CP Violation

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1. Introduction on CP Violation

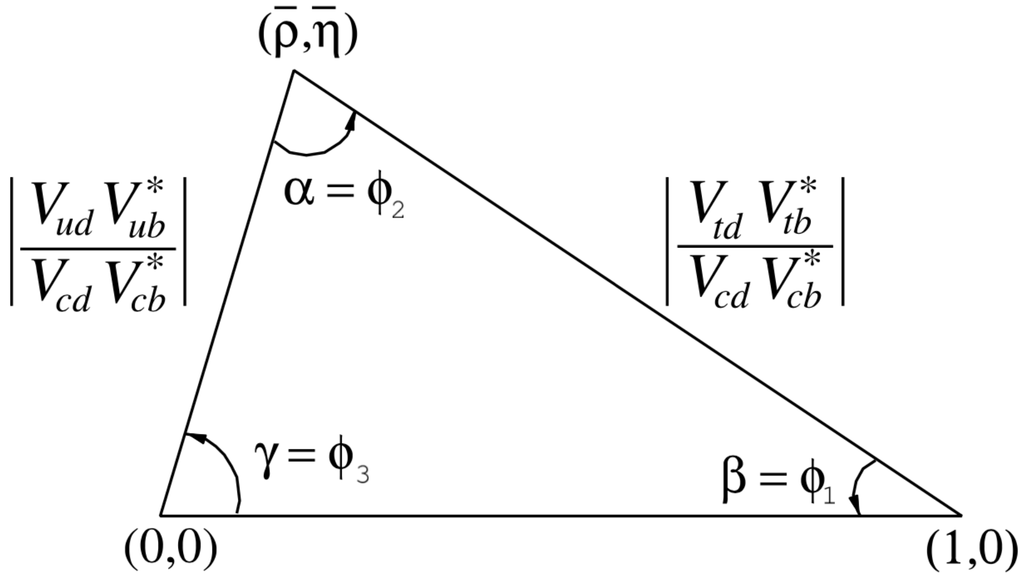
2. Bottom-baryon CPV

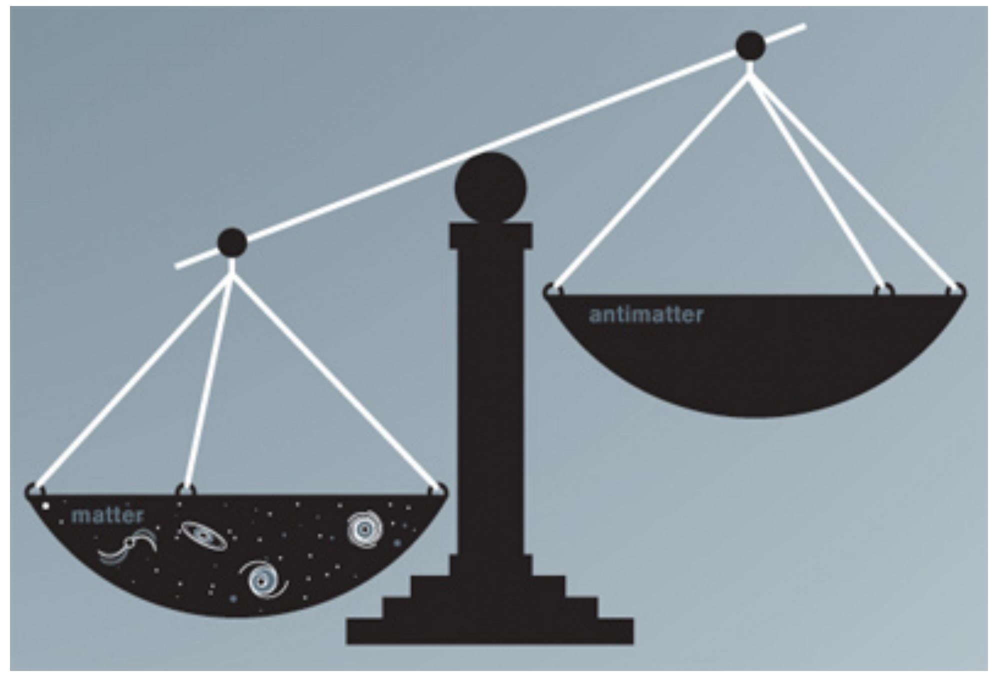
3. Charm-baryon CPV

4. CPV observables

CPV is a crown jewel

- Particle physics: study symmetries and symmetry breakings.
- Parity violation and Charge-Parity violation (CPV) are very important in the construction of the SM.
- The **only one phase** in the 18 SM parameters. Testing the CKM triangle unitarity.
- C and CP violation are required for the **matter-antimatter asymmetry in the Universe**, but the **SM CPV is much smaller** than required. There must exist new source of CPV.
- CPV is the key problem of flavor physics.





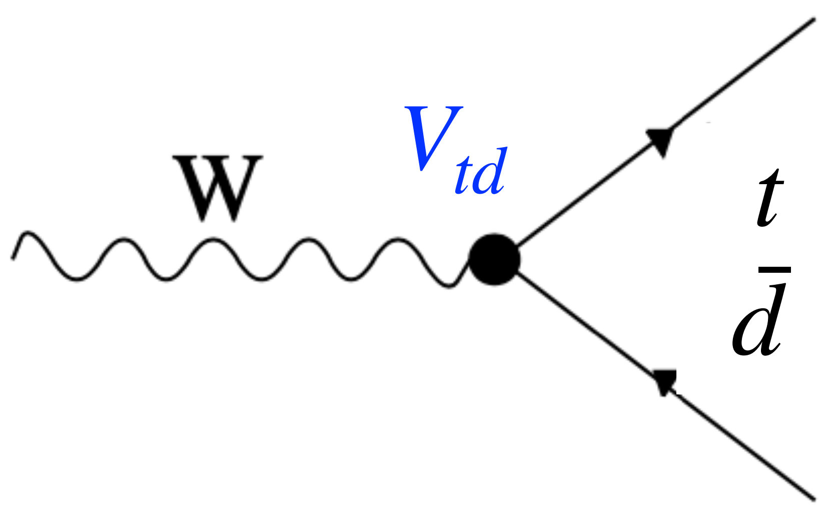
History of CP Violation

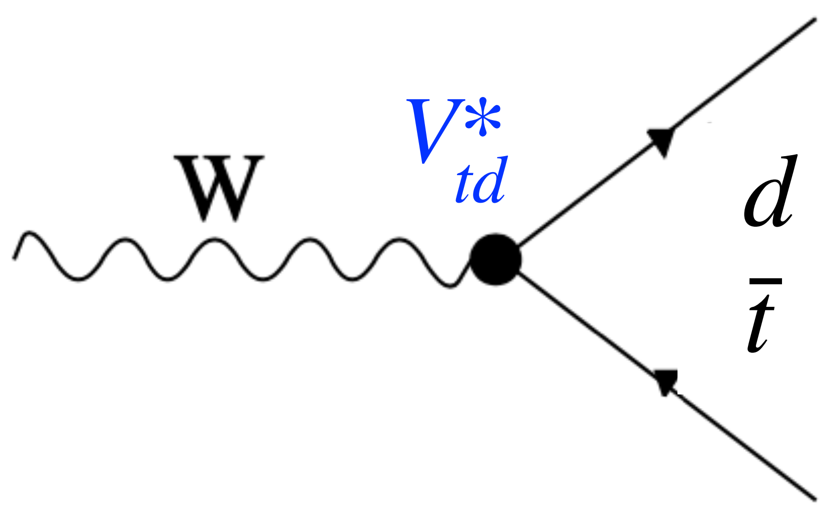
CPV from the Kobayashi-Maskawa mechanism

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$V_{\mathrm{CKM}} \neq V^*_{\mathrm{CKM}}$

$$\mathscr{L}^{cc}_{\mathrm{weak}} = -\frac{g_2}{\sqrt{2}} V_{ij}\, \bar{u}_i \gamma^\mu (1-\gamma_5) d_j W^+_\mu - \frac{g_2}{\sqrt{2}} V^*_{ij}\, \bar{d}_j \gamma^\mu (1-\gamma_5) u_i W^-_\mu$$





$$\bar{A}(\bar{i} \to \bar{f}) \neq A(i \to f)$$

CPV in measurements

Definition: $$A_{CP} = \frac{\Gamma(i \to f) - \Gamma(\bar{i} \to \bar{f})}{\Gamma(i \to f) + \Gamma(\bar{i} \to \bar{f})} = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}$$

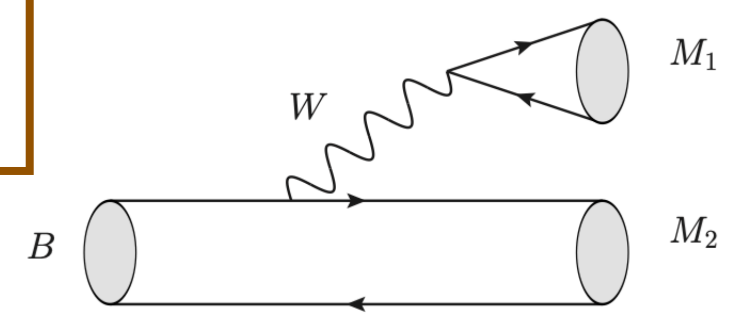
$$V_{\rm CKM} \leftrightarrow V^*_{\rm CKM}$$

$$A_f = |a_1|e^{i(\delta_1+\phi_1)} + |a_2|e^{i(\delta_2+\phi_2)}$$
$$\overline{A}_{\overline{f}} = |a_1|e^{i(\delta_1-\phi_1)} + |a_2|e^{i(\delta_2-\phi_2)}$$

$\phi_{1,2}$: weak phases, flip signs under $A_f \leftrightarrow \overline{A}_{\bar{f}}$

$\delta_{1,2}$: strong phases, keep signs under $A_f \leftrightarrow \overline{A}_{\bar{f}}$

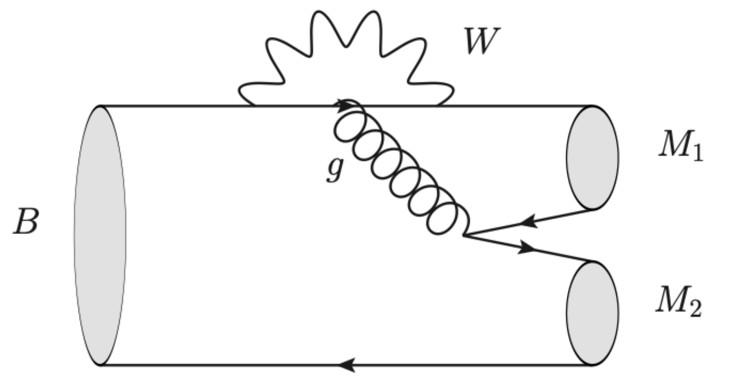
$$\boxed{A_{CP} = -\frac{2|a_1a_2|\sin(\delta_2-\delta_1)\sin(\phi_2-\phi_1)}{|a_1|^2+|a_2|^2+2|a_1a_2|\cos(\delta_2-\delta_1)\cos(\phi_2-\phi_1)}}$$



(a) T

CPV conditions: 1. At least two amplitudes
2. with different weak phases
3. with different strong phases

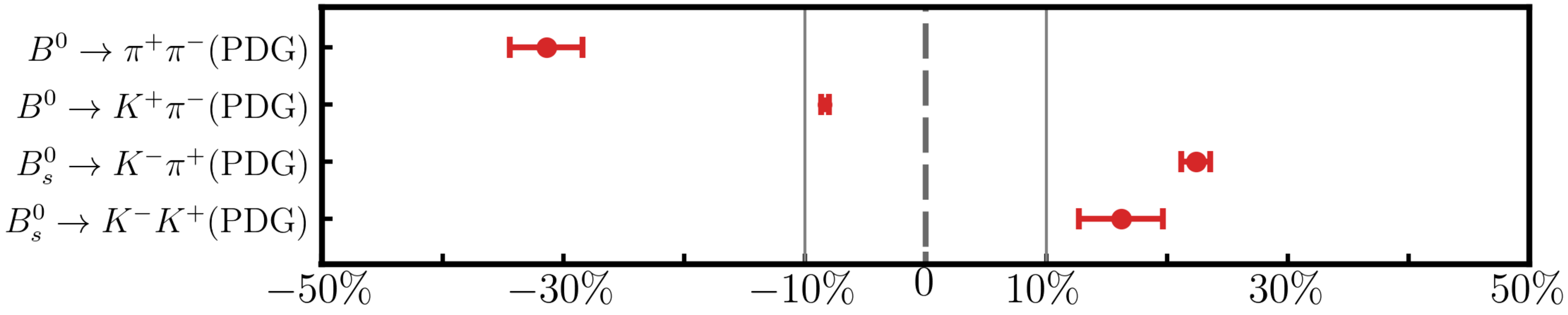
Tree + Penguin



(c) $P,\ P^C_{\rm EW}$

2000s: B-meson CPV

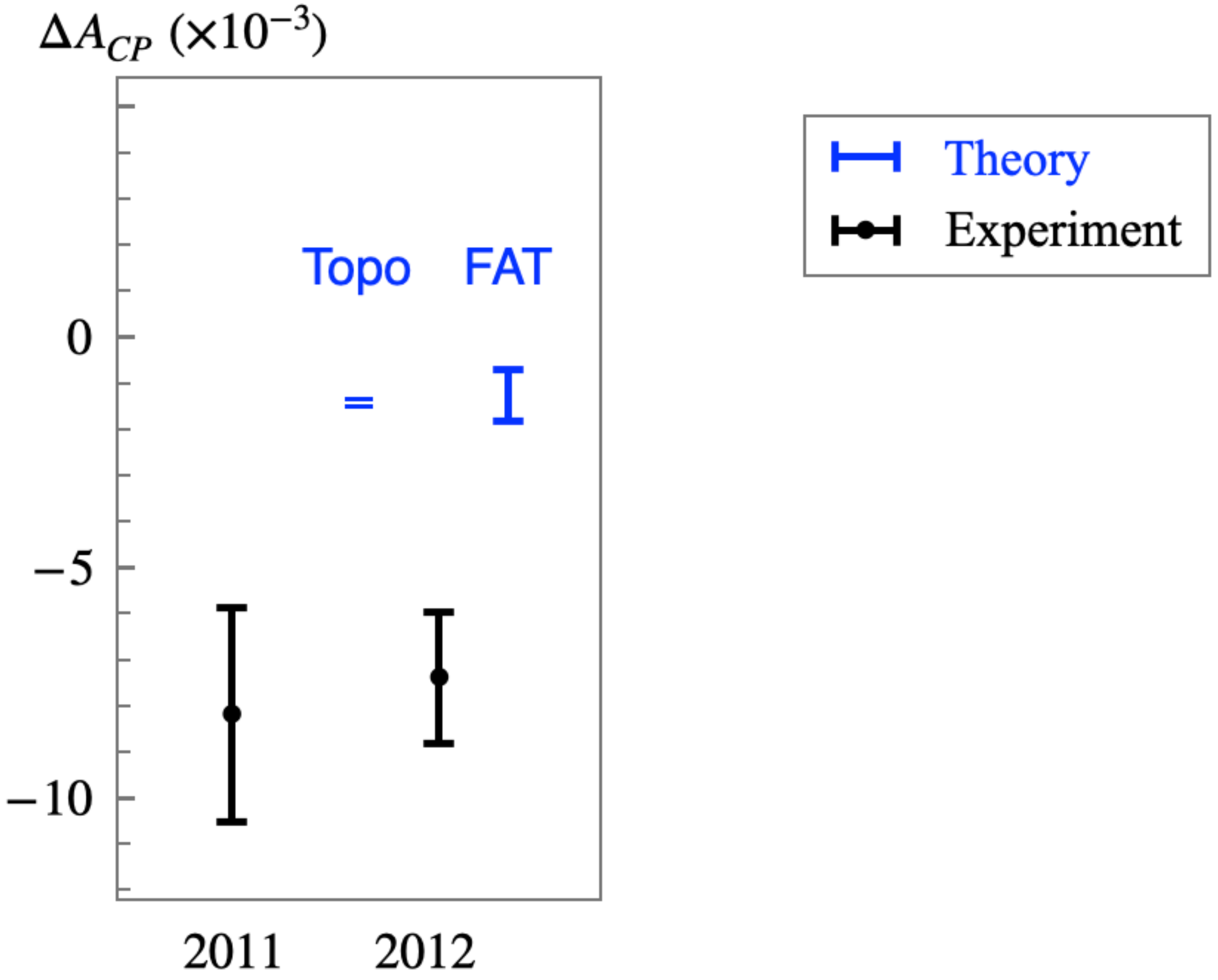
- B-meson CPV : Order of 10%



直接CP破坏(%)	GFA	QCDF	2000 PQCD	2004 exp.
$B \to \pi^+\pi^-$	-5 ± 3	-6 ± 12	$+30 \pm 20$	$+32 \pm 4$
$B \to K^+\pi^-$	$+10 \pm 3$	$+5 \pm 9$	-17 ± 5	-8.3 ± 0.4

- PQCD successfully predicted CPV in B meson decays

2010s: Charm CPV



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

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

Topo: topological approach + QCDF

H.Y.Cheng, C.W.Chiang, 2012

FAT: factorization-assisted topology (FAT)

H.n.Li, C.D.Lu, **F.S.Yu**, 2012

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

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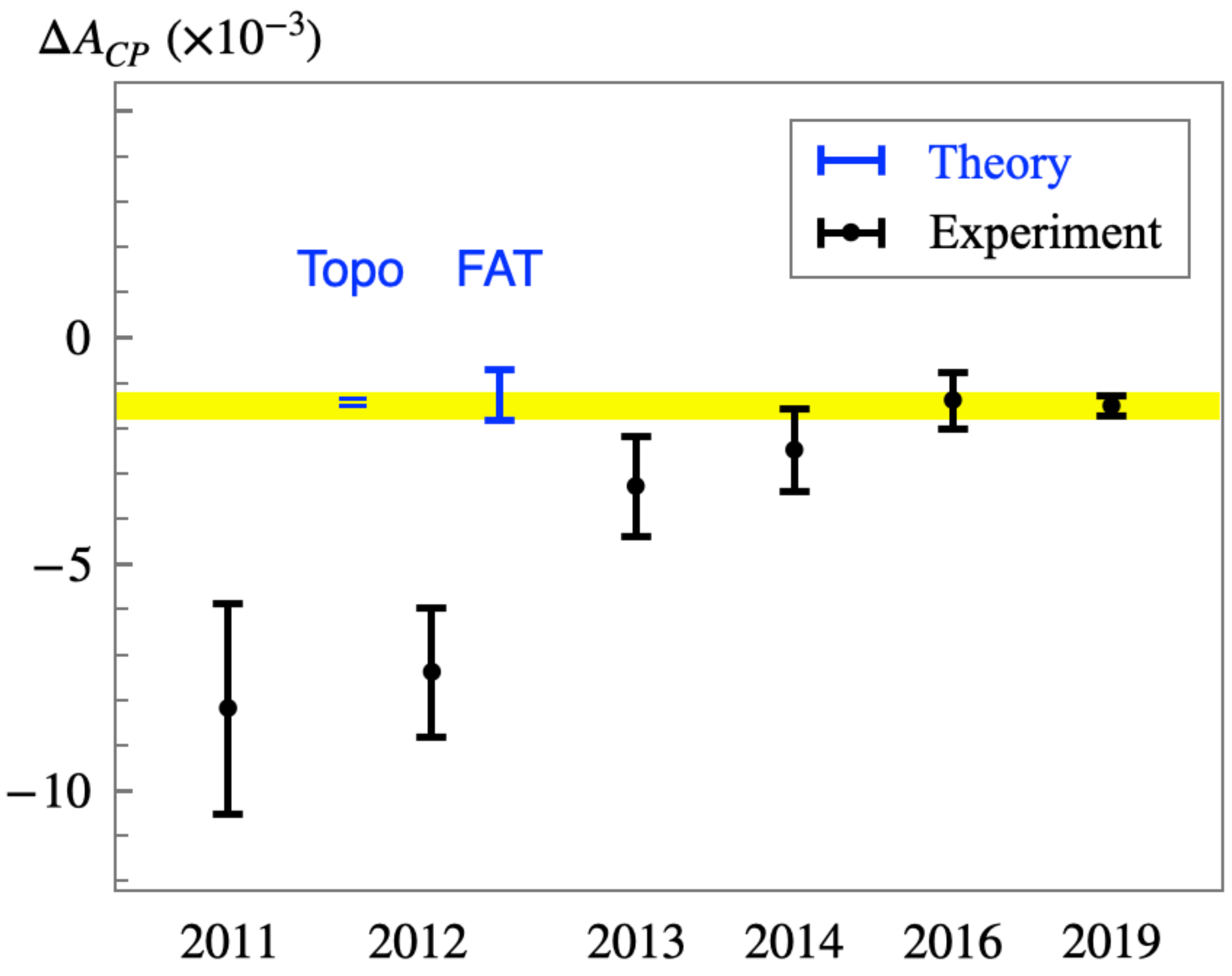

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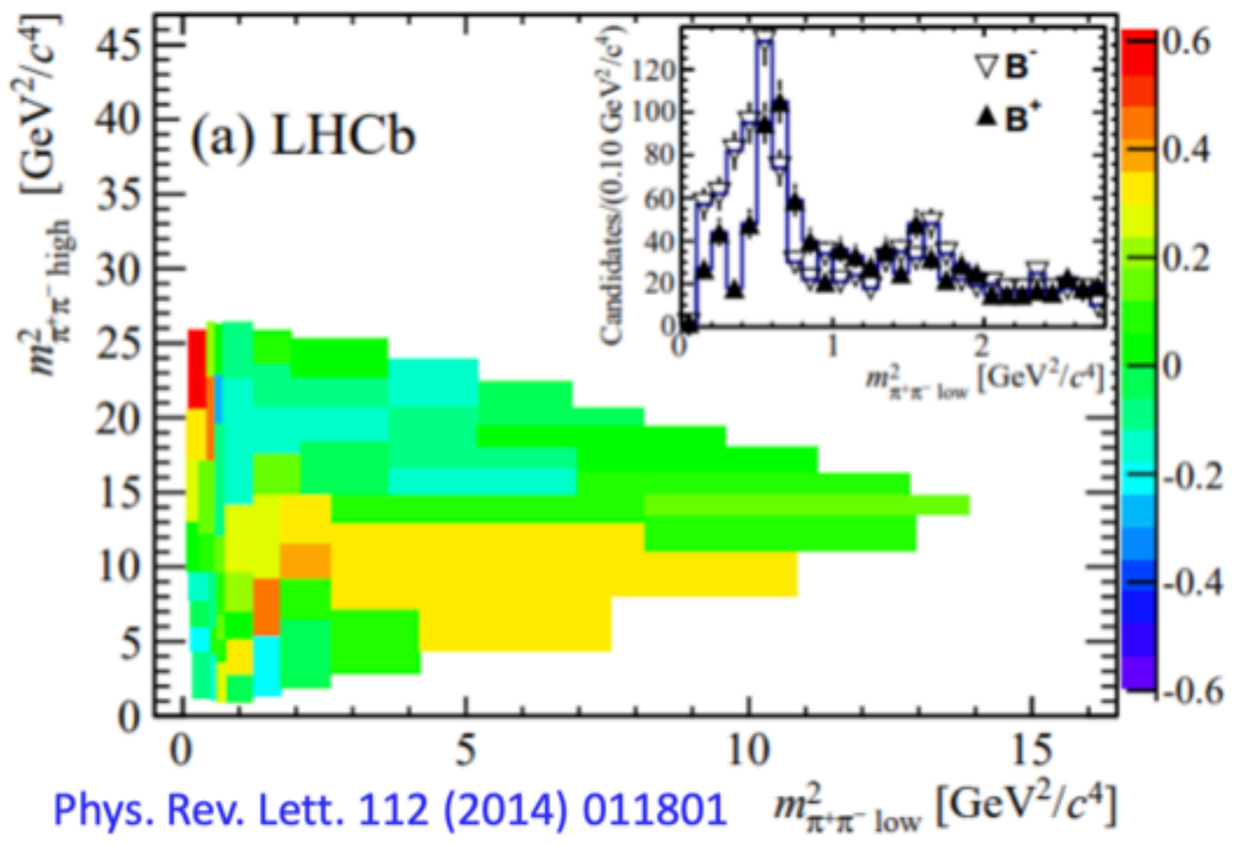
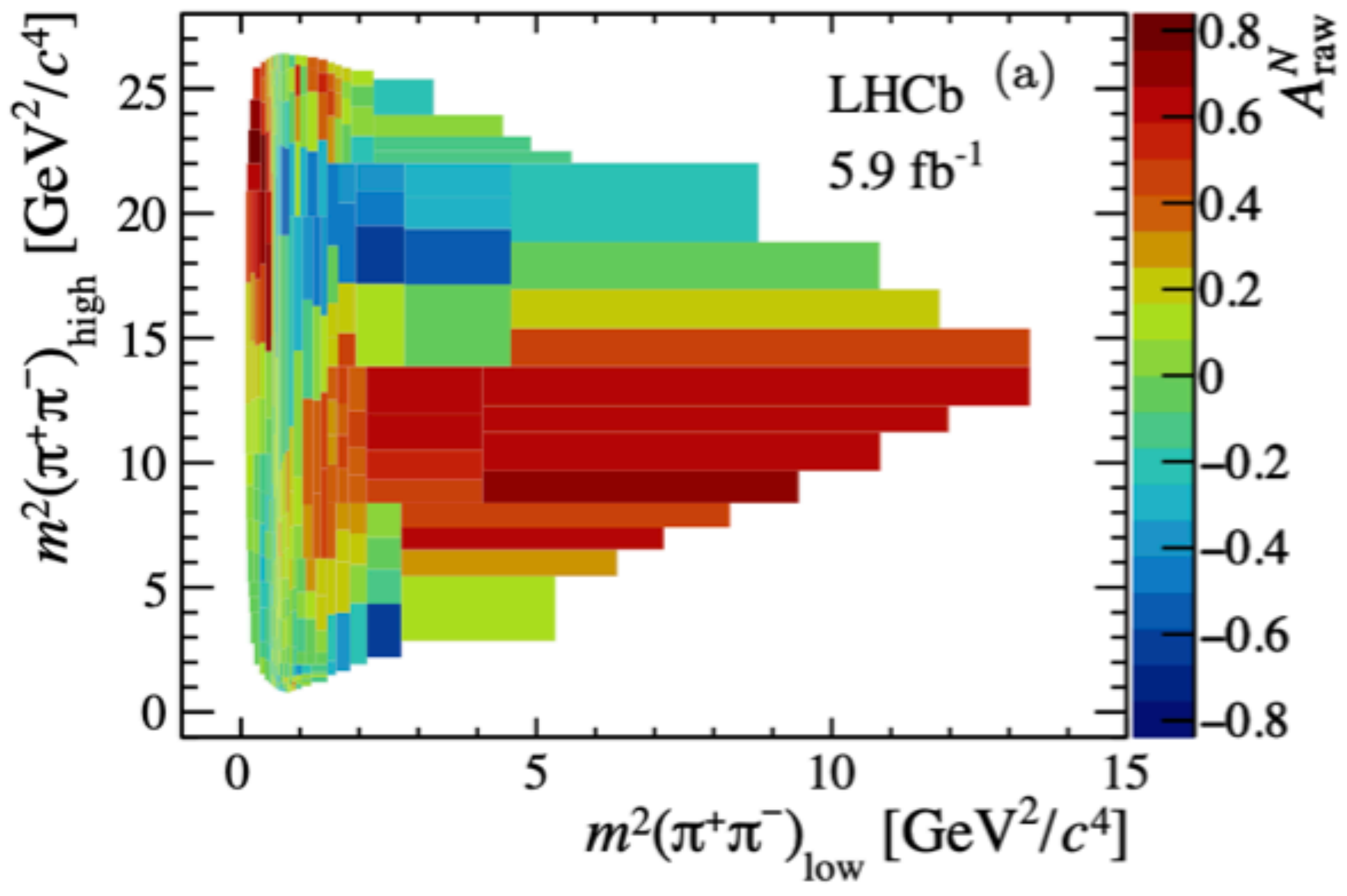
Exp: LHCb, PRL122, 211803 (2019)

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

2010s: CPV of 3-body B decays





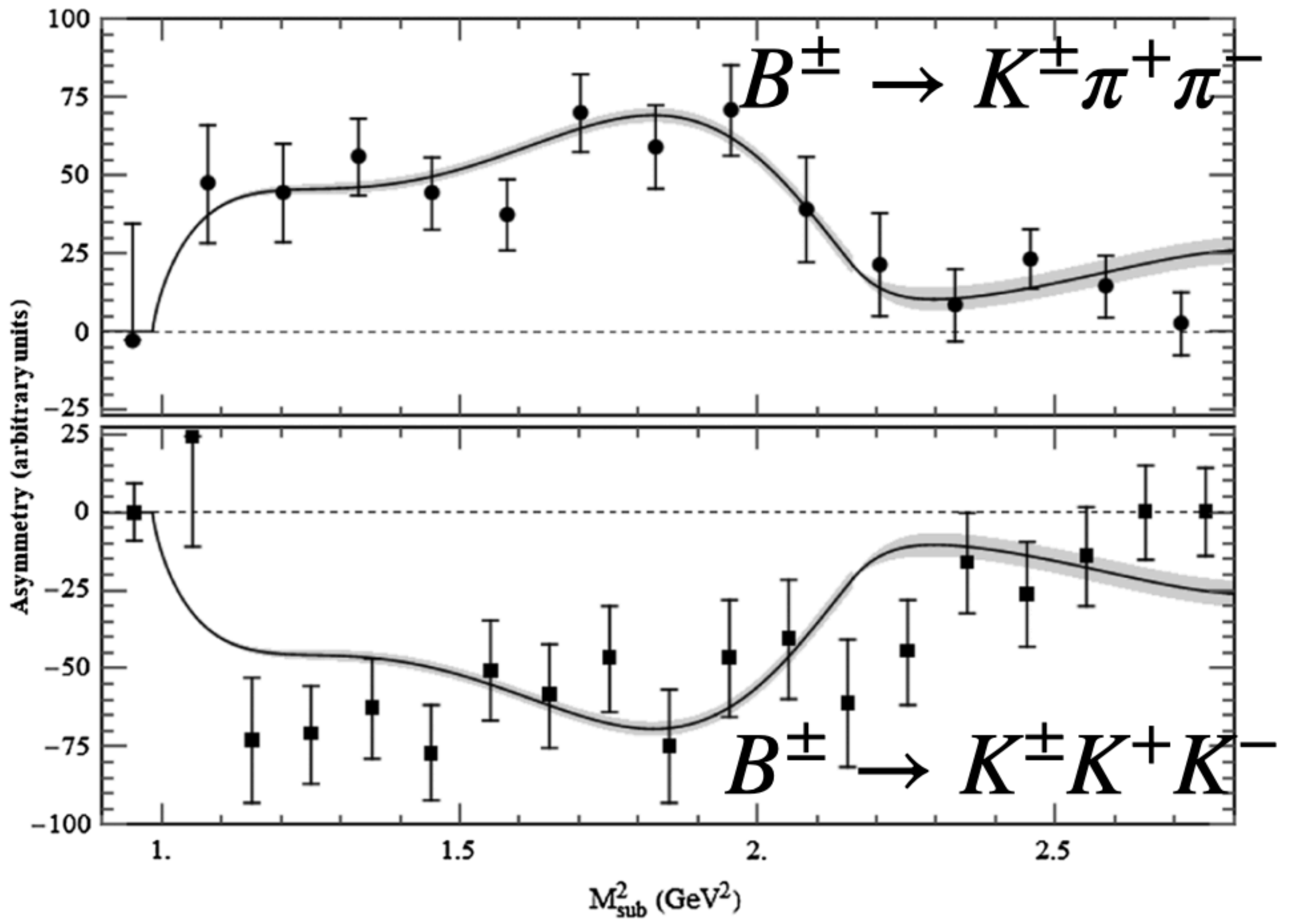
- 三类CPV来源

1. 同一共振过程，传统直接CPV：$B^- \to f_2(1270)\pi^-$， Acp~40%
2. 不同共振态之间的干涉（同一末态）：$\rho^0 + f_0(500)$的干涉，Acp~(50-60)%
3. 不同末态之间的干涉：$\pi\pi \leftrightarrow K\bar{K}$散射，单个振幅最大的CPV：$-66\,\%$

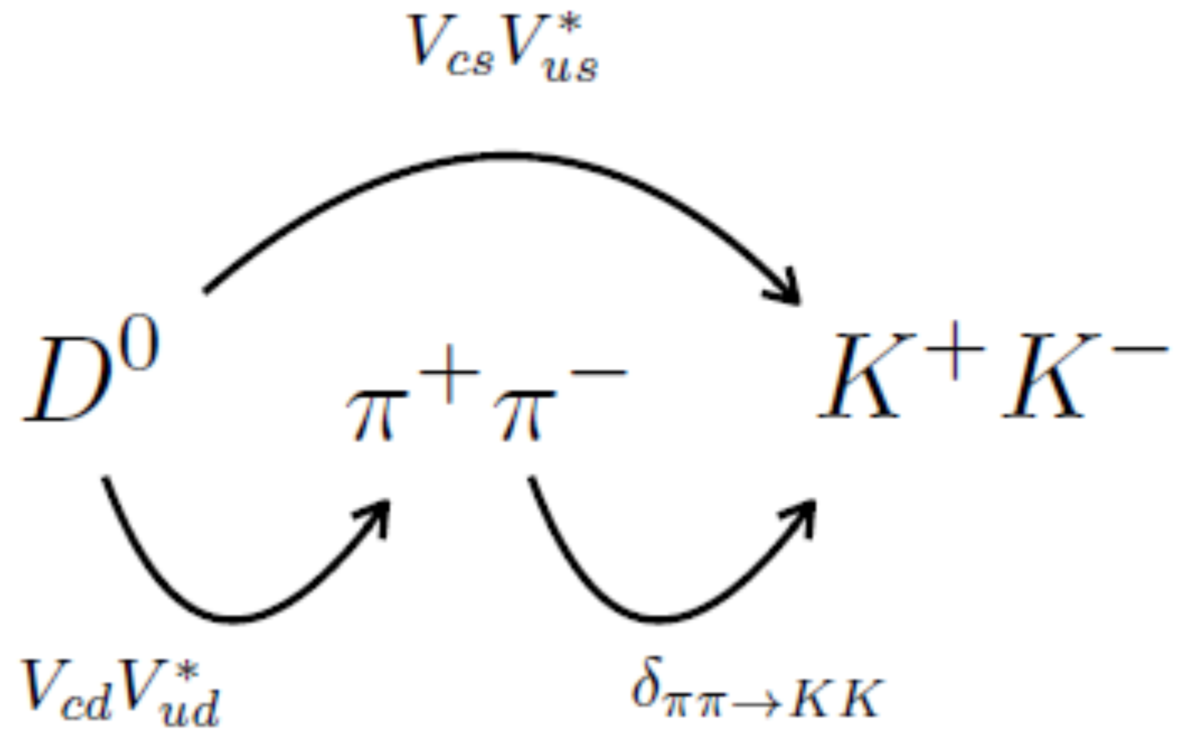
Final-state rescatterings

- Rescattering mechanism for CPV in $B^- \to (\pi^+\pi^-)K^-$, $(K^+K^-)K^-$. Model-independent analysis of $\pi\pi \to K\bar{K}$ data [Bediaga, Frederico, Lourenco, 2013; H.Y.Cheng, C.K.Chua, 2020; Álvarez Garrote, Cuervo, Magalhães, Peláez, PRL2023]

$$\begin{pmatrix} A(B^- \to \pi^+\pi^- P^-) \\ A(B^- \to K^+K^- P^-) \end{pmatrix}^{\text{FSI}}_{\text{S-wave}} = S^{1/2} \begin{pmatrix} A(B^- \to \pi^+\pi^- P^-) \\ A(B^- \to K^+K^- P^-) \end{pmatrix}_{\text{S-wave}}$$



- Rescattering mechanism for charm CPV. Model-independent analysis of $\pi\pi \to K\bar{K}$ data [Bediaga, Frederico, Magalhaes, PRL2023; Pich, Solomonidi, Silva, PRD2023].



$$|\Delta A_{CP}^{\text{short-distance}}| < 2 \times 10^{-4} \quad \text{v.s.} \quad \Delta A_{CP}^{\text{FSI}} = -(6.4 \pm 1.8) \times 10^{-4}$$

2020s: Baryonic CPV

- **Hyperon**: BESIII [Nature Physics 2019; Nature 2022]:

$$A^{\alpha}_{CP}(\Lambda^0 \to p\pi^-) = (2.5 \pm 4.8) \times 10^{-3}, \quad (\xi_P - \xi_S)(\Xi^- \to \Lambda^0\pi^-) = (1.2 \pm 3.5) \times 10^{-2} \text{ rad}$$

-SM estimates: $10^{-4} \sim 10^{-5}$ [Donoghue, X.G.He, Pakvasa, 1986]

- **Charmed baryon**: LHCb [JHEP 2018]

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

-SM estimates: $10^{-3} \sim 10^{-4}$ [X.G.He, C.W.Liu, 2024][C.P.Jia, H.Y.Jiang, J.P.Wang, FSY, 2024]

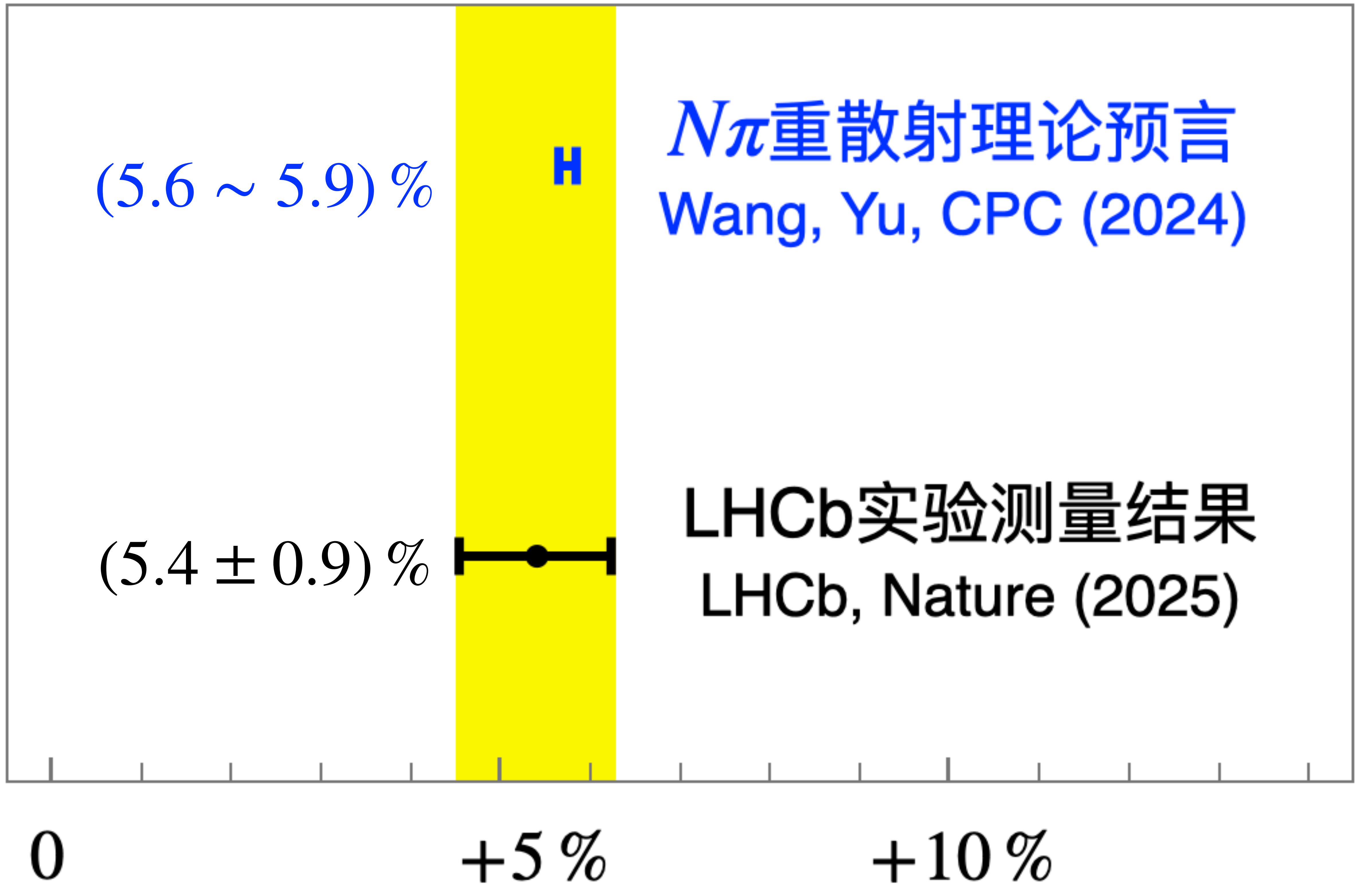
- **Bottom baryon**: LHCb reported first observation of CPV in $\Lambda_b \to pK\pi\pi$ [Nature 2025]

$$A_{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (2.45 \pm 0.46 \pm 0.10)\,\%$$

-SM estimates: $1\,\% \sim 5\,\%$ [J.P.Wang, F.S.Yu, 2024][J.J.Han, et al, 2025]

2020s: Baryonic CPV

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



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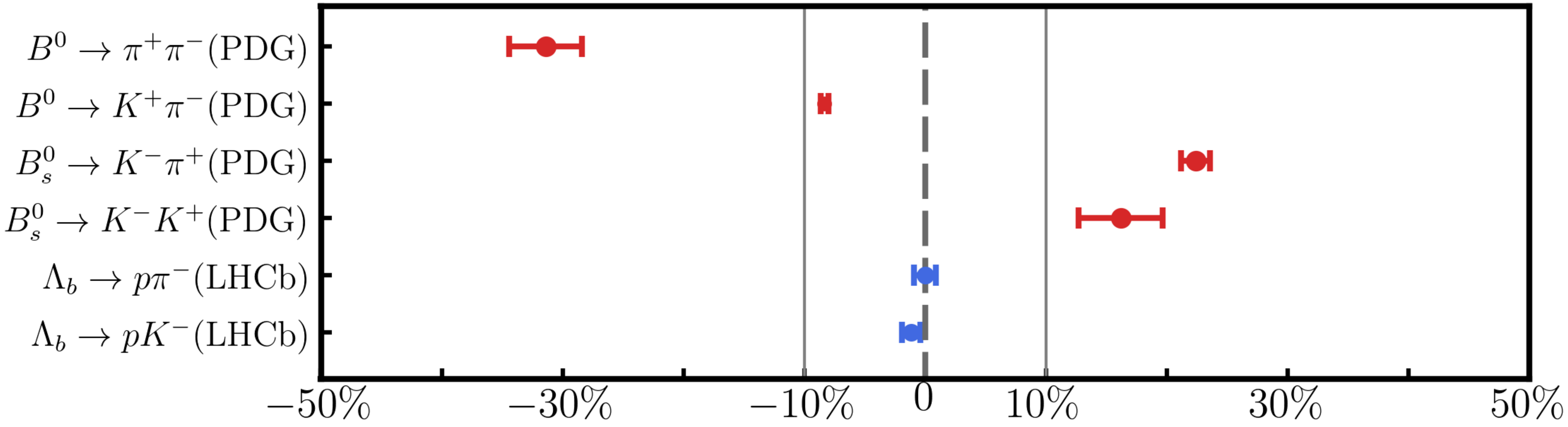
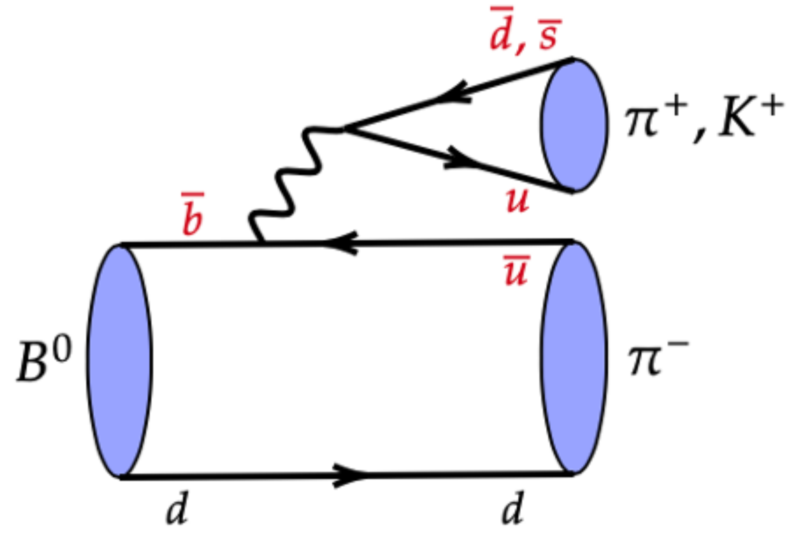
CPV puzzle of b-baryon

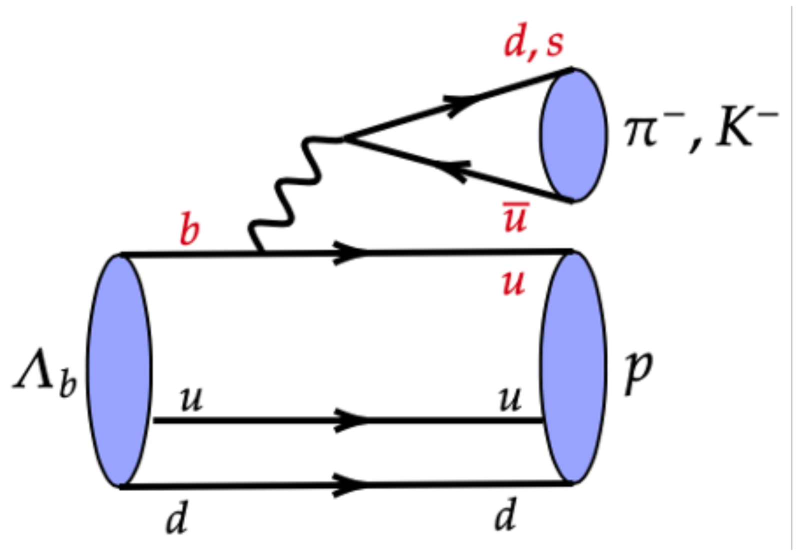
- Precision of b-baryon CPV measurements reaches the order **1%** [LHCb, 2024]

$$A_{CP}(\Lambda_b^0 \to p\pi^-) = (0.2 \pm 0.8 \pm 0.4)\,\%\,, \quad A_{CP}(\Lambda_b^0 \to pK^-) = (-1.1 \pm 0.7 \pm 0.4)\,\%$$

- CPV in some B-meson decays are as large as **10%**:







CPV cancelled between S- and P-waves

$$\mathscr{M} = \bar{u}_p \, (\, S \, + \, P \, \gamma_5 \,) \, u_{\Lambda_b}$$

- **Tree operators:** $(V-A)(V-A)$

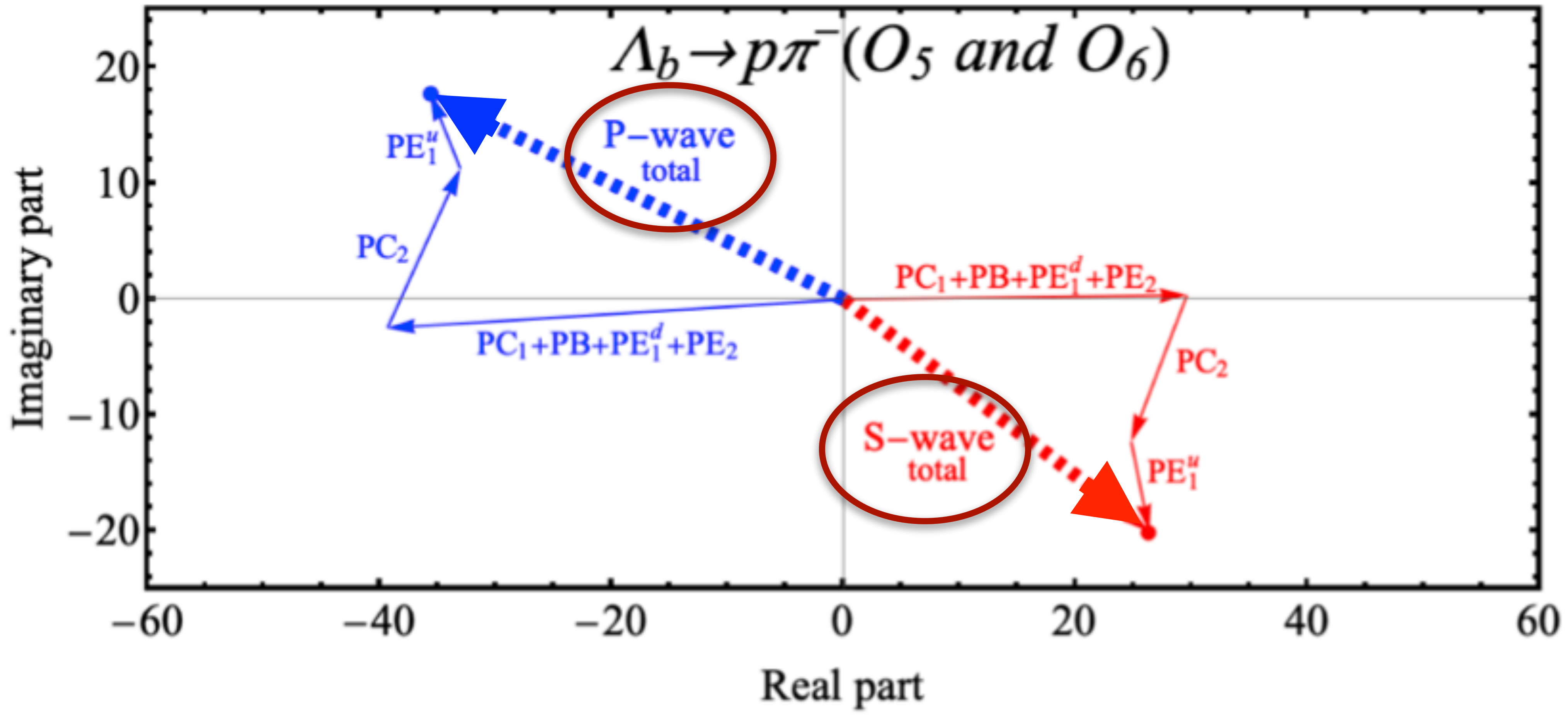
$$\bar{u}\gamma_\mu(1-\gamma_5)b\bar{d}\gamma^\mu(1-\gamma_5)u$$

$$\Rightarrow \bar{u}_p(1+\gamma_5)u_{\Lambda_b} \quad \Rightarrow \quad \boxed{S_T \approx P_T}$$

- **Penguin operators:** $(V-A)(V+A)$

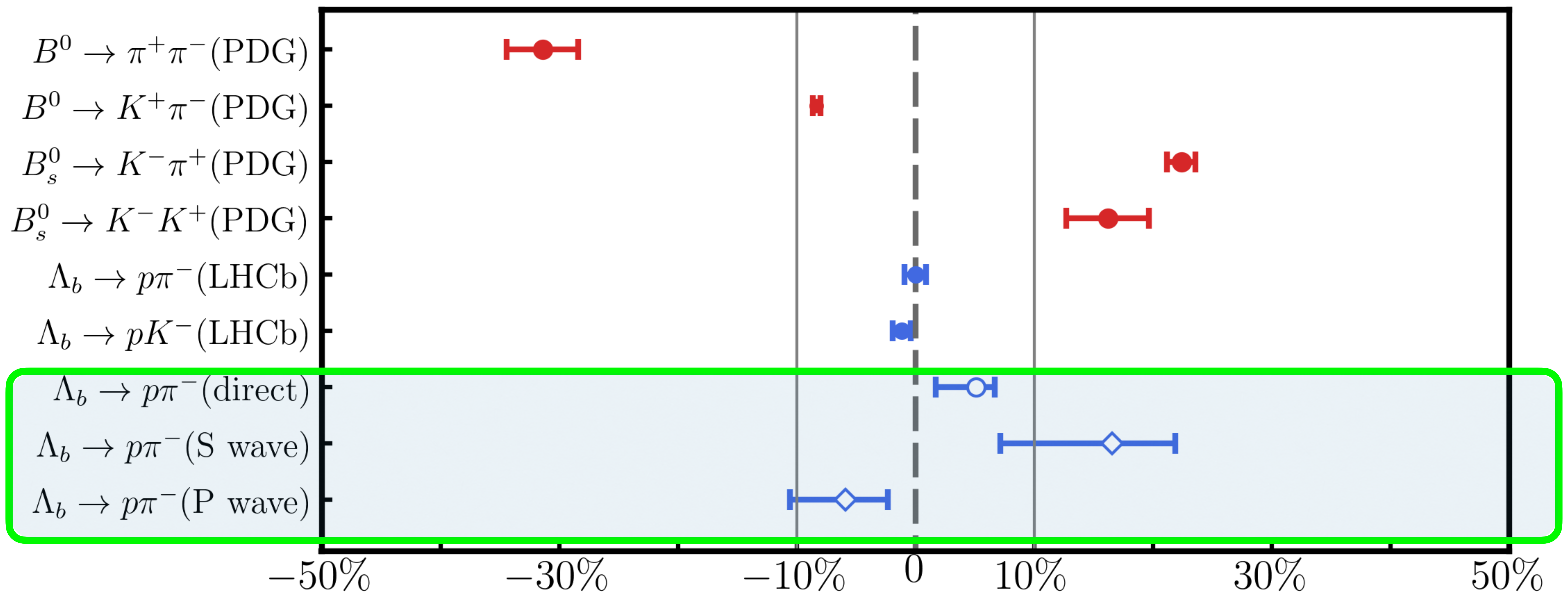
$$\bar{d}\gamma_\mu(1-\gamma_5)b\bar{u}\gamma^\mu(1+\gamma_5)u$$

$$\Rightarrow \bar{u}_p(1-\gamma_5)u_{\Lambda_b} \quad \Rightarrow \quad \boxed{S_{PC_2} \approx -P_{PC_2}}$$



J.J.Han, J.X,Yu, Y.Li, H.n.Li, J.P.Wang, Z.J.Xiao, **FSY**, PRL134,221801(2025)

CPV cancelled between S- and P-waves



J.J.Han, J.X,Yu, Y.Li, H.n.Li, J.P.Wang, Z.J.Xiao, **FSY**, PRL134,221801(2025)

•LHCb:

2503.16954 (Nature)

small CP asymmetries in beauty-baryon decays imply that the dynamics in baryon decays are more complicated than in meson decays. For instance, the CP asymmetries for various angular-momentum amplitudes of the same resonance may cancel[38]. This discovery of

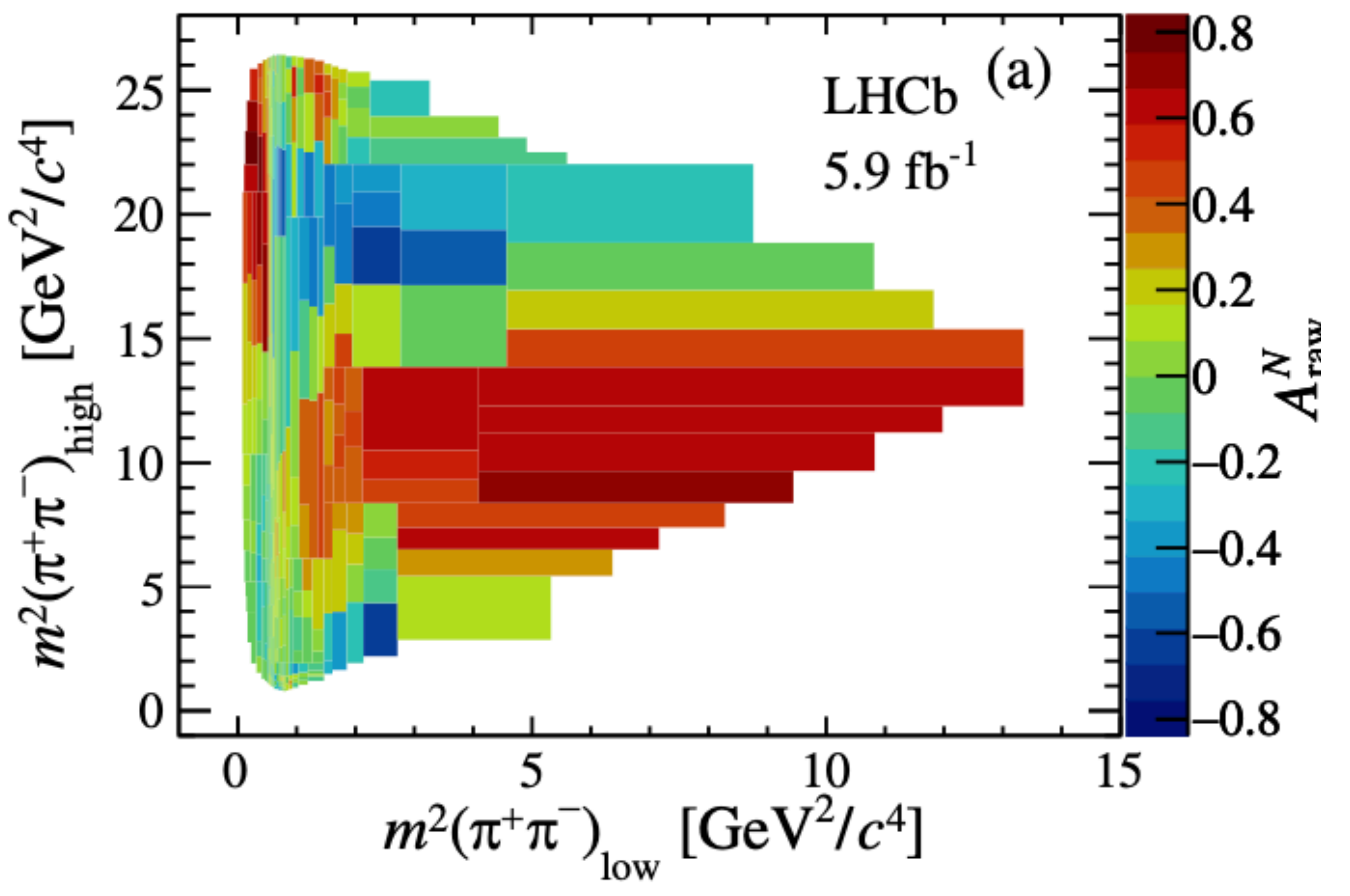
38. Han, J.-J. et al. Establishing CP violation in *b*-baryon decays. *Phys. Rev. Lett.* **134**, 221801 (2025).

Multi-body decays

- For first observation of baryon CPV, it must be multi-body decays of Λ_b.
- More resonances, more partial waves, more chances for large CPV.
- Large CPV in multi-body decays of B mesons.

$$\mathcal{A}_{B^+\to K^+K^-\pi^+} = -0.115 \pm 0.008\,,$$
$$\mathcal{A}_{B^+\to K^+K^-K^+} = -0.0365 \pm 0.0036\,,$$
$$\mathcal{A}_{B^+\to \pi^+\pi^-\pi^+} = 0.076 \pm 0.005\,,$$

$B^+ \to \pi^+\pi^-\pi^+$

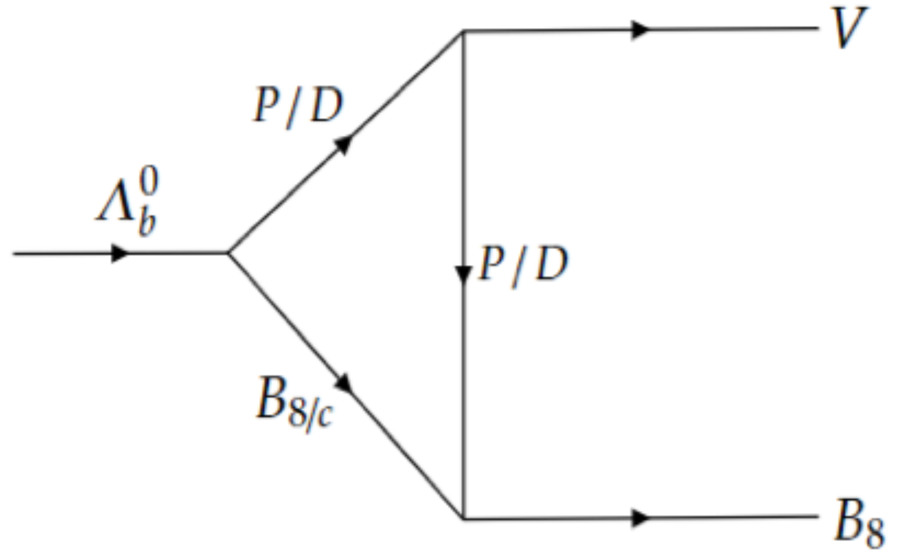


- Large regional CPV: Promising to measure CPV in some regions.
- Large data samples in $\Lambda_b^0 \to ph^-h^+h^-,\, h=\pi, K$

Multi-body decays of Λ_b

- Single resonance: Hadronic triangle diagrams

Z.D.Duan, J.P.Wang, et al, 2024;
Q.Qin, H.Q.Shang, T.L.Feng, et al, 2025



- Multiple resonances: Too many resonances, and with large uncertainties

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

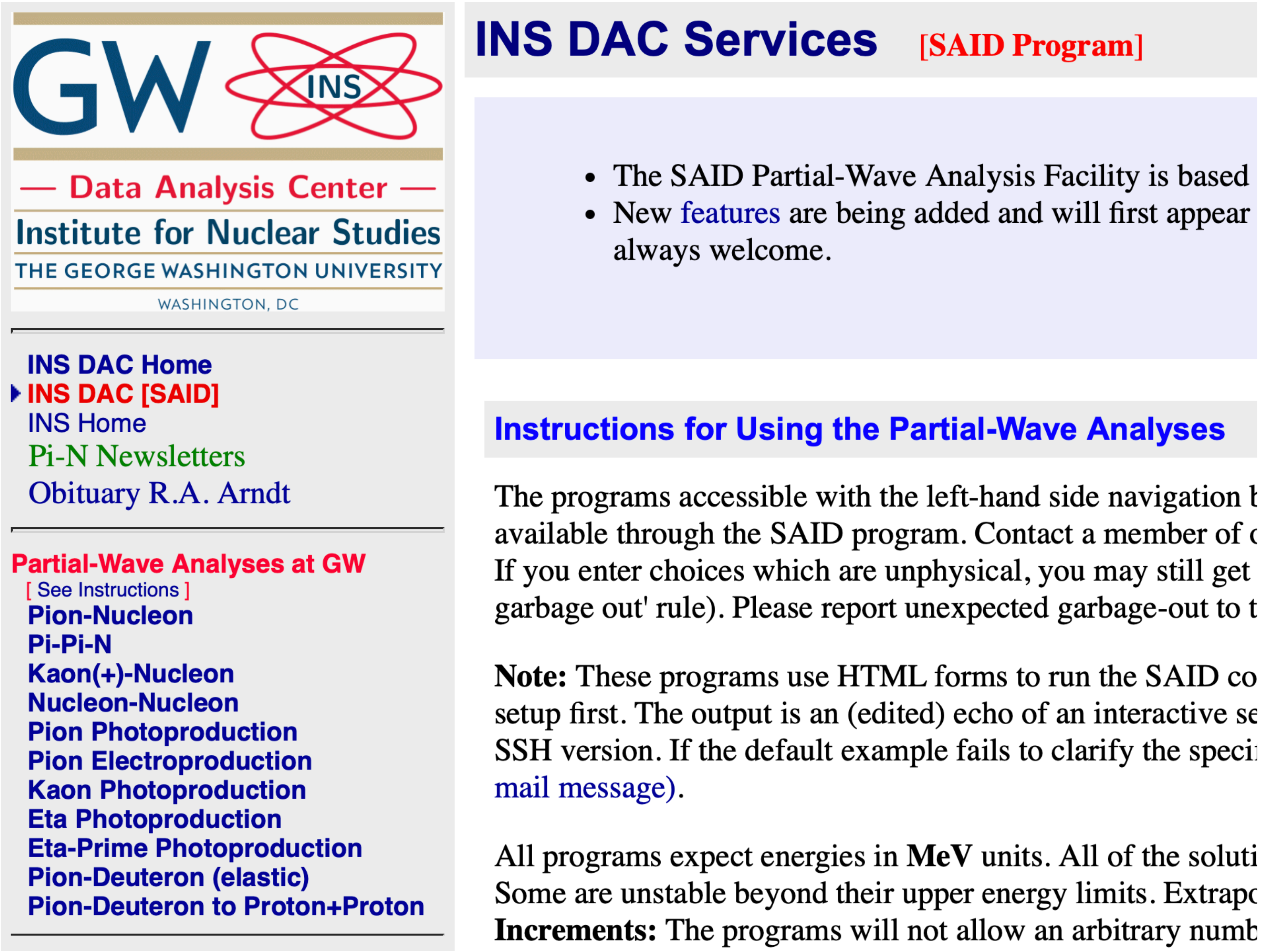
$N(1700)$ BREIT-WIGNER MASS	1650 to 1800 (≈ 1720) MeV
$N(1700)$ BREIT-WIGNER WIDTH	100 to 300 (≈ 200) MeV
$N(1710)$ BREIT-WIGNER MASS	1680 to 1740 (≈ 1710) MeV
$N(1710)$ BREIT-WIGNER WIDTH	80 to 200 (≈ 140) MeV
$N(1720)$ BREIT-WIGNER MASS	1680 to 1750 (≈ 1720) MeV
$N(1720)$ BREIT-WIGNER WIDTH	150 to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


GW INS

— Data Analysis Center —

Institute for Nuclear Studies

THE GEORGE WASHINGTON UNIVERSITY

WASHINGTON, DC

INS DAC Home

INS DAC [SAID]

INS Home

Pi-N Newsletters

Obituary R.A. Arndt

Partial-Wave Analyses at GW

[See Instructions]

Pion-Nucleon

Pi-Pi-N

Kaon(+)-Nucleon

Nucleon-Nucleon

Pion Photoproduction

Pion Electroproduction

Kaon Photoproduction

Eta Photoproduction

Eta-Prime Photoproduction

Pion-Deuteron (elastic)

Pion-Deuteron to Proton+Proton

INS DAC Services [SAID Program]

- The SAID Partial-Wave Analysis Facility is based
- New features are being added and will first appear always welcome.

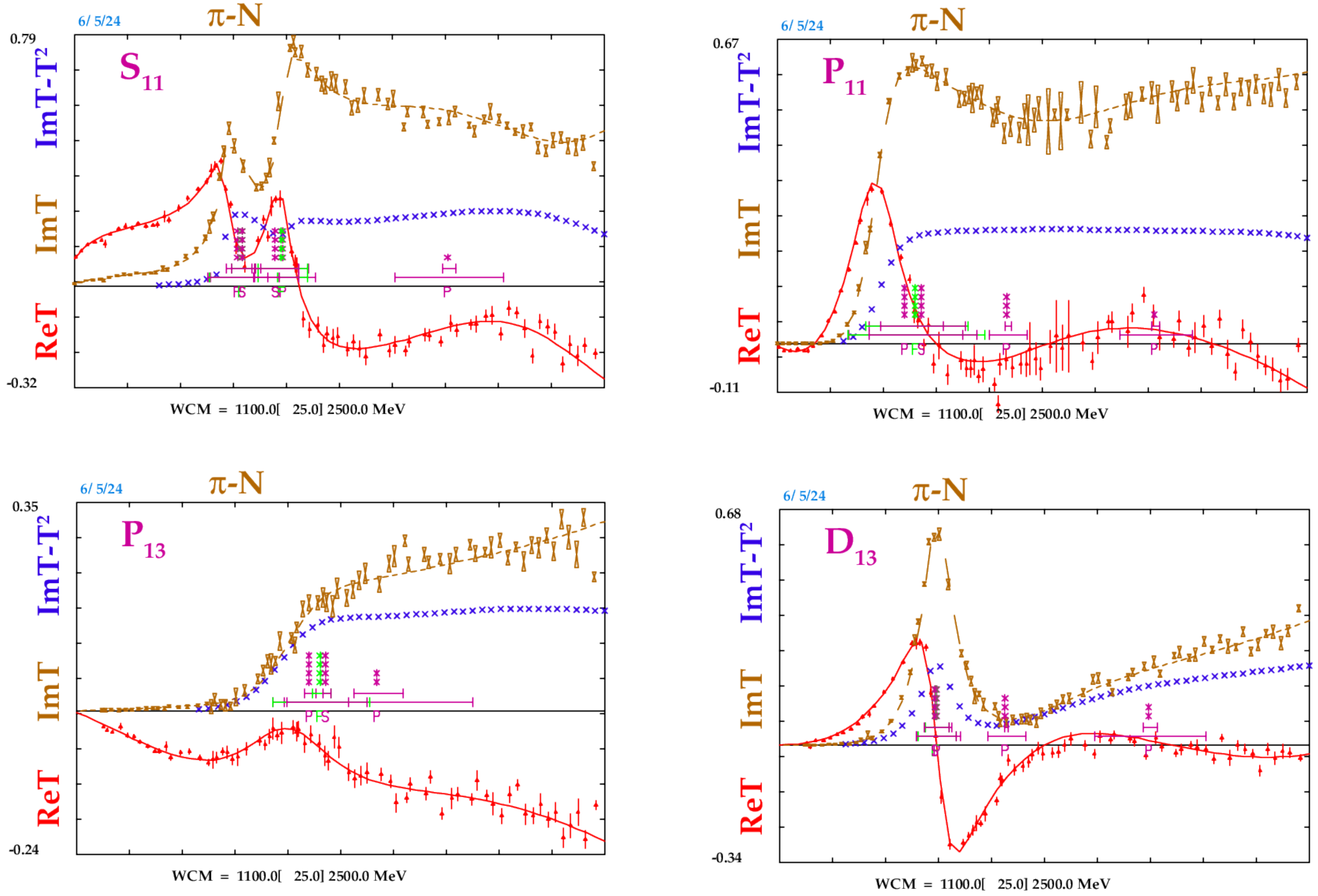
Instructions for Using the Partial-Wave Analyses

The programs accessible with the left-hand side navigation b available through the SAID program. Contact a member of o If you enter choices which are unphysical, you may still get garbage out' rule). Please report unexpected garbage-out to t

Note: These programs use HTML forms to run the SAID co setup first. The output is an (edited) echo of an interactive se SSH version. If the default example fails to clarify the speci mail message).

All programs expect energies in **MeV** units. All of the soluti Some are unstable beyond their upper energy limits. Extrapo **Increments:** The programs will not allow an arbitrary numb

$N\pi \to N\pi$

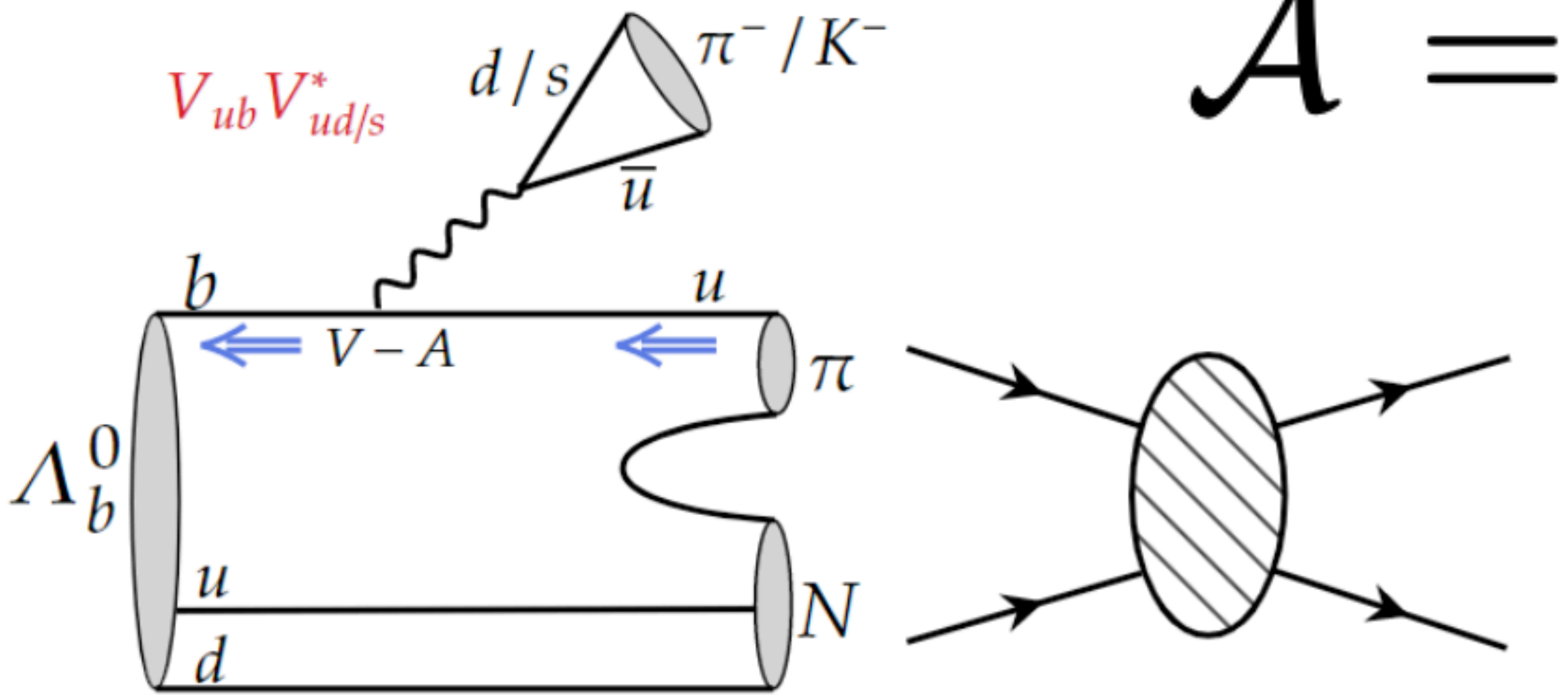


- Partial-wave amplitudes with strong phases!
- Data driven, **model independent**. Skip resonances, more precise strong phases.

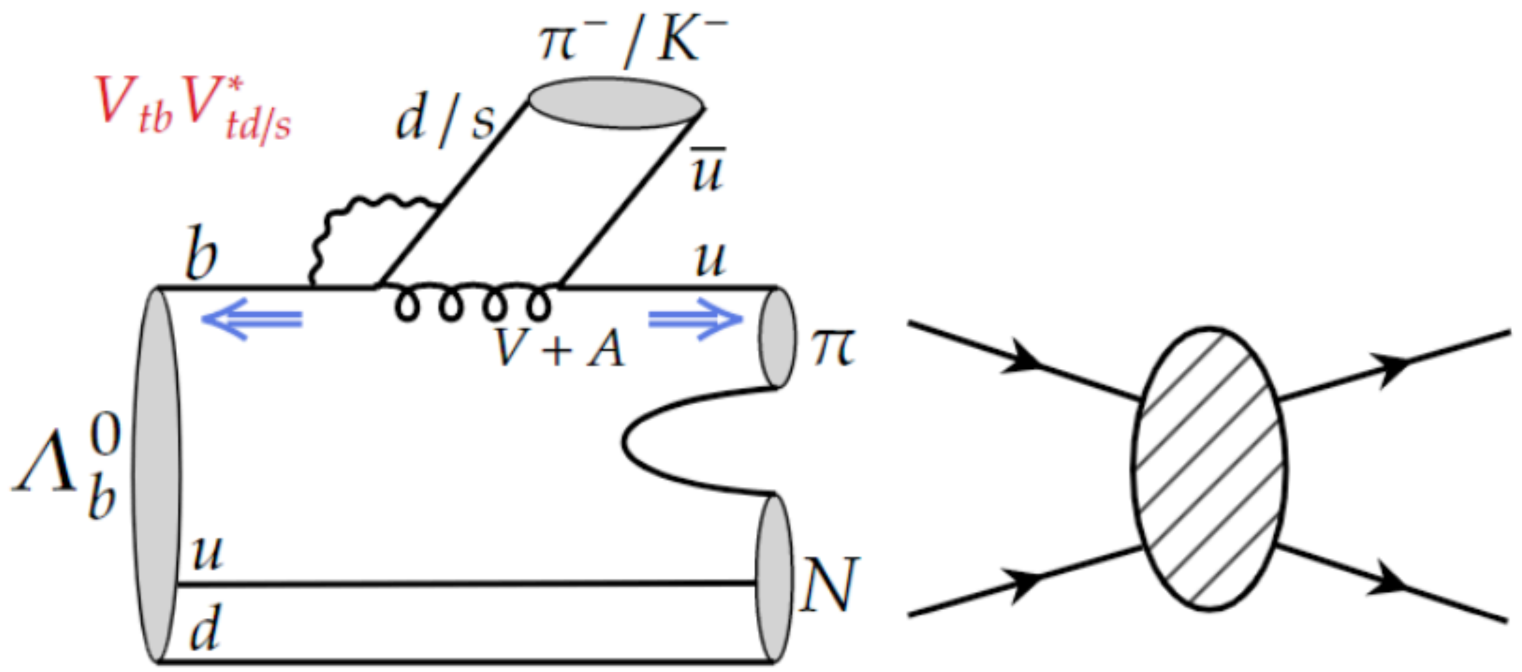
CPV via $N\pi$ rescatterings

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

•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 (CPC)

CPV with $N\pi$ scatterings

	decay processes	Scenarios	global CPV	CPV of $\cos\theta < 0$	CPV of $\cos\theta > 0$
$N\pi \to \Delta^{++}\pi^-$ $m_{N\pi} \in [1.2, 1.9]$GeV	$\Lambda_b^0 \to (\Delta^{++}\pi^-)K^- \to (p\pi^+\pi^-)K^-$	S1	5.9%	8.0%	3.6%
		S2	5.8%	6.3%	5.3%
		S3	5.6%	4.3%	7.0%
$N\pi \to \Delta^{++}\pi^-$ $m_{N\pi} \in [1.2, 1.9]$GeV	$\Lambda_b^0 \to (\Delta^{++}\pi^-)\pi^-$	S1	−4.1%	−5.4%	−2.4%
		S2	−3.9%	−3.9%	−3.9%
		S3	−3.6%	−2.3%	−5.3%
$N\pi \to p\pi^0$ $m_{N\pi} \in [1.1, 2.5]$GeV	$\Lambda_b^0 \to (p\pi^0)K^-$	S1	5.8%	8.2%	2.7%
		S2	5.8%	8.0%	3.0%
		S3	5.8%	7.8%	3.3%
$N\pi \to p\pi^0$ $m_{N\pi} \in [1.1, 2.5]$GeV	$\Lambda_b^0 \to (p\pi^0)\pi^-$	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: $f_1 = 0.9$, $g_1 = 1.1$

J.P.Wang, **FSY**, 2407.04110 (CPC2024)

CPV with $N\pi$ scatterings

July, 2024

decay processes	Scenarios	global CPV	CPV of $\cos\theta < 0$	CPV of $\cos\theta > 0$
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J.P.Wang, **FSY**, CPC48,101002(2024)[arXiv:2407.04110]

•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 (Nature)

using scattering data to extract the hadronic amplitude[29]. An estimate of the CP asymmetry in $\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$ decays made by applying this method using π–nucleon scattering data[37] aligns with the measurement in this work[29].

29. Wang, J.-P. & Yu, F.-S. CP violation of baryon decays with $N\pi$ rescatterings. *Chin. Phys. C* **48**, 101002 (2024).

CPV with $N\pi$ scatterings

July, 2024

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J.P.Wang, **FSY**, CPC48,101002(2024)[arXiv:2407.04110]

•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

This is not the end, but a beginning…

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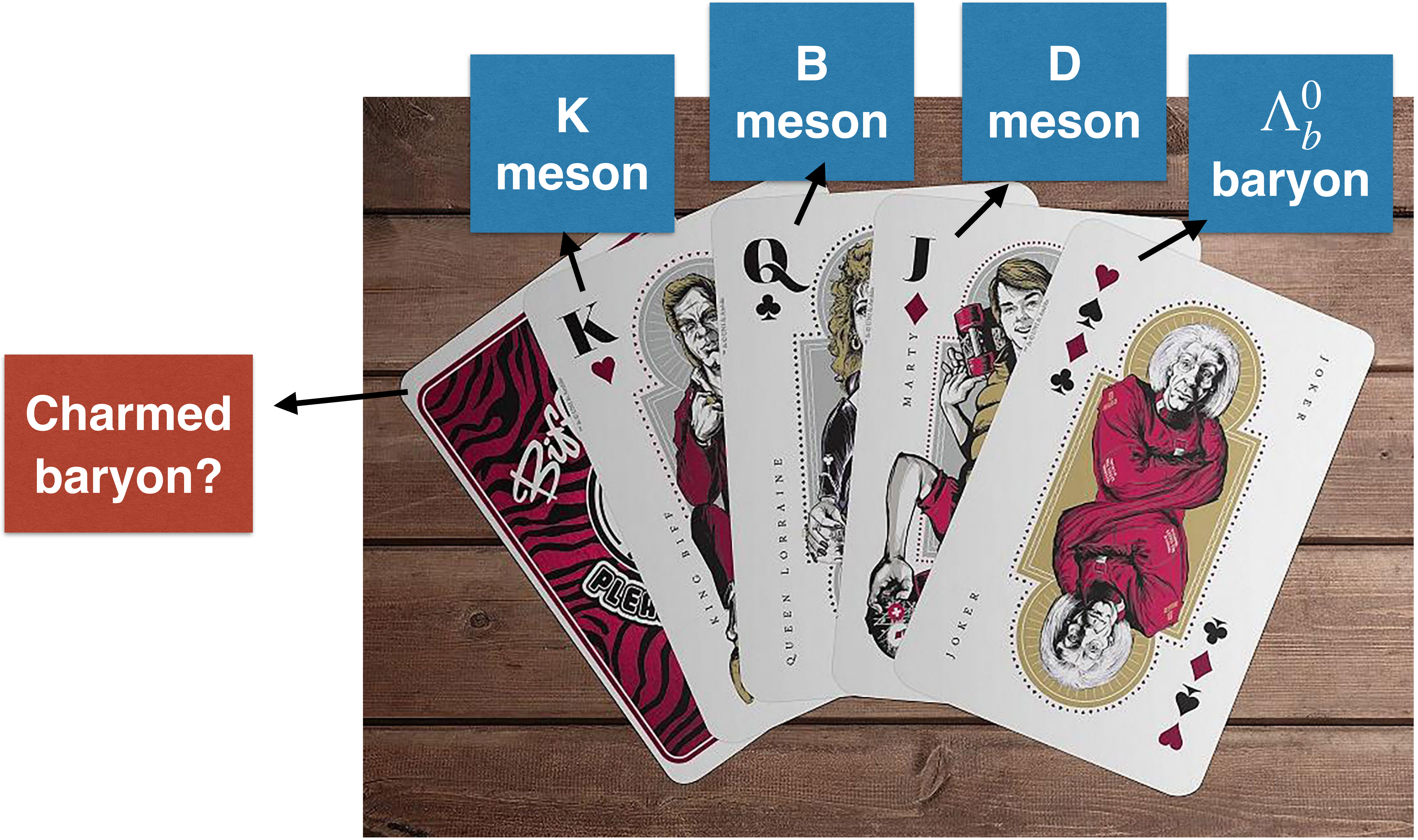
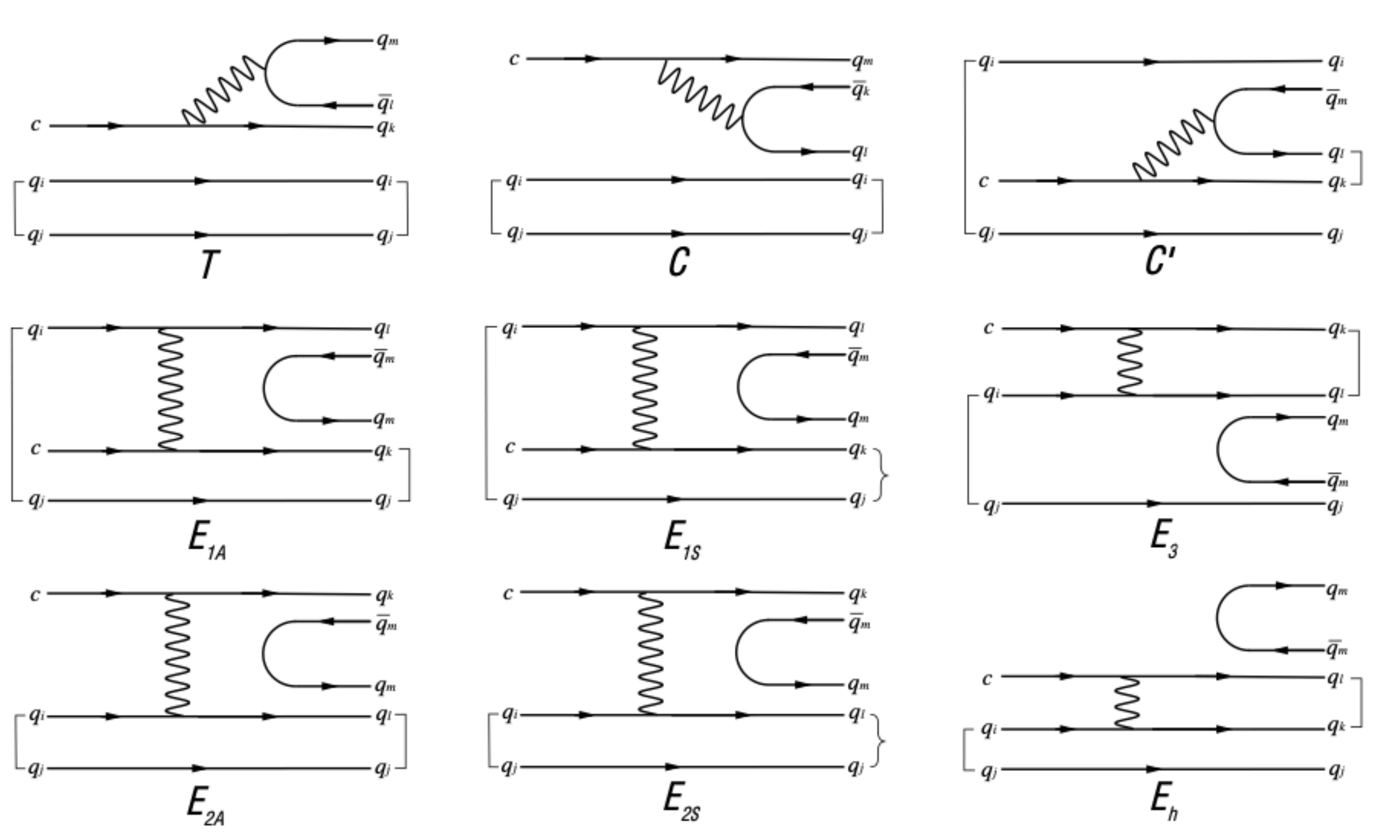
Next card to be turned: CPV of charmed baryon?



Charm-baryon decays

- Benefited from BESIII measurements on Λ_c^+ decays, and Belle and LHCb as well
- SU(3) symmetry representations extracted from data [C.Q.Geng, C.W.Liu, 2018-2022]. Topological diagrams can be extracted finally. [Zhong, Xu, Cheng, 2024]



Channel	$10^2\mathcal{B}$	α	$\lvert A\rvert$	$\lvert B\rvert$	$\delta_P-\delta_S$	$10^2\mathcal{B}_{\rm exp}$	$\alpha_{\rm exp}$
$\Lambda_c^+\to\Lambda^0\pi^+$	1.31 ± 0.05	-0.76 ± 0.01	2.76 ± 0.25	16.96 ± 0.39	-2.92 ± 0.29	1.29 ± 0.05	-0.76 ± 0.01[19, 26]
$\Lambda_c^+\to\Sigma^0\pi^+$	1.26 ± 0.05	-0.48 ± 0.02	4.07 ± 0.86	15.48 ± 2.29	2.08 ± 0.04	1.27 ± 0.06	-0.47 ± 0.03[19, 26]
$\Lambda_c^+\to\Sigma^+\pi^0$	1.27 ± 0.05	-0.48 ± 0.02	4.07 ± 0.86	15.48 ± 2.29	2.08 ± 1.15	1.25 ± 0.09	-0.49 ± 0.03[19, 25]
$\Lambda_c^+\to\Sigma^+\eta$	0.33 ± 0.04	-0.93 ± 0.05	2.30 ± 0.35	9.48 ± 1.16	-2.80 ± 0.16	0.32 ± 0.04[19, 25]	-0.99 ± 0.06[25]
$\Lambda_c^+\to\Sigma^+\eta'$	0.39 ± 0.11	-0.45 ± 0.07	3.81 ± 1.44	23.04 ± 3.84	-4.25 ± 0.08	0.44 ± 0.15[19, 25]	-0.46 ± 0.07[25]
$\Lambda_c^+\to\Xi^0K^+$	0.41 ± 0.03	-0.16 ± 0.13	3.89 ± 0.19	2.43 ± 2.10	-2.15 ± 0.65	0.55 ± 0.07	0.01 ± 0.16[7]
$\Lambda_c^+\to\Lambda^0K^+$	0.0639 ± 0.0030	-0.56 ± 0.05	1.09 ± 0.18	3.32 ± 0.59	2.17 ± 0.06	0.0635 ± 0.0031[19, 26]	-0.585 ± 0.052[26]
$\Lambda_c^+\to\Sigma^0K^+$	0.0376 ± 0.0032	-0.54 ± 0.08	0.40 ± 0.15	3.86 ± 0.26	2.56 ± 0.44	0.0382 ± 0.0051[19, 26]	-0.55 ± 0.20[26]
$\Lambda_c^+\to\Sigma^+K_S$	0.0377 ± 0.0032	-0.54 ± 0.08	0.40 ± 0.15	3.86 ± 0.26	2.56 ± 0.44	0.047 ± 0.014	
$\Lambda_c^+\to n\pi^+$	0.063 ± 0.009	-0.78 ± 0.13	1.01 ± 0.14	2.43 ± 0.38	3.81 ± 0.30	0.066 ± 0.013	
$\Lambda_c^+\to p\pi^0$	0.0176 ± 0.0034	-0.11 ± 0.75	0.64 ± 0.13	0.94 ± 0.66	4.59 ± 1.70	$0.0156^{+0.0075}_{-0.0061}$[20]	
$\Lambda_c^+\to pK_S$	1.57 ± 0.07	0.01 ± 0.31	1.41 ± 1.51	18.68 ± 0.79	1.54 ± 0.82	1.59 ± 0.07	0.18 ± 0.45
$\Lambda_c^+\to p\eta$	0.151 ± 0.008	0.07 ± 0.37	1.01 ± 0.53	5.46 ± 0.67	1.48 ± 0.45	0.149 ± 0.008[19, 20, 27]	
$\Lambda_c^+\to p\eta'$	0.052 ± 0.009	-0.54 ± 0.19	0.77 ± 0.30	4.72 ± 0.73	2.29 ± 0.13	0.049 ± 0.009	
$\Xi_c^0\to\Xi^-\pi^+$	2.83 ± 0.10	-0.72 ± 0.03	4.51 ± 0.79	31.47 ± 1.31	2.76 ± 0.32	1.80 ± 0.52[21]	-0.64 ± 0.05
$\Xi_c^+\to\Xi^0\pi^+$	0.9 ± 0.2	-0.93 ± 0.07	2.27 ± 0.30	8.21 ± 1.16	-3.5 ± 0.23	1.6 ± 0.8	

- CPV of charmed baryon predicted at the order of 10^{-4} under SU(3) flavor symmetry, but can be enhanced to be 10^{-3} by the final-state-interaction effects [He, Liu, 2024][Jia, Jiang, Wang, FSY, 2024]

FSI for CPV of charmed baryon

- Global fit for the long-distance penguin topological diagrams [X.G.He, C.W.Liu, '24; H.Y.Cheng, F.Xu, H.Zhong, '25]

$$A_{CP}(\Xi_c^0 \to pK^-) - A_{CP}(\Xi_c^0 \to \Sigma^+\pi^-) = -(1.44 \pm 0.35) \times 10^{-3}$$

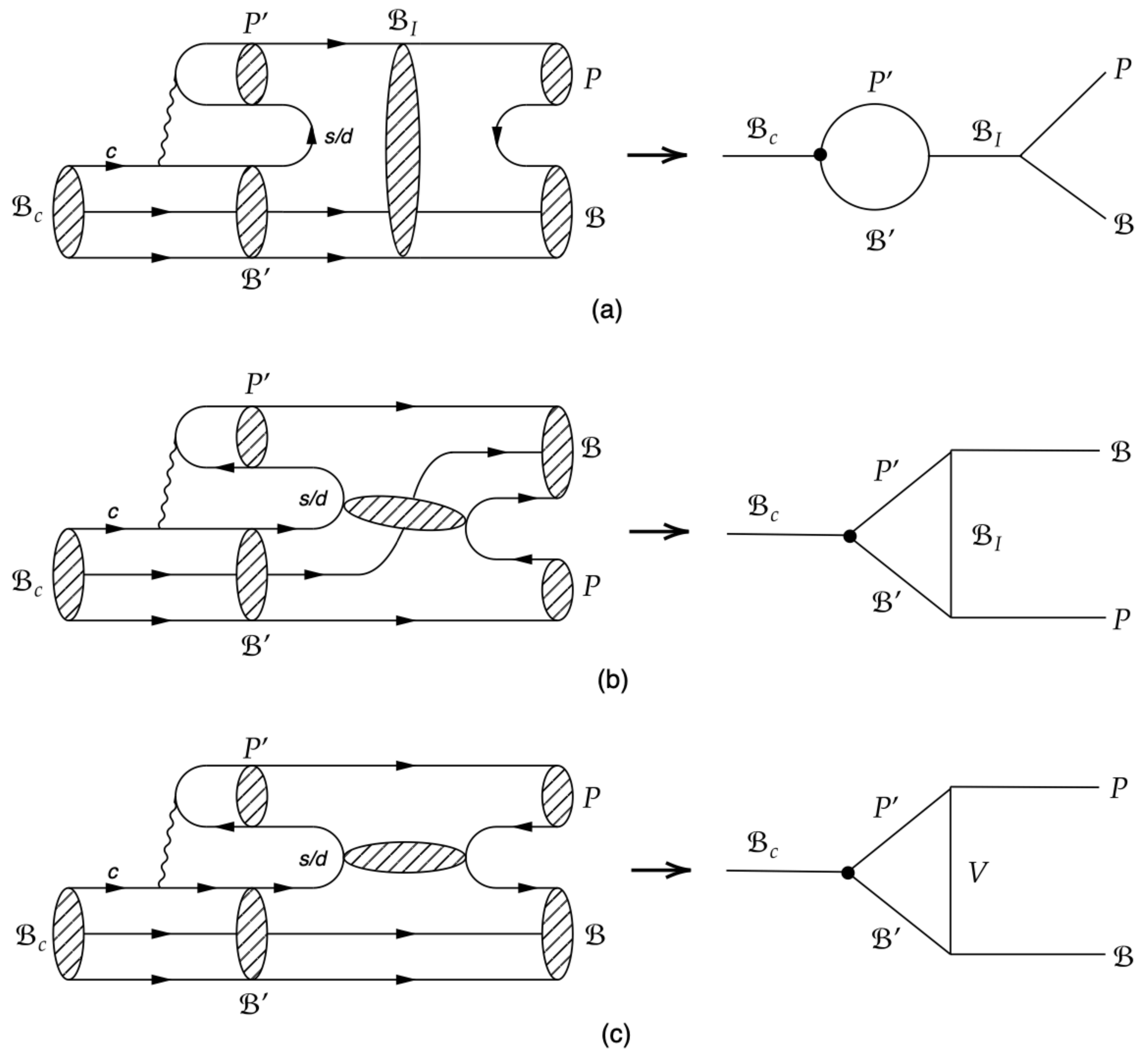
$$A_{CP}^{\alpha}(\Xi_c^0 \to pK^-) - A_{CP}^{\alpha}(\Xi_c^0 \to \Sigma^+\pi^-) = (3.57 \pm 0.36) \times 10^{-3}$$

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

Based on C.Q.Geng, X.G.He, X.N.Jin, C.W.Liu, C.Yang, '23

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

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



FSI for CPV of charmed baryon

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

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

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

1. Introduction on CP Violation

2. Bottom-baryon CPV

3. Charm-baryon CPV

4. CPV observables

Observables

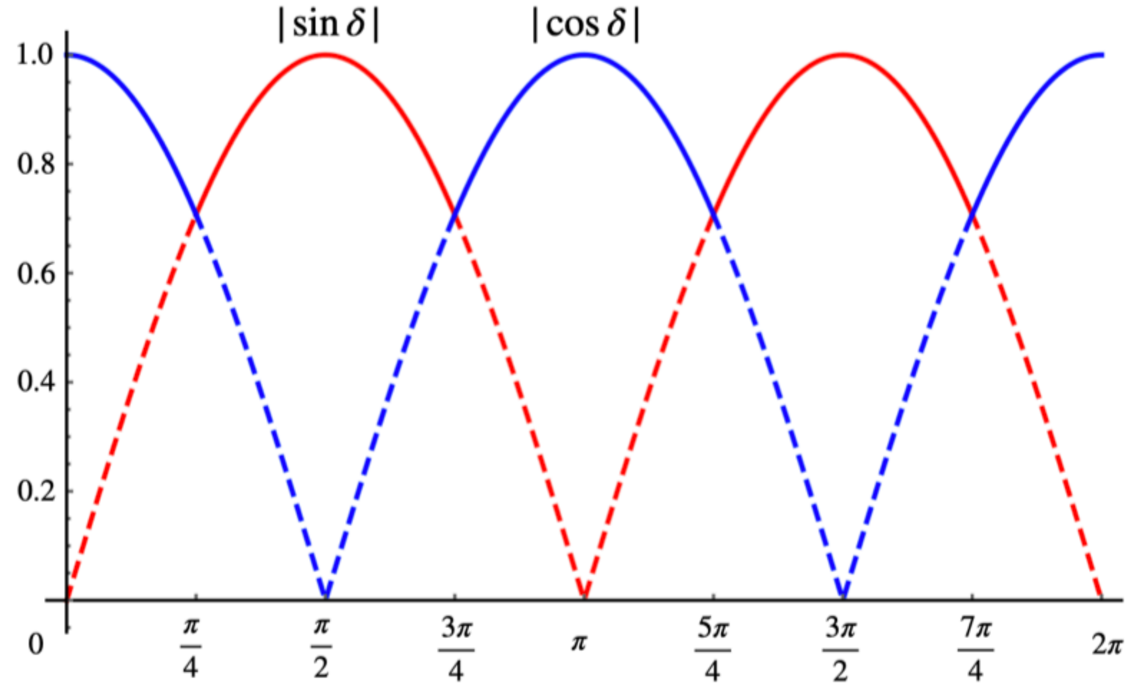
- Baryons have nonzero spins which can construct more observables and thus are helpful to find large CPV for measurements.
- Direct CPV in the decays: $a_{CP}^{\text{dir}} \propto \sin\delta_s \sin\phi_w$. Sensitive to the strong phases.
- T-odd triple product: $\beta \propto (\vec{s}_1 \times \vec{s}_2)\cdot\vec{p}$ 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]
- Time-reversal asymmetries in $\Lambda_b \to \Lambda V$ [C.Q.Geng, C.W.Liu, 2021]

Complimentary?

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

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



Complementary observables

- **Why $\cos\delta_s$?**

CPV: $a_{CP} \propto \langle O \rangle - \langle (CP) O (CP^\dagger) \rangle$

  - 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, $UQ_-U^\dagger = Q_-$

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

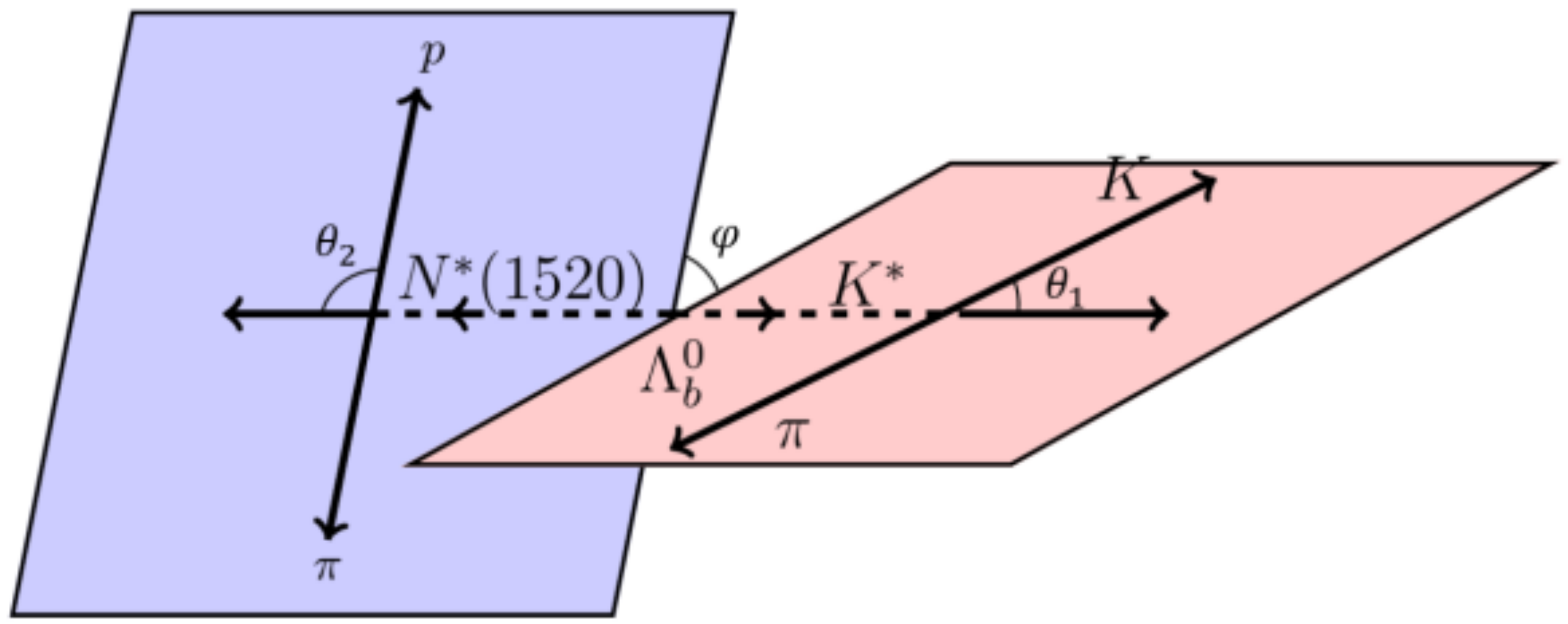
$$a_{CP}^{\text{T-even}} \propto \sum_{m,n} Re(A_m^* A_n - \bar{A}_m^* \bar{A}_n) \propto \sin\delta_s \sin\phi_w$$

complimentary

J.P.Wang, Q.Qin, **FSY**, 2211.07332

Complementary in angular distributions

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



$s_{1,2} = \sin\theta_{1,2}$, $c_{1,2} = \cos\theta_{1,2}$

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

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

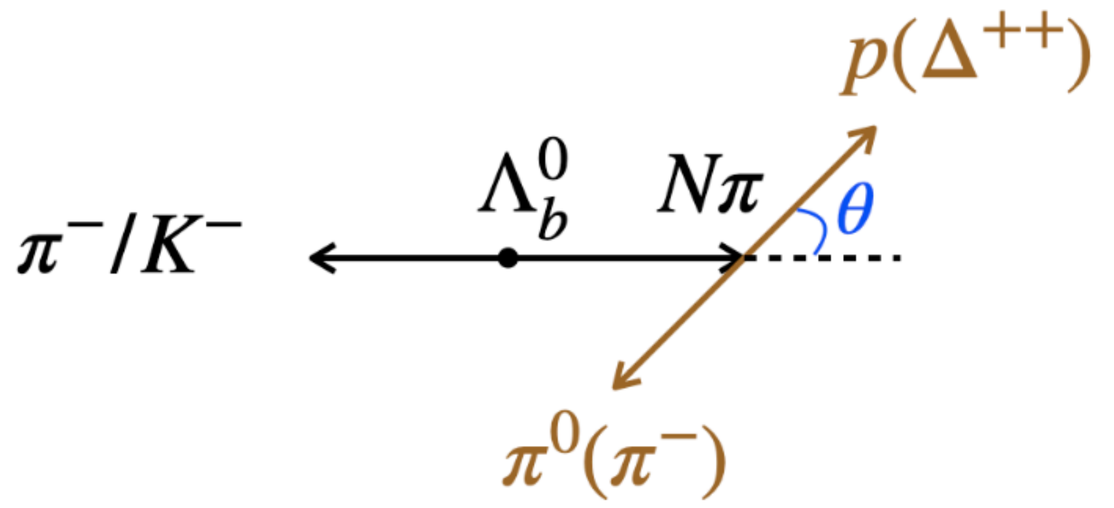
- Triple-product of momentum, $(\vec{p}_1 \times \vec{p}_2)\cdot\vec{p}_3$, is not good. $\sin\varphi$ with $\sin\theta_1\cos\theta_1\sin\theta_2\cos\theta_2$
- Angular distributions of resonant contributions are necessary. It is more clear in theory.

J.P.Wang, Q.Qin, **FSY**, 2411.18323

CPV of Legendre moments

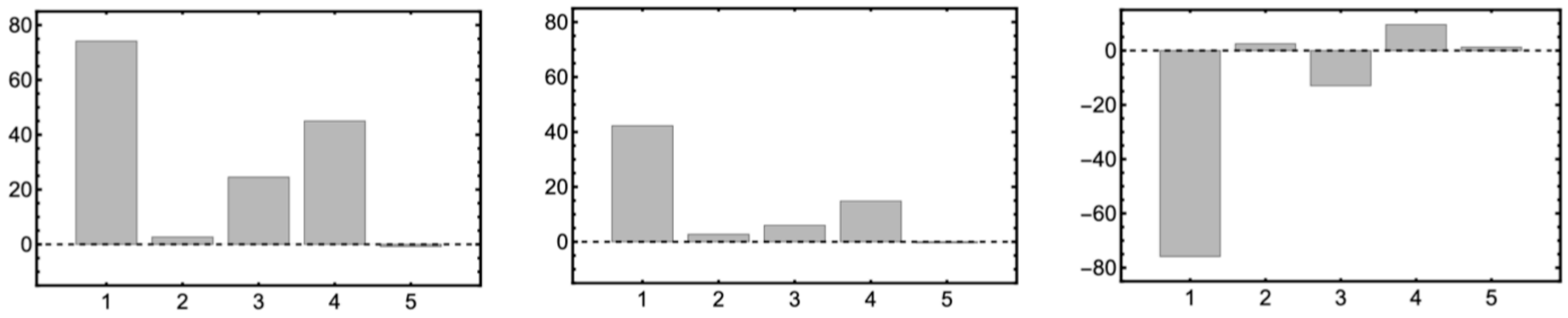
- Partial wave CPV based on the Legendre decomposition [Z.H.Zhang, X.H.Guo, 2021,2025]

$$\frac{d\Gamma}{d\cos\theta} \propto \sum_{n=0} \mathcal{L}_n P_n(\cos\theta)$$



$\Lambda_b^0 \to (\Delta^{++}\pi^-)K^-$: $\mathscr{L}_n = (1, -0.10, 0.20, -0.05, 0.009, 0.05)$

$\Lambda_b^0 \to (\Delta^{++}\pi^-)K^-$



J.P.Wang, **FSY**, 2407.04110 (CPC2024)

Up-Down asymmetry

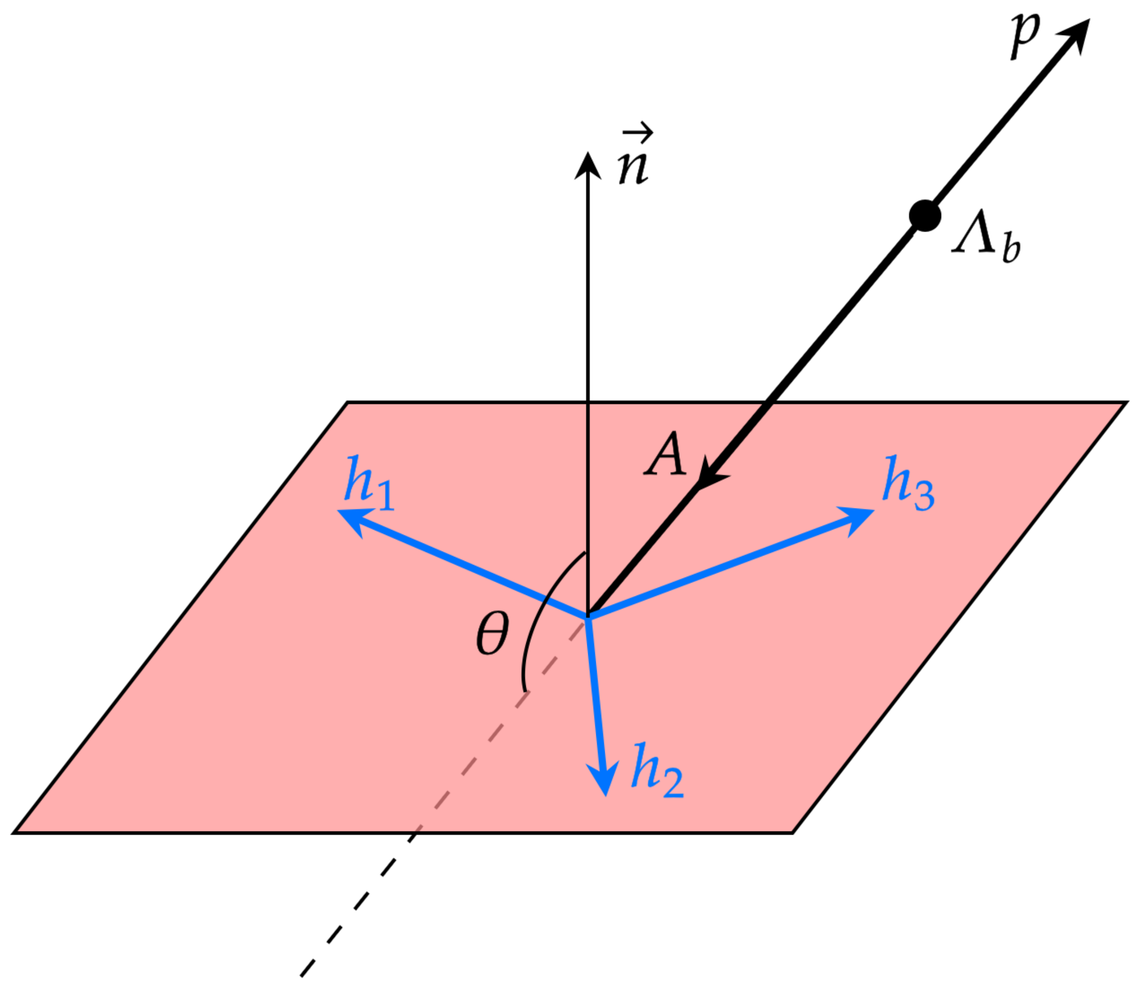
- How to measure the large partial-wave CPV?
- They usually need the polarizations of baryons.
- But the angular distributions may help.

$$\Lambda_b^0 \to p a_1(\to \pi\pi\pi) \qquad \Lambda_b^0 \to p K_1(\to K\pi\pi)$$

$$\frac{d\Gamma}{d\cos\theta} \supset R\, \mathcal{R}e(S^T P_2^*)\ \cos\theta$$

$$A_{UD} \equiv \frac{\Gamma(\cos\theta > 0) - \Gamma(\cos\theta < 0)}{\Gamma(\cos\theta > 0) + \Gamma(\cos\theta < 0)} = R\, \mathcal{R}e(S^T P_2^*)$$

$$A_{CP}^{UD} = \frac{A_{UD} + \bar{A}_{UD}}{A_{UD} - \bar{A}_{UD}}$$



	A_{CP}^{UD}
$\Lambda_b \to p a_1^-(1260)$	$-0.24^{+0.08}_{-0.13}$
$\Lambda_b \to p K_1^-(1270)$ $(\theta_K = 30°)$	$0.26^{+0.04}_{-0.10}$
$\Lambda_b \to p K_1^-(1270)$ $(\theta_K = 60°)$	$0.40^{+0.04}_{-0.09}$

J.P.Wang, Q.Qin, **FSY**, 2411.18323;
J.J.Han, J.X,Yu, Y.Li, H.n.Li, J.P.Wang, Z.J.Xiao, **FSY**, 2409.02821 (PRL)

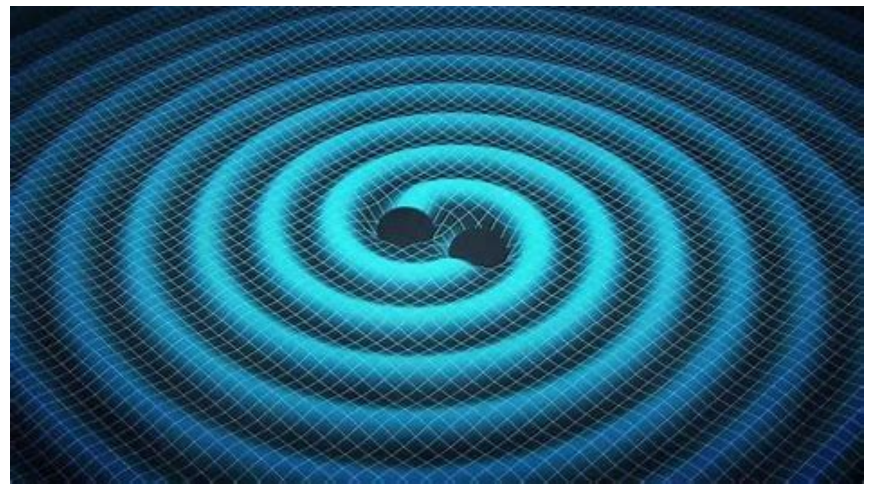
Summary

- Baryon CPV is now firstly observed in $\Lambda_b \to pK^-\pi^+\pi^-$
- It is a new horizon in particle physics.
- We find that the partial-wave CPVs are large but cancelled, resulting in small CPV of baryon decays.
- We propose a new CPV mechanism via $N\pi$ rescatterings. Our prediction is manifested by LHCb.
- Next generation: new CPV observables, charm-baryon CPV

Thank you!

Backup (I)

New horizon

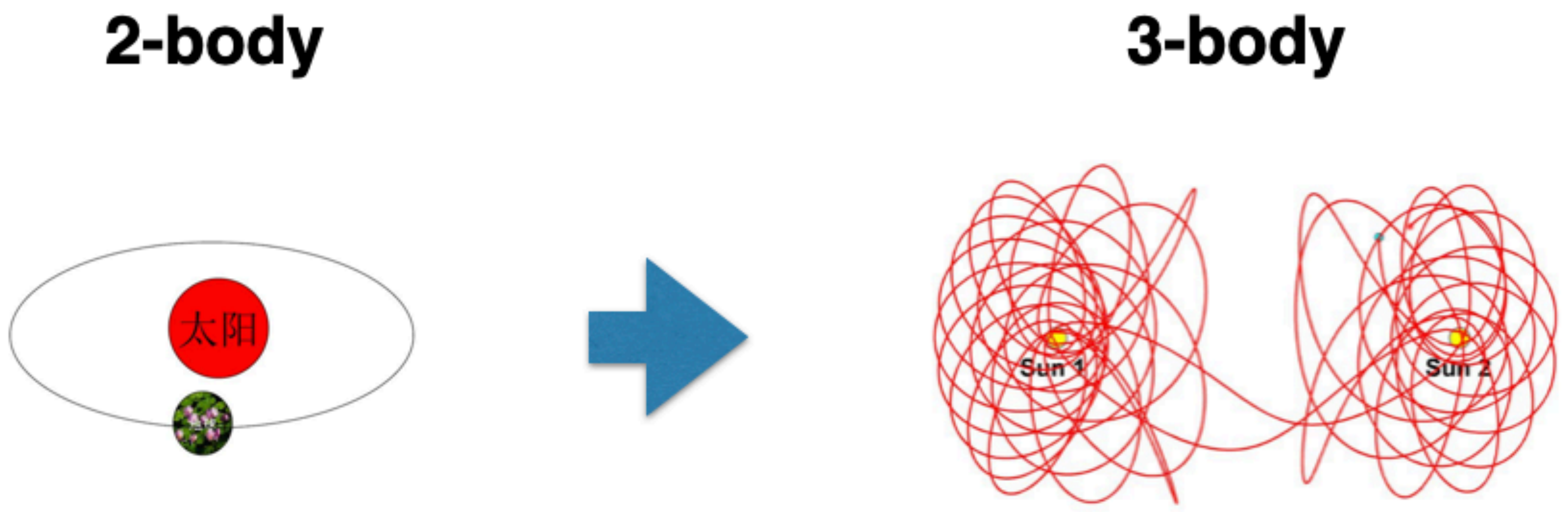


- Observation of gravitational waves

  => not only confirm the General Relativity,

  => but also open the Multi-messenger era of cosmology.

- Meson -> Baryon : More is different.
- New QCD dynamics: exclusive baryon.
- High power dominated, partial-wave CPV destruction, $N\pi$ rescatterings



Fu-Sheng Yu

Partial-wave CPVs are large, but cancelled with each other

	$A_{CP}^{\rm dir}$	$A_{CP}^{S\text{-wave}}(\kappa_S)$	$A_{CP}^{P\text{-wave}}(\kappa_P)$	A_{CP}^{α}	A_{CP}^{β}	A_{CP}^{γ}
$\Lambda_b \to p\pi^-$	$0.05^{+0.02}_{-0.03}$	$0.17^{+0.05}_{-0.09}$ (49%)	$-0.06^{+0.04}_{-0.05}$ (51%)	$0.02^{+0.01}_{-0.02}$	$0.22^{+0.08}_{-0.05}$	$0.11^{+0.05}_{-0.06}$
$\Lambda_b \to pK^-$	$-0.06^{+0.03}_{-0.02}$	$-0.05^{+0.05}_{-0.04}$ (94%)	$-0.21^{+0.39}_{-0.46}$ (6%)	$0.04^{+0.03}_{-0.04}$	$-0.44^{+0.08}_{-0.04}$	$0.02^{+0.06}_{-0.05}$

	$A_{CP}^{\rm dir}$	$A_{CP}^{S^T\text{-wave}}(\kappa_{S^T})$	$A_{CP}^{(D+S^L)\text{-wave}}(\kappa_{D+S^L})$	$A_{CP}^{P_1\text{-wave}}(\kappa_{P_1})$	$A_{CP}^{P_2\text{-wave}}(\kappa_{P_2})$	$A_{CP}^{\mathcal{J}}$
$\Lambda_b \to p\rho^-$	$0.03^{+0.03}_{-0.05}$	$0.01^{+0.01}_{-0.04}$ (7%)	$0.02^{+0.07}_{-0.03}$ (44%)	$0.03^{+0.04}_{-0.12}$ (45%)	$0.17^{+0.04}_{-0.06}$ (4%)	$-0.01^{+0.01}_{-0.01}$
$\Lambda_b \to pK^{*-}$	$-0.05^{+0.10}_{-0.16}$	$-0.15^{+0.12}_{-0.06}$ (6%)	$0.27^{+0.09}_{-0.27}$ (33%)	$-0.23^{+0.10}_{-0.18}$ (55%)	$-0.14^{+0.02}_{-0.10}$ (6%)	$0.02^{+0.04}_{-0.05}$

	$A_{CP}^{\rm dir}$	$A_{CP}^{S^T\text{-wave}}(\kappa_{S^T})$	$A_{CP}^{(D+S^L)\text{-wave}}(\kappa_{D+S^L})$	$A_{CP}^{P_1\text{-wave}}(\kappa_{P_1})$	$A_{CP}^{P_2\text{-wave}}(\kappa_{P_2})$	A_{CP}^{UD}
$\Lambda_b \to pa_1^-(1260)$	$-0.01^{+0.04}_{-0.03}$	$-0.22^{+0.10}_{-0.10}$ (6%)	$-0.11^{+0.03}_{-0.07}$ (46%)	$0.18^{+0.11}_{-0.06}$ (40%)	$-0.24^{+0.07}_{-0.13}$ (8%)	$-0.24^{+0.08}_{-0.13}$
$\Lambda_b \to pK_1^-(1270)$ $(\theta_K = 30^\circ)$	$0.09^{+0.08}_{-0.05}$	$0.34^{+0.02}_{-0.06}$ (8%)	$-0.11^{+0.12}_{-0.08}$ (42%)	$0.19^{+0.17}_{-0.15}$ (42%)	$0.33^{+0.04}_{-0.05}$ (8%)	$0.26^{+0.04}_{-0.10}$
$\Lambda_b \to pK_1^-(1270)$ $(\theta_K = 60^\circ)$	$0.07^{+0.05}_{-0.06}$	$0.46^{+0.02}_{-0.09}$ (9%)	$0.06^{+0.11}_{-0.08}$ (37%)	$-0.07^{+0.09}_{-0.10}$ (45%)	$0.46^{+0.06}_{-0.07}$ (9%)	$0.40^{+0.04}_{-0.09}$

- This is a general feature in baryon decays, $\Lambda_b \to pP,\ pV,\ pA$

J.J.Han, J.X,Yu, Y.Li, H.n.Li, J.P.Wang, Z.J.Xiao, **FSY**, 2409.02821