Theoretical Overview of CP Violation in Hadron Decays

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味物理讲座 @ Sanya, 2026.02.02

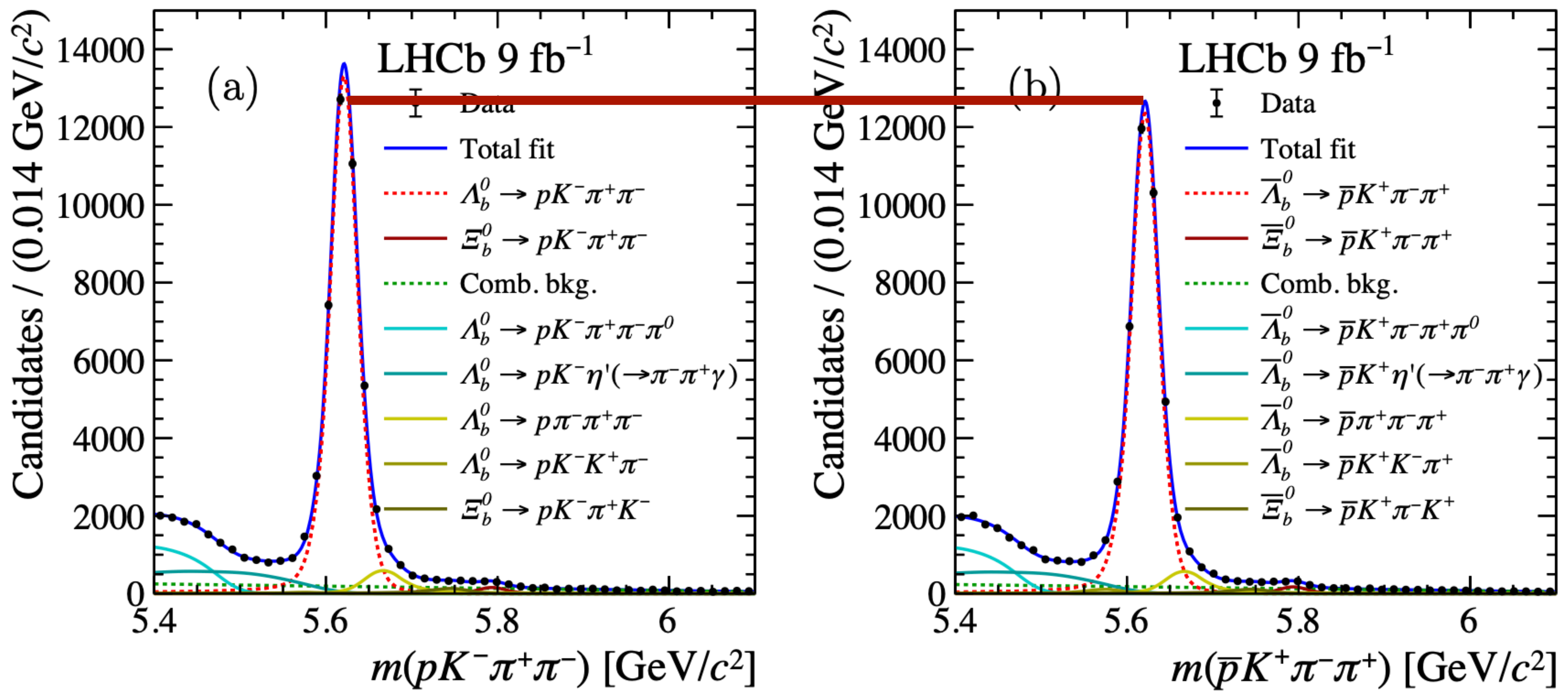
1. Introduction on CP Violation

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

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

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

$$5.2\sigma$$



LHCb, Nature [arXiv: 2503.16954]

More interesting CP violation

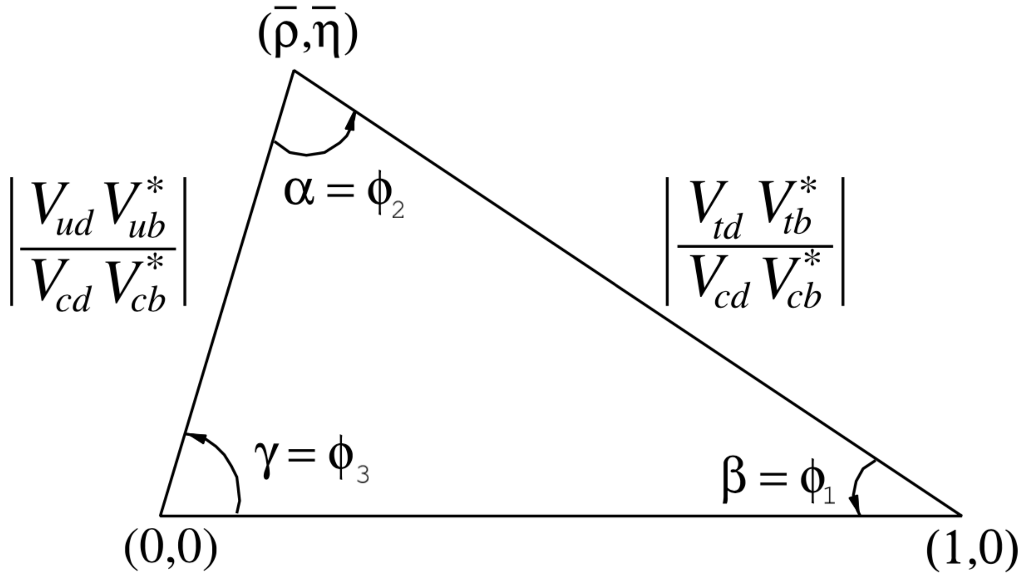
Regional CPV

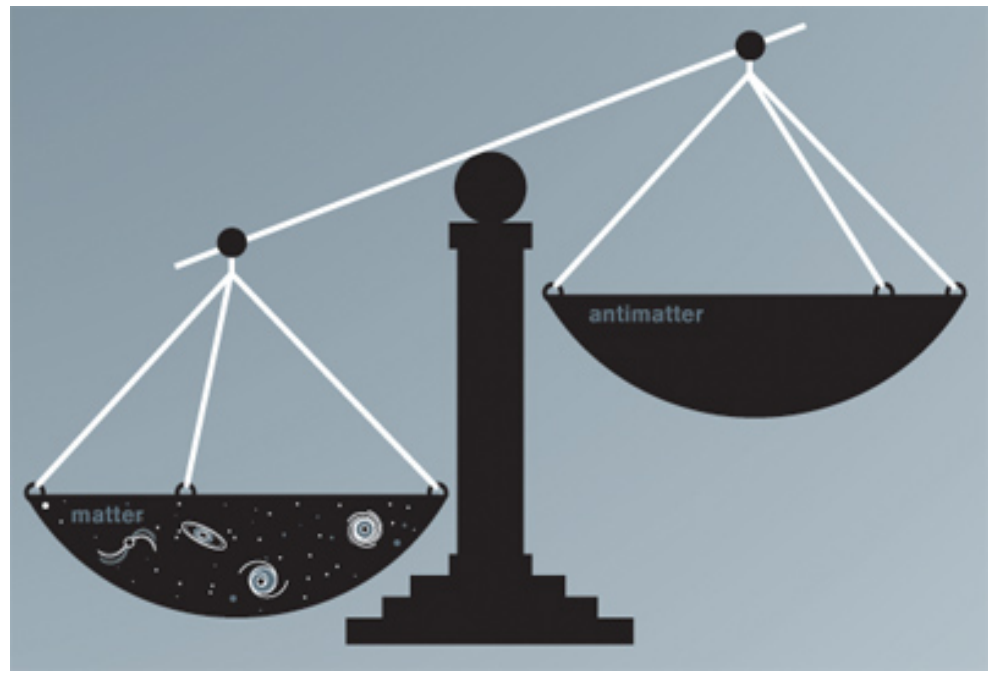
Decay topology	Mass region (GeV/c^2)	$\mathcal{A}_{CP}$	
$\Lambda_b^0 \to R(pK^-)R(\pi^+\pi^-)$	$m_{pK^-} < 2.2$ $m_{\pi^+\pi^-} < 1.1$	$(5.3 \pm 1.3 \pm 0.2)\%$	4.0σ
$\Lambda_b^0 \to R(p\pi^-)R(K^-\pi^+)$	$m_{p\pi^-} < 1.7$ $0.8 < m_{\pi^+K^-} < 1.0$ or $1.1 < m_{\pi^+K^-} < 1.6$	$(2.7 \pm 0.8 \pm 0.1)\%$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

LHCb, Nature [arXiv: 2503.16954]

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.



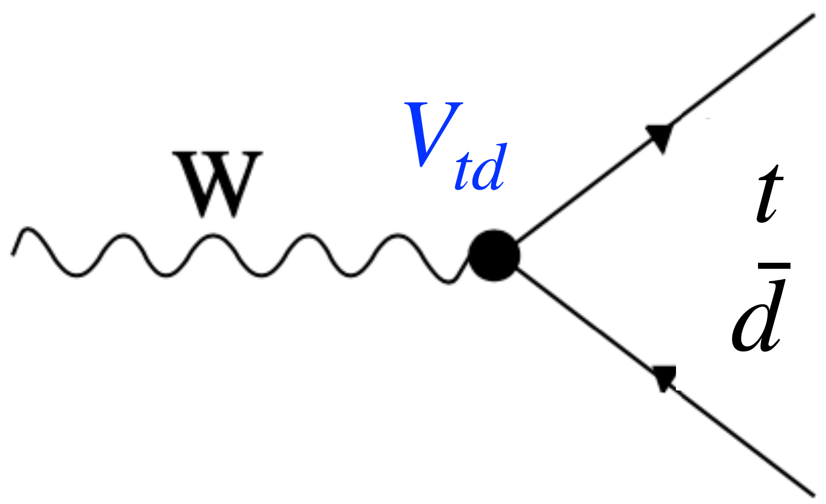


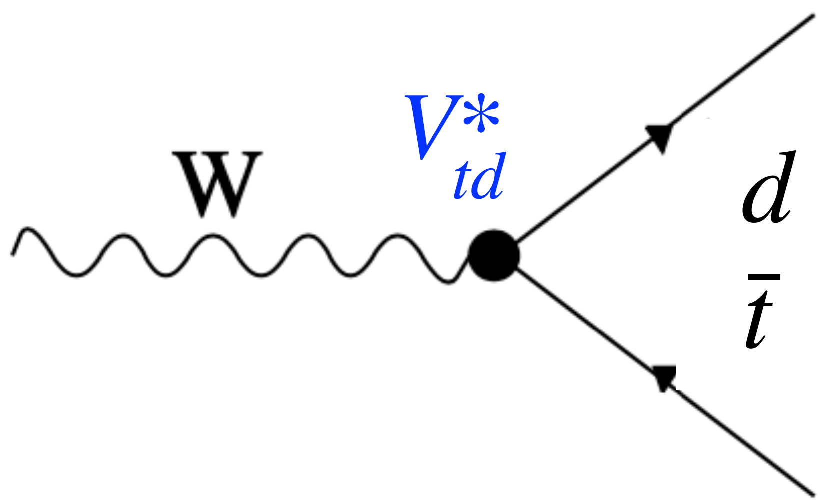
CPV from the Kobayashi-Maskawa mechanism

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

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

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





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

CPV in measurements

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

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

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

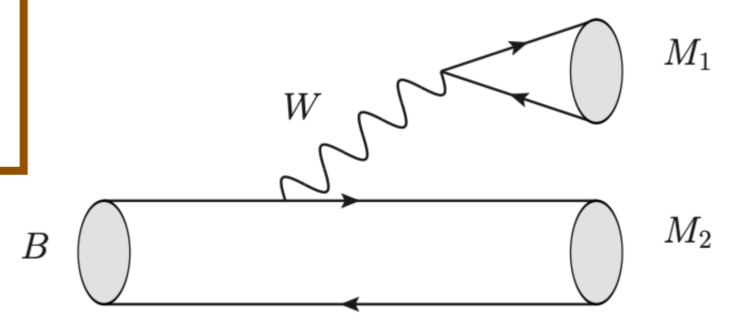
$\phi_{1,2}$: weak phases, flip signs under $A_f \leftrightarrow \overline{A}_{\bar{f}}$

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

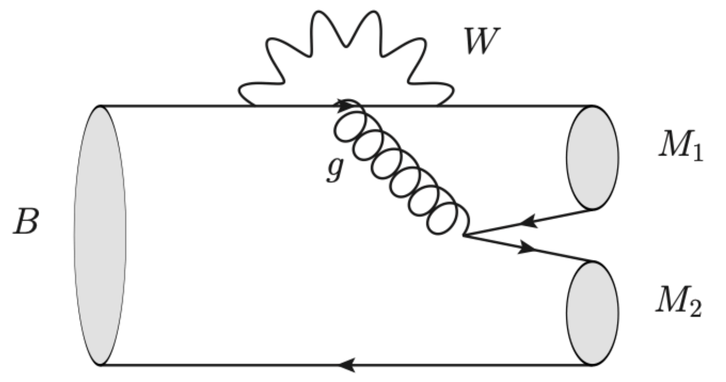
$$A_{CP} = -\frac{2|a_1 a_2|\sin(\delta_2-\delta_1)\sin(\phi_2-\phi_1)}{|a_1|^2+|a_2|^2+2|a_1 a_2|\cos(\delta_2-\delta_1)\cos(\phi_2-\phi_1)}$$

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

→ Tree + Penguin



(a) T

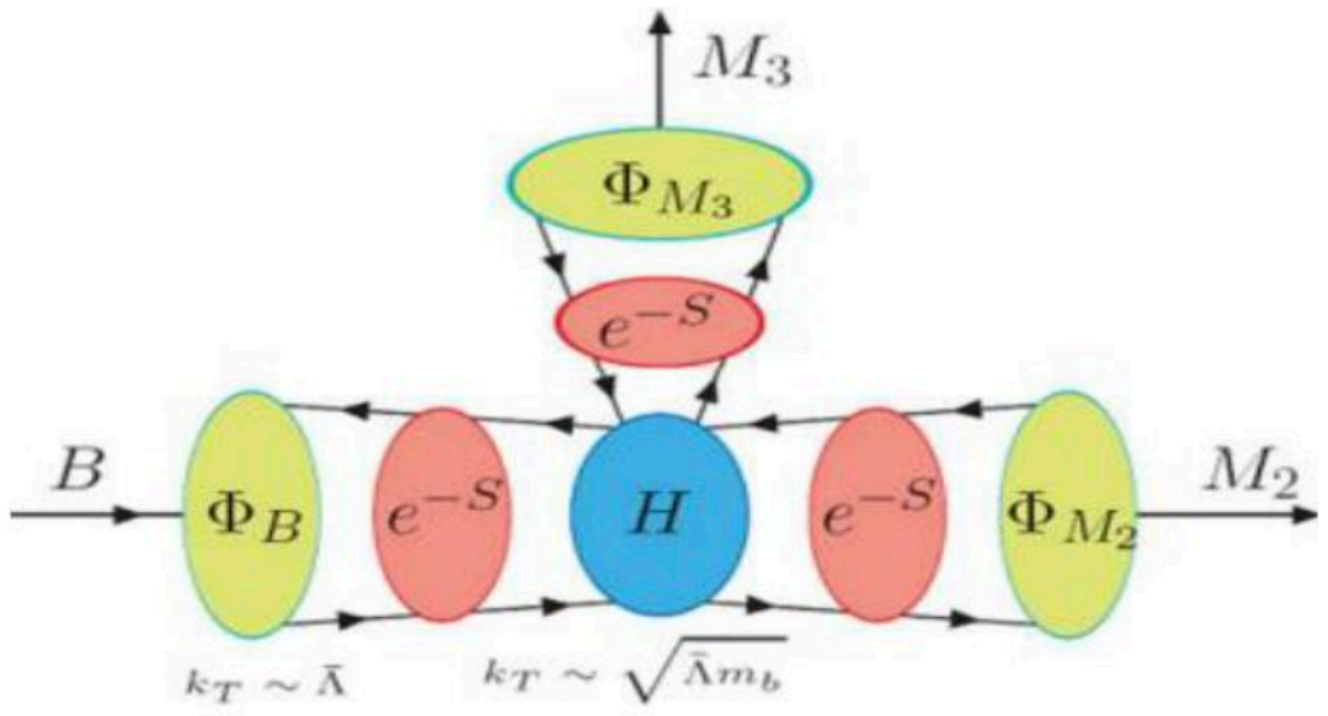


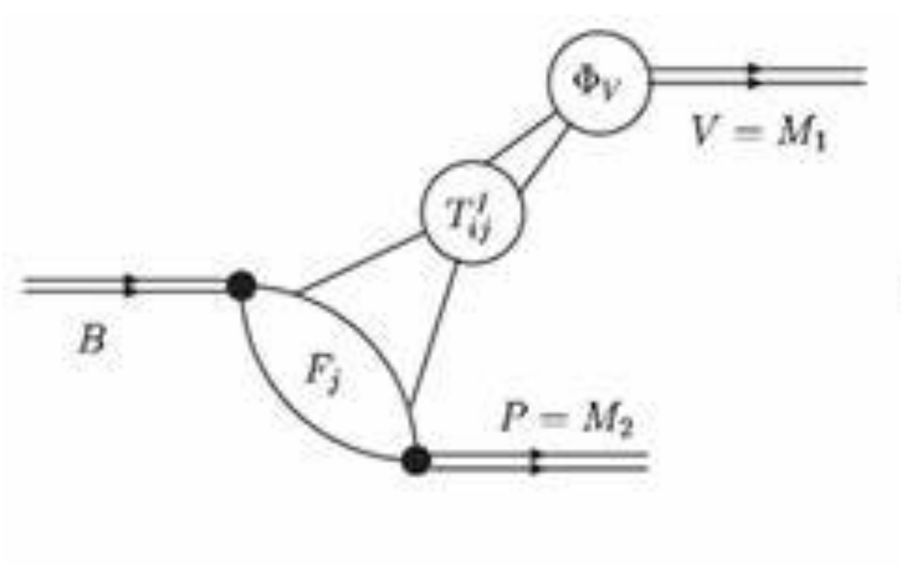
(c) $P,\ P^C_{\mathrm{EW}}$

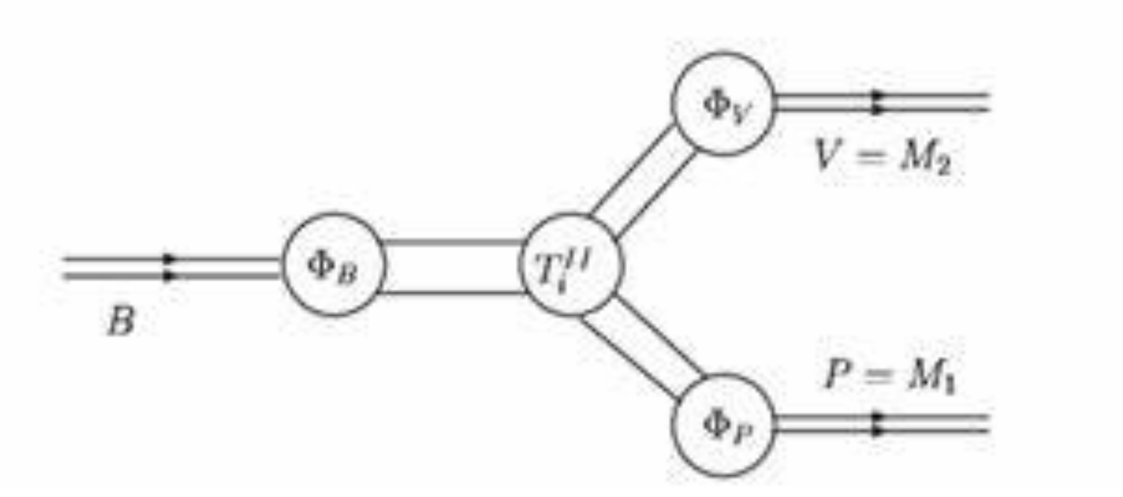
Dawn of Baryonic Era

2000s: B-meson CPV

2000s: QCDF, PQCD, SCET —— Golden Age



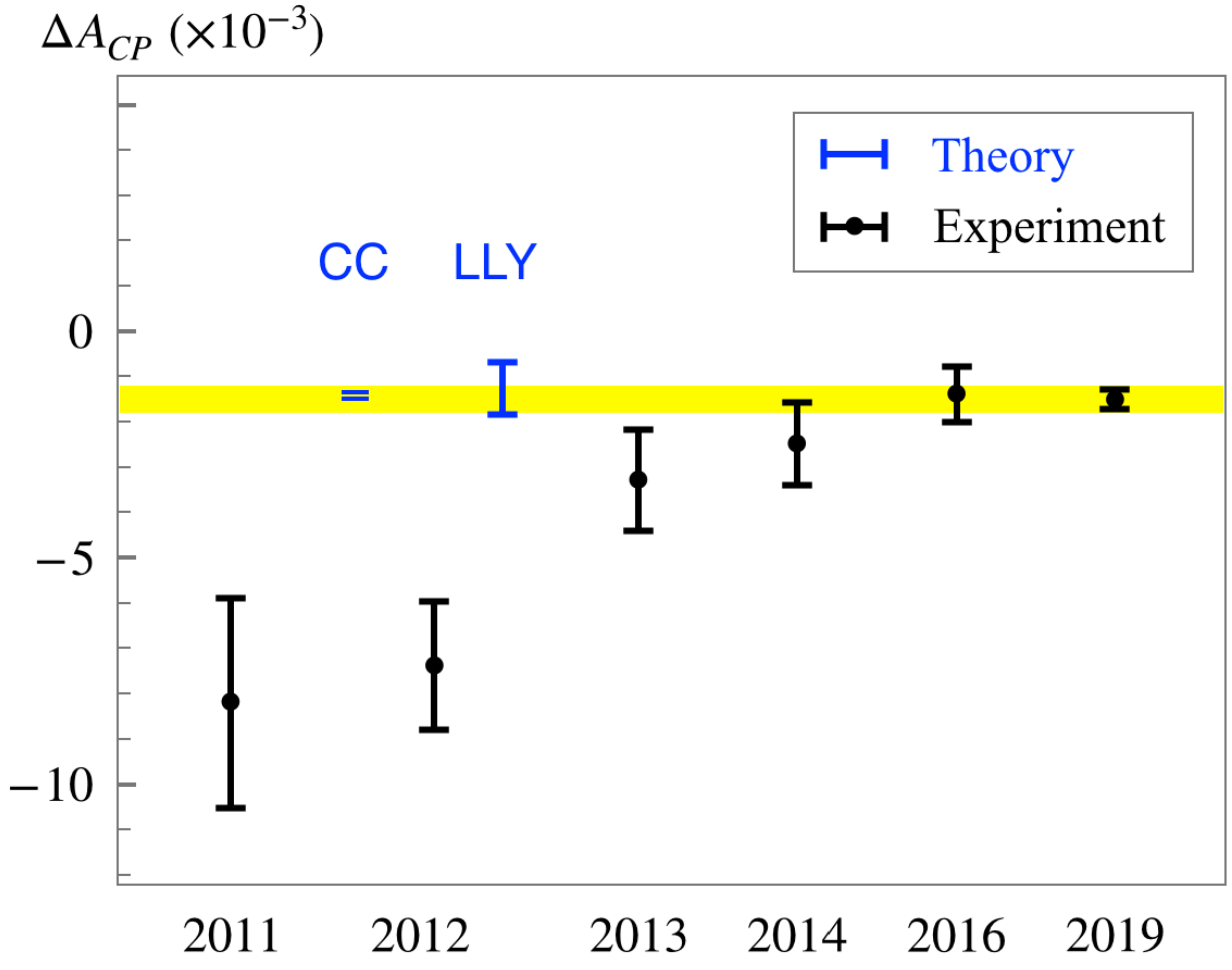




See Ying Li's talk

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

2010s: Charm CPV



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

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

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

CC: topological approach + QCDF

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

LLY: factorization-assisted topology (FAT)

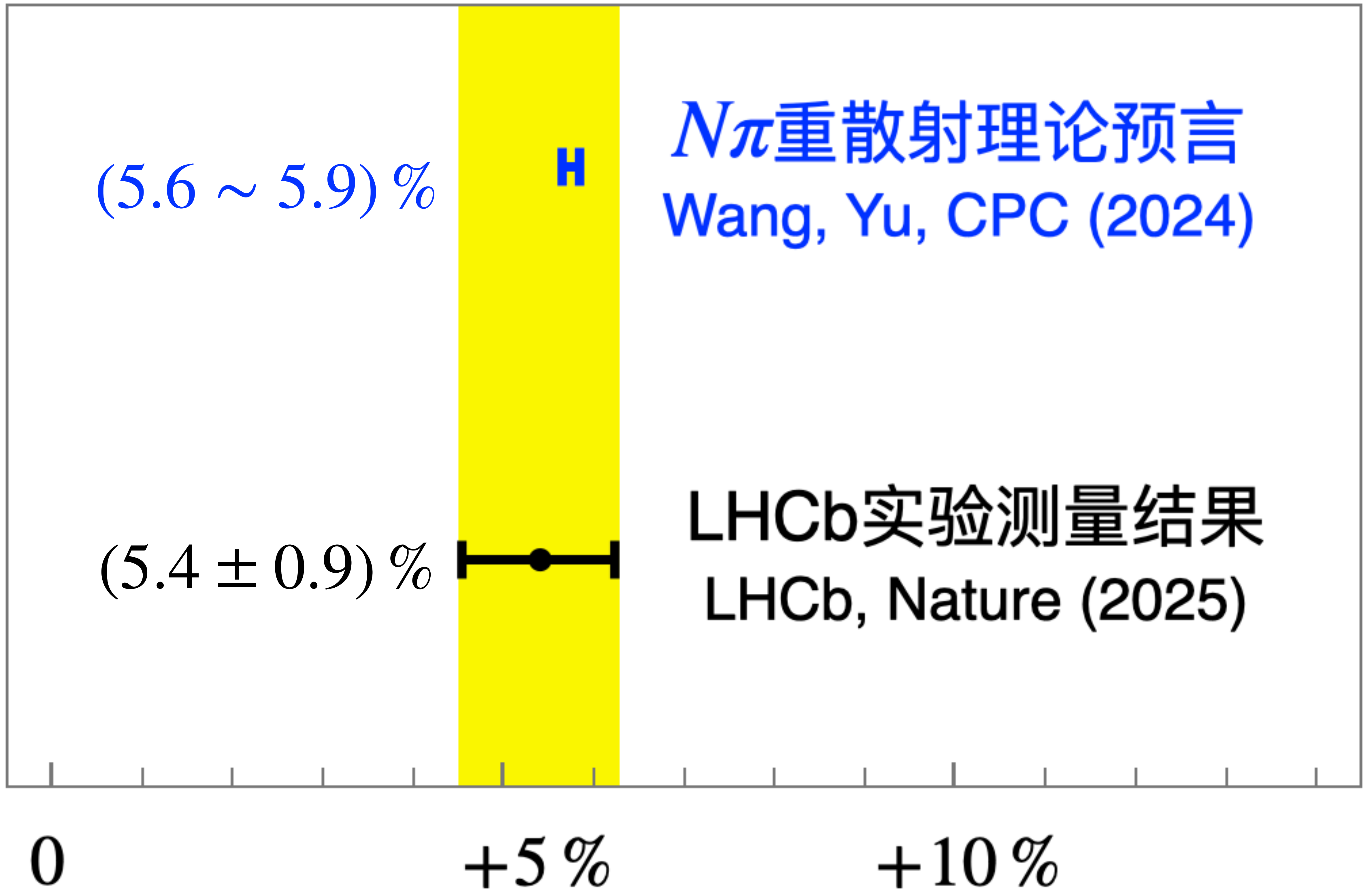
H.n.Li, C.D.Lu, **F.S.Yu**, 2012

Exp: LHCb, PRL122, 211803 (2019)

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

2020s: Baryon CPV

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



Baryon CPV before 2020: Experiments

- 2017, 3σ evidence in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ using T-odd CPV [LHCb, Nat.Phys.]
- 2018, CPV in $\Lambda_b^0 \to p\pi^-,\ pK^-$ are 1% or even smaller [LHCb, PLB]

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

- 2019, multi-body decays have large data samples [LHCb, EPJC]

Decay mode	Signal yields X_b^0	Signal yields $\overline{X}_b^0$
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	2335 ± 56	2264 ± 55
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	6807 ± 92	6232 ± 89
$\Lambda_b^0 \to pK^-K^+\pi^-$	555 ± 38	630 ± 38
$\Lambda_b^0 \to pK^-K^+K^-$	2312 ± 54	2248 ± 54

$\Lambda_b^0 \to pa_1(1260)^-$	422 ± 23	425 ± 23
$\Lambda_b^0 \to \Delta(1232)^{++}\pi^-\pi^-$	783 ± 30	771 ± 29
$\Lambda_b^0 \to N(1520)^0\rho(770)^0$	241 ± 16	230 ± 16
$\Lambda_b^0 \to pK_1(1410)^-$	548 ± 26	488 ± 25
$\Lambda_b^0 \to \Delta(1232)^{++}K^-\pi^-$	998 ± 37	895 ± 34
$\Lambda_b^0 \to \Lambda(1520)\rho(770)^0$	167 ± 14	160 ± 14
$\Lambda_b^0 \to N(1520)^0K^*(892)^0$	977 ± 33	856 ± 31
$\Lambda_b^0 \to \Lambda(1520)\phi(1020)$	192 ± 15	172 ± 14
$\Lambda_b^0 \to (pK^-)_{\text{high-mass}}\phi(1020)$	548 ± 25	542 ± 25

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

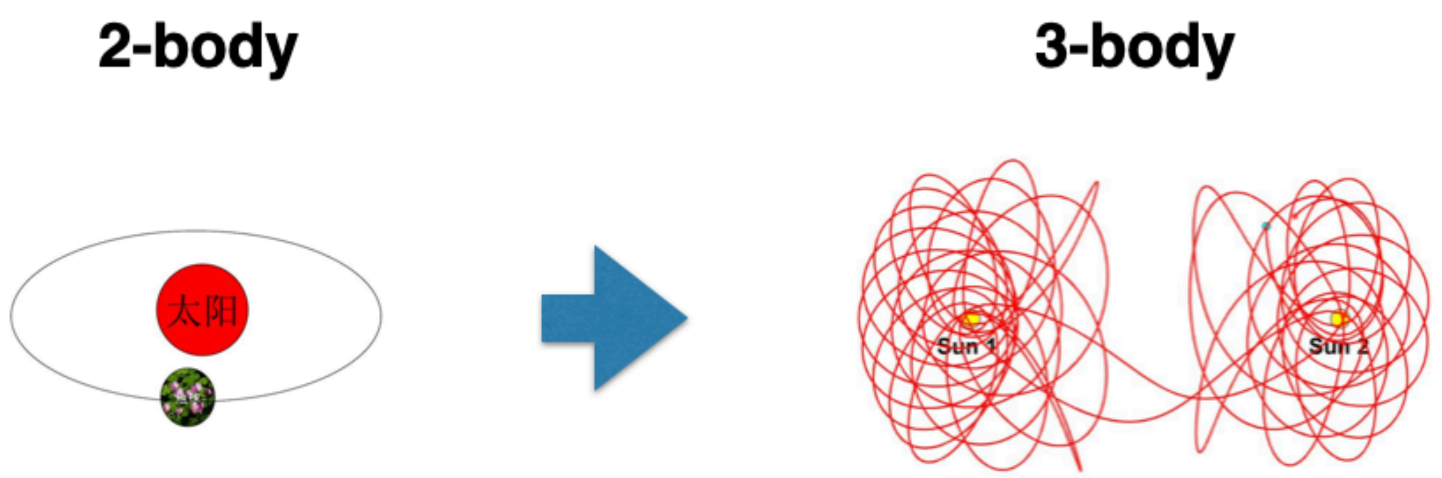
LHCb: $\Lambda_b^0 \to p\pi^+\pi^-\pi^-$, 3σ ,
Nature Physics 2017

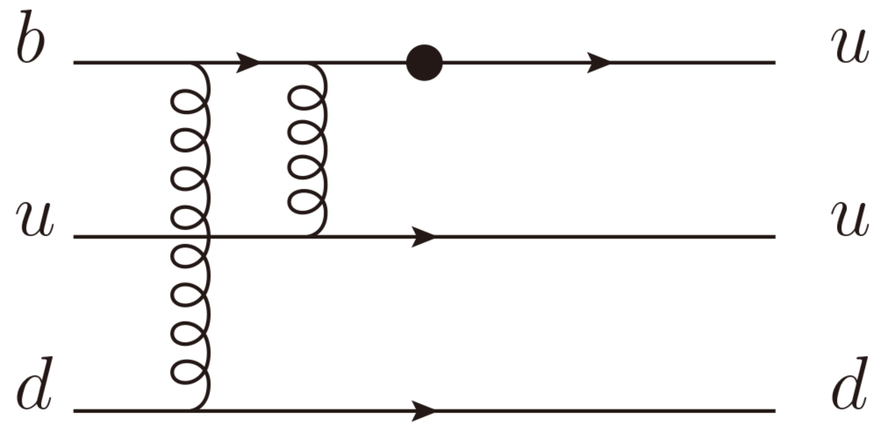
Decays of the Λ_b^0 (*bud*) baryon to final states consisting of hadrons with no charm quarks are predicted to have non-negligible *CP* asymmetries in the SM, as large as 20% for certain three-body decay modes[13]. It is important to measure the size and nature of these *CP* asymmetries in as many decay modes as possible, to determine

13. Hsiao, Y. K. & Geng, C. Q. Direct *CP* violation in Λ_b^0 decays. *Phys. Rev. D* **91**, 116007 (2015).

Predict Baryon CPV

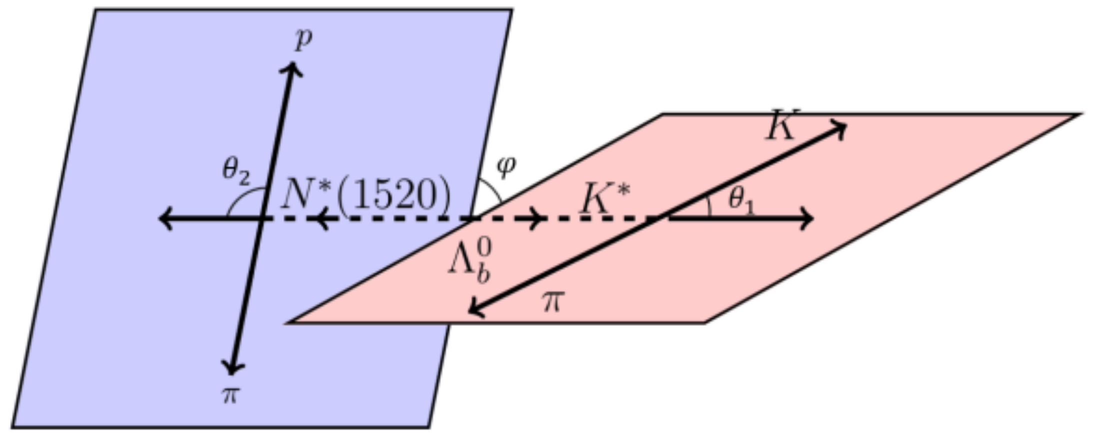
1. Decay dynamics





More is different.

2. Observables



- T-odd triple products $(\vec{p}_1 \times \vec{p}_2) \cdot \vec{p}_3$, 3σ signal in $\Lambda_b \to p\pi\pi\pi$[LHCb2017]. Defined by kinematics, but unclear relation to the decay amplitudes.

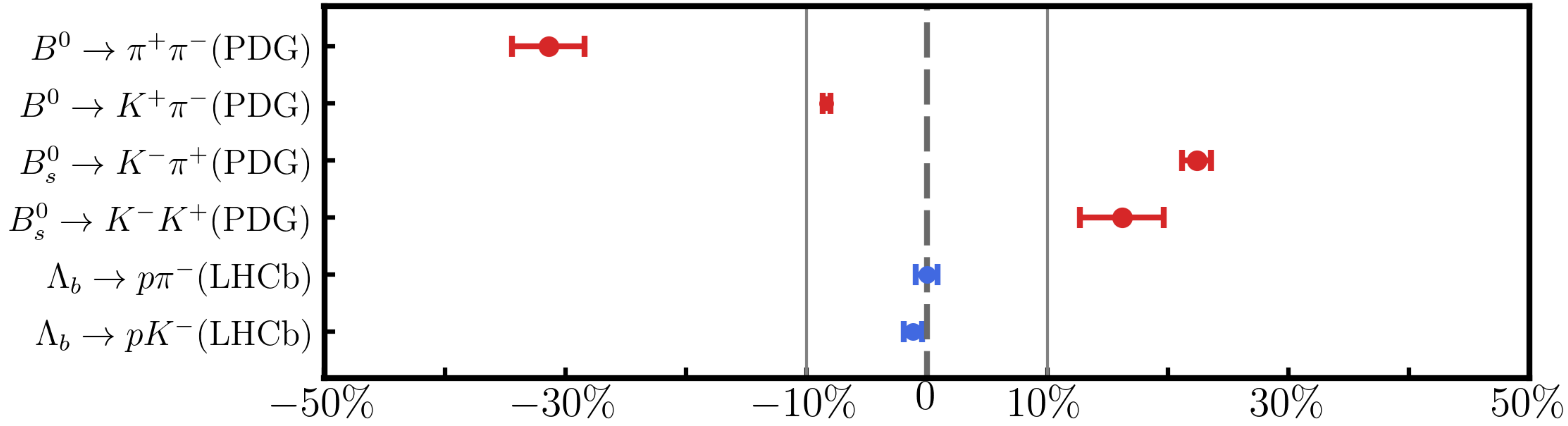
2. Dynamics of baryon decays

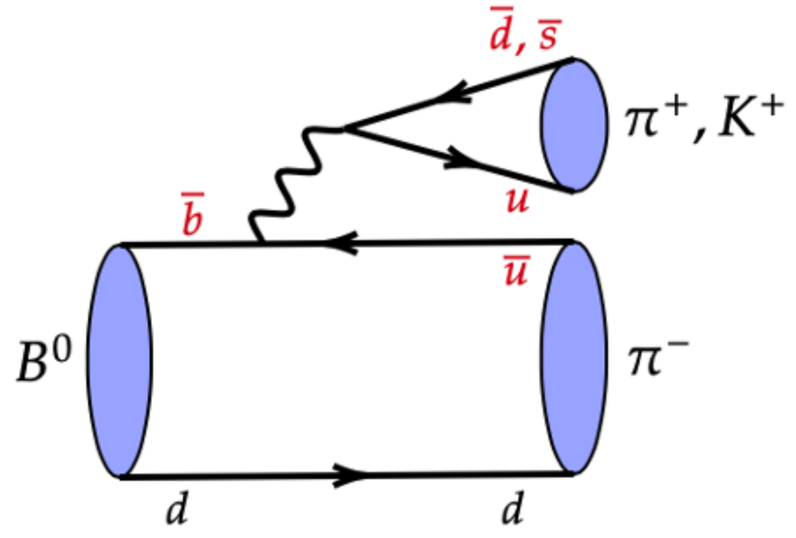
CPV puzzle of b-baryon

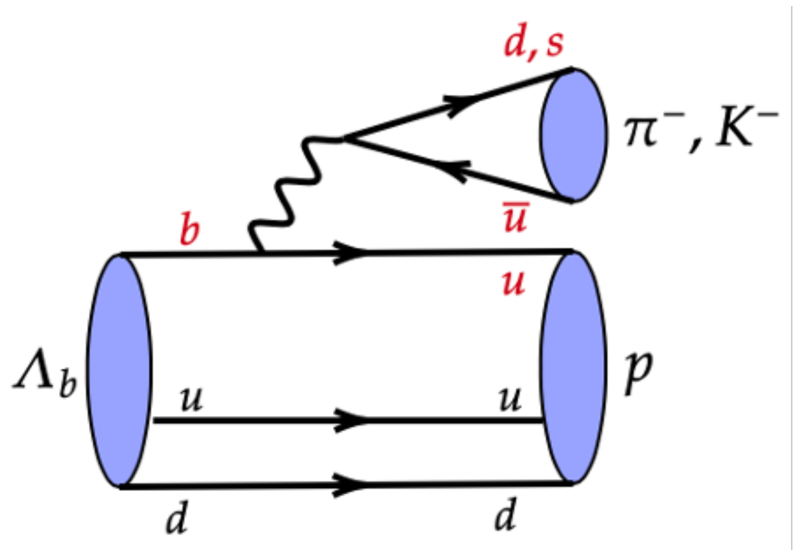
- Precision of b-baryon CPV measurements reaches the order **1%** [LHCb, 2024]

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

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







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$\Lambda_b \to p$ 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)
$f_1^{\Lambda_b \to p}(0)$	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

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

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

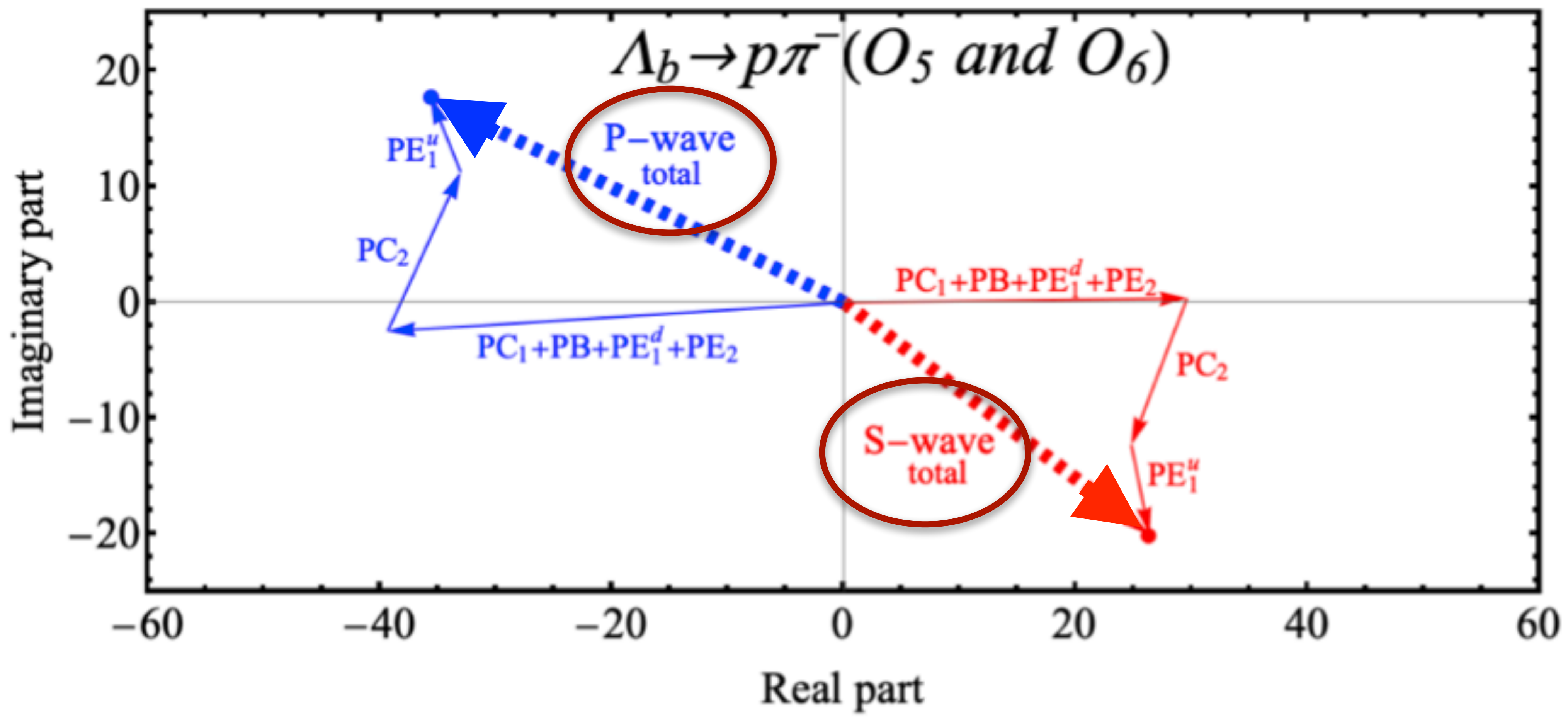
$$\bar{u}\gamma_\mu(1-\gamma_5)b\bar{d}\gamma^\mu(1-\gamma_5)u$$

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

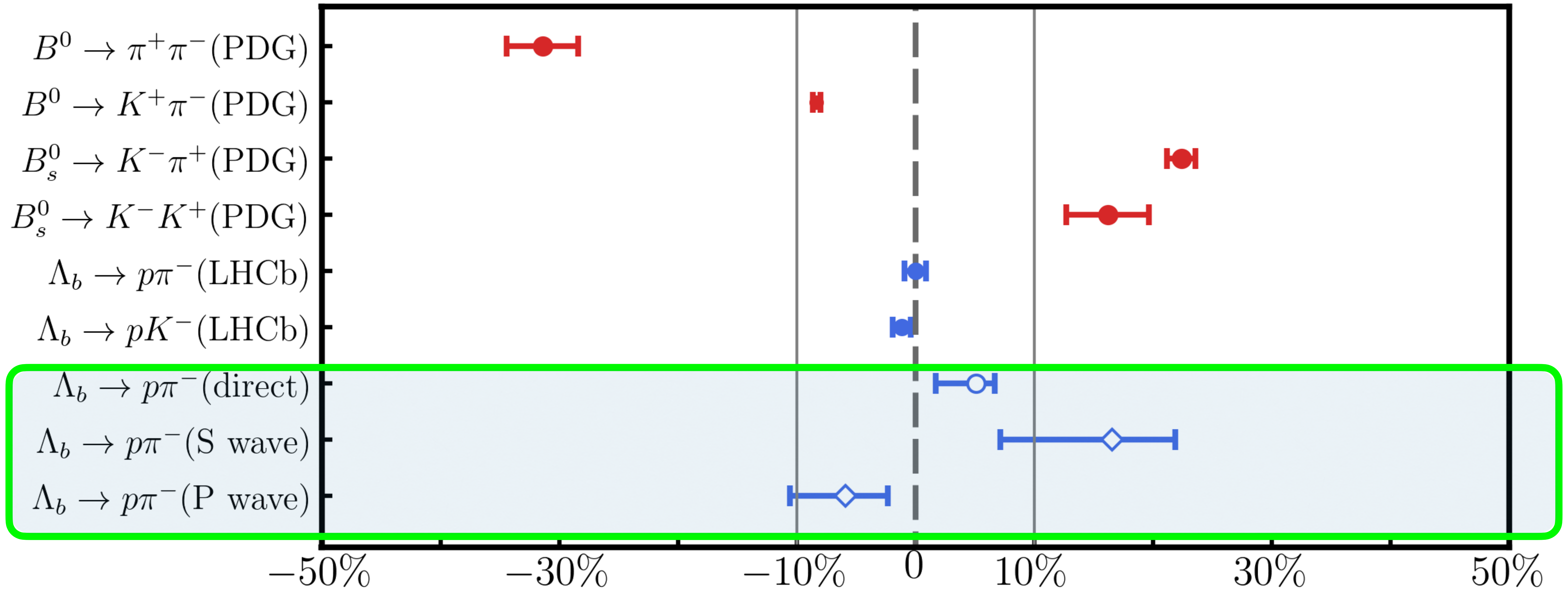
- **Penguin operators:** $(V-A)(V+A)$

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

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



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:

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

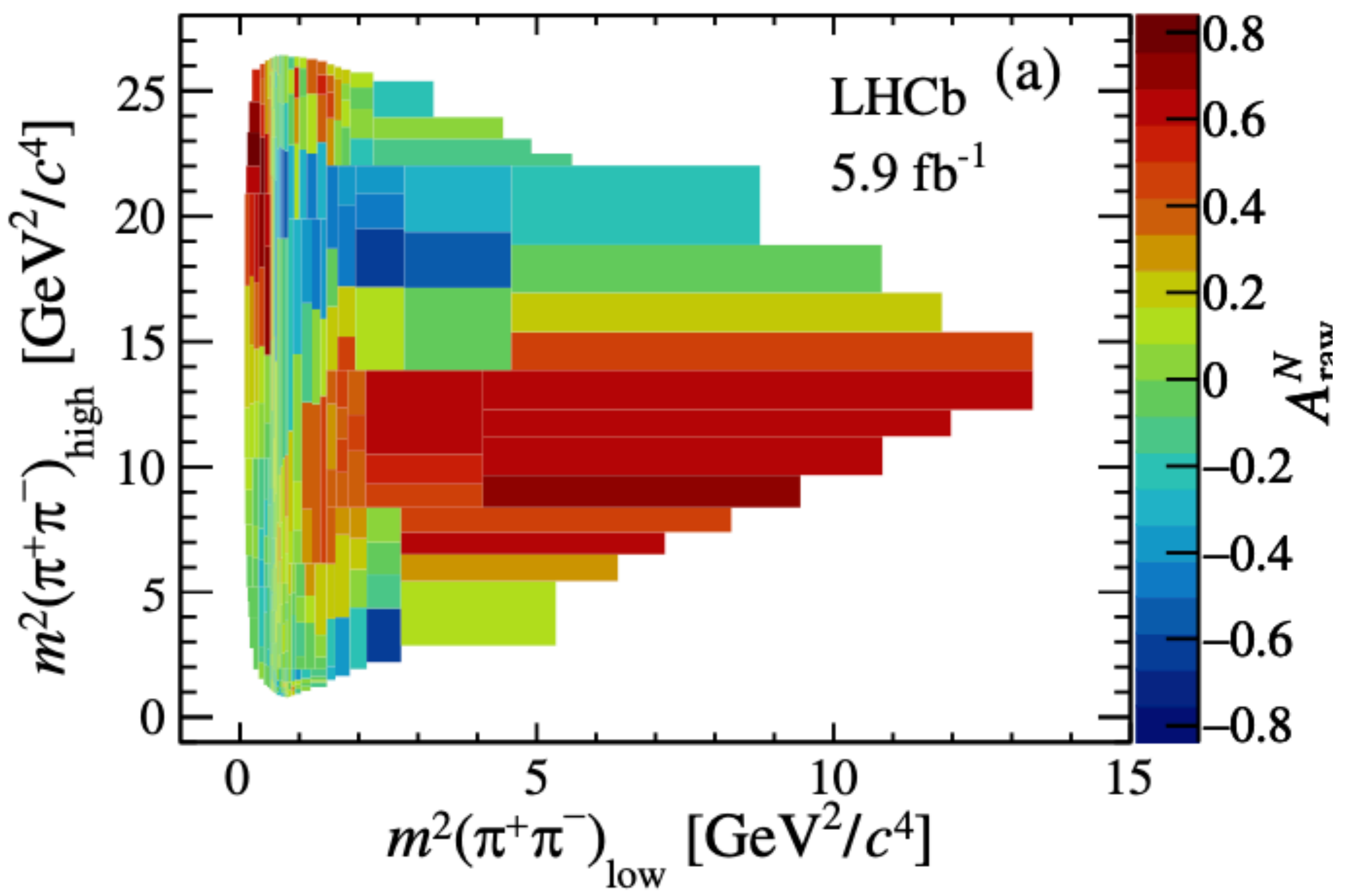
38. Han, J.-J. et al. Establishing CP violation in b-baryon decays. *Phys. Rev. Lett.* **134**, 221801 (2025).

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.

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

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

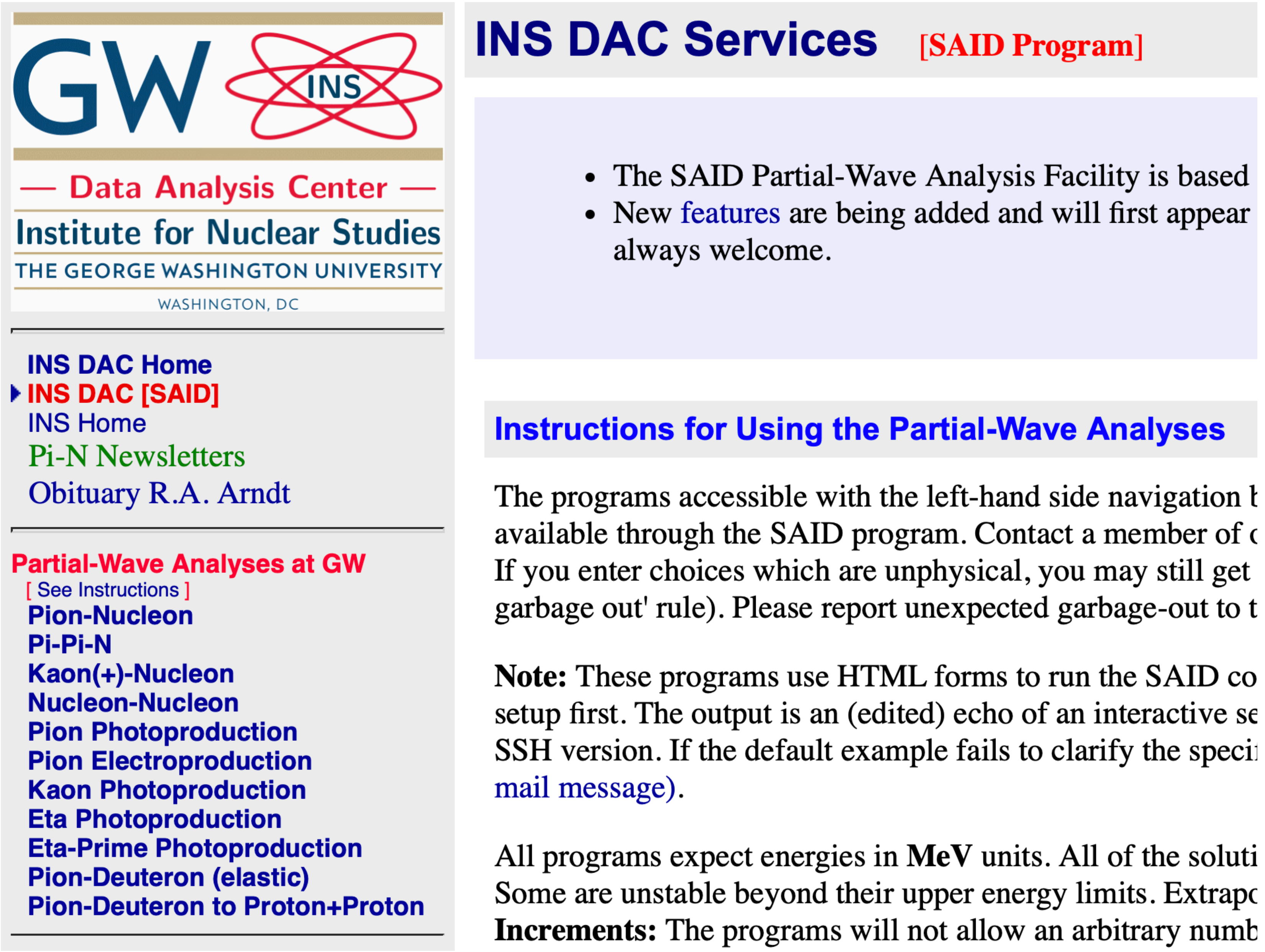


- Large regional CPV: Promising to measure CPV in some regions.
- Large data samples in $\Lambda_b^0 \to ph^-h^+h^-,\, h=\pi, K$

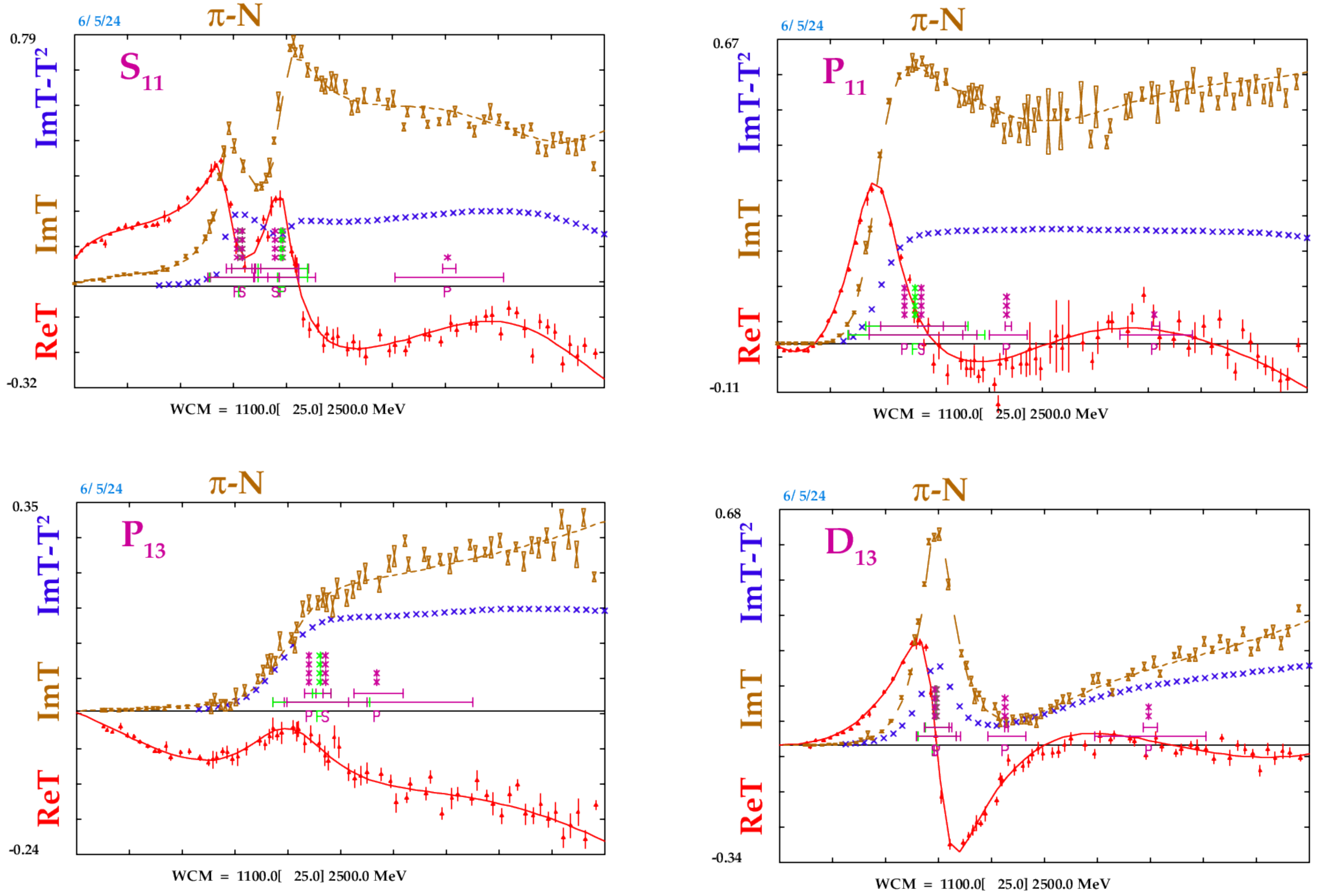
$N\pi$ scatterings

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

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



$N\pi \rightarrow N\pi$



- Partial-wave amplitudes with strong phases!

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

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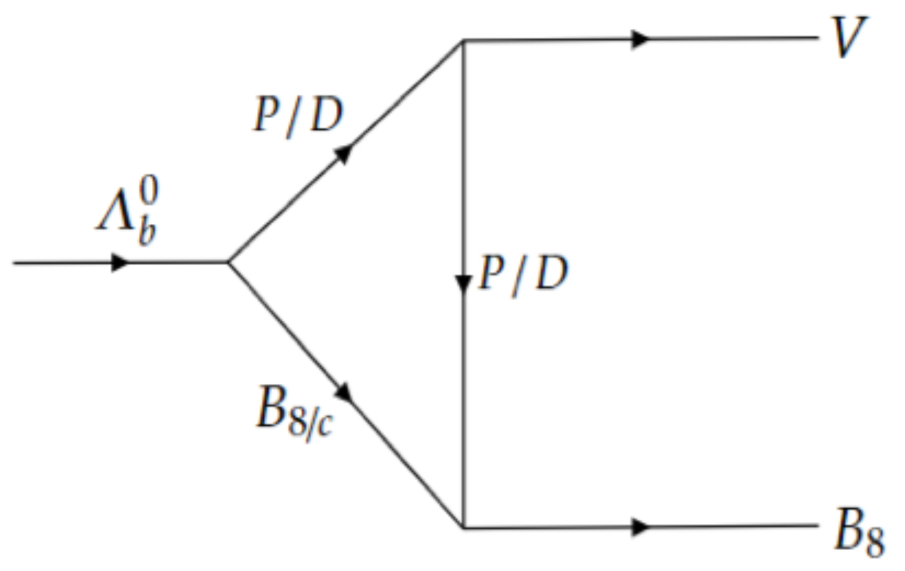
Multi-body decays of Λ_b

- 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

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

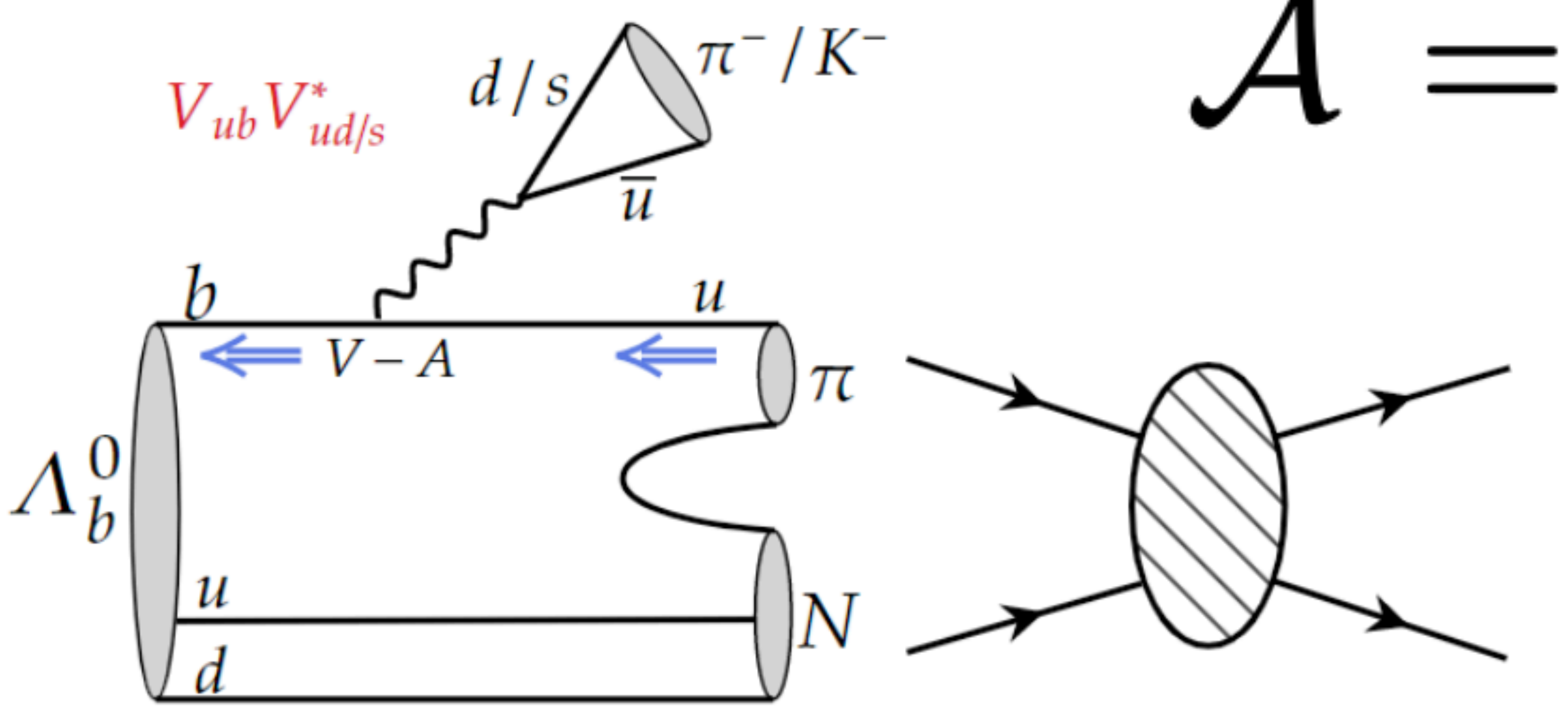
$N(1700)$ BREIT-WIGNER MASS	1650 to 1800 (≈ 1720) MeV
$N(1700)$ BREIT-WIGNER WIDTH	100 to 300 (≈ 200) MeV
$N(1710)$ BREIT-WIGNER MASS	1680 to 1740 (≈ 1710) MeV
$N(1710)$ BREIT-WIGNER WIDTH	80 to 200 (≈ 140) MeV
$N(1720)$ BREIT-WIGNER MASS	1680 to 1750 (≈ 1720) MeV
$N(1720)$ BREIT-WIGNER WIDTH	150 to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

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

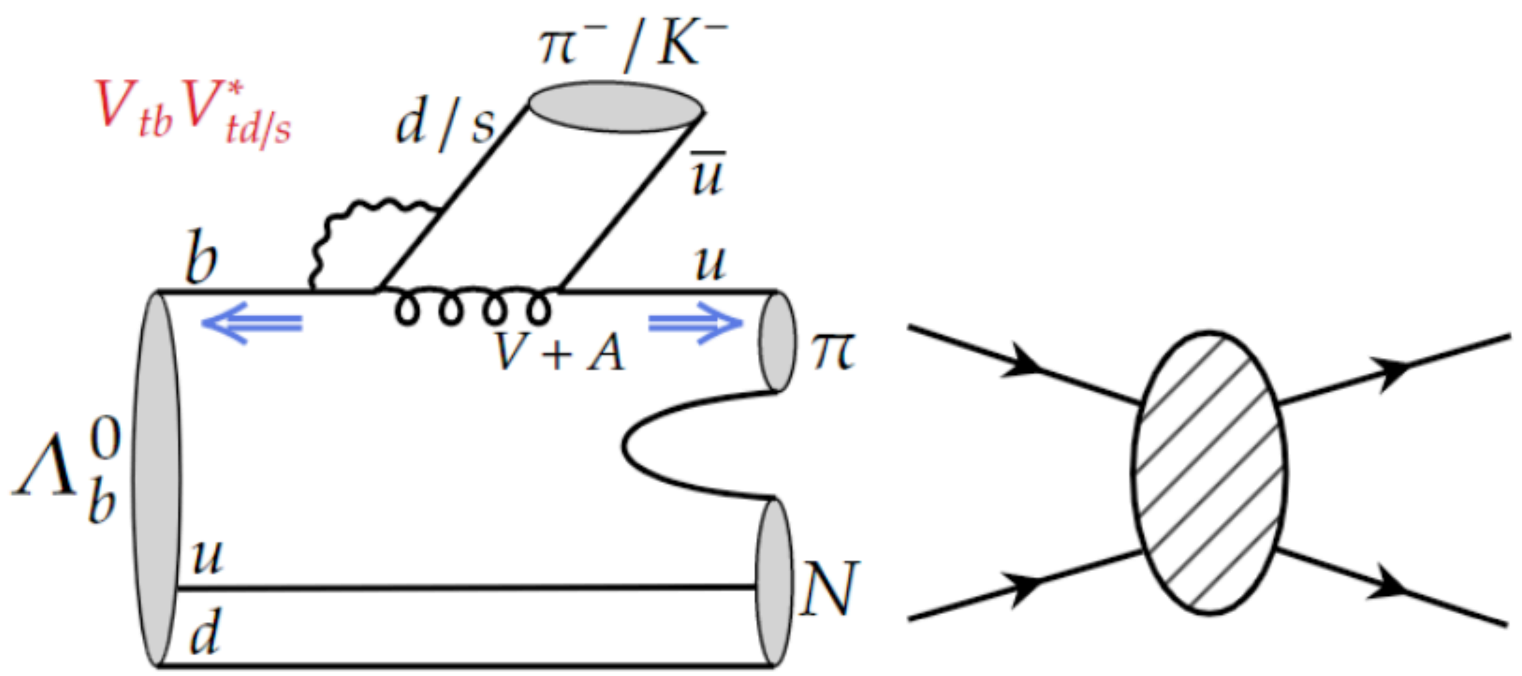
CPV via $N\pi$ rescatterings

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

•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 $\cos\theta > 0$
	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%

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).

3. Observables of baryon CPV

Observables

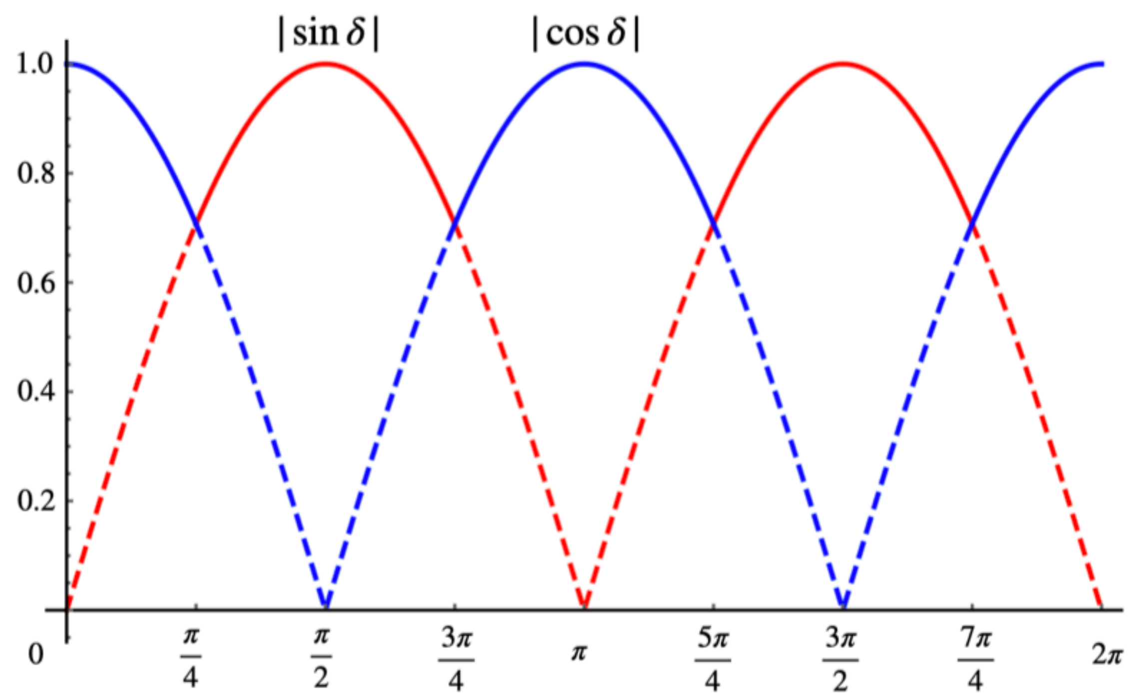
- Baryons have nonzero spins which can construct more observables and thus are helpful to find large CPV for measurements.
- Direct CPV in the decays: $a_{CP}^{\text{dir}} \propto \sin\delta_s \sin\phi_w$. Sensitive to the strong phases.
- T-odd triple product: $\beta \propto (\vec{s}_1 \times \vec{s}_2)\cdot\vec{p}$ 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, He, 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, $UQ_-U^\dagger = Q_-$

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

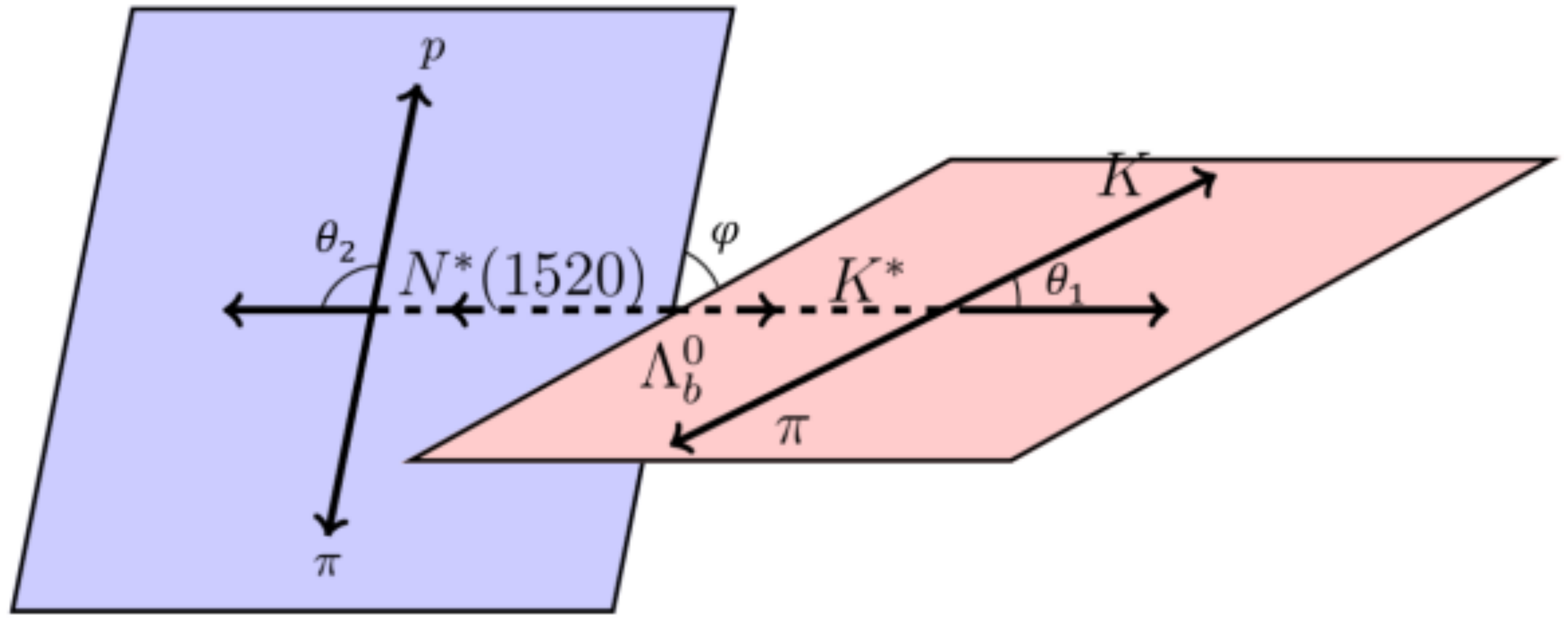
$$a_{CP}^{\text{T-even}} \propto \sum_{m,n} Re(A_m^* A_n - \bar{A}_m^* \bar{A}_n) \propto \sin\delta_s \sin\phi_w$$

complimentary

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

Complementary in angular distributions

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



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

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

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

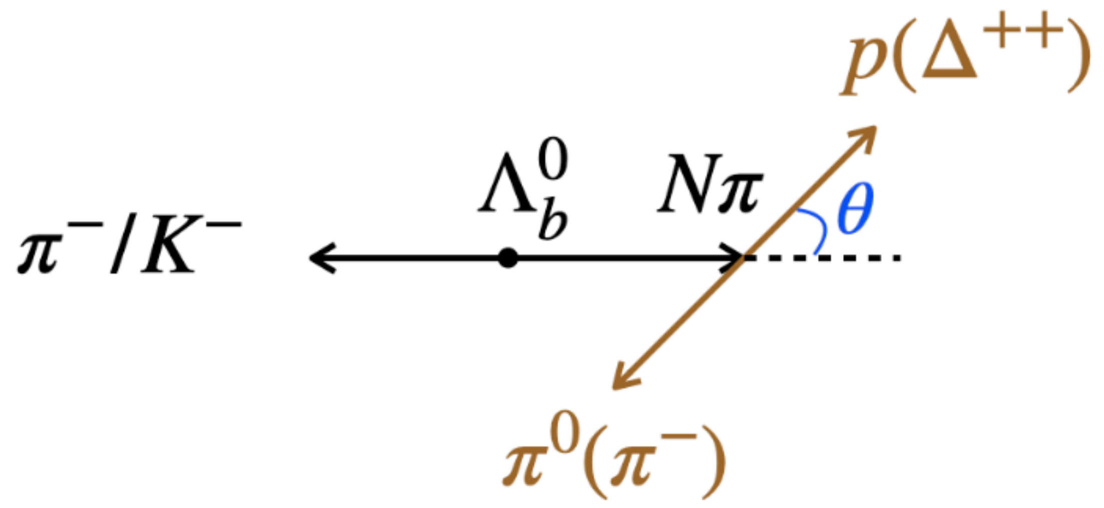
- Triple-product of momentum, $(\vec{p}_1 \times \vec{p}_2)\cdot\vec{p}_3$, is not good. $\sin\varphi$ with $\sin\theta_1\cos\theta_1\sin\theta_2\cos\theta_2$
- Angular distributions of resonant contributions are necessary. It is more clear in theory.

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

CPV of Legendre moments

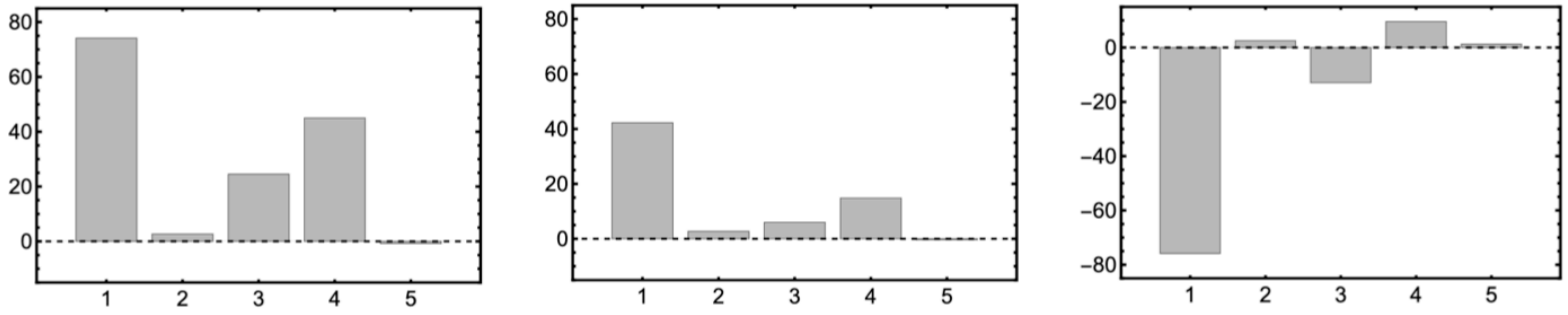
- Partial wave CPV based on the Legendre decomposition [Z.H.Zhang, X.H.Guo, 2021,2025]

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



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

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



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

Up-Down asymmetry

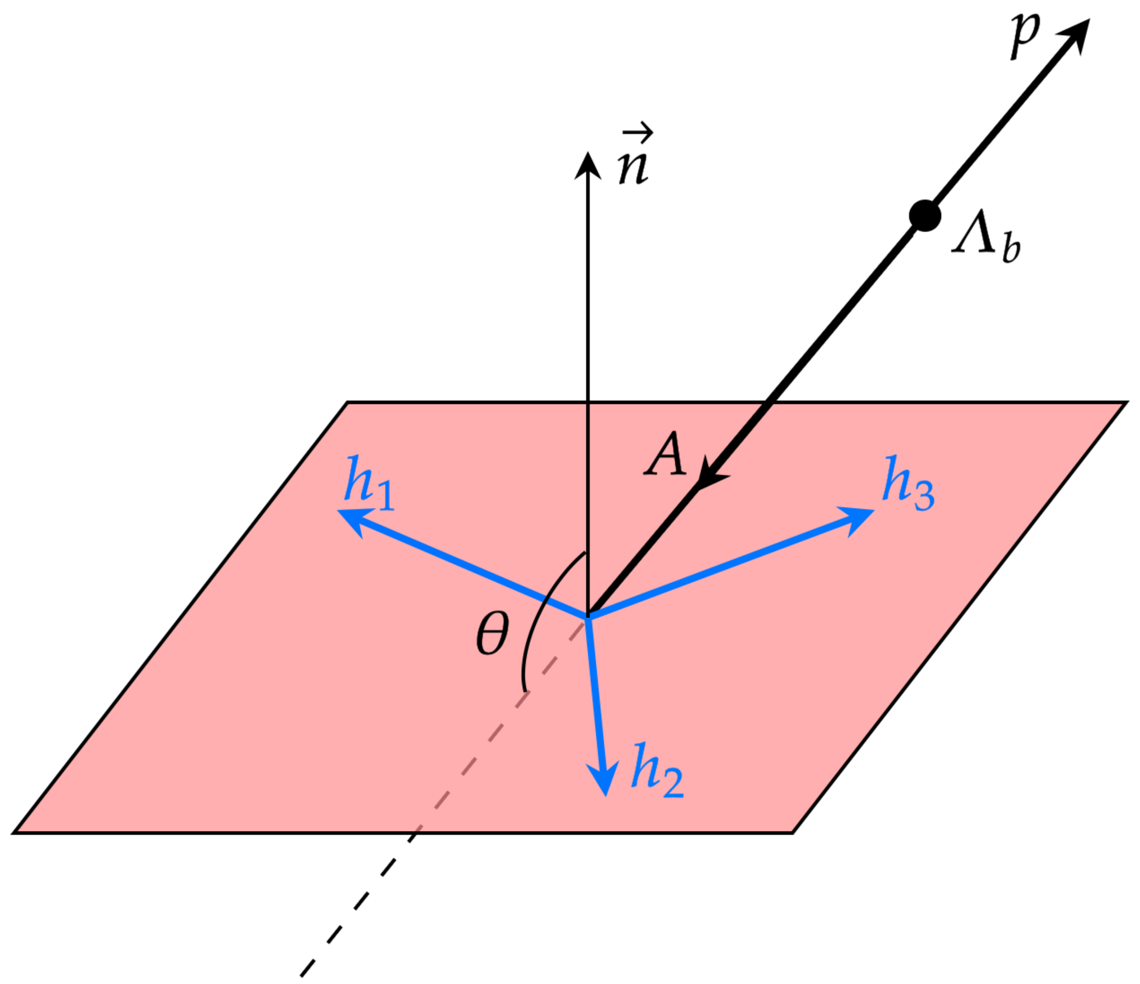
- How to measure the large partial-wave CPV?
- They usually need the polarizations of baryons.
- But the angular distributions may help.

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

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

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

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



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

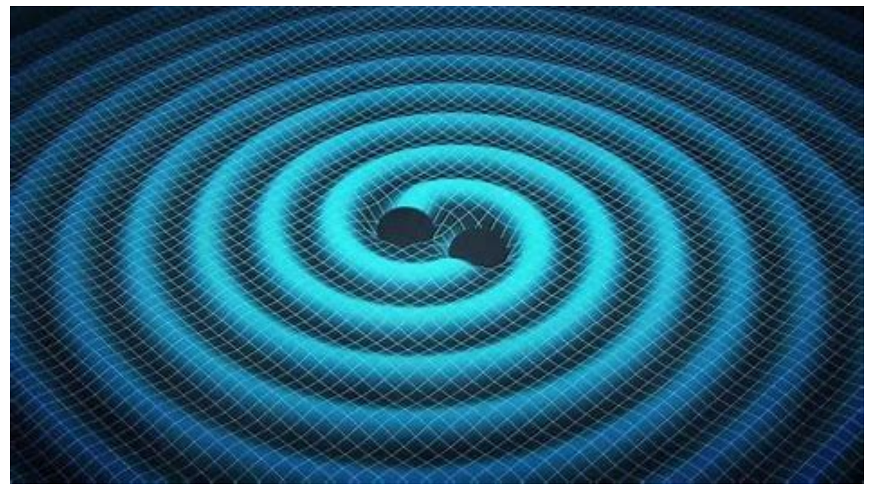
J.P.Wang, Q.Qin, **FSY**, 2411.18323;
J.J.Han, J.X,Yu, Y.Li, H.n.Li, J.P.Wang, Z.J.Xiao, **FSY**, 2409.02821 (PRL)

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, CPV of charmed baryon or hyperon

Thank you!

New horizon

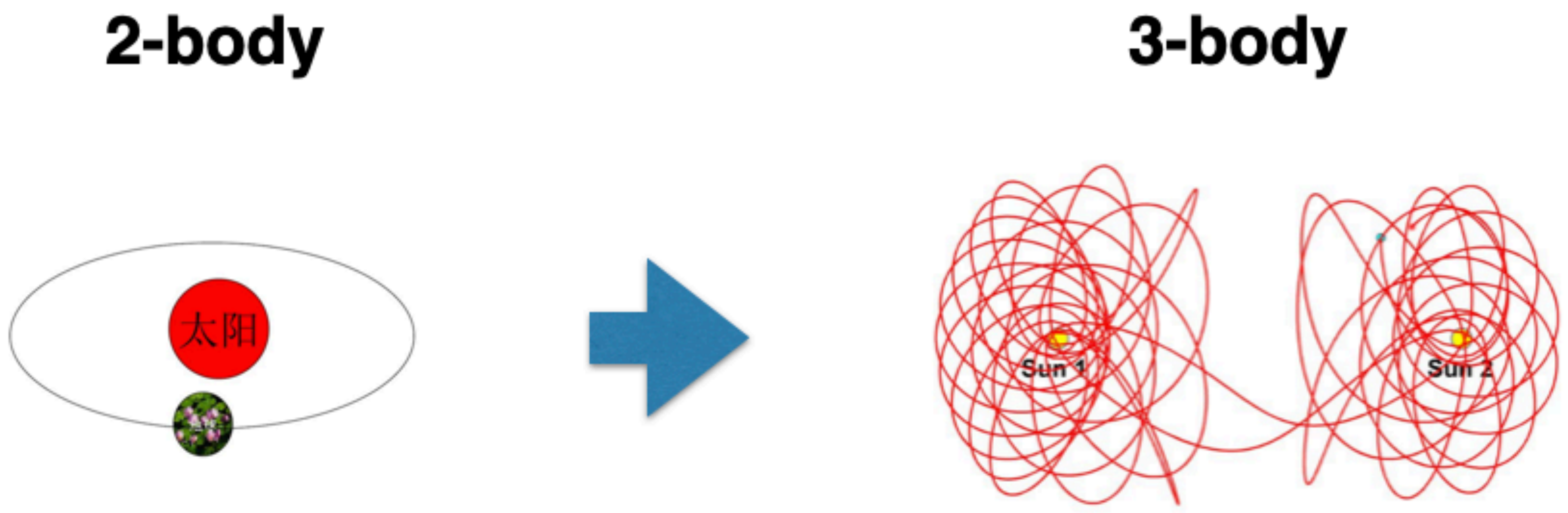


- Observation of gravitational waves

  => 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



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