

重子衰变中正反粒子不对称 的理论新进展



于福升
兰州大学

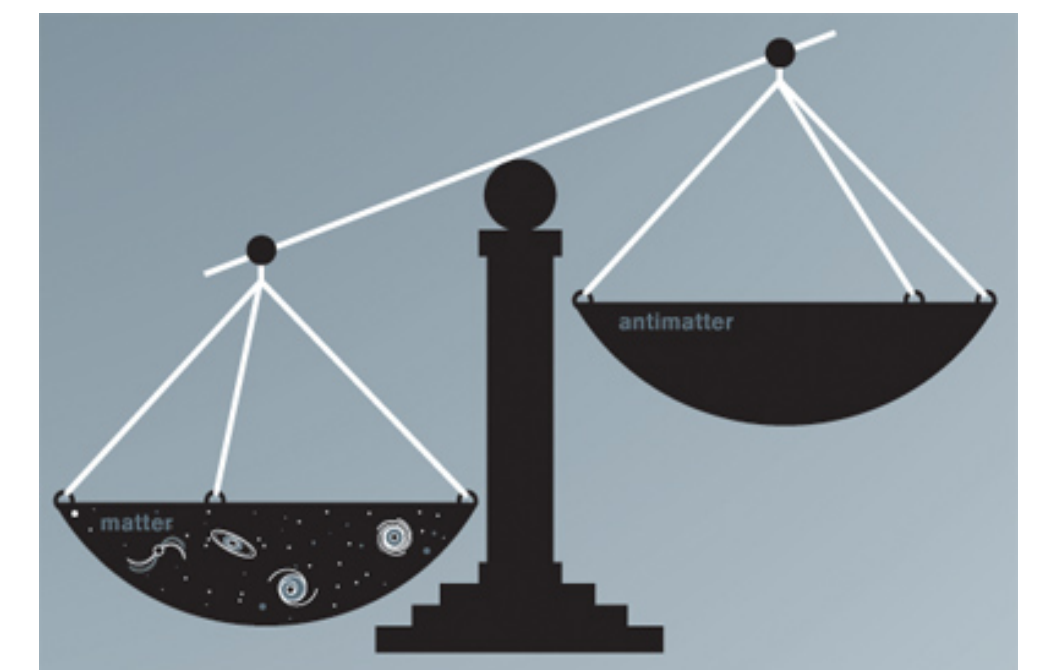
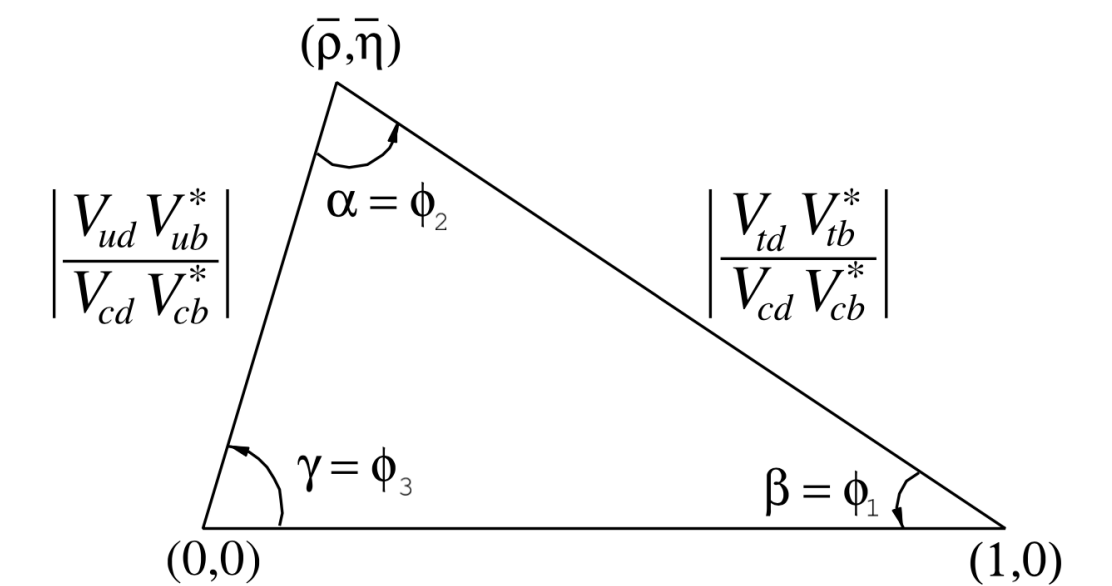
堅守 · 奮斗

中科大见微学术沙龙, 2026.4.24

1. Why Baryonic CP Violation?

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.

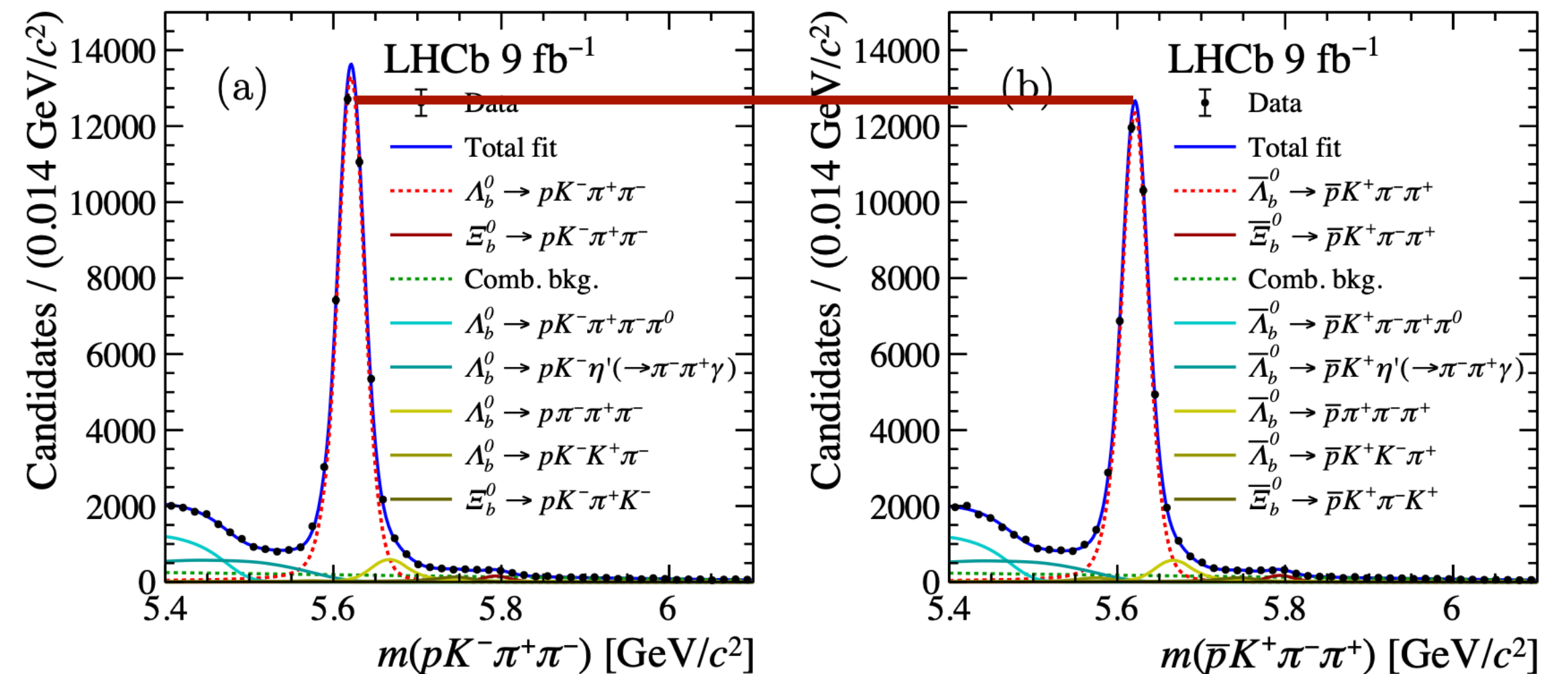


A new horizon in particle physics: First observation of baryon CP violation

$$\Lambda_b^0 \rightarrow pK^- \pi^+ \pi^-$$

$$\mathcal{A}_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$$

5.2σ



LHCb, Nature 643, 1223 (2025)

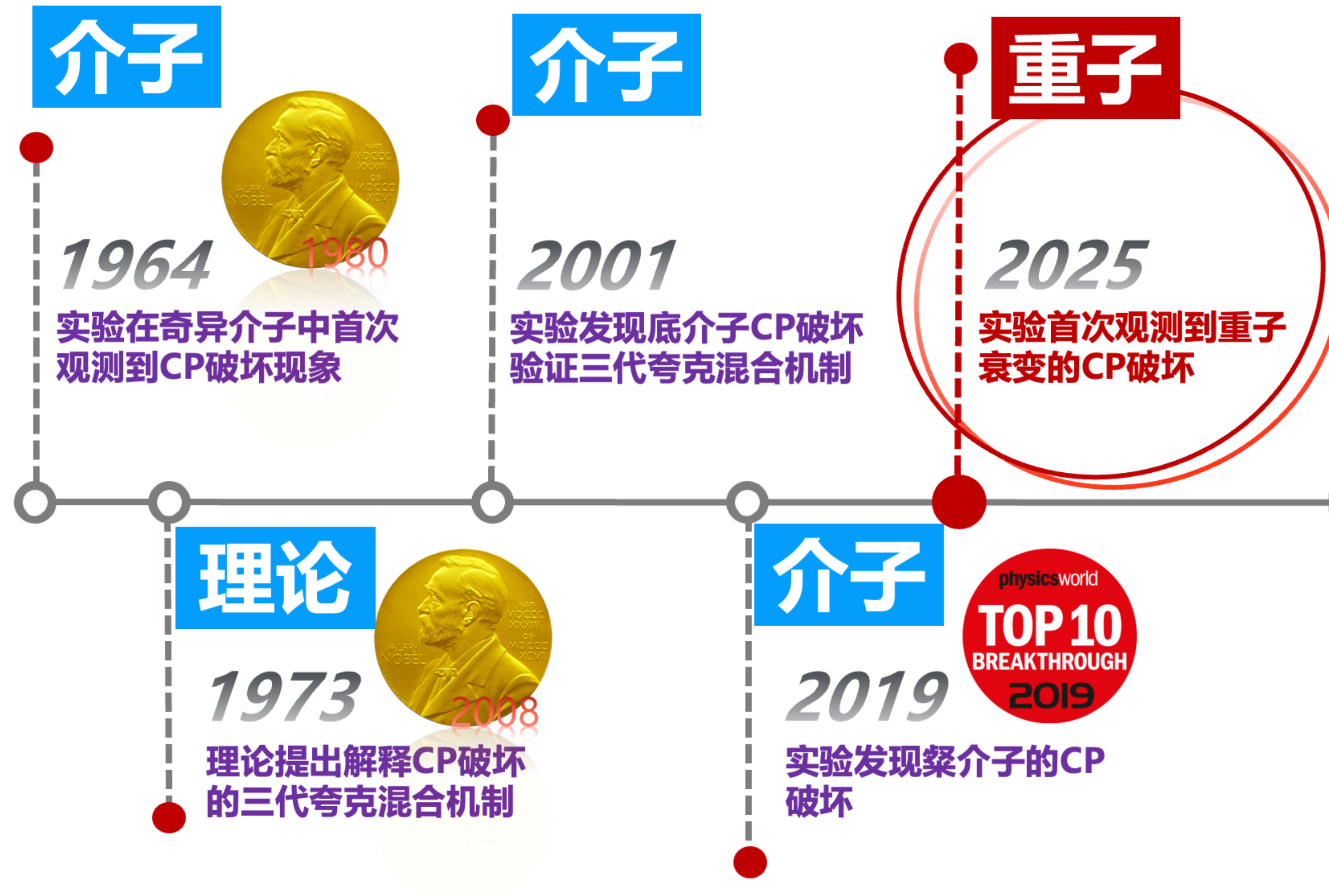
More interesting CP violation

Regional CPV

Decay topology	Mass region (GeV/c ²)	\mathcal{A}_{CP}	
$\Lambda_b^0 \rightarrow R(pK^-)R(\pi^+\pi^-)$	$m_{pK^-} < 2.2$ $m_{\pi^+\pi^-} < 1.1$	$(5.3 \pm 1.3 \pm 0.2)\%$	4.0σ
$\Lambda_b^0 \rightarrow R(p\pi^-)R(K^-\pi^+)$	$m_{p\pi^-} < 1.7$ $0.8 < m_{\pi^+K^-} < 1.0$ or $1.1 < m_{\pi^+K^-} < 1.6$	$(2.7 \pm 0.8 \pm 0.1)\%$	3.3σ
$\Lambda_b^0 \rightarrow R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$	6.0σ
$\Lambda_b^0 \rightarrow R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.0 \pm 1.2 \pm 0.3)\%$	1.6σ

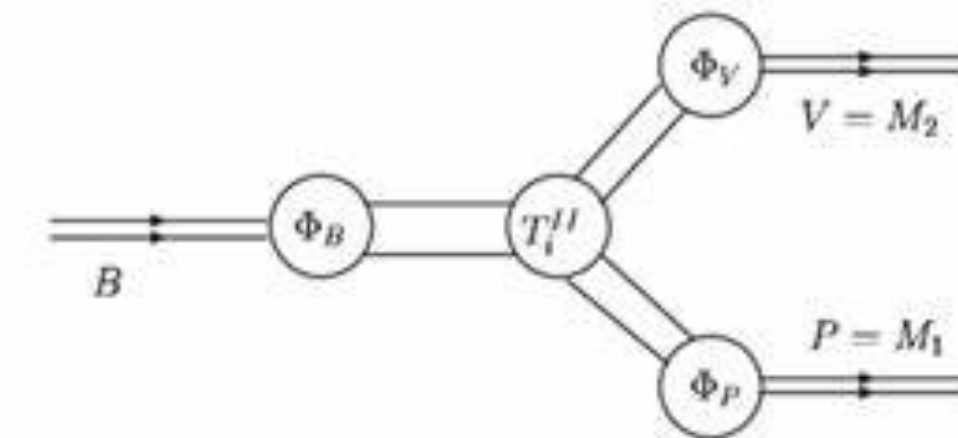
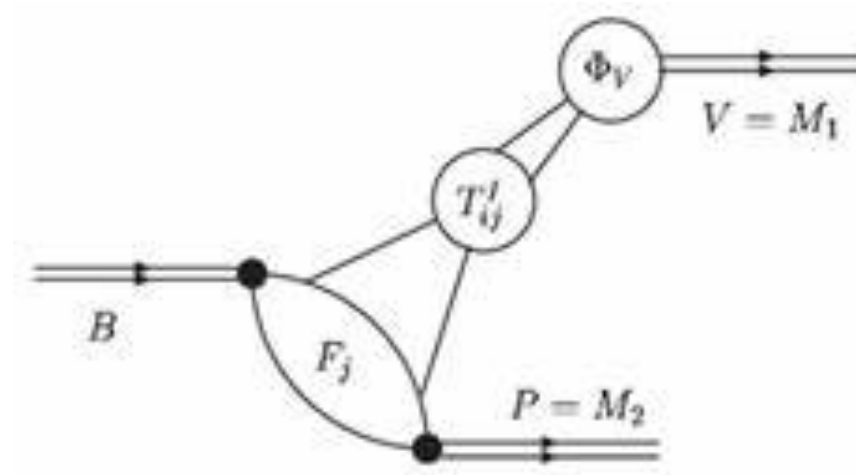
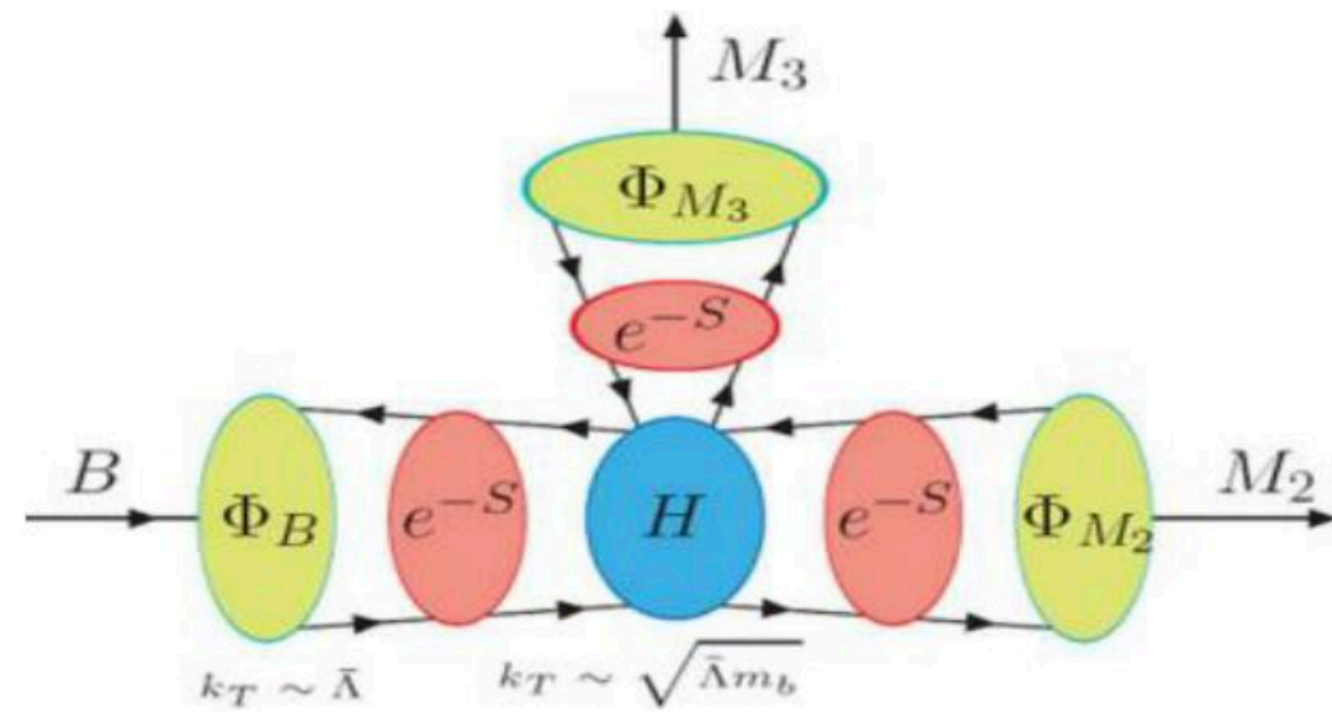
LHCb, Nature [arXiv: 2503.16954]

Dawn of Baryonic Era



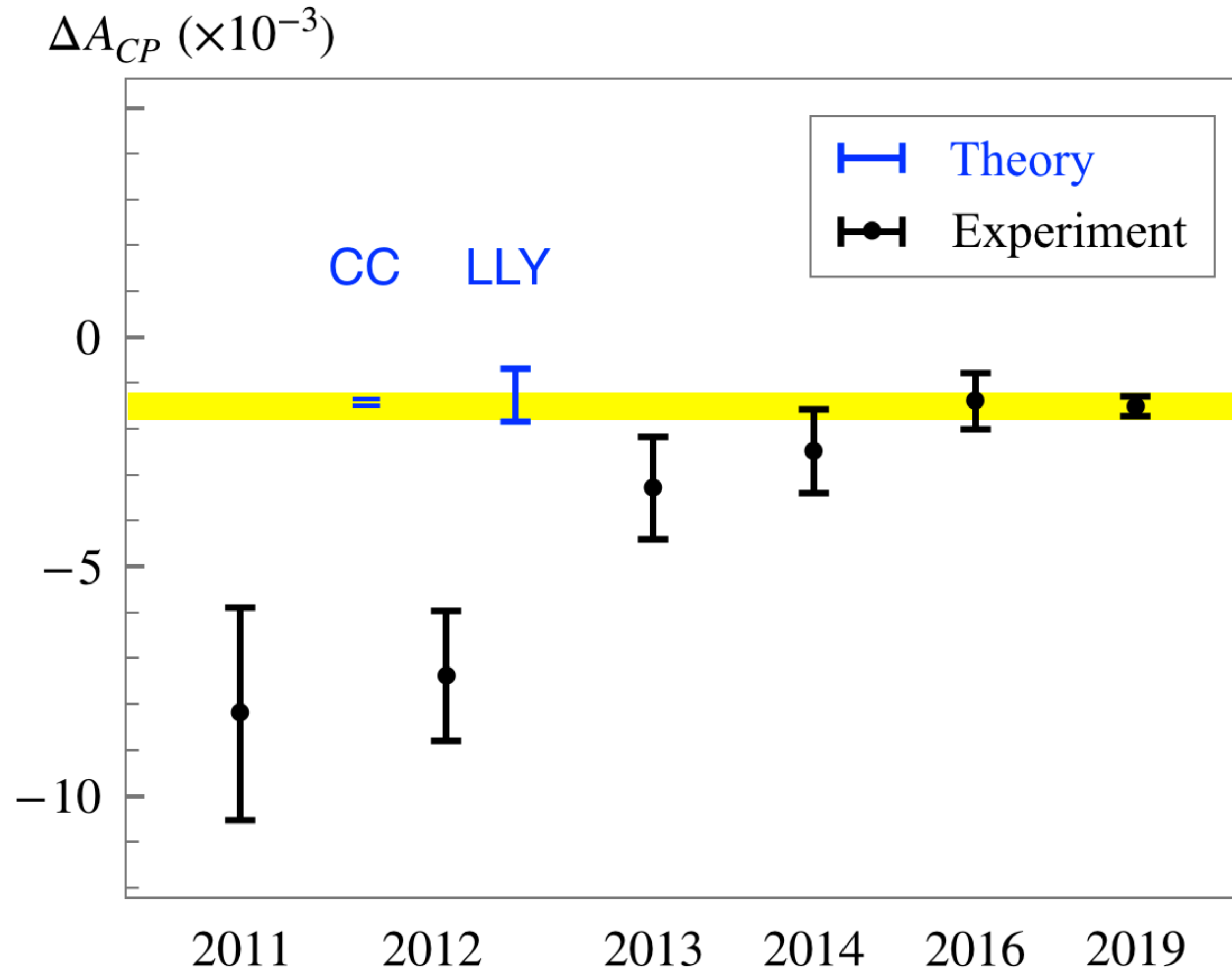
2000s: B-meson CPV

2000s: QCDF, PQCD, SCET — — Golden Age



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

2010s: Charm CPV



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

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

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

CC: topological approach + QCDF

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

LLY: factorization-assisted topology (FAT)

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

Exp: LHCb, PRL122, 211803 (2019)

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

Baryon CPV before 2020s: Experiments

- 2017, 3σ evidence in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ [LHCb, Nature Physics]
- 2019, CPV in $\Lambda \rightarrow p\pi$ [BESIII, Nature Physics]
- 2022, CPV in $\Xi^- \rightarrow \Lambda^0\pi^-$ [BESIII, Nature]
- CPV in beauty hadrons are expected to be large, but...
- 2018, CPV in $\Lambda_b^0 \rightarrow p\pi^-, pK^-$ are 1% or even smaller [LHCb, PLB]

$$A_{CP}(\Lambda_b^0 \rightarrow p\pi^-) = (-3.5 \pm 1.7 \pm 2.0) \%, \quad A_{CP}(\Lambda_b^0 \rightarrow pK^-) = (-2.0 \pm 1.3 \pm 1.0) \%$$

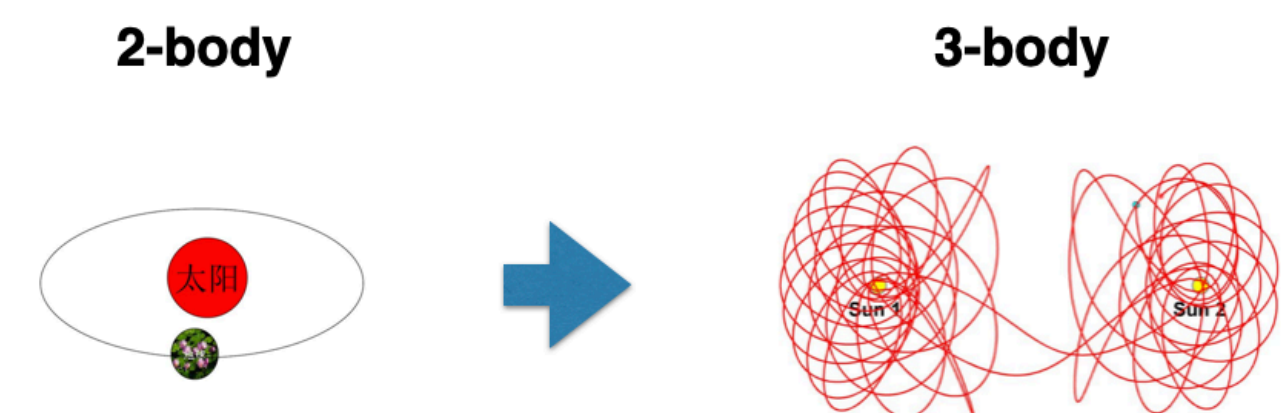
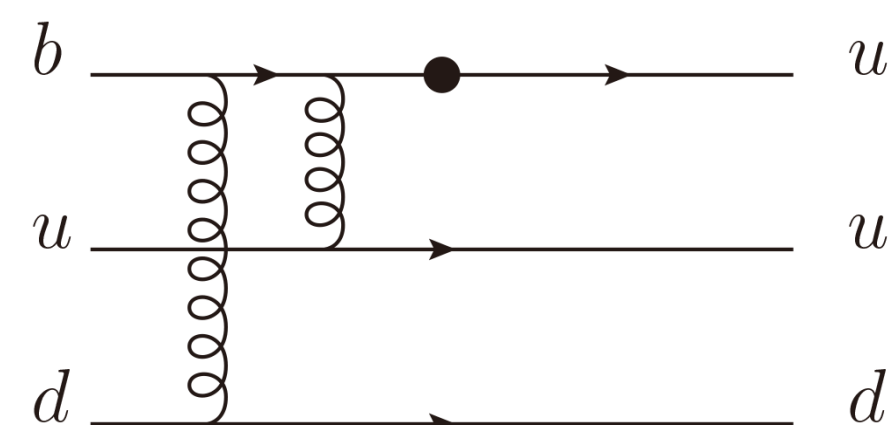
Baryon CPV before 2020: Theory

- **PQCD**: Y.M.Wang, C.D.Lu, et al, 2009
- **Generalized Factorization**: Y.K,Hsiao, C.Q.Geng, 2015, 2017
- **QCDF**: H.W.Ke, Z.T.Wei, 2018

	EXP	GF	PQCD	QCDF
$Br(\Lambda_b \rightarrow p\pi)[\times 10^{-6}]$	4.3 ± 0.8	$4.2_{-0.7}$	$4.66^{+2.22}_{-1.81}$	$4.11 \sim 4.57$
$Br(\Lambda_b \rightarrow pK)[\times 10^{-6}]$	5.1 ± 0.9	$4.8_{-0.7}$	$1.82^{+0.97}_{-1.07}$	$1.70 \sim 3.15$
$A_{CP}(\Lambda_b \rightarrow p\pi)[\%]$	-2.5 ± 2.9	$-3.9_{-0.2}$	-32^{+49}_{-1}	$-3.74 \sim -3.08$
$A_{CP}(\Lambda_b \rightarrow pK)[\%]$	-2.5 ± 2.2	$5.8_{-0.2}$	-3^{+25}_{-4}	$8.1 \sim 11.4$

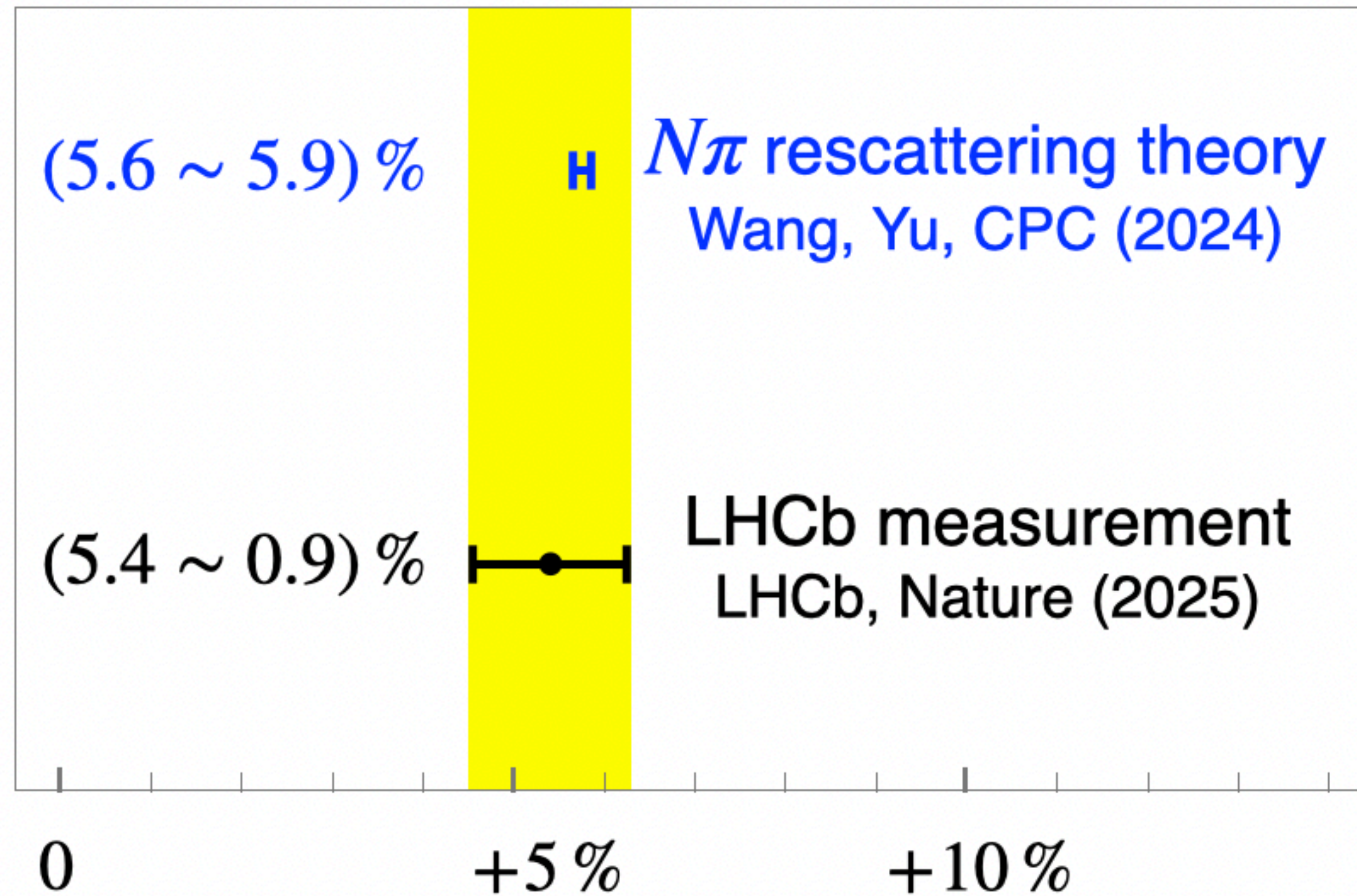
- SCET: **leading-power is one order of magnitude smaller** than the total one
 - Leading power: $\xi_{\Lambda}(0) = -0.012$ [W.Wang, 2011]
 - Total form factor: $\xi_{\Lambda}(0) = 0.18$ [Y.L.Shen, Y.M.Wang, 2016]

• **More is different**



2020s: Baryon CPV

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



2. Dynamics of baryon decays

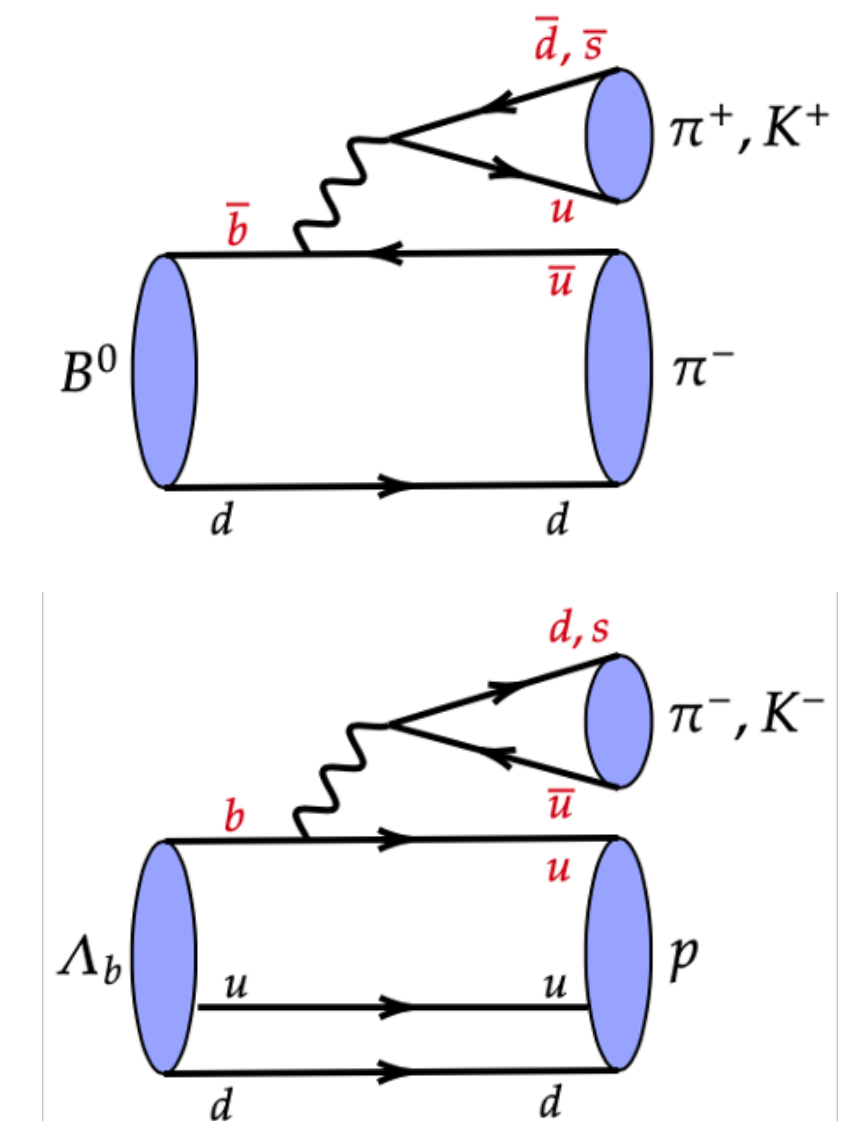
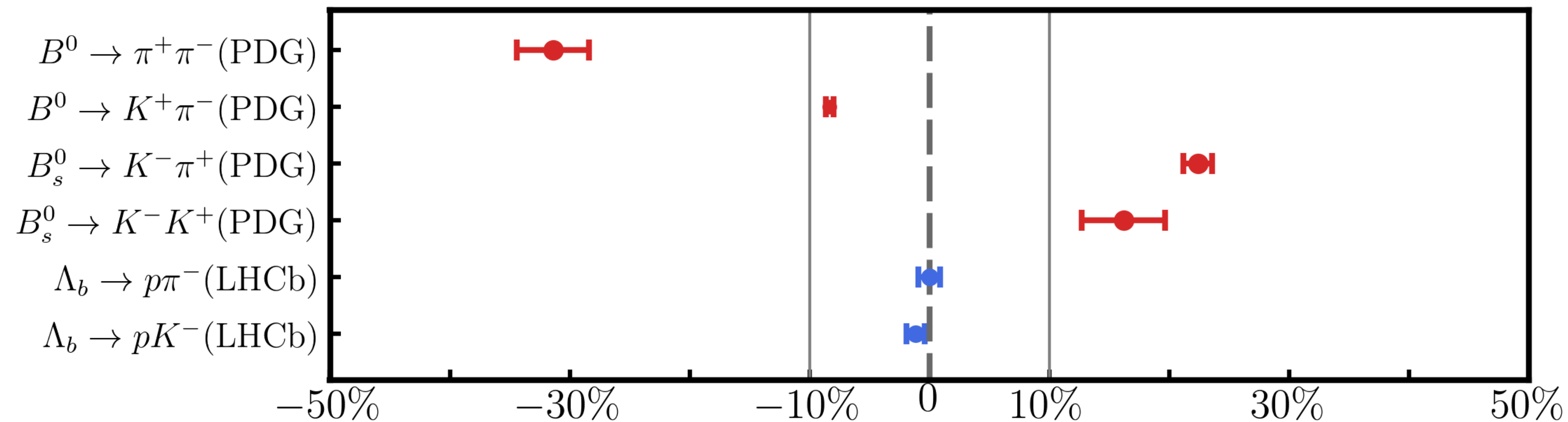
two-body v.s. multi-body

CPV puzzle of b-baryon

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

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

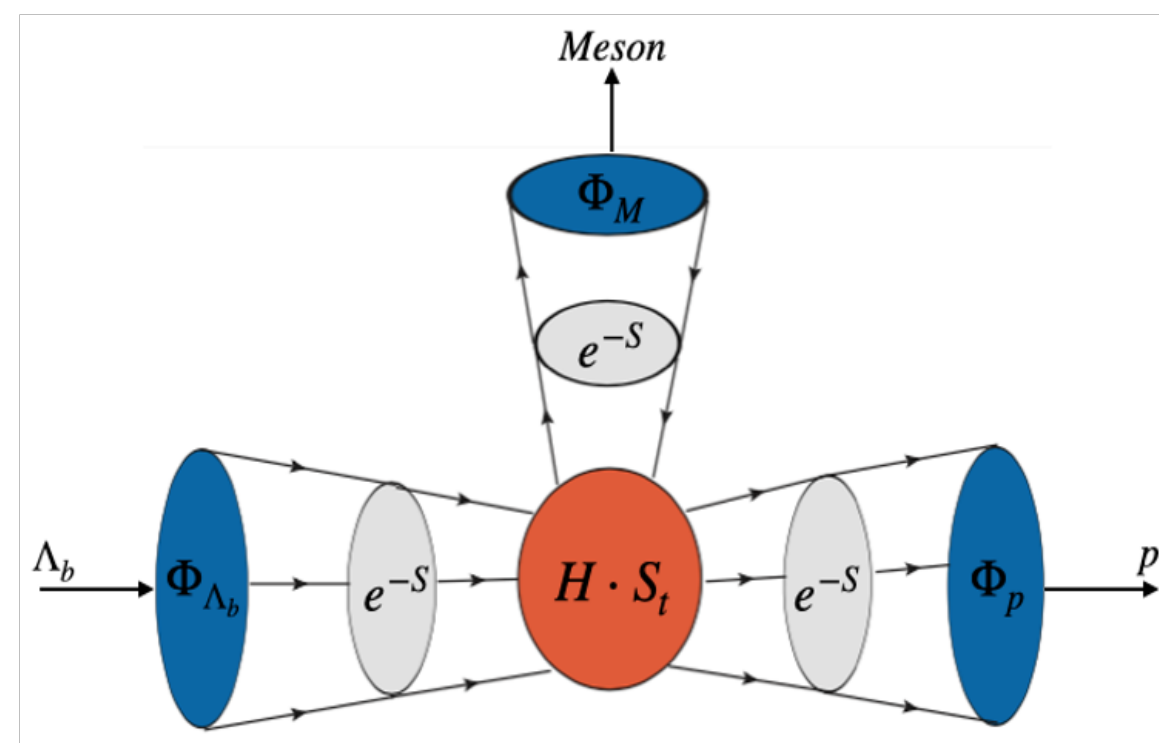
- CPV in some B-meson decays are as large as **10%**:



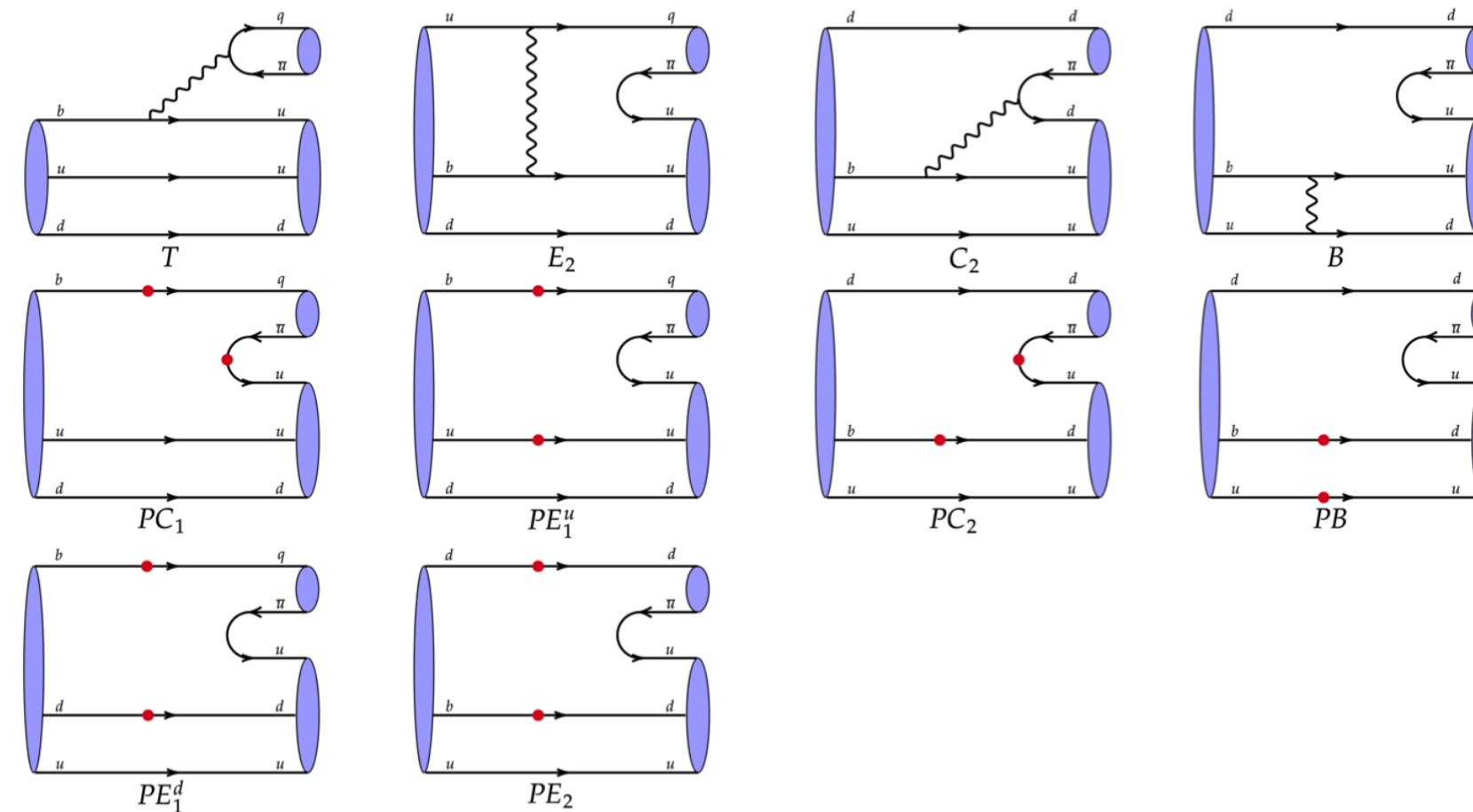
- Whoever starts to study baryonic CPV should solve this problem firstly.

PQCD approach of b-baryon decays

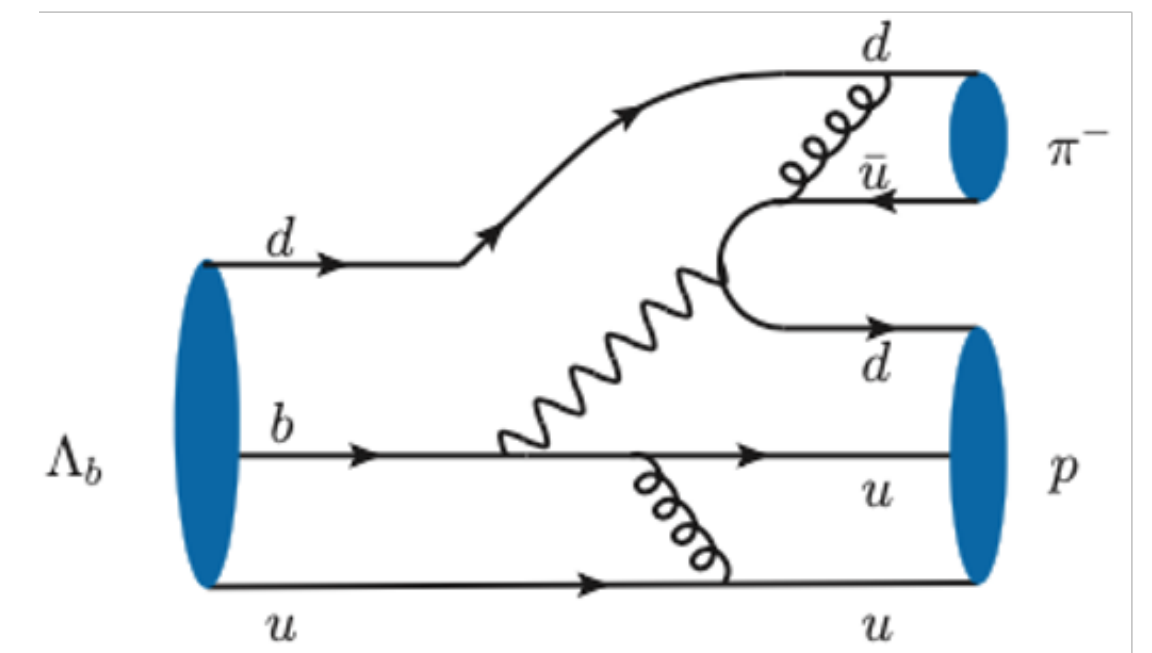
- Based on k_T factorization, avoiding end-point divergence.
- Convolution with hard kernels, distribution amplitudes, and Sudakov factors.
- Can calculate all the topological diagrams.



Illustration



Topological diagrams



Feynman diagram

$\Lambda_b \rightarrow p$ form factors in PQCD

- In 2009, form factors are two orders smaller than LatticeQCD/experiments, considering only the **leading twist** of LCDAs [C.D.Lu, Y.M.Wang, et al, 2009]
- In 2022, results with **high-twist** LCDAs are consistent with Lattice QCD [Han, Li, Li, Shen, Xiao, **FSY**, 2022]. Consistent with power counting by SCET [W.Wang, 2011].

	Lattice/exp	PQCD(2009)	PQCD(2022)
$f_1^{\Lambda_b \rightarrow p}(0)$	0.22 ± 0.08	0.002 ± 0.001	0.27 ± 0.12

	twist-3	twist-4	twist-5	twist-6	total
exponential					
twist-2	0.0007	-0.00007	-0.0005	-0.000003	0.0001
twist-3 ⁺⁻	-0.0001	0.002	0.0004	-0.000004	0.002
twist-3 ⁻⁺	-0.0002	0.0060	0.000004	0.00007	0.006
twist-4	0.01	0.00009	0.25	0.0000007	0.26
total	0.01	0.008	0.25	0.00007	$0.27 \pm 0.09 \pm 0.07$

CPV cancelled between S- and P-waves

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

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

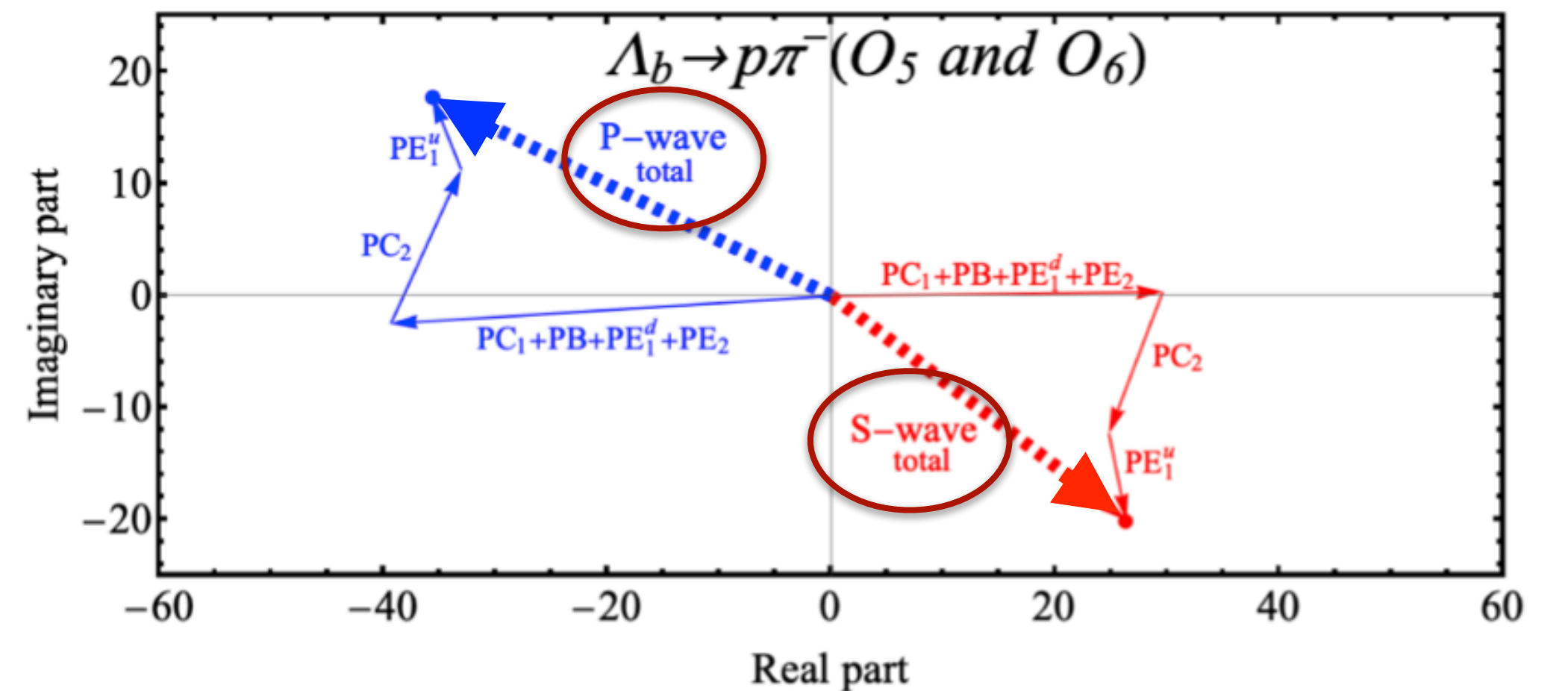
$$\bar{u} \gamma_\mu (1 - \gamma_5) b \bar{d} \gamma^\mu (1 - \gamma_5) u$$

$$\Rightarrow \bar{u}_p (1 + \gamma_5) u_{\Lambda_b} \Rightarrow S_{\mathcal{T}} \approx P_{\mathcal{T}}$$

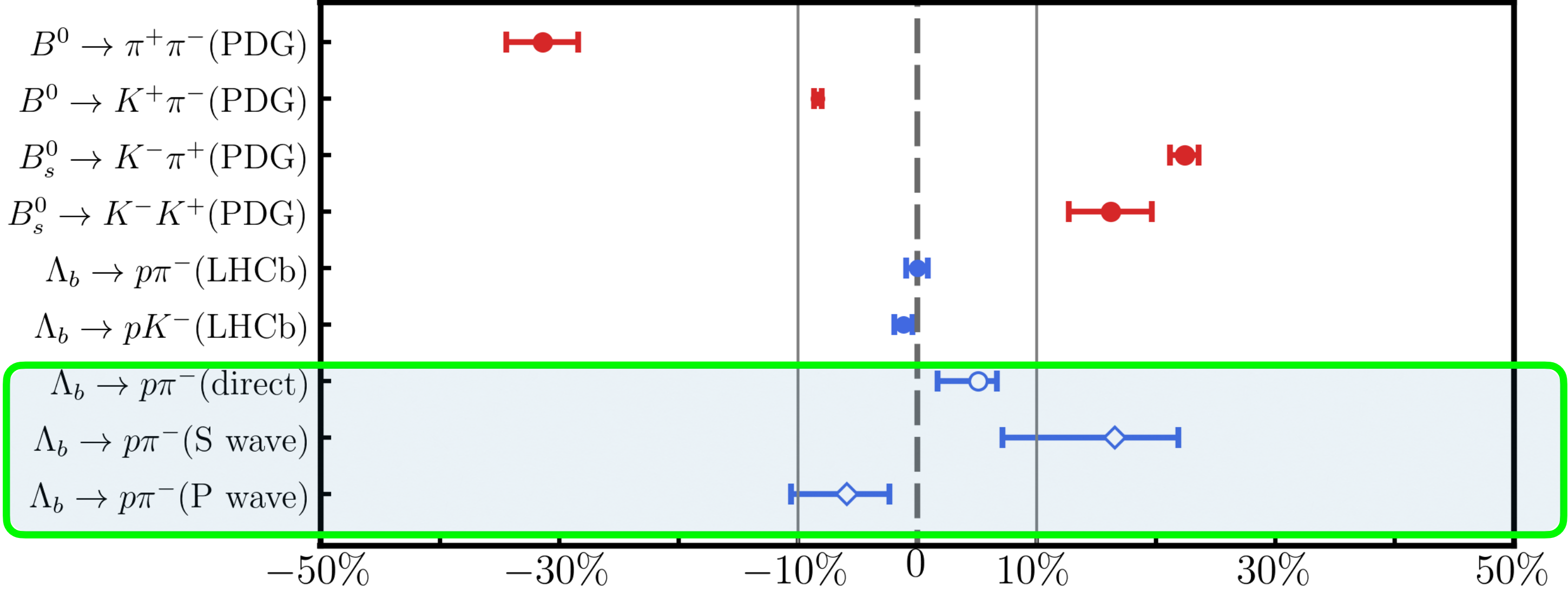
- **Penguin operators:** $(V - A)(V + A)$

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

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



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:

Nature 643, 1223
(2025)

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 cancel³⁸. This discovery of

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

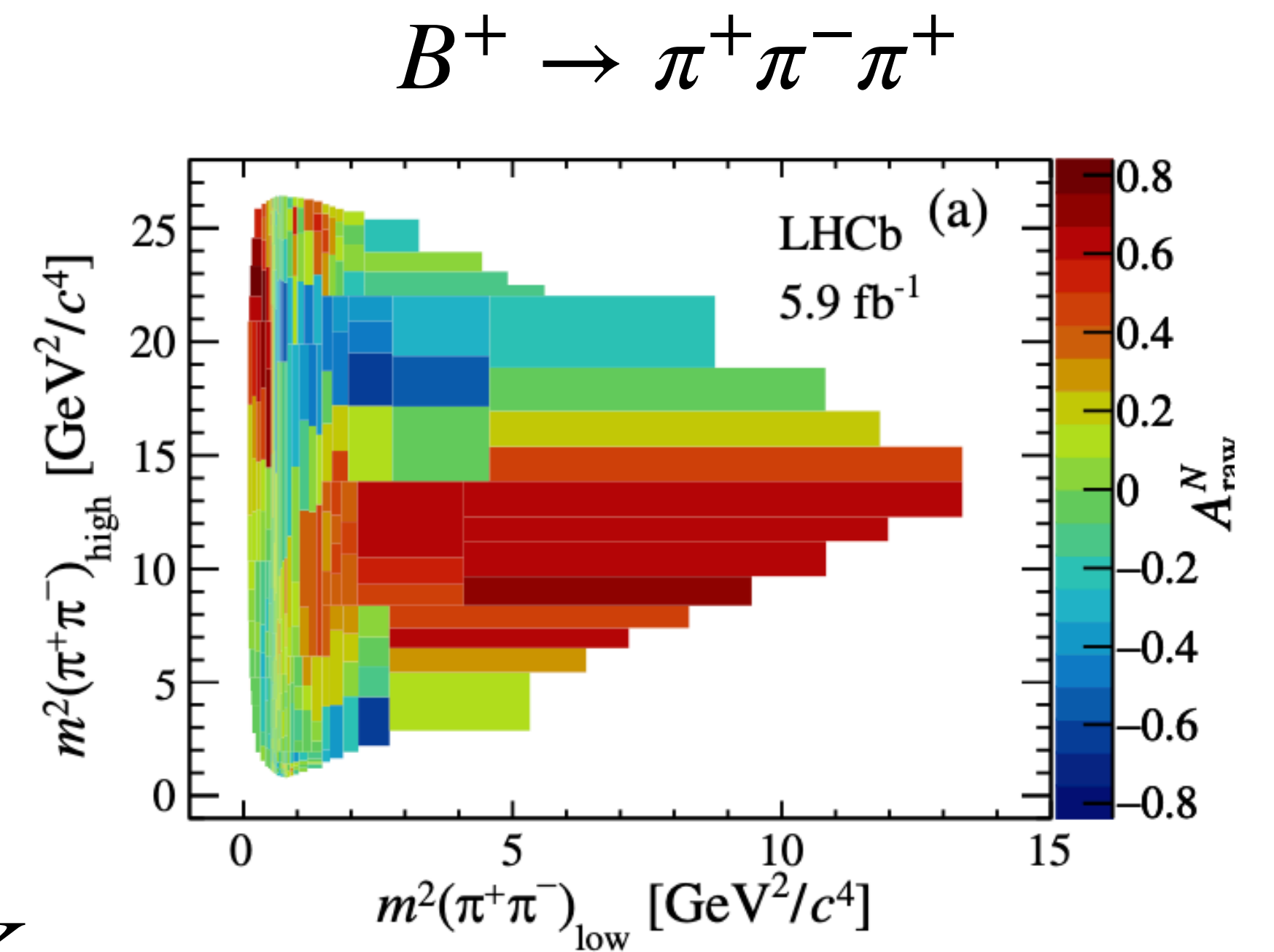
Multi-body decays

- 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.

$$\begin{aligned} \mathcal{A}_{B^+ \rightarrow K^+ K^- \pi^+} &= -0.115 \pm 0.008, \\ \mathcal{A}_{B^+ \rightarrow K^+ K^- K^+} &= -0.0365 \pm 0.0036, \\ \mathcal{A}_{B^+ \rightarrow \pi^+ \pi^- \pi^+} &= 0.076 \pm 0.005, \end{aligned}$$

- Large regional CPV: Promising to measure CPV in some regions.

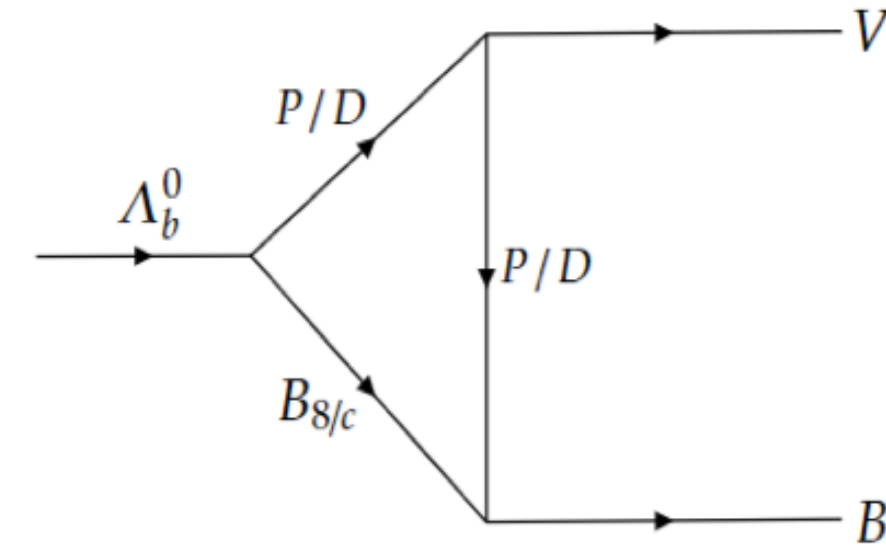
- Large data samples in $\Lambda_b^0 \rightarrow p h^- h^+ h^-, h = \pi, K$



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/>

— 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.

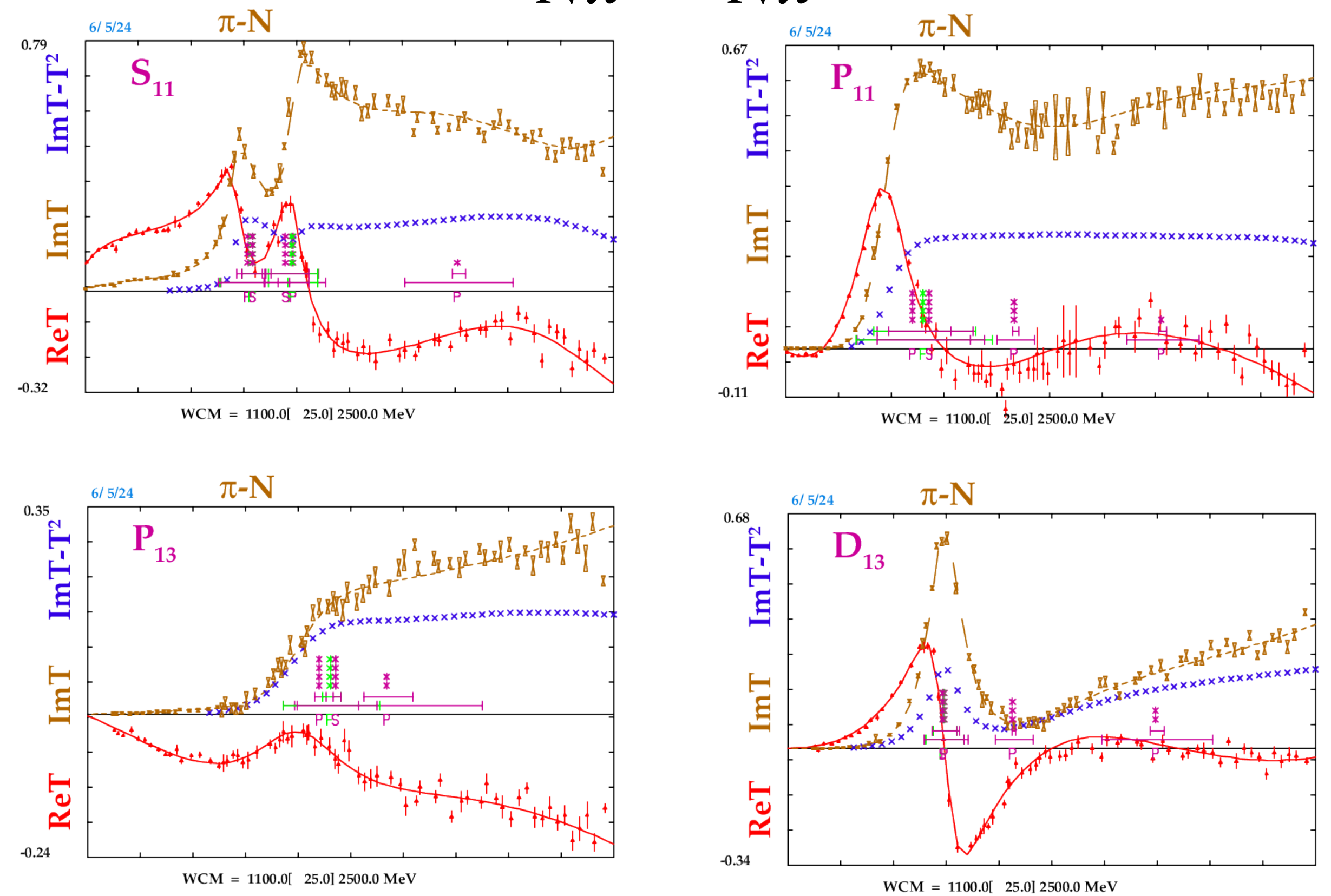
Instructions for Using the Partial-Wave Analyses

The programs accessible with the left-hand side navigation t available through the SAID program. Contact a member of c 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. Extrapc
Increments: The programs will not allow an arbitrary numb

$N\pi \rightarrow N\pi$

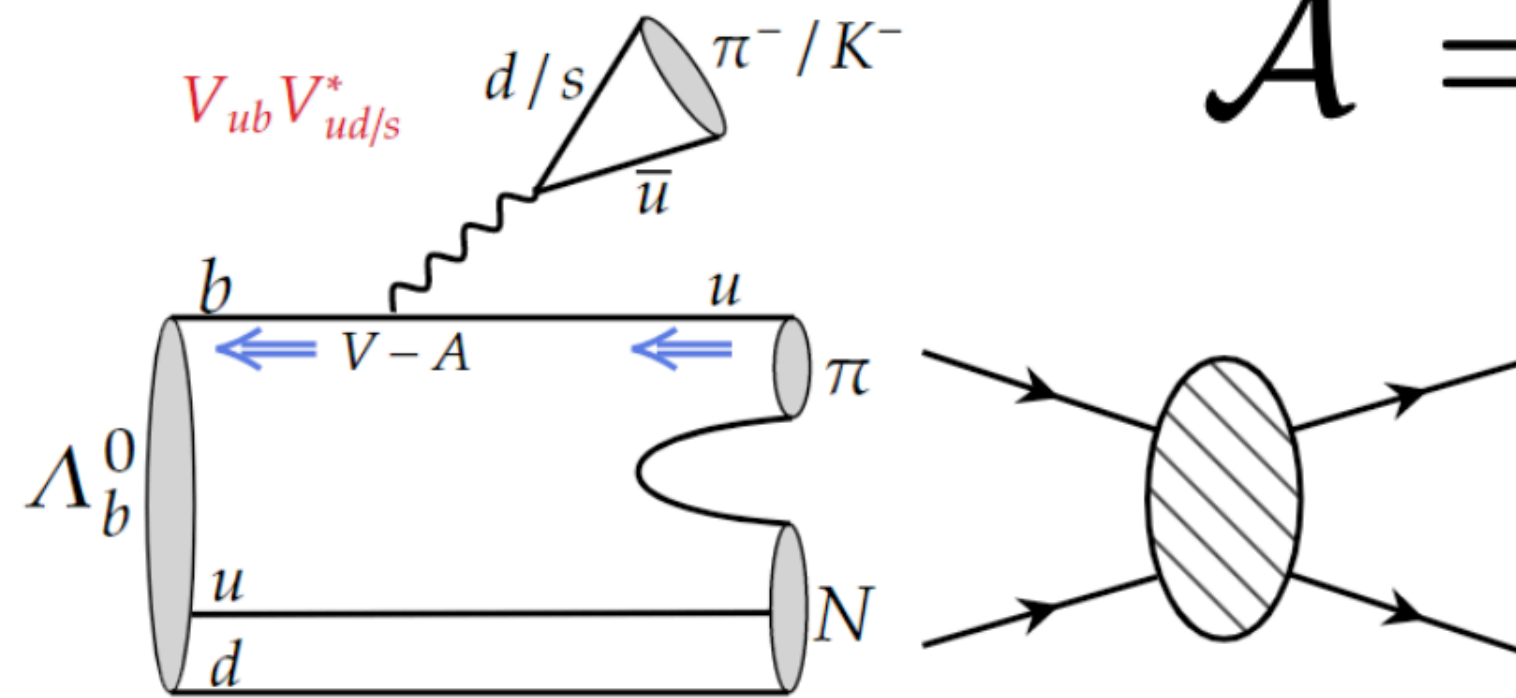


- Partial-wave amplitudes with strong phases!
- Data driven, **model independent**. Circumvent N^* , more precise strong phases.

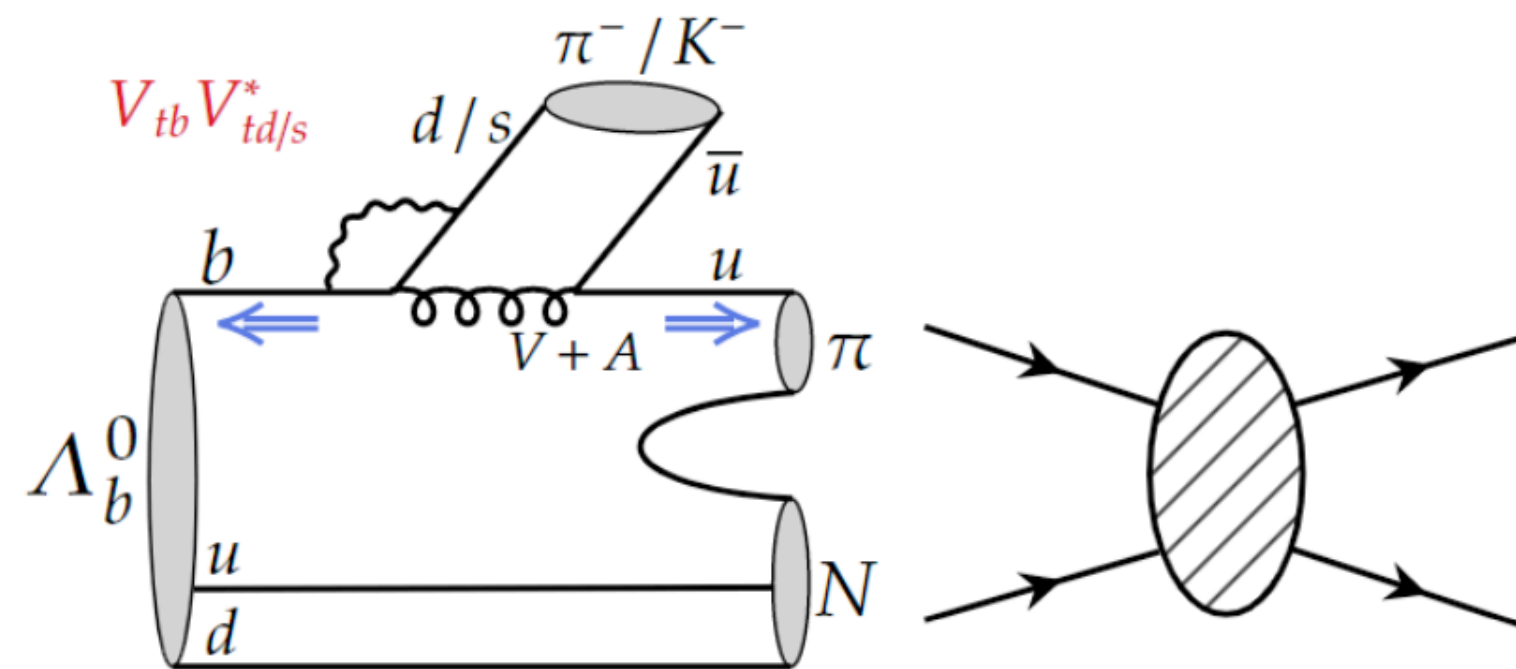
CPV via $N\pi$ rescatterings

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

•Tree:



•Penguin:



- Different chirality
- ➔ different helicity
- ➔ different partial waves
- ➔ PWA interference
- ➔ difference of strong phases
- ➔ **CPV**

•Short-distance weak decays

•weak phases

•Long-distance

$N\pi \rightarrow N\pi, N\pi\pi$

•strong phases

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

CPV with $N\pi$ scatterings

decay processes	Scenarios	global CPV	CPV of $\cos\theta < 0$	CPV of $\cos\theta > 0$
$N\pi \rightarrow \Delta^{++}\pi^-$ $m_{N\pi} \in [1.2, 1.9]\text{GeV}$	S1	5.9%	8.0%	3.6%
	$\Lambda_b^0 \rightarrow (\Delta^{++}\pi^-)K^-$ S2	5.8%	6.3%	5.3%
	$\rightarrow (p\pi^+\pi^-)K^-$ S3	5.6%	4.3%	7.0%
$N\pi \rightarrow \Delta^{++}\pi^-$ $m_{N\pi} \in [1.2, 1.9]\text{GeV}$	S1	-4.1%	-5.4%	-2.4%
	$\Lambda_b^0 \rightarrow (\Delta^{++}\pi^-)\pi^-$ S2	-3.9%	-3.9%	-3.9%
	S3	-3.6%	-2.3%	-5.3%
$N\pi \rightarrow p\pi^0$ $m_{N\pi} \in [1.1, 2.5]\text{GeV}$	S1	5.8%	8.2%	2.7%
	$\Lambda_b^0 \rightarrow (p\pi^0)K^-$ S2	5.8%	8.0%	3.0%
	S3	5.8%	7.8%	3.3%
$N\pi \rightarrow p\pi^0$ $m_{N\pi} \in [1.1, 2.5]\text{GeV}$	S1	-3.9%	-3.9%	-3.7%
	$\Lambda_b^0 \rightarrow (p\pi^0)\pi^-$ 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: $f_1 = 0.9$, $g_1 = 1.1$

CPV with $N\pi$ scatterings

July, 2024

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

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

•LHCb:

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

March, 2025

using scattering data to extract the hadronic amplitude²⁹. An estimate of the CP asymmetry in $\Lambda_b^0 \rightarrow R(p\pi^+\pi^-)K^-$ decays made by applying this method using π -nucleon scattering data³⁷ aligns with the measurement in this work²⁹.

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

2503.16954
(Nature)

CPV with $N\pi$ scatterings

July, 2024

decay processes	Scenarios	global CPV	CPV of $\cos\theta < 0$	CPV of $\cos\theta > 0$
$\Lambda_b^0 \rightarrow (\Delta^{++}\pi^-)K^-$ $\rightarrow (p\pi^+\pi^-)K^-$	S1	5.9%	8.0%	3.6%
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J.P.Wang, **FSY**, CPC48,101002(2024)[arXiv:2407.04110]

•LHCb:

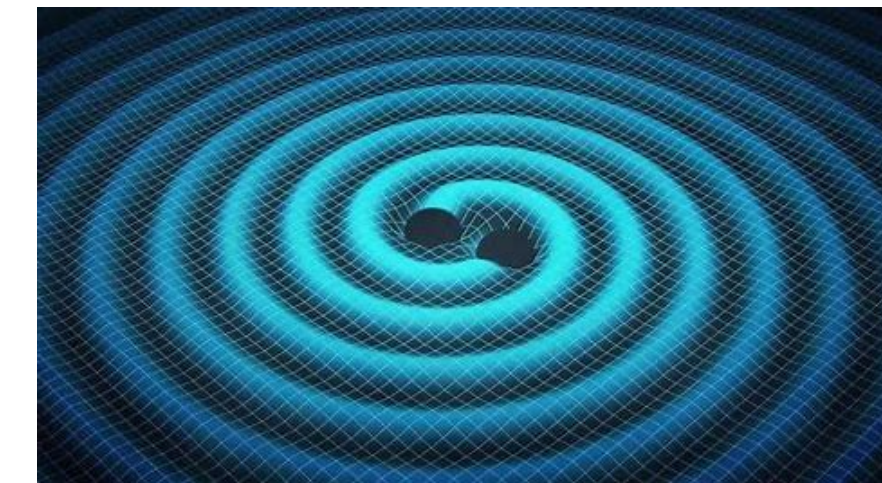
$\Lambda_b^0 \rightarrow R(p\pi^+\pi^-)K^-$ $m_{p\pi^+\pi^-} < 2.7$ $(5.4 \pm 0.9 \pm 0.1)\%$ 6.0σ

March, 2025

This is not the end, but a beginning...

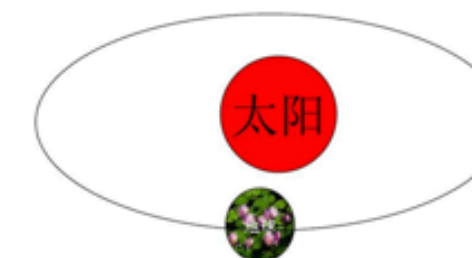
New horizon

- Observation of gravitational waves
 - => not only confirm the General Relativity,
 - => but also open the Multi-messenger era of cosmology.

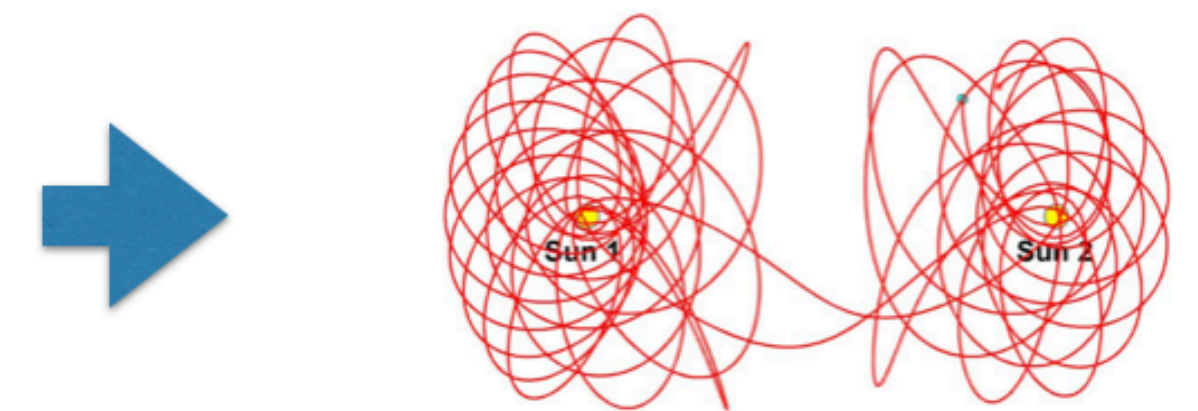


- Meson \rightarrow Baryon : More is different.
- New QCD dynamics: exclusive baryon.
- High power dominated, partial-wave CPV destruction, $N\pi$ rescatterings

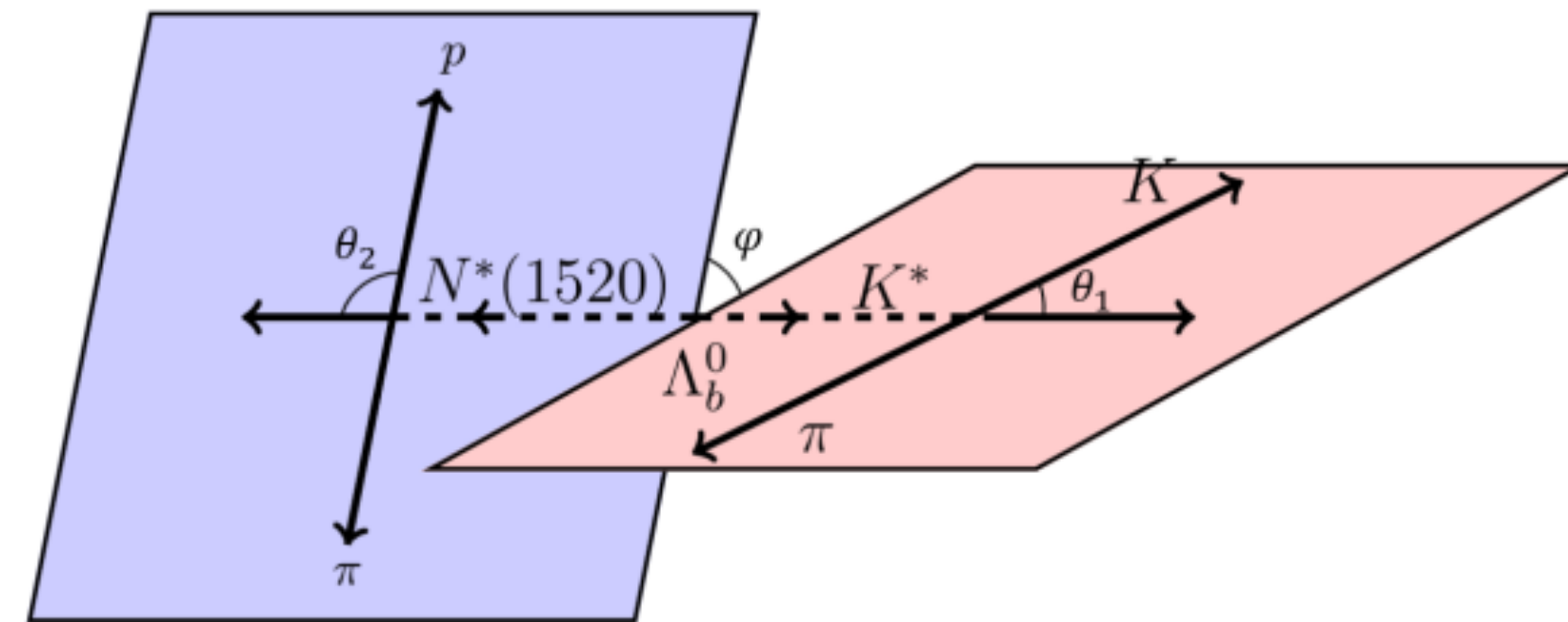
2-body



3-body



3. Multi-dimensional Probes



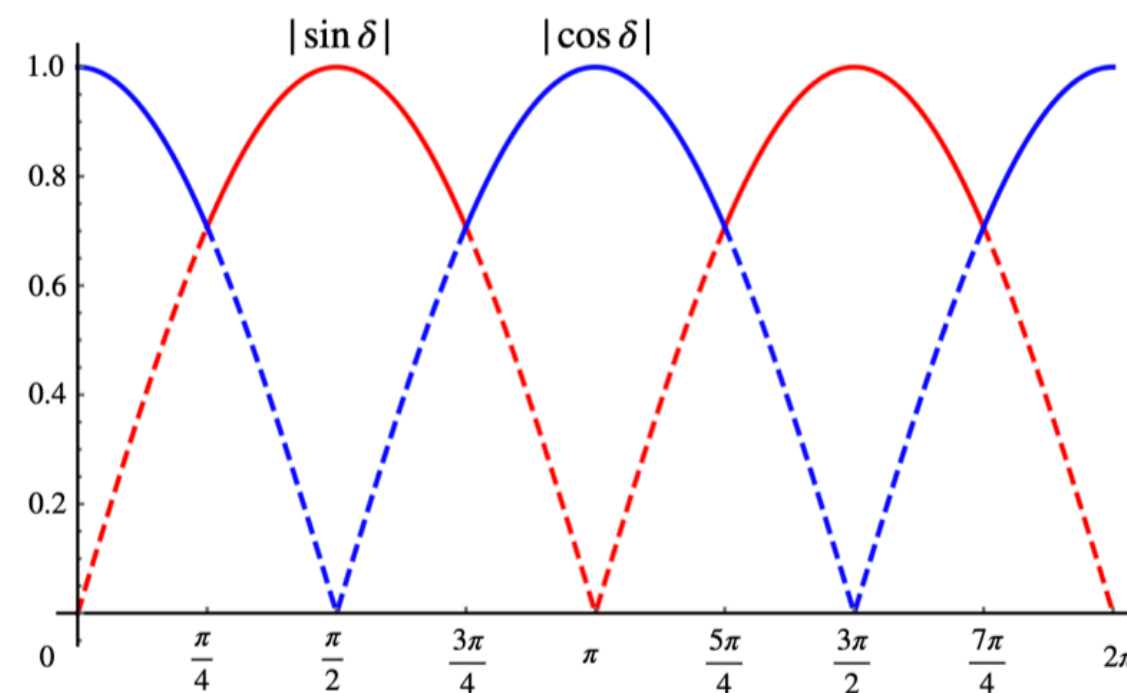
Observables

- 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 $\Lambda \rightarrow p\pi$ [Lee, Yang, 1957]
It was found that $a_{CP}^{\beta} \propto \beta + \bar{\beta} \propto \cos \delta_s \sin \phi_w$ [Donoghue, He, Pakvasa, 1985]
- Time-reversal asymmetries in $\Lambda_b \rightarrow \Lambda V$ [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, $UQ_-U^\dagger = Q_-$

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

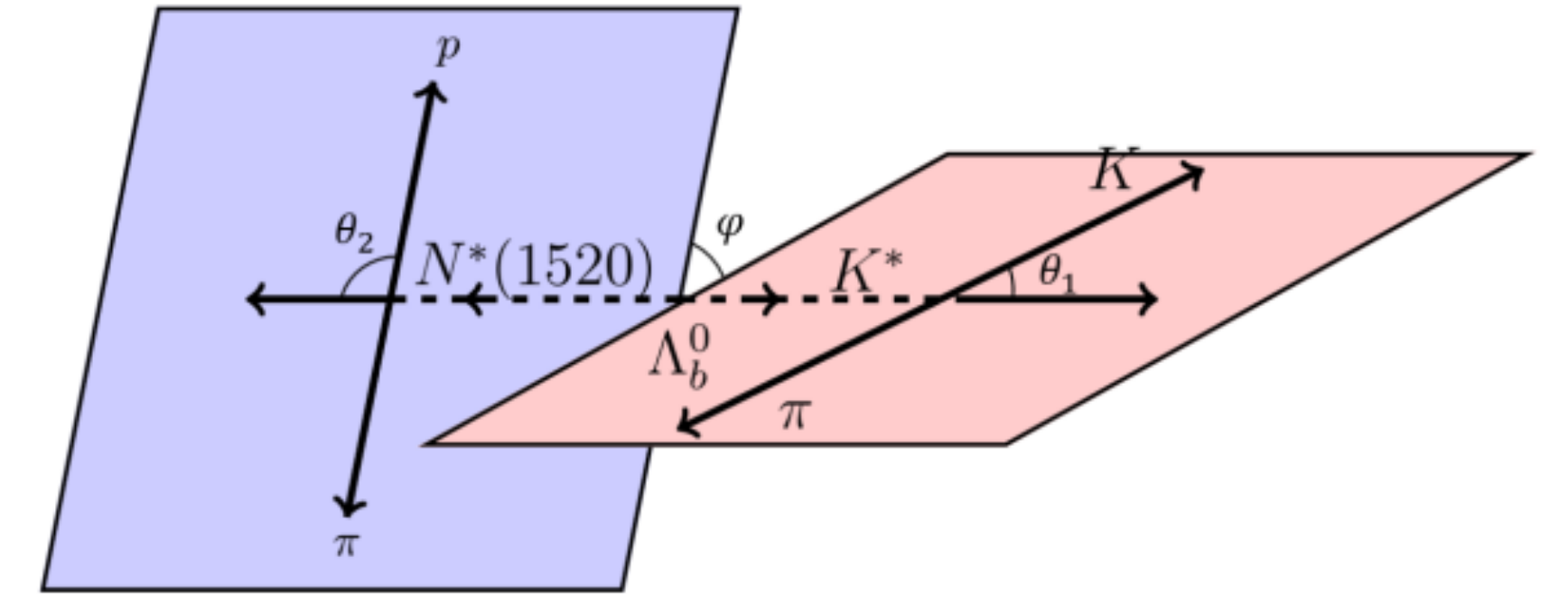
$$a_{CP}^{\text{T-even}} \propto \sum_{m,n} \text{Re}(A_m^* A_n - \bar{A}_m^* \bar{A}_n) \propto \sin \delta_s \sin \phi_w$$

Complementary

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

Complementary in angular distributions

$$\begin{aligned} \frac{d\Gamma}{dc_1 dc_2 d\varphi} \propto & - \frac{s_1^2 s_2^2}{\sqrt{3}} \text{Im} \left(\mathcal{H}_{+1,+\frac{3}{2}} \mathcal{H}_{-1,-\frac{1}{2}}^* + \mathcal{H}_{+1,+\frac{1}{2}} \mathcal{H}_{-1,-\frac{3}{2}}^* \right) \sin 2\varphi \\ & + \frac{s_1^2 s_2^2}{\sqrt{3}} \text{Re} \left(\mathcal{H}_{+1,+\frac{3}{2}} \mathcal{H}_{-1,-\frac{1}{2}}^* + \mathcal{H}_{+1,+\frac{1}{2}} \mathcal{H}_{-1,-\frac{3}{2}}^* \right) \cos 2\varphi \\ & - \frac{4s_1 c_1 s_2 c_2}{\sqrt{6}} \text{Im} \left(\mathcal{H}_{+1,+\frac{3}{2}} \mathcal{H}_{0,+\frac{1}{2}}^* + \mathcal{H}_{0,-\frac{1}{2}} \mathcal{H}_{-1,-\frac{3}{2}}^* \right) \sin \varphi \\ & + \frac{4s_1 c_1 s_2 c_2}{\sqrt{6}} \text{Re} \left(\mathcal{H}_{+1,+\frac{3}{2}} \mathcal{H}_{0,+\frac{1}{2}}^* + \mathcal{H}_{0,-\frac{1}{2}} \mathcal{H}_{-1,-\frac{3}{2}}^* \right) \cos \varphi \end{aligned}$$



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

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

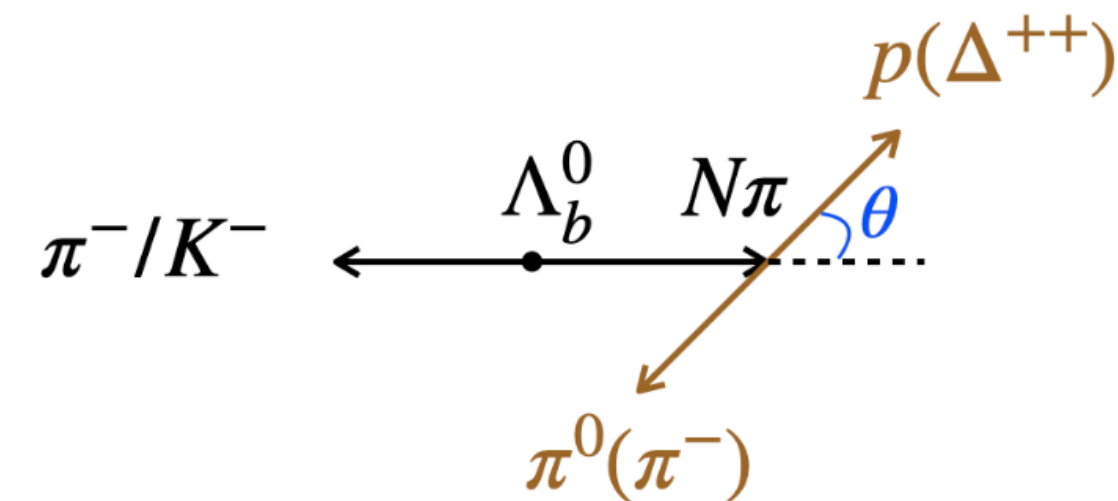
$$\sin 2\varphi = 2 \sin \varphi \cos \varphi \propto [(\vec{p}_1 \times \vec{p}_2) \cdot (\vec{p}_3 \times \vec{p}_4)][(\vec{p}_1 \times \vec{p}_2) \cdot \vec{p}_4].$$

- 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.

CPV of Legendre moments

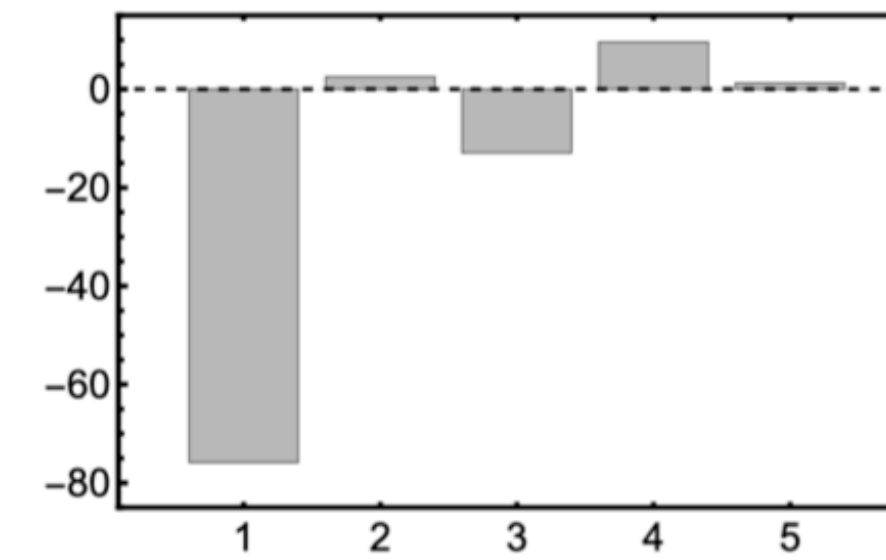
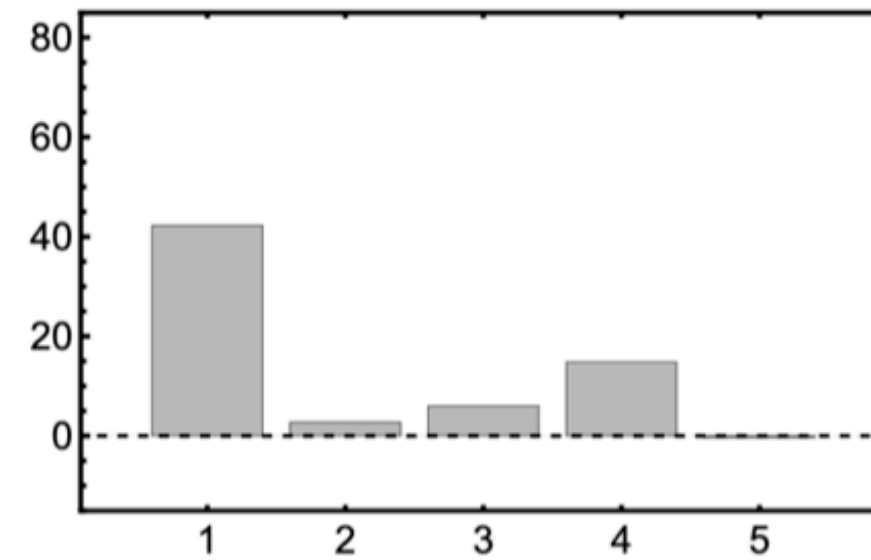
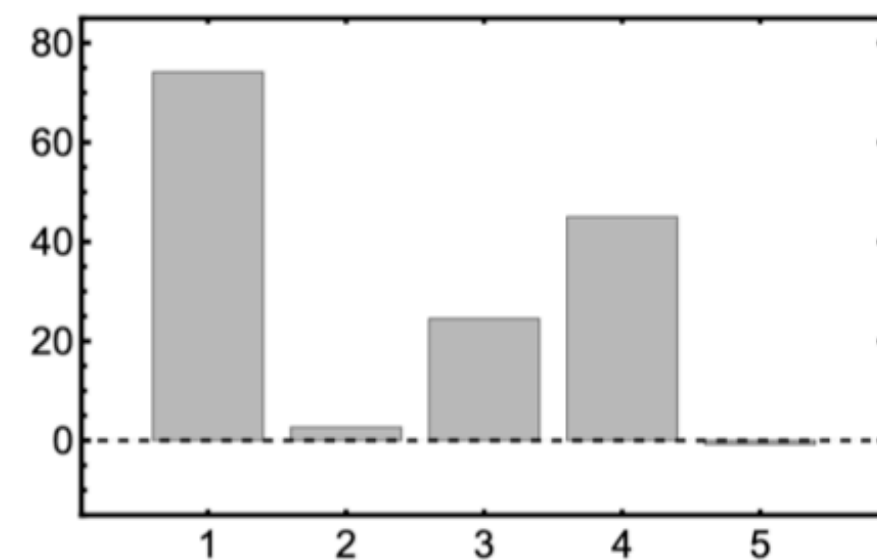
- Partial wave CPV based on the Legendre decomposition [Z.H.Zhang, X.H.Guo, 2021,2025]

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



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

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



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.

$$\Lambda_b^0 \rightarrow p a_1(\rightarrow \pi\pi\pi) \quad \Lambda_b^0 \rightarrow p K_1(\rightarrow K\pi\pi)$$

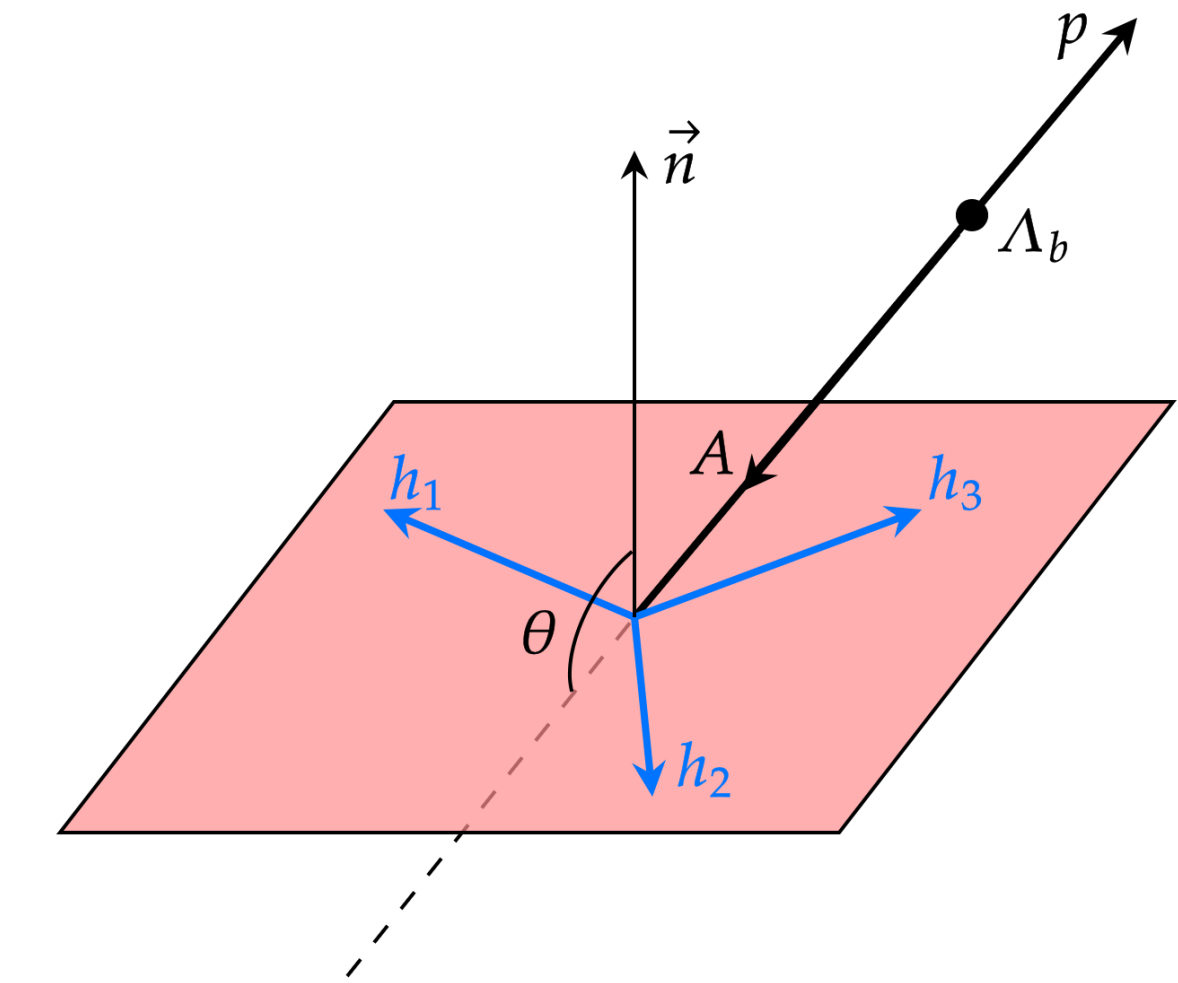
$$\frac{d\Gamma}{d\cos\theta} \supset R \operatorname{Re}(S^T P_2^*) \cos\theta$$

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

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

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)



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

Summary

- Baryon CPV is now firstly observed in $\Lambda_b \rightarrow pK^- \pi^+ \pi^-$
- 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

Thank you!

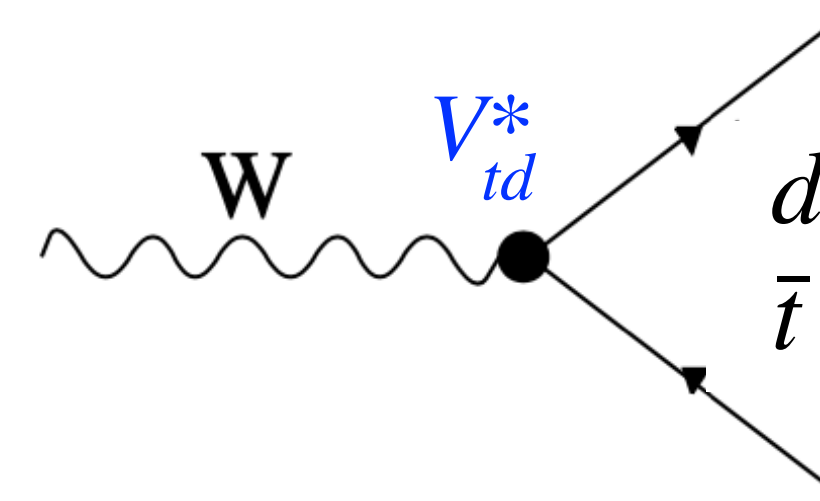
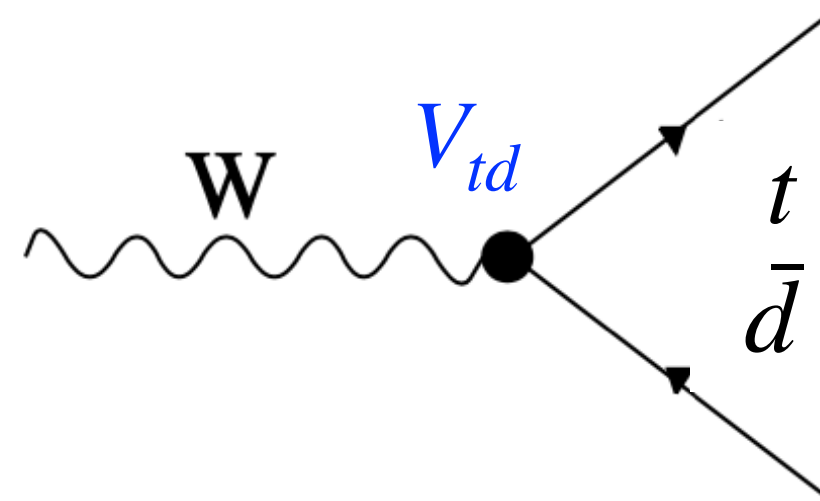
Backups

CPV from the Kobayashi-Maskawa mechanism

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

$$V_{CKM} \neq V_{CKM}^*$$

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



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

CPV in measurements

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

$$V_{CKM} \leftrightarrow V_{CKM}^*$$

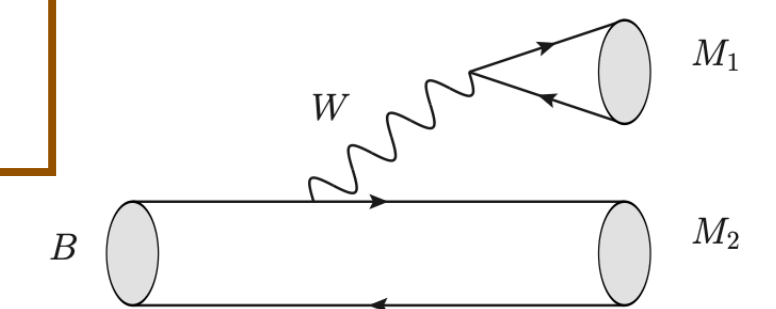
$$A_f = |a_1|e^{i(\delta_1 + \phi_1)} + |a_2|e^{i(\delta_2 + \phi_2)}$$

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

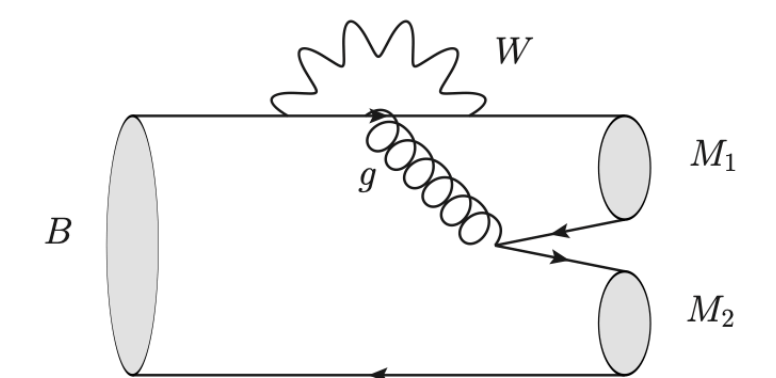
$$\bar{A}_{\bar{f}} = |a_1|e^{i(\delta_1 - \phi_1)} + |a_2|e^{i(\delta_2 - \phi_2)}$$

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

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

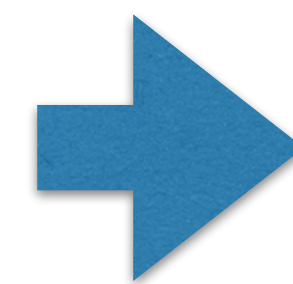


(a) T



(c) P, P_{EW}^C

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



Tree + Penguin

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

	A_{CP}^{dir}	$A_{CP}^{S\text{-wave}}(\kappa_S)$	$A_{CP}^{P\text{-wave}}(\kappa_P)$	A_{CP}^α	A_{CP}^β	A_{CP}^γ
$\Lambda_b \rightarrow p\pi^-$	$0.05^{+0.02}_{-0.03}$	$0.17^{+0.05}_{-0.09}$ (49%)	$-0.06^{+0.04}_{-0.05}$ (51%)	$0.02^{+0.01}_{-0.02}$	$0.22^{+0.08}_{-0.05}$	$0.11^{+0.05}_{-0.06}$
$\Lambda_b \rightarrow pK^-$	$-0.06^{+0.03}_{-0.02}$	$-0.05^{+0.05}_{-0.04}$ (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}^{dir}	$A_{CP}^{S^T\text{-wave}}(\kappa_{ST})$	$A_{CP}^{(D+S^L)\text{-wave}}(\kappa_{D+SL})$	$A_{CP}^{P_1\text{-wave}}(\kappa_{P_1})$	$A_{CP}^{P_2\text{-wave}}(\kappa_{P_2})$	$A_{CP}^{\mathcal{J}}$
$\Lambda_b \rightarrow p\rho^-$	$0.03^{+0.03}_{-0.05}$	$0.01^{+0.01}_{-0.04}$ (7%)	$0.02^{+0.07}_{-0.03}$ (44%)	$0.03^{+0.04}_{-0.12}$ (45%)	$0.17^{+0.04}_{-0.06}$ (4%)	$-0.01^{+0.01}_{-0.01}$
$\Lambda_b \rightarrow pK^{*-}$	$-0.05^{+0.10}_{-0.16}$	$-0.15^{+0.12}_{-0.06}$ (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}^{dir}	$A_{CP}^{S^T\text{-wave}}(\kappa_{ST})$	$A_{CP}^{(D+S^L)\text{-wave}}(\kappa_{D+SL})$	$A_{CP}^{P_1\text{-wave}}(\kappa_{P_1})$	$A_{CP}^{P_2\text{-wave}}(\kappa_{P_2})$	A_{CP}^{UD}
$\Lambda_b \rightarrow pa_1^-(1260)$	$-0.01^{+0.04}_{-0.03}$	$-0.22^{+0.10}_{-0.10}$ (6%)	$-0.11^{+0.03}_{-0.07}$ (46%)	$0.18^{+0.11}_{-0.06}$ (40%)	$-0.24^{+0.07}_{-0.13}$ (8%)	$-0.24^{+0.08}_{-0.13}$
$\Lambda_b \rightarrow pK_1^-(1270)$ ($\theta_K = 30^\circ$)	$0.09^{+0.08}_{-0.05}$	$0.34^{+0.02}_{-0.06}$ (8%)	$-0.11^{+0.12}_{-0.08}$ (42%)	$0.19^{+0.17}_{-0.15}$ (42%)	$0.33^{+0.04}_{-0.05}$ (8%)	$0.26^{+0.04}_{-0.10}$
$\Lambda_b \rightarrow pK_1^-(1270)$ ($\theta_K = 60^\circ$)	$0.07^{+0.05}_{-0.06}$	$0.46^{+0.02}_{-0.09}$ (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, $\Lambda_b \rightarrow pP, pV, pA$