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Establishing *CP* Violation in *b*-Baryon Decays

第十四届“晨光杯”青年优秀论文评选

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Phys.Rev.Lett.134(2025)221801

Establishing *CP* Violation in *b*-Baryon Decays

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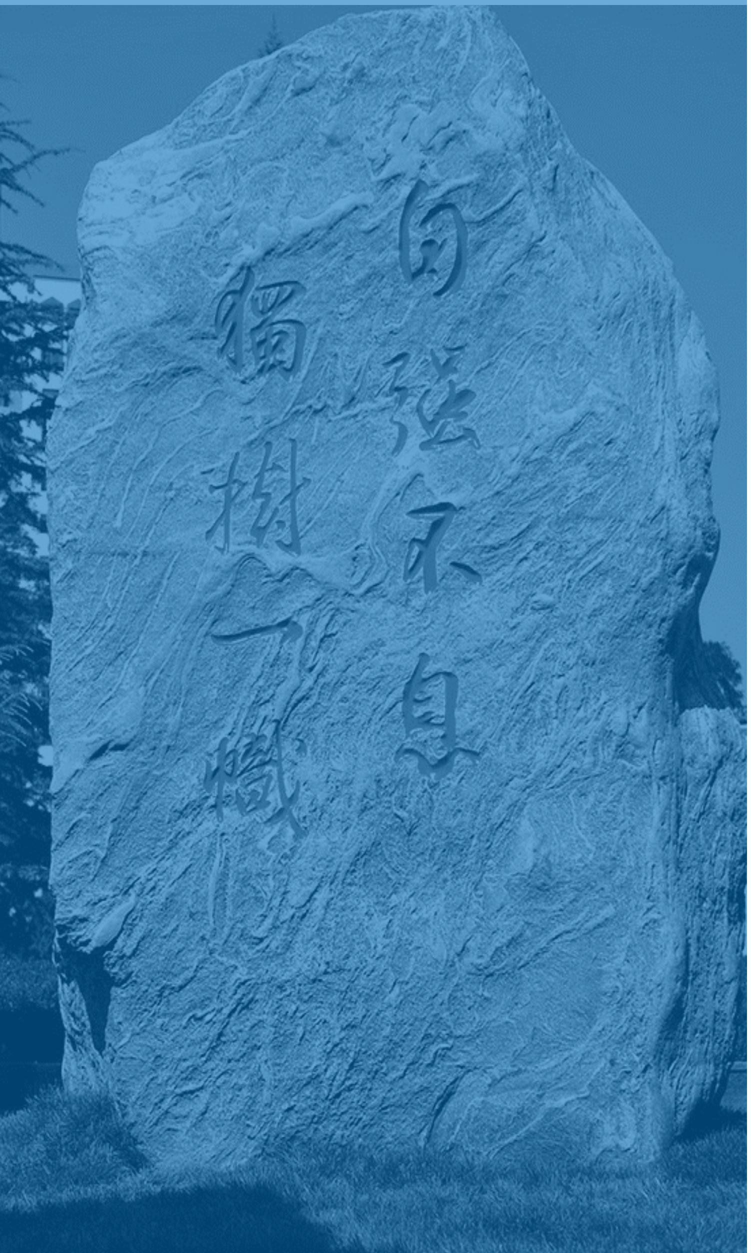
(Received 31 December 2024; revised 7 May 2025; accepted 15 May 2025; published 4 June 2025)



Motivation

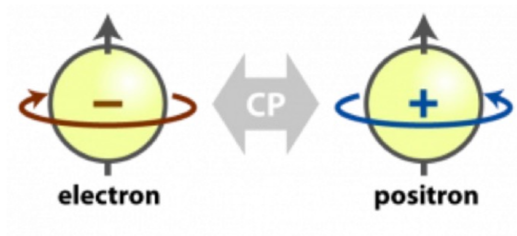
Mechanism of baryon CPV

Prediction of baryon CPV

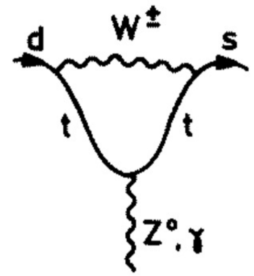
Summary

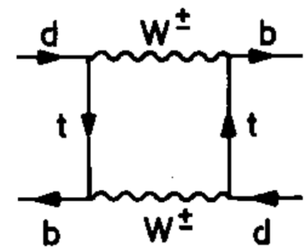
CP violation

- CPV relates to parameters in SM, is helpful to search NP indirectly.

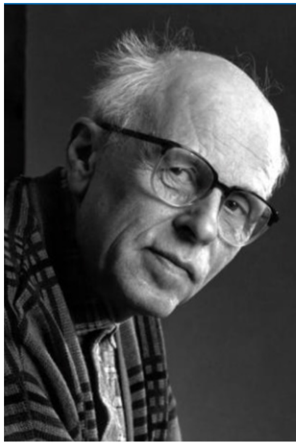


CP: 电荷共轭+宇称变换

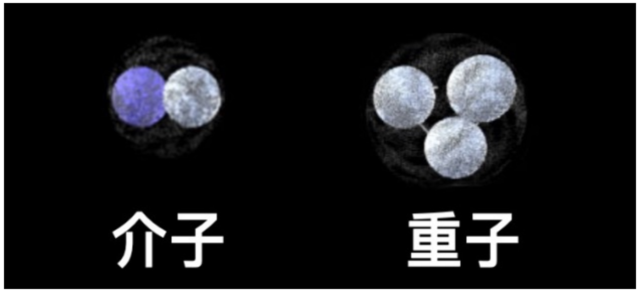




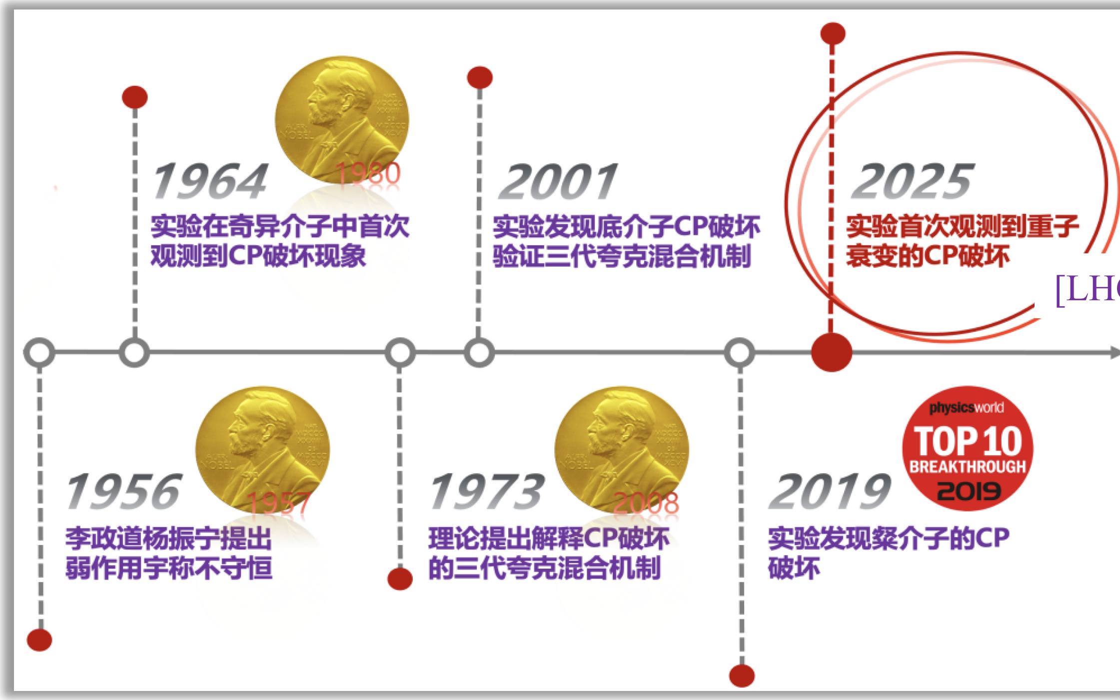
- Three conditions for Matter-antimatter asymmetry: [Sakharov JETP Lett.(1967)]
  - Interaction to violate baryon number;
  - C and CP violation;
  - Deviate thermal equilibrium



- Baryon CPV is more crucial, as visible matter in Universe is made of baryons.



Observation of baryon CP violation

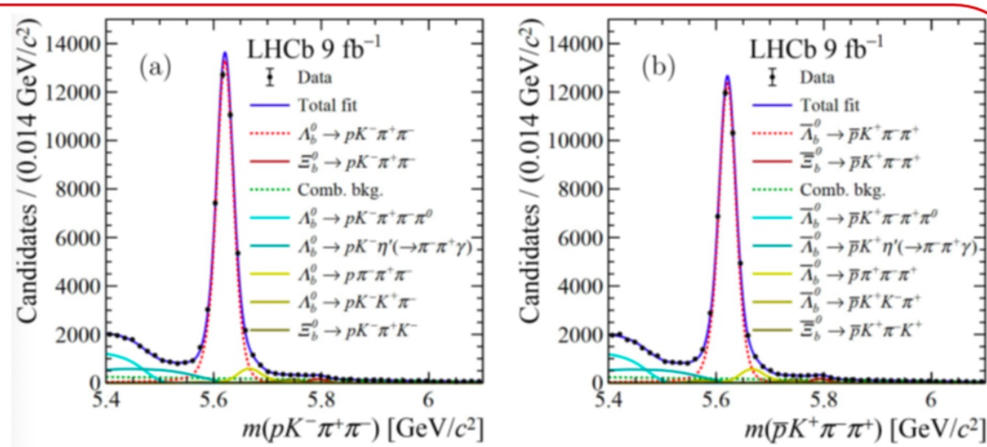


[LHCb Nature(2025)]

$$\Lambda_b^0 \to p\pi^+\pi^-K^-$$

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

5.2σ

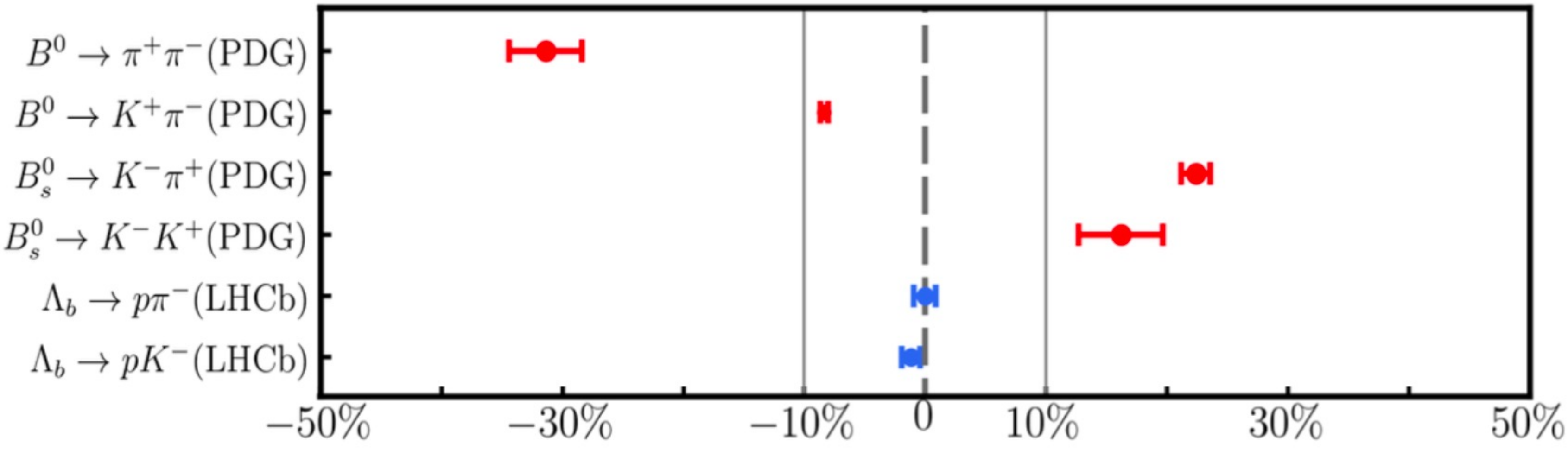


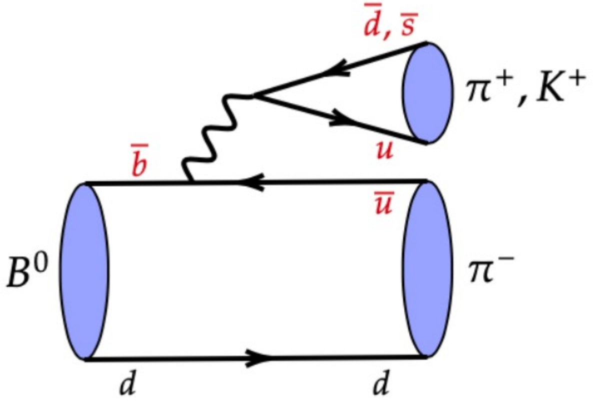
Puzzle of b-baryon CPV

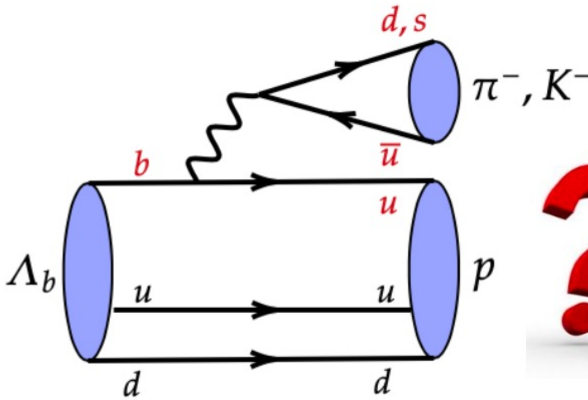
- Why baryon two-body CPV small?

$$A_{CP}(\Lambda_b \to p\pi^-) = (0.20 \pm 0.83 \pm 0.37)\%$$
$$A_{CP}(\Lambda_b \to pK^-) = (-1.14 \pm 0.67 \pm 0.36)\%$$

- LHCb, 2024







$\Lambda_b \to p\pi^-, pK^-$

- Baryons have half-integer spin, and thus two partial wave amplitudes.

$$\mathcal{A}(\Lambda_b \to p\pi^-, pK^-) = i\bar{u}_p(S + P\gamma_5)u_{\Lambda_b}$$

$$A_{CP}^{dir} \equiv \frac{\Gamma(\Lambda_b\to ph^-)-\bar{\Gamma}(\bar{\Lambda}_b\to\bar{p}h^+)}{\Gamma(\Lambda_b\to ph^-)+\bar{\Gamma}(\bar{\Lambda}_b\to\bar{p}h^+)}$$

$$= \frac{M_+^2\left(|S|^2-|\bar{S}|^2\right)+M_-^2|P|^2-|\bar{P}|^2}{M_+^2(|S|^2+|\bar{S}|^2)+M_-^2|P|^2+|\bar{P}|^2}$$

$$= \frac{|S|^2}{|S|^2+\frac{M_-^2}{M_+^2}\frac{1+A_{CP}^S}{1+A_{CP}^P}|P|^2}A_{CP}^S + \frac{\frac{M_-^2}{M_+^2}|P|^2}{\frac{1+A_{CP}^P}{1+A_{CP}^S}|S|^2+\frac{M_-^2}{M_+^2}|P|^2}A_{CP}^P$$

$$\approx \frac{|S|^2}{|S|^2+|P|^2}A_{CP}^S + \frac{|P|^2}{|S|^2+|P|^2}A_{CP}^P$$

$$A_{CP}^S \equiv \frac{|S|^2-|\bar{S}|^2}{|S|^2+|\bar{S}|^2} = \frac{-2r_S sin\Delta\phi sin\Delta\delta_S}{1+r_S^2+2r_S cos\Delta\phi cos\Delta\delta_S},$$

$$A_{CP}^P \equiv \frac{|P|^2-|\bar{P}|^2}{|P|^2+|\bar{P}|^2} = \frac{-2r_P sin\Delta\phi sin\Delta\delta_P}{1+r_P^2+2r_P cos\Delta\phi cos\Delta\delta_P}$$

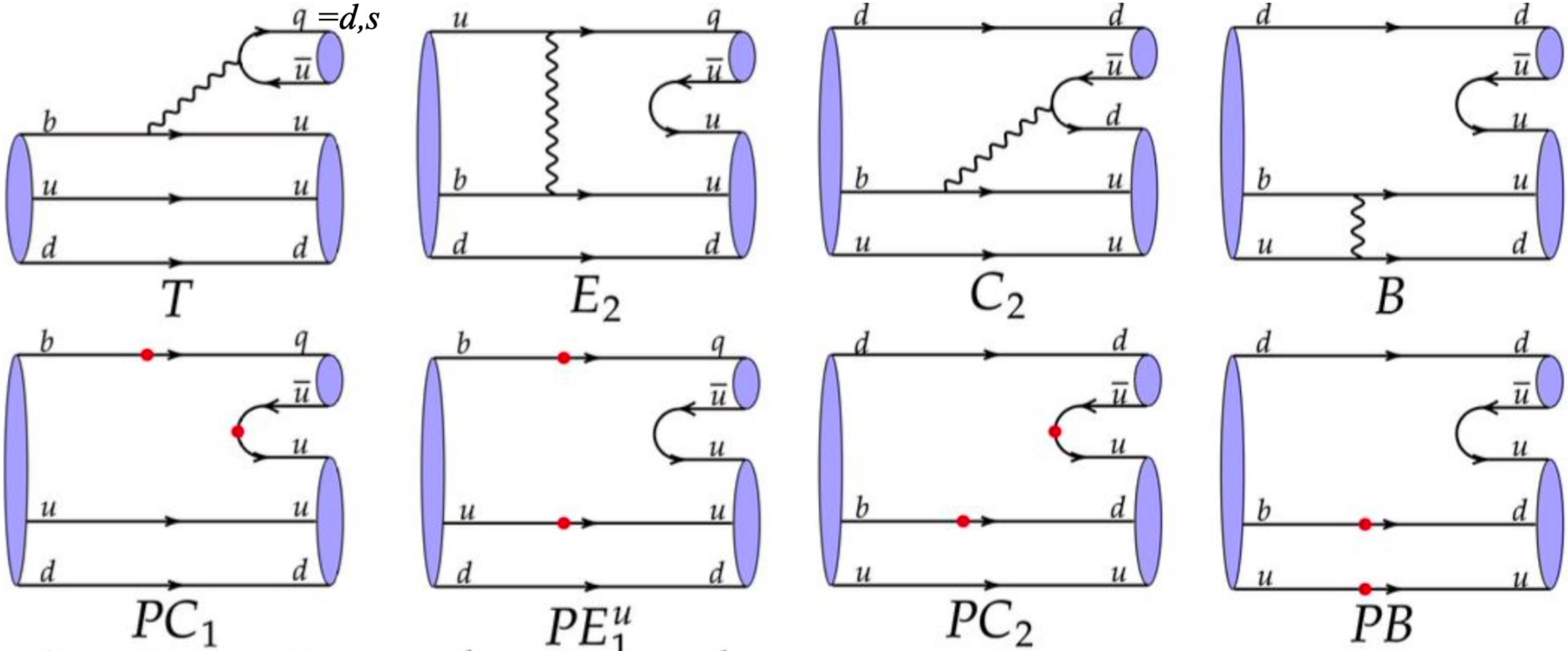
partial-wave CPVs

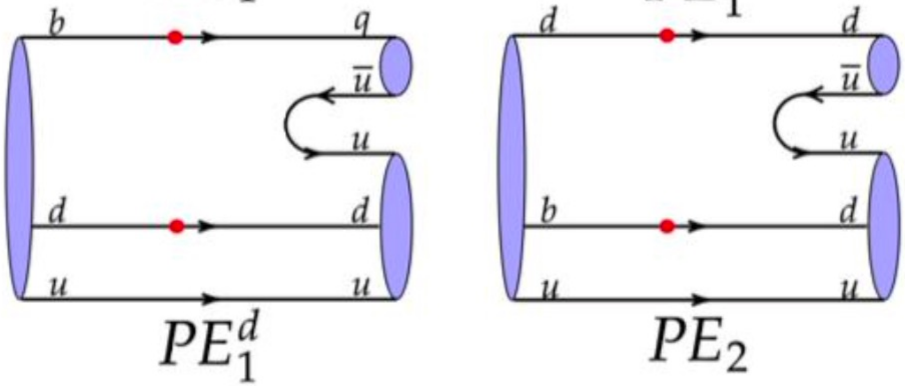
$$\Delta\delta_S = \delta_{\mathcal{P}}^S - \delta_{\mathcal{T}}^S$$

$$\Delta\delta_P = \delta_{\mathcal{P}}^P - \delta_{\mathcal{T}}^P$$

strong phase difference

Topological diagrams





$$\frac{|C_2|}{|T|} \sim \frac{|E_2|}{|T|} \sim \frac{|B|}{|T|} \sim \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{m_b}\right)$$

[A.Leibovich, Z.Ligeti, I.Stewart, M.Wise, Phys.Lett.B (2024)]

Explain CPVs of $\Lambda_b \to p\pi^-, pK^-$

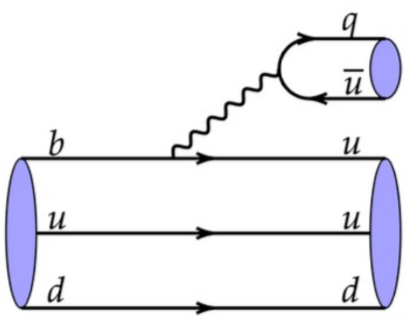
- Baryons have half-integer spin, and thus two partial wave amplitudes.

$$\mathcal{A}(\Lambda_b \to p\pi^-, pK^-) = i\bar{u}_p(S + P\gamma_5)u_{\Lambda_b}$$

$$S\ wave\quad S = \boxed{\lambda_{\mathcal{T}}|S_{\mathcal{T}}|e^{i\delta^S_{\mathcal{T}}}} + \boxed{\lambda_{\mathcal{P}}|S_{\mathcal{P}}|e^{i\delta^S_{\mathcal{P}}}}$$

$$P\ wave\quad P = \boxed{\lambda_{\mathcal{T}}|P_{\mathcal{T}}|e^{i\delta^P_{\mathcal{T}}}} + \boxed{\lambda_{\mathcal{P}}|P_{\mathcal{P}}|e^{i\delta^P_{\mathcal{P}}}}$$

Tree **Penguin**



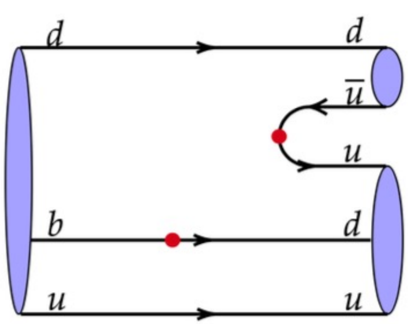
T

$$\sim q^\mu \bar{u}_p\gamma_\mu(1-\gamma_5)u_{\Lambda_b} \sim \bar{u}_p(1+\gamma_5)u_{\Lambda_b}$$

$$\Delta\delta_{S-wave} = \delta^{S-wave}_{PC_2} - \delta^{S-wave}_{T}$$

different by π

$$\Delta\delta_{P-wave} = \delta^{P-wave}_{PC_2} - \delta^{P-wave}_{T}$$



PC_2

$$\sim \bar{u}_p(1+\gamma_5)(\gamma_5 \not{p}_\pi)(\not{p}_{\Lambda_b}\gamma_5)\not{p}_p(1-\gamma_5)u_{\Lambda_b} \sim \bar{u}_p(1-\gamma_5)u_{\Lambda_b}$$

CPVs in PQCD

- Strong phases need to be determined by QCD calculations
- Based on k_T factorization, PQCD approach has successfully predicted B meson CPV

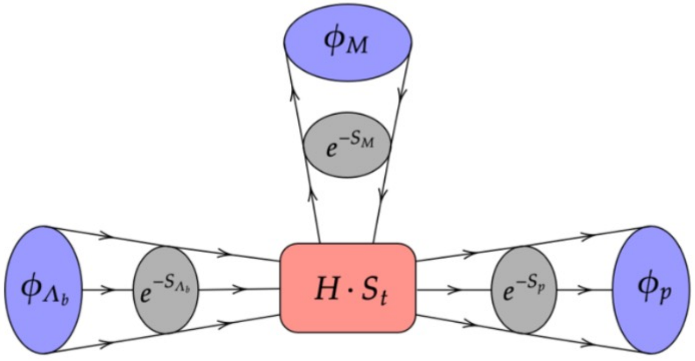
$C_{\pi\pi}(B \to \pi^+\pi^-)\%$	$A_{CP}(B \to K^+\pi^-)\%$
~ -40 [Lü,Ukai,Yang,2000]	~ -18 [Keum,Li,Sanda,2000]
$-30 \pm 25 \pm 4$ [BaBar,2002]	$-19 \pm 10 \pm 3$ [BaBar,2001]
$-12.8^{+3.48}_{-3.29}$ [Chai,Cheng,Ju,Yan, Lü,Xiao,2022]	$-5.43^{+2.25}_{-2.34}$ [Chai,Cheng,Ju,Yan, Lü,Xiao,2022]
-31.4 ± 3 [PDG]	-8.31 ± 0.31 [PDG]

- Amplitudes are expressed as convolution of hard kernels and LCDAs

[Sterman,Hsiang-nan Li,1995~2000]

$$\mathcal{M} = \langle pM | H_{eff} | \Lambda_b \rangle$$
$$\sim \int [d^4k_p][d^4k_M][d^4k_{\Lambda_b}]\Psi_p([k_p],\mu)\Psi_M([k_M],\mu)\Psi_{\Lambda_b}([k_{\Lambda_b}],\mu) \cdot C_i(\mu)H([k_p],[k_M],[k_{\Lambda_b}],\mu)$$
$$\sim \int_0^1 [dx_p]\,[dx_M][dx_{\Lambda_b}] \int [d^2k_p^T]\,[d^2k_M^T][d^2k_{\Lambda_b}^T]\phi_p([x_p],\mu)\phi_M([x_M],\mu)\phi_{\Lambda_b}([x_{\Lambda_b}],\mu)$$
$$\cdot\, C_i(\mu)H([x_p,k_p^T],[x_M,k_M^T],[x_{\Lambda_b},k_{\Lambda_b}^T],\mu)$$

- Free of end-point singularity



Results of $\Lambda_b \to p\pi^-$

TABLE V. Invariant amplitudes of the $\Lambda_b \to p\pi^-$ decay classified by topologies without the CKM matrix elements. in unit of 10^{-9}

$\Lambda_b \to p\pi^-$	$\lvert S \rvert$	$\delta^S(^\circ)$	Real(S)	Imag(S)	$\lvert P \rvert$	$\delta^P(^\circ)$	Real(P)	Imag(P)
T^f	707.17	0.00	707.17	0.00	1004.44	0.00	1004.44	0.00
T^{nf}	51.72	−96.64	−5.98	−51.38	267.72	−97.92	−36.90	−265.17
$T^f + T^{nf}$	703.07	−4.19	701.19	−51.38	1003.22	−15.33	967.54	−265.17
C_2	29.37	154.96	−26.61	12.43	41.51	179.80	−41.51	0.14
E_2	66.94	−145.26	−55.01	−38.14	72.58	119.94	−36.23	62.89
B	10.40	112.64	−4.00	9.60	23.65	−122.56	−12.73	−19.93
Tree	619.26	−6.26	615.57	−67.49	904.75	−14.21	877.08	−222.06
PC_1^f	58.44	0.00	58.44	0.00	2.90	0.00	2.90	0.00
PC_1^{nf}	1.24	−115.38	−0.53	−1.12	11.16	−95.25	−1.02	−11.11
$PC_1^f + PC_1^{nf}$	57.91	−1.11	57.90	−1.12	11.27	−80.38	1.88	−11.11
PC_2	13.36	−116.10	−5.88	−12.00	14.93	71.96	4.62	14.20
PE_1^u	9.48	−87.62	0.39	−9.47	8.83	114.44	−3.65	8.04
PB	1.36	−51.30	0.85	−1.06	1.55	−159.86	−1.46	−0.53
$PE_1^d + PE_2$	3.87	−98.18	−0.55	−3.83	1.41	−12.55	1.37	−0.31
Penguin	59.45	−27.54	52.71	−27.49	10.65	74.93	2.77	10.28

S波的强相位

P波的强相位

Results of baryon CPV

$$A_{CP}^{dir} = \frac{|S|^2}{|S|^2 + \frac{M_-^2}{M_+^2}\frac{1+A_{CP}^S}{1+A_{CP}^P}|P|^2} A_{CP}^{S-wave} + \frac{\frac{M_-^2}{M_+^2}|P|^2}{\frac{1+A_{CP}^P}{1+A_{CP}^S}|S|^2 + \frac{M_-^2}{M_+^2}|P|^2} A_{CP}^{P-wave}$$

	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}
$\Lambda_b \to p\pi^-$	$0.05^{+0.02}_{-0.03}$	$\boxed{0.17^{+0.05}_{-0.09}(49\%)}$	$\boxed{-0.06^{+0.04}_{-0.05}(51\%)}$	$0.02^{+0.01}_{-0.02}$	$0.22^{+0.08}_{-0.05}$	$0.11^{+0.05}_{-0.06}$
$\Lambda_b \to pK^-$	$-0.06^{+0.03}_{-0.02}$	$-0.05^{+0.05}_{-0.04}(94\%)$	$-0.21^{+0.39}_{-0.46}(6\%)$	$0.04^{+0.03}_{-0.04}$	$-0.44^{+0.08}_{-0.04}$	$0.02^{+0.06}_{-0.05}$

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

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

Predictions of large CPV in $\Lambda_b \to pa_1, pK_1$

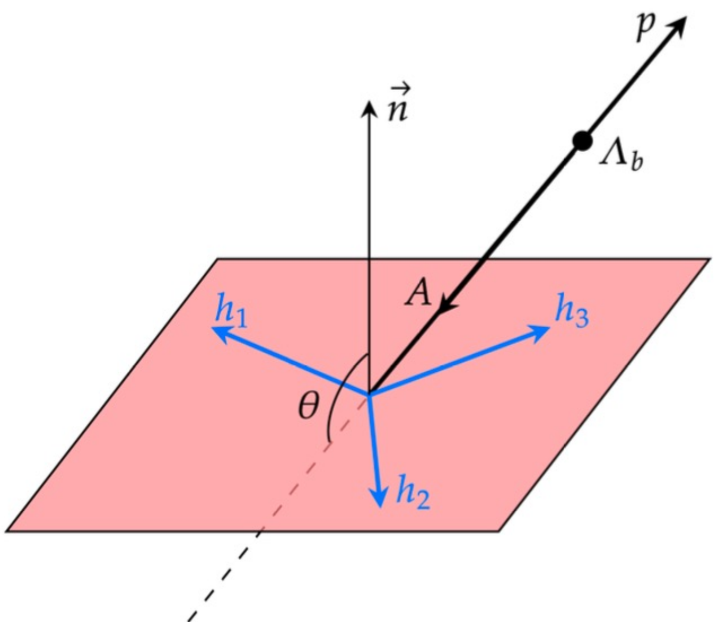
- The angle distribution for $\Lambda_b \to pa_1^- \to p\pi^-\pi^+\pi^-$:

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

- up-down asymmetry :

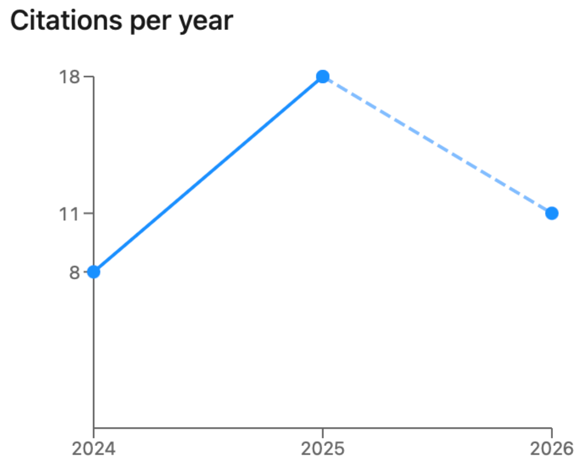
$$A_{UD} \equiv \frac{\Gamma(\cos\theta > 0) - \Gamma(\cos\theta < 0)}{\Gamma(\cos\theta > 0) + \Gamma(\cos\theta < 0)} = R\,\mathcal{R}e(S^T P_2^*)$$

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



[J.P.Wang,Q.Qin,F.S.Yu,2024]

	a_{UD}	A_{CP}^{UD}
$\Lambda_b \to pa_1^-(1260)$	$-0.09^{+0.00+0.01+0.02+0.00}_{-0.01-0.01-0.01-0.01}$	$-0.24^{+0.03+0.05+0.05+0.03}_{-0.03-0.09-0.06-0.06}$
$\Lambda_b \to pK_1^-(1270)(30°)$	$-0.19^{+0.03+0.02+0.01+0.01}_{-0.02-0.02-0.01-0.02}$	$0.26^{+0.02+0.03+0.01+0.00}_{-0.03-0.08-0.04-0.04}$
$\Lambda_b \to pK_1^-(1400)(30°)$	$-0.38^{+0.06+0.10+0.05+0.00}_{-0.06-0.09-0.07-0.03}$	$0.72^{+0.05+0.13+0.07+0.05}_{-0.05-0.23-0.03-0.12}$
$\Lambda_b \to pK_1^-(1270)(60°)$	$-0.24^{+0.04+0.04+0.01+0.00}_{-0.02-0.03-0.02-0.03}$	$0.40^{+0.02+0.03+0.02+0.01}_{-0.01-0.04-0.03-0.07}$
$\Lambda_b \to pK_1^-(1400)(60°)$	$-0.04^{+0.02+0.02+0.01+0.02}_{-0.01-0.05-0.03-0.01}$	$-0.19^{+0.12+0.14+0.00+0.06}_{-0.18-0.19-0.20-0.00}$

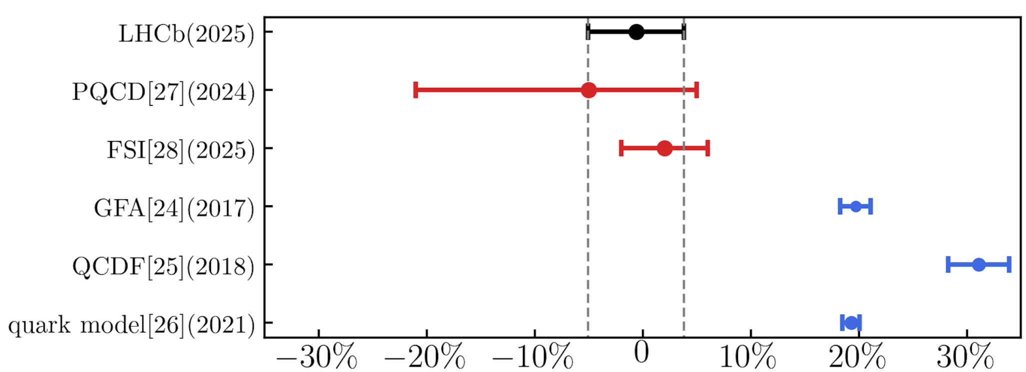


[LHCb Nature(2025)]"…… the generally small CP asymmetries in beauty-baryon decays imply that the dynamics in baryon decays are more complicated than in meson decays. For instance, the CP asymmetries for various angular-momentum amplitudes of the same resonance may cancel [38] ……"

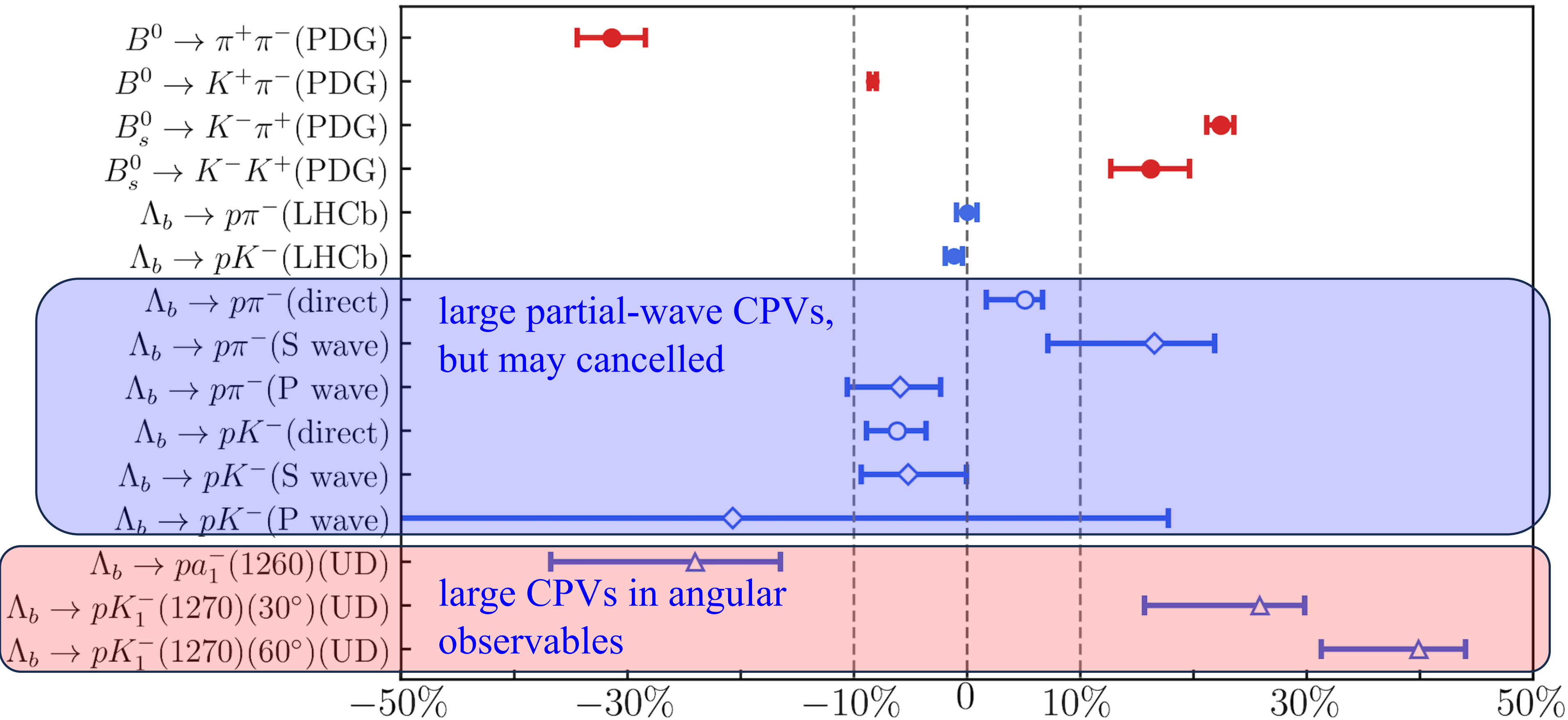
38. Han, J,-J. et al. Establishing CP violation in *b*-baryon decays. *Phys.Rev.Lett*. **134**, 221801 (2025).

[LHCb JHEP(2025)]"…… The vanishing CP asymmetry observed for the $\Lambda_b^0 \to p K_S^0 \pi^-$ decay in the $K^*(892)^-$ mass region, significantly smaller than the approximately 20% effect predicted by the GFA [24], the QCDF approach [25], and the LFQM approach [26], is in agreement with the hypothesis of a cancellation mechanism among the contributing partial waves, as proposed in Refs. [27,28] ……"

[27] J.-J. Han *et al.*, *Establishing CP violation in b-baryon decays*, Phys. Rev. Lett. **134** (2025) 221801, arXiv:2409.02821.



Summary



- **Jia-Jie Han**, Ji-Xin Yu, Ya Li, Hsiang-nan Li, Jian-Peng Wang, Zhen-Jun Xiao, Fu-Sheng Yu, **Physical Review Letters 134 (2025) 221801**.
- **Jia-Jie Han**, Ji-Xin Yu, Ya Li, Hsiang-nan Li, Jian-Peng Wang, Zhen-Jun Xiao, Fu-Sheng Yu, **Physical Review D 112 (2025) 053007.**