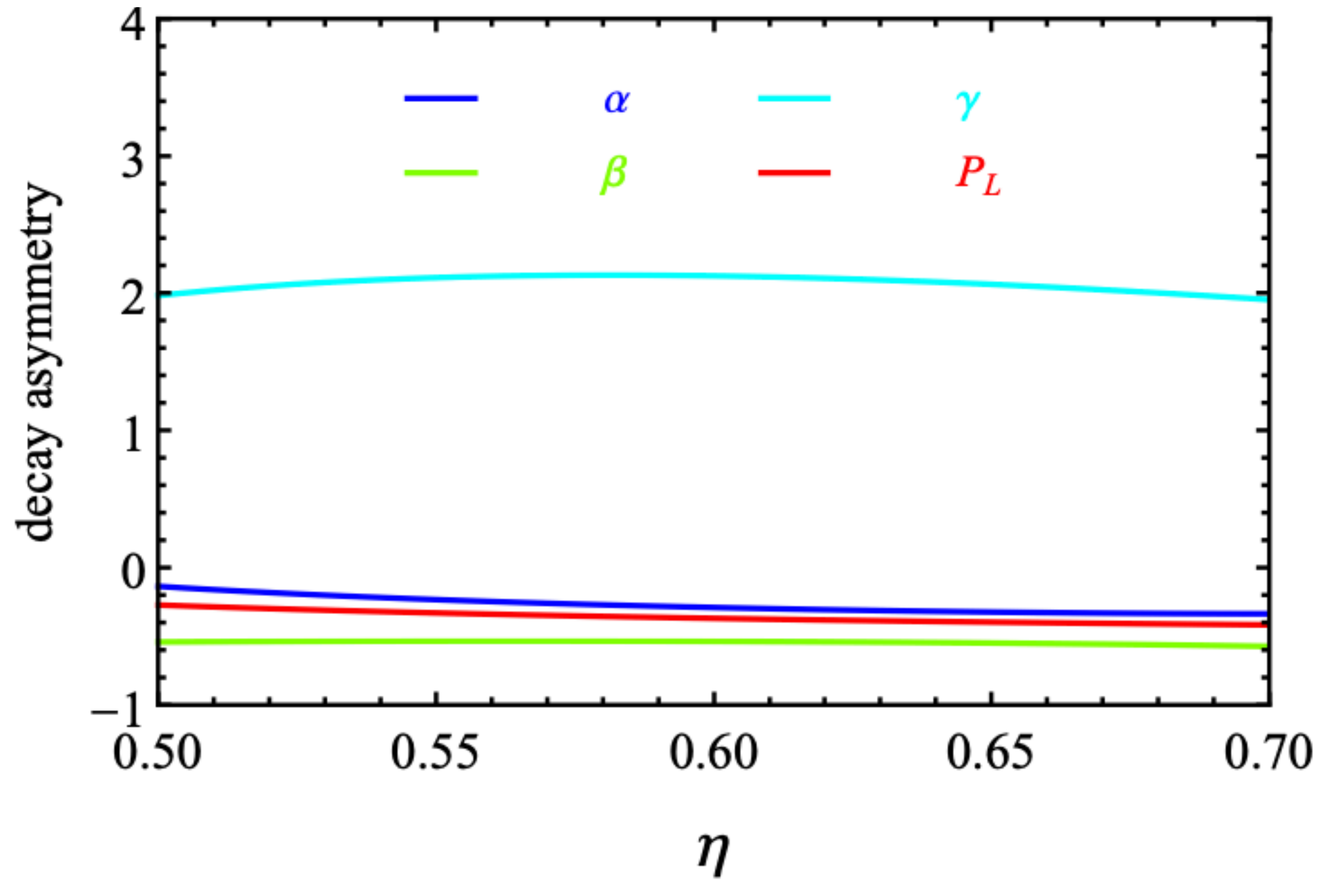
$$\alpha = \frac{\left|H_{1,\frac{1}{2}}\right|^2 - \left|H_{-1,-\frac{1}{2}}\right|^2}{\left|H_{1,\frac{1}{2}}\right|^2 + \left|H_{-1,-\frac{1}{2}}\right|^2}$$

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

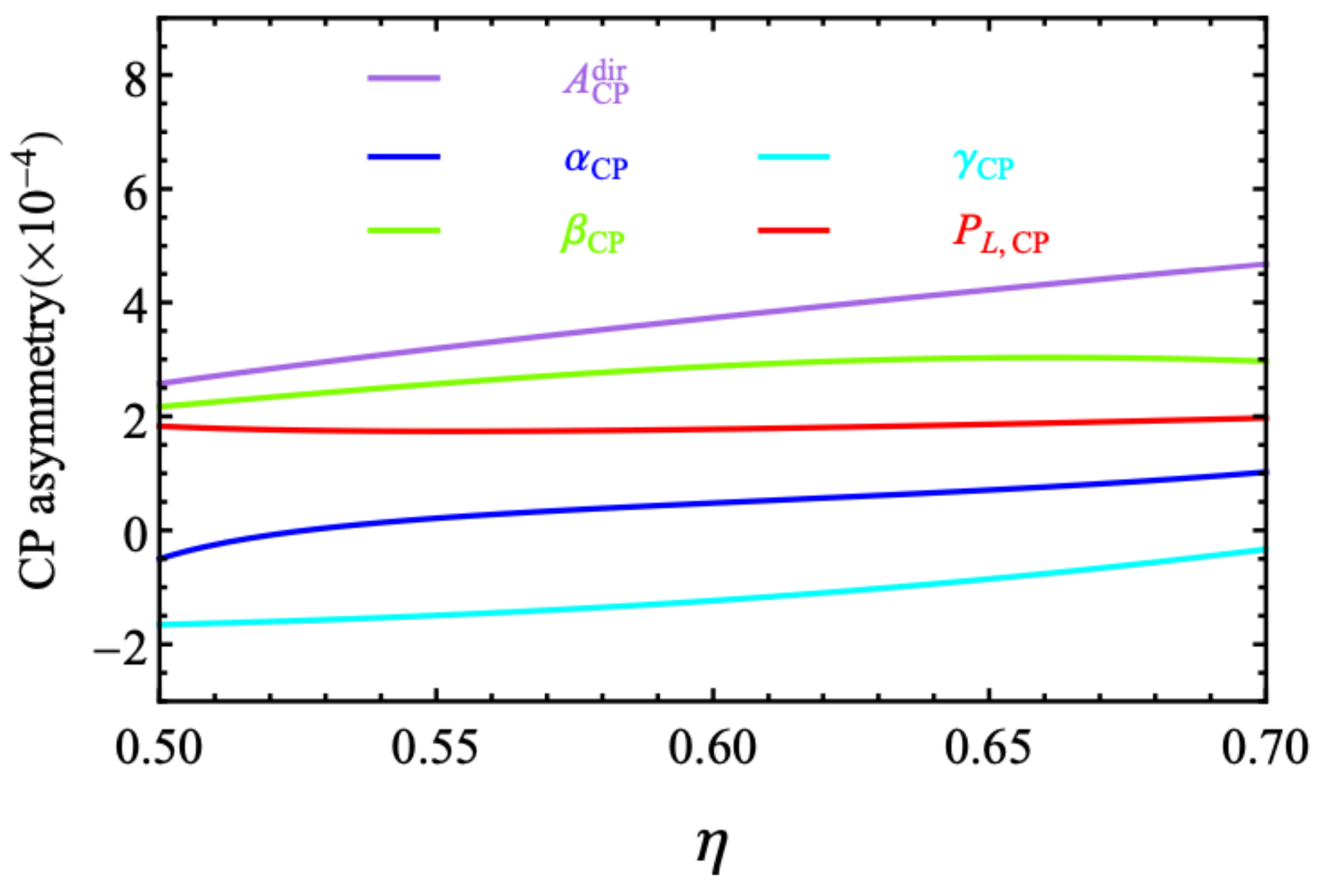
Branching fractions



Decay asymmetries



CPV



CP violation

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

TABLE V: The CP asymmetries($\times 10^{-4}$) of $\Lambda_c^+\to\mathcal{B}_8 V$ processes with $\eta=0.6\pm0.1$

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

C.P.Jia, H.Y.Jiang, J.P.Wang, FSY, 2408.14959

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Multi-body decays

- Current most precise measurement of CPV of charmed baryon decays:

$$A_{CP}(\Lambda_c \to pK^+K^-) - A_{CP}(\Lambda_c \to p\pi^+\pi^-) = (3.0 \pm 9.1 \pm 6.1) \times 10^{-3}$$ LHCb, '18

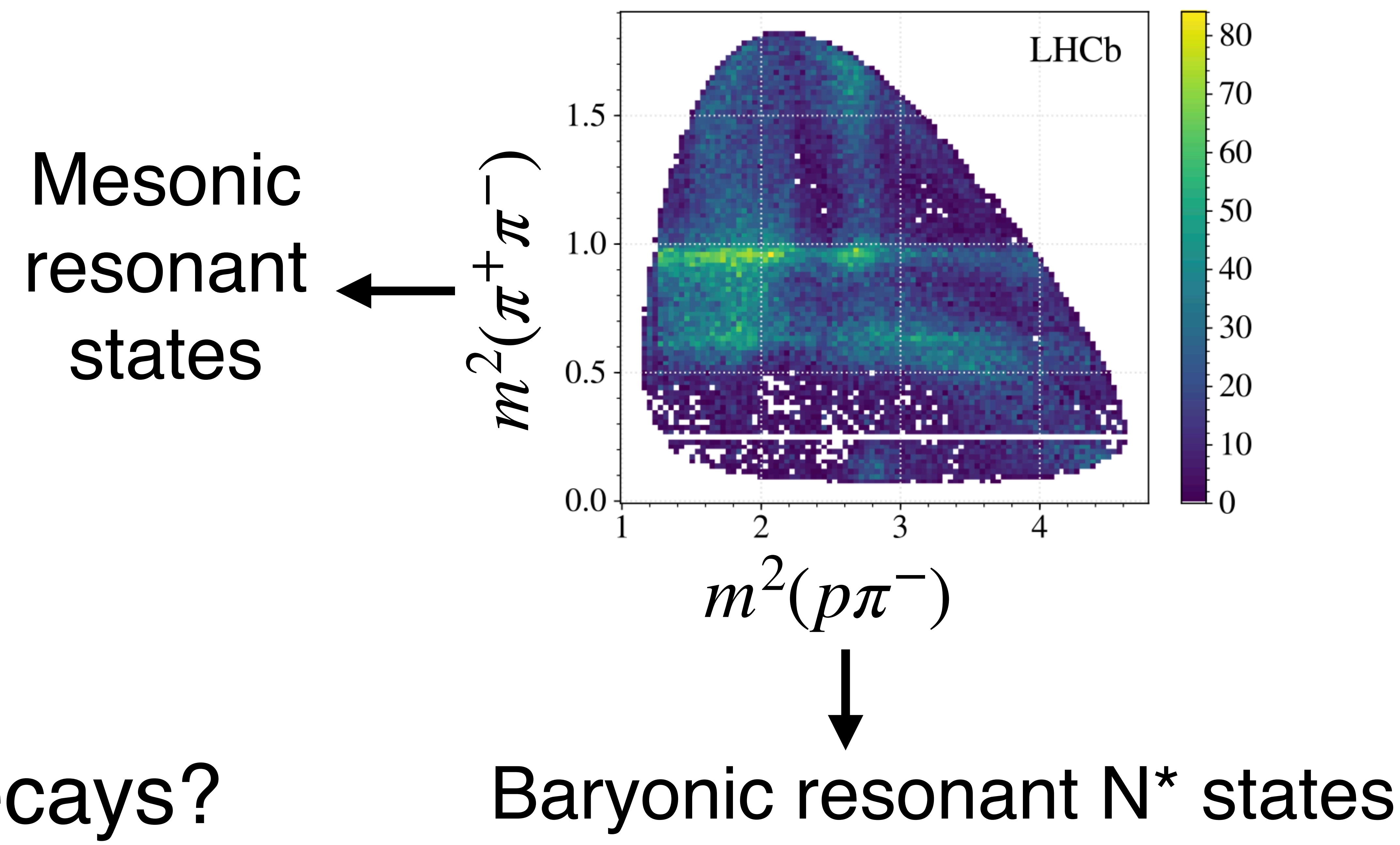
$\Xi_c^+ \to pK^-\pi^+$: no CPV LHCb, '20

- The above three-body decays have large data samples at LHCb

- First observation of baryonic CPV is four-body decays, $\Lambda_b^0 \to pK^-\pi^+\pi^-$

LHCb, 2503.16954

$\Lambda_c^+ \to p\pi^+\pi^-$



- How can we predict CPV of multi-body decays?

Multi-body decays of $\Lambda_{b,c}$

- Advantage: more resonances, more chances for large CPV
- Disadvantage: Too many resonances, and with large uncertainties

$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	****
$N(1720)$	$3/2^+$	****

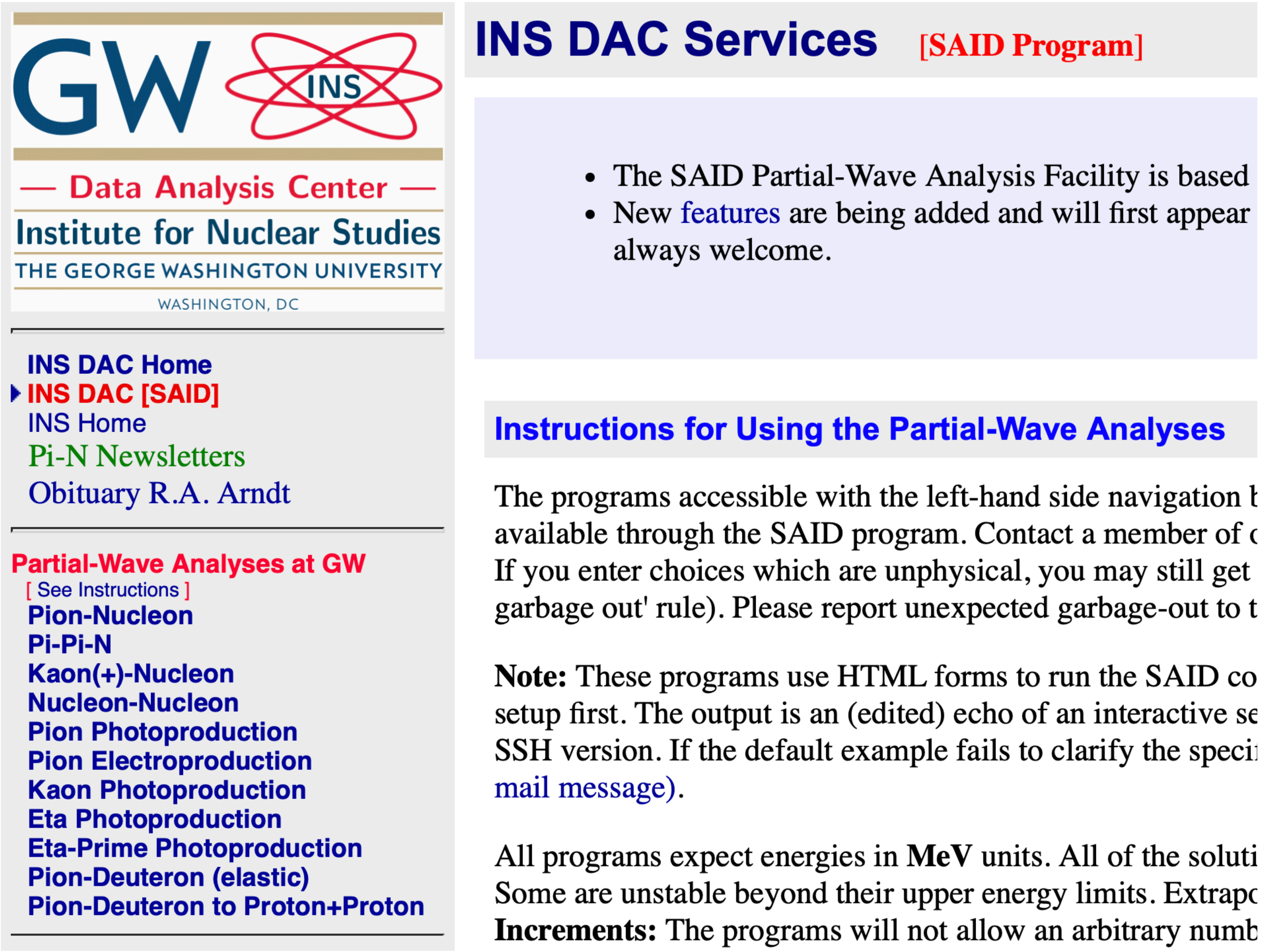
$N(1700)$ BREIT-WIGNER MASS	1650 to 1800 ($\approx$ 1720) MeV
$N(1700)$ BREIT-WIGNER WIDTH	100 to 300 ($\approx$ 200) MeV
$N(1710)$ BREIT-WIGNER MASS	1680 to 1740 ($\approx$ 1710) MeV
$N(1710)$ BREIT-WIGNER WIDTH	80 to 200 ($\approx$ 140) MeV
$N(1720)$ BREIT-WIGNER MASS	1680 to 1750 ($\approx$ 1720) MeV
$N(1720)$ BREIT-WIGNER WIDTH	150 to 400 ($\approx$ 250) MeV

- Close to each other, with large decay widths. No clear dominant one.

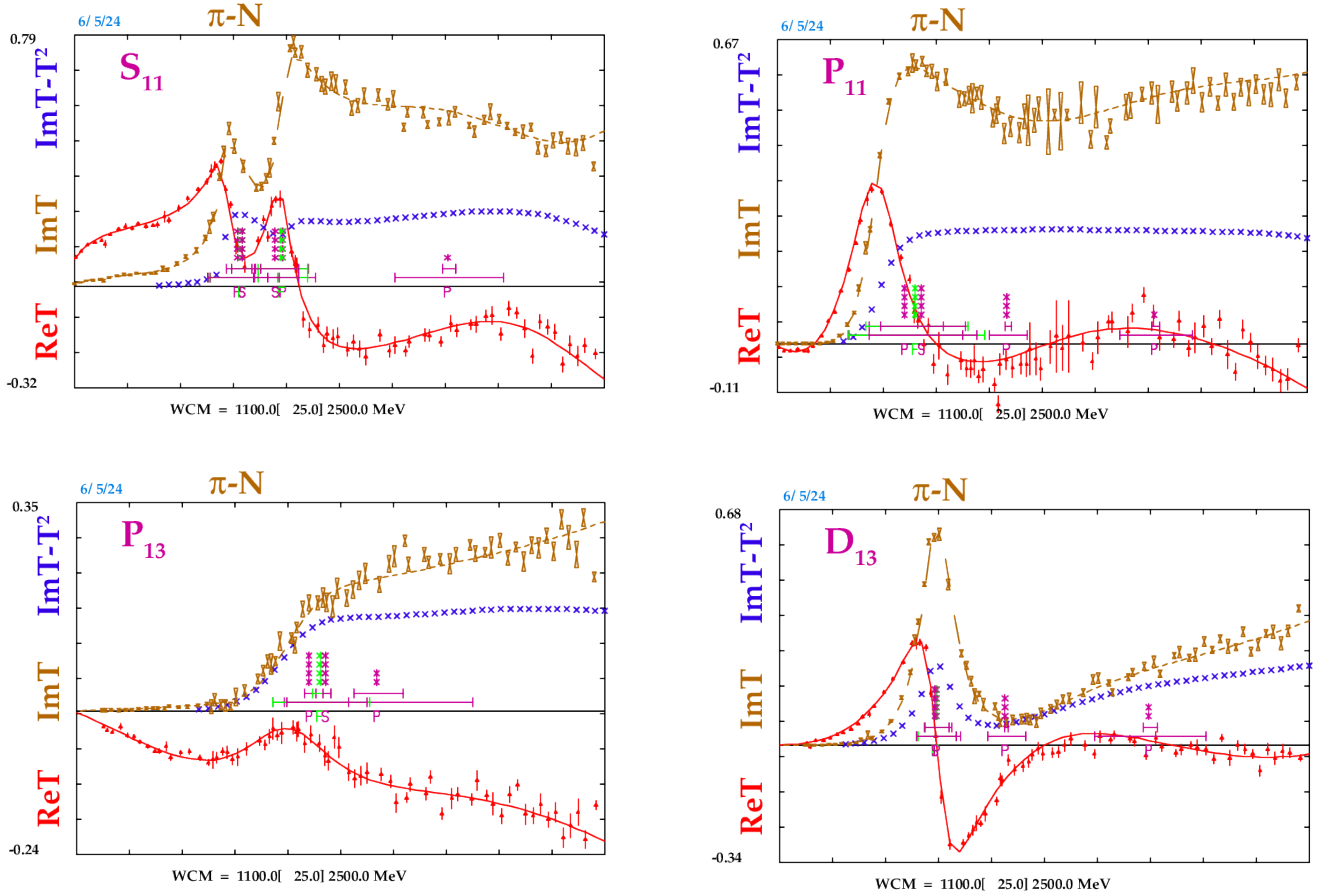
$N\pi$ scatterings

- N^* usually from $N\pi$ scatterings
- Data from SAID program

https://gwdac.phys.gwu.edu/



$N\pi \to N\pi$



- Partial-wave amplitudes with strong phases!

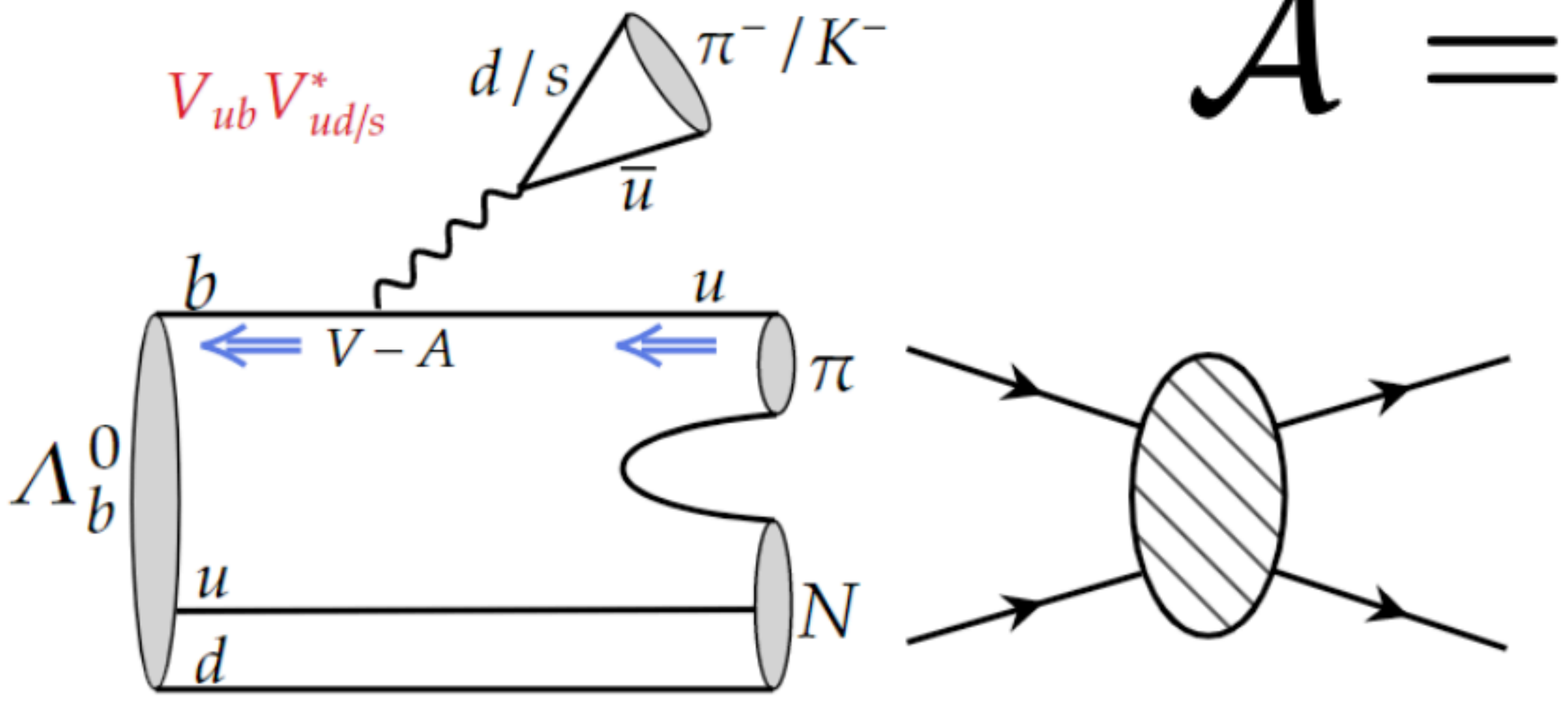
- Data driven, **model independent**. Circumvent N*, more precise strong phases.

Fu-Sheng Yu

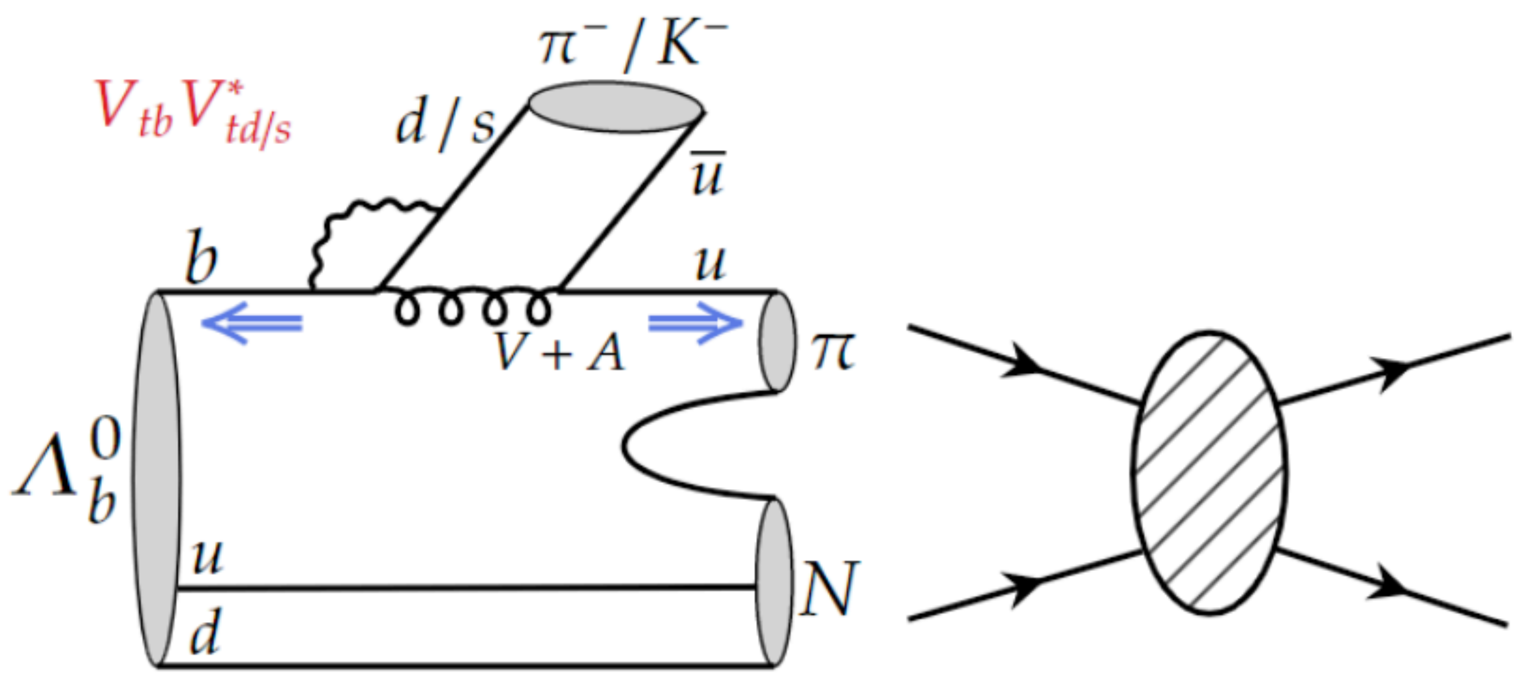
CPV via $N\pi$ rescatterings

$$\mathcal{A} = \mathcal{S}^{1/2}\mathcal{A}_0$$

• Tree:



• Penguin:



• Short-distance weak decays

• weak phases

• Long-distance $N\pi \to N\pi,\ N\pi\pi$

• strong phases

- Different chirality

➡ different helicity

➡ different partial waves

➡ PWA interference

➡ difference of strong phases

➡ **CPV**

J.P.Wang, **FSY**, 2407.04110

CPV with $N\pi$ scatterings

$N\pi \to \Delta^{++}\pi^-$

$m_{N\pi} \in [1.2, 1.9]\text{GeV}$

decay processes	Scenarios	global CPV	CPV of $\cos\theta < 0$	CPV of $\cos\theta > 0$
$\Lambda_b^0 \to (\Delta^{++}\pi^-)K^- \to (p\pi^+\pi^-)K^-$	S1	5.9%	8.0%	3.6%
	S2	5.8%	6.3%	5.3%
	S3	5.6%	4.3%	7.0%
$\Lambda_b^0 \to (\Delta^{++}\pi^-)\pi^-$	S1	−4.1%	−5.4%	−2.4%
	S2	−3.9%	−3.9%	−3.9%
	S3	−3.6%	−2.3%	−5.3%
$\Lambda_b^0 \to (p\pi^0)K^-$	S1	5.8%	8.2%	2.7%
	S2	5.8%	8.0%	3.0%
	S3	5.8%	7.8%	3.3%
$\Lambda_b^0 \to (p\pi^0)\pi^-$	S1	−3.9%	−3.9%	−3.7%
	S2	−3.9%	−3.8%	−4.3%
	S3	−3.8%	−3.6%	−4.8%

S1: $f_1 = 1.1,\ g_1 = 0.9$, S2: $f_1 = g_1 = 1.0$, and S3: $f_1 = 0.9,\ g_1 = 1.1$

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CPV with $N\pi$ scatterings

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$N\pi \to \Delta^{++}\pi^-$

$m_{N\pi} \in [1.2, 1.9]$GeV

decay processes	Scenarios	global CPV	CPV of $\cos\theta < 0$	CPV of $\cos\theta > 0$
	S1	5.9%	8.0%	3.6%
$\Lambda_b^0 \to (\Delta^{++}\pi^-)K^-$	S2	5.8%	6.3%	5.3%
$\to (p\pi^+\pi^-)K^-$	S3	5.6%	4.3%	7.0%

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•LHCb:

$\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$	6.0σ

March, 2025

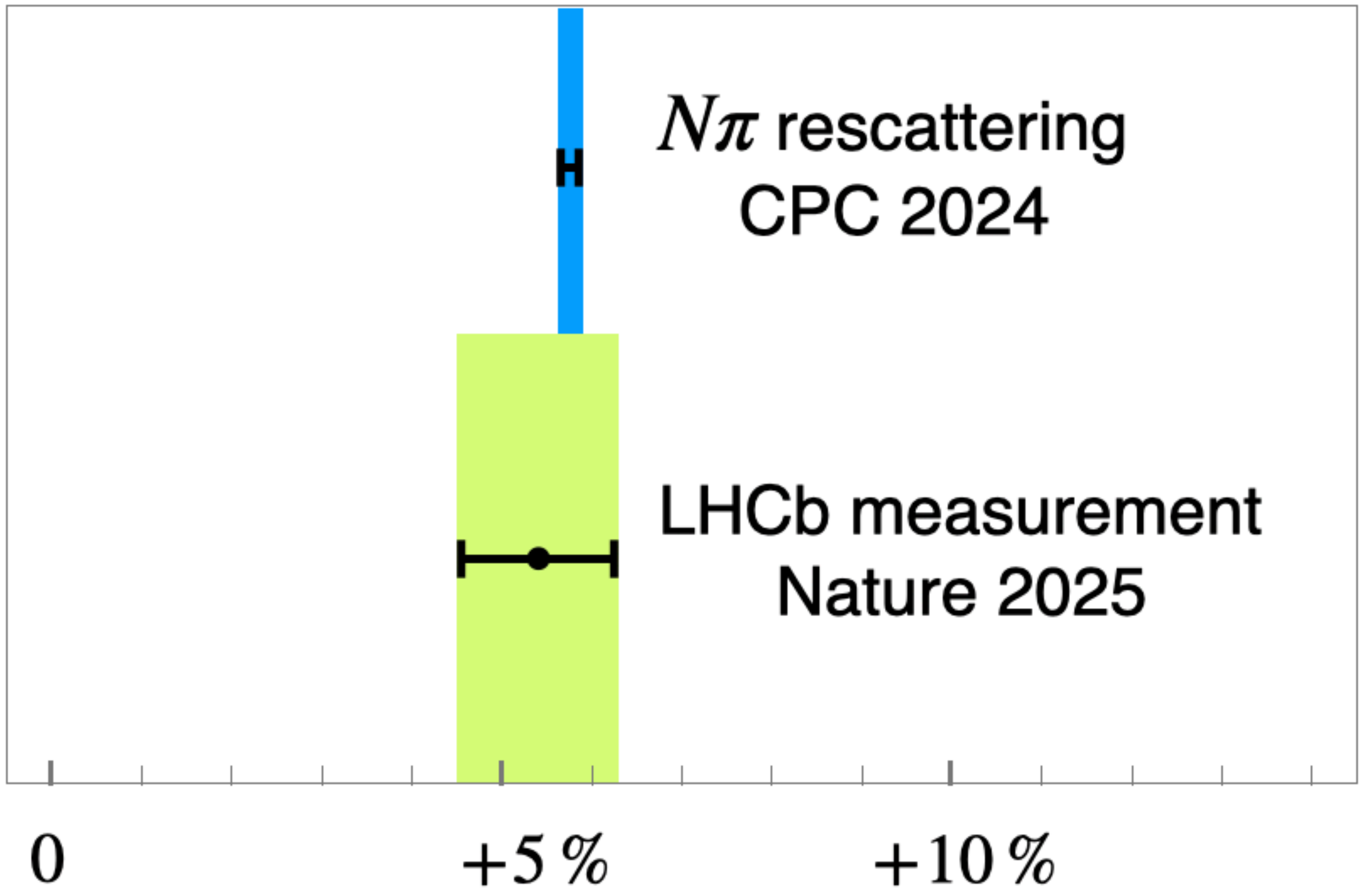
2503.16954

a model-independent investigation of angular distributions [36] or utilising scattering data to extract the hadronic amplitude [28]. Applying this method using $\pi^+ n \to p\pi^+\pi^-$ scattering data [37], an estimate of the *CP* asymmetry in $\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$ decays aligns with the measurement in this work.

[28] J.-P. Wang and F.-S. Yu, *CP violation of baryon decays with $N\pi$ rescatterings*, Chin. Phys. **C48** (2024) 101002, arXiv:2407.04110.

CPV with $N\pi$ scatterings

$$A_{CP}(\Lambda_b^0 \to R(p\pi^+\pi^-)K^-)$$



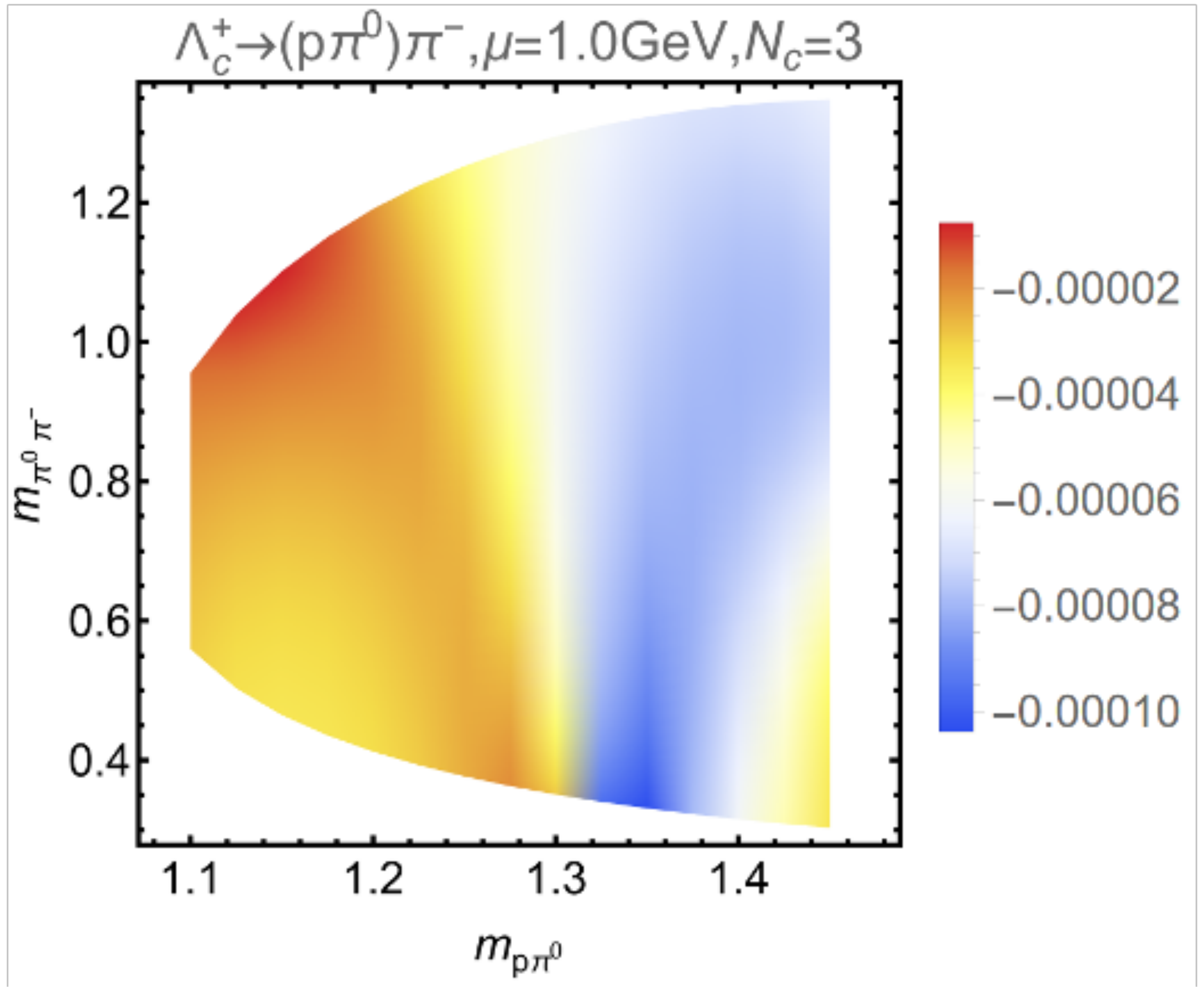
CPV of charm-baryon decays with $N\pi$ rescatterings

$\Lambda_c^+ \to (p\pi^-)\pi^+$ with $N\pi \to p\pi^-$

$A_{CP} \sim 1 \times 10^{-4}$

Cancellation of CPV between γ^μ and $\gamma^\mu\gamma_5$

$a_4 + Ra_6$ v.s. $a_4 - Ra_6$



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.
- New CPV mechanism via $N\pi$ rescatterings works well for prediction on the first observation of baryonic CPV in $\Lambda_b^0 \to (p\pi^+\pi^-)K^-$. It can be applied to CPV of charmed baryon decays.

Thank you very much!