

A panoramic view of Lanzhou University's campus and surrounding cityscape under a blue sky with light clouds. The university's main building is prominent in the foreground, surrounded by greenery. In the background, the city of Lanzhou is visible with various buildings and hills.

自强不息 獨樹一幟

WELCOME TO LANZHOU UNIVERSITY

# Prediction of CPV in $b$ -baryon decays

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2026·03 第五届强子与重味物理理论和实验联合研讨会@河北师范大学

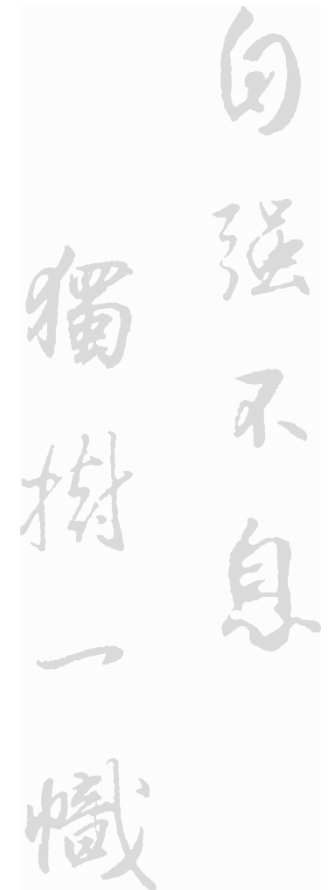


Introduction

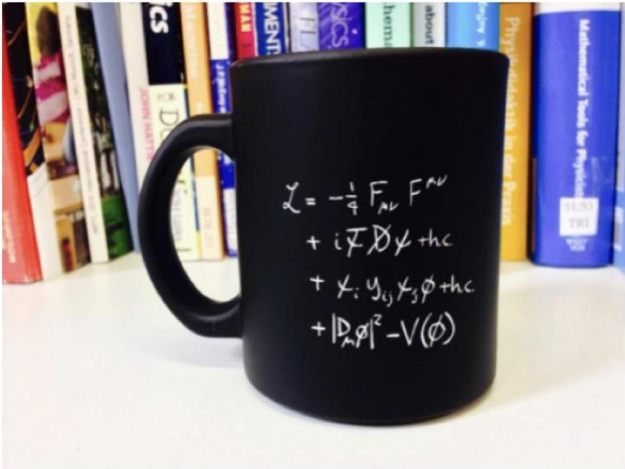
CPV in two-body decay

CPV in multi-body decay

Summary and outlook



# Standard Model



$$SU(3) \otimes SU(2) \otimes U(1)$$

three generations of matter (fermions)			interactions / forces (bosons)		
	I	II	III		
mass	≈ 2.2 MeV	≈ 1.3 GeV	≈ 173 GeV	0	≈ 125 GeV
charge	+2/3	+2/3	+2/3	0	0
spin	1/2	1/2	1/2	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> Higgs
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>γ</b> photon	
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>W</b> W boson	
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>Z</b> Z boson	

➤ Standard Model achieves great success,

➤ But still remains some puzzles: dark matter, dark energy, neutrino oscillation, **matter asymmetry in Universe**, .....

$$Y_B^{obs} \approx 8 \times 10^{-11} \quad Y_B^{SM} \approx 7 \times 10^{-20} \quad [Astron. Astrophys.594 A13(2016)]$$

➤ How to understand matter asymmetry, suppose that the Big Bang produced equal numbers of positive and negative baryons ?



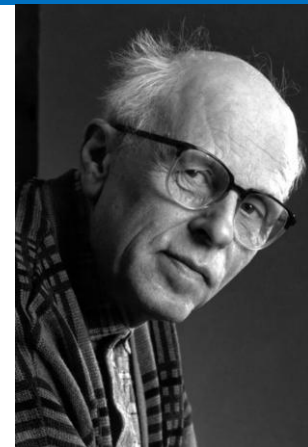
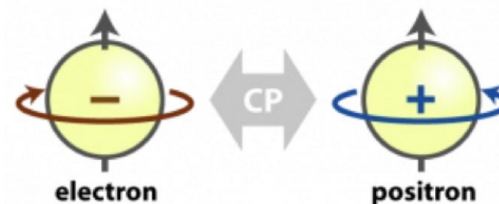
# CP violation

➤ Matter-antimatter asymmetry in the Universe

[Science 109 (2005) 5731]

➤ Three conditions for Matter-antimatter asymmetry:

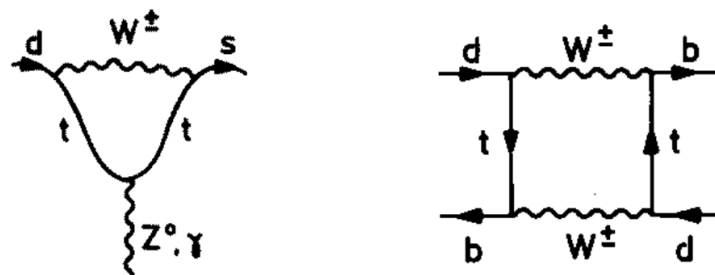
- Interaction to violate baryon number;
- **C and CP violation;**
- Deviate thermal equilibrium



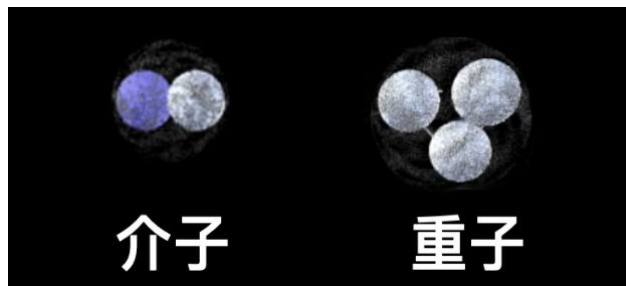
CP: 电荷共轭+宇称变换

[Sakharov JETP Lett.(1967)]

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

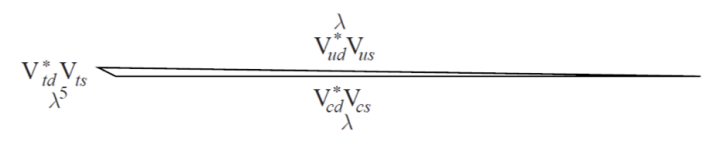


➤ Baryon CPV is more crucial, as visible matter in Universe is made of baryons.



## 超子

- SM:  $\mathcal{O}(10^{-5} \sim 10^{-4})$  [Donoghue, X.G.He, Pakvasa, 1986]
- BESIII [Nature, 2022]  $A_{CP}^\alpha(\Lambda \rightarrow p\pi^-) = (2.5 \pm 4.8) \times 10^{-3}$

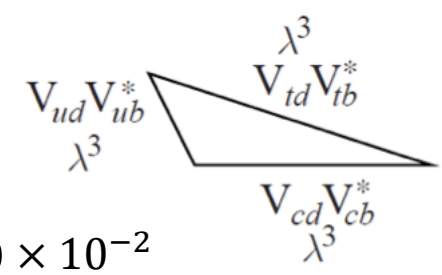


## 粲重子

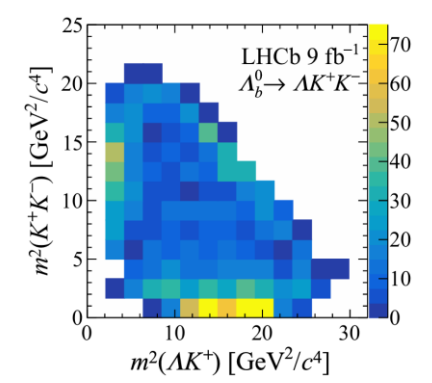
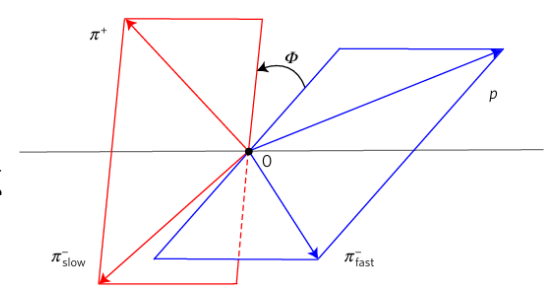
- [X.G.He, C.W.Liu, 2024]
- SM:  $\mathcal{O}(10^{-3} \sim 10^{-4})$  [C.P.Jia, H.Y.Jiang, J.P.Wang, F.S.Yu, 2024]
- LHCb [JHEP, 2018]  $A_{CP}(\Lambda_c \rightarrow pK^+K^-/p\pi^+\pi^-) = (3.0 \pm 9.1 \pm 6.1) \times 10^{-3}$

## 底重子

- SM estimates  $\sim 10\%$  due to large weak phase difference
- 两体衰变直接CP破坏  $A_{CP}(\Lambda_b^0 \rightarrow pK^-) = (-1.1 \pm 0.7 \pm 0.4) \times 10^{-2}$   
 $A_{CP}(\Lambda_b^0 \rightarrow p\pi^-) = (-0.2 \pm 0.8 \pm 0.4) \times 10^{-2}$



- 多体衰变三重积CP破坏
- 多体衰变Dalitz局域CP破坏



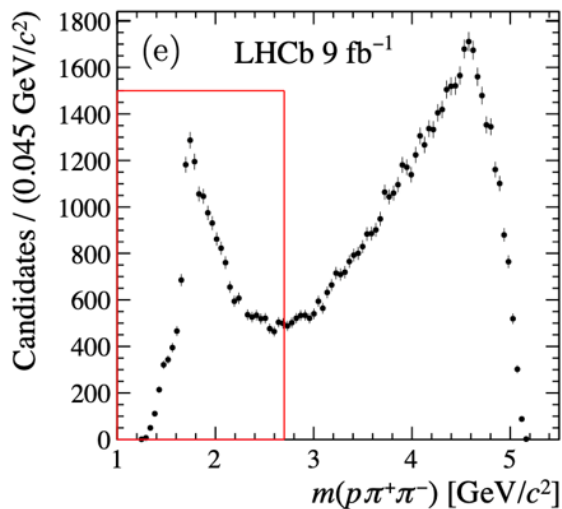
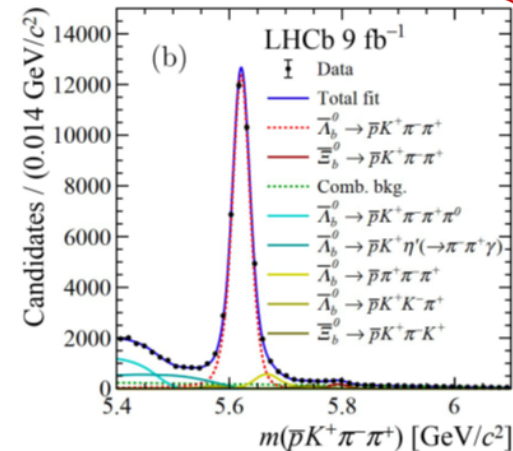
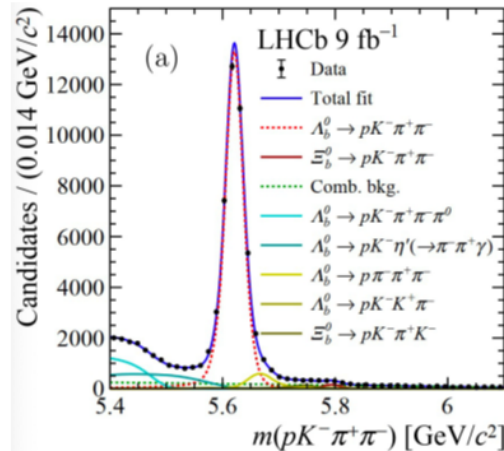
[LHCb, 2412.13958]  
 [LHCb, PRL 134 (2025)]  
 [LHCb, Nature Physics 13 (2017)]

## ➤ LHCb实验组首次发现重子衰变CP破坏

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

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

$5.2\sigma$



[LHCb Nature(2025)]

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

$6.0\sigma$

## ➤ 实验发现之前

- 理论上最关键的科学问题：什么样的观测量和衰变道是寻找重子CP破坏的最佳选择？

## ➤ 理论该做什么



观测量：研究新的CP破坏观测量，提高重子CP破坏发现的可能性

[Zhen-Hua Zhang, et.al.]  
[J.P.Wang, Q.Qin, F.S.Yu]

动力学：发展末态重散射的动力学方法，预言重子CP破坏

[HJJ, J.X.Yu, Y.Li, H.n.Li, J.P.Wang, Z.J.Xiao, F.S.Yu, PQCD(2025)]  
[J.P.Wang, F.S.Yu, FSI(2024)]



## 2. Two-body decays

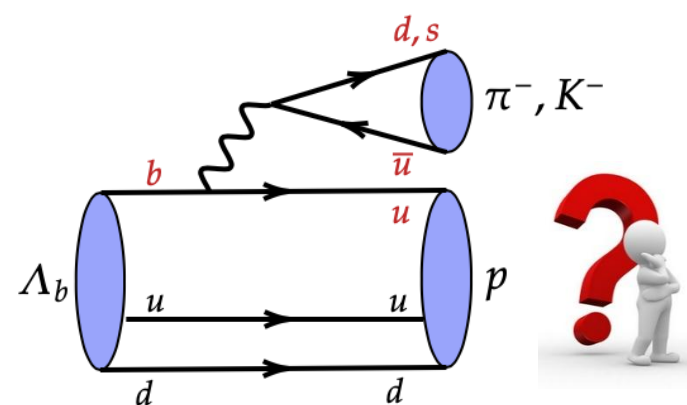
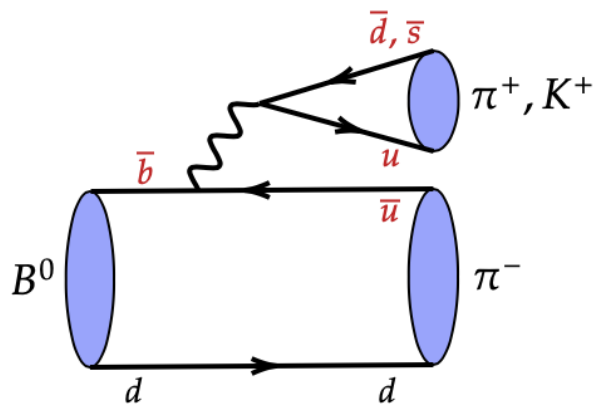
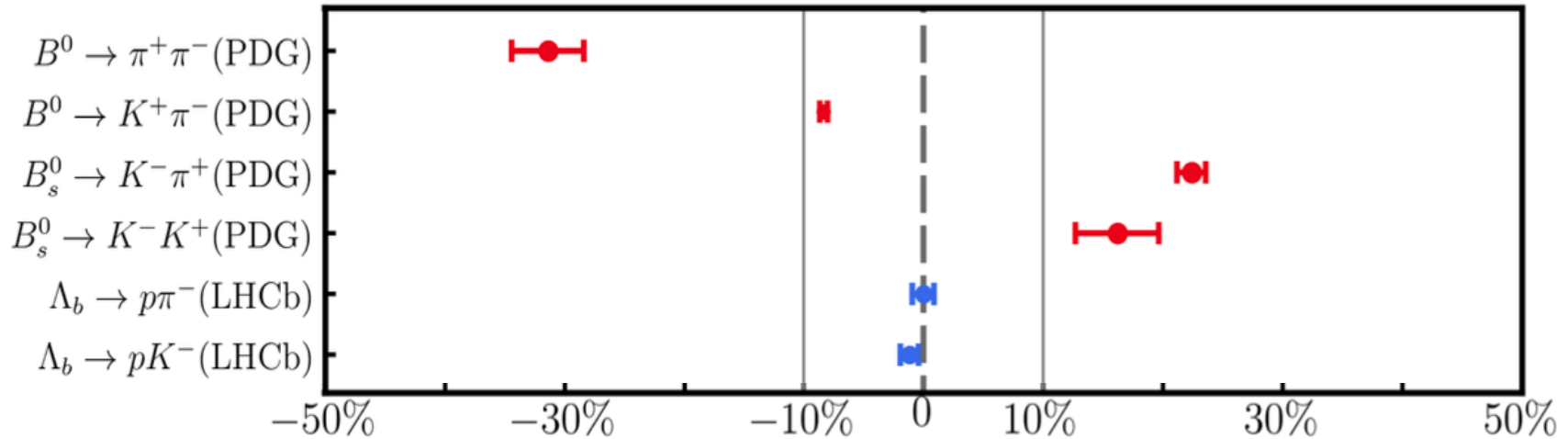
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# Puzzle of $b$ -baryon CPV

➤ Why baryon two-body CPV small?

$$A_{CP}(\Lambda_b \rightarrow p\pi^-) = (0.20 \pm 0.83 \pm 0.37)\% \quad \text{➤ LHCb, 2024}$$

$$A_{CP}(\Lambda_b \rightarrow pK^-) = (-1.14 \pm 0.67 \pm 0.36)\%$$



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

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

$$\mathcal{A}(\Lambda_b \rightarrow ph) = i\bar{u}_p(S + P\gamma_5)u_{\Lambda_b}$$

$$\begin{array}{l}
 S \text{ wave} \quad S = \underbrace{\lambda_{\mathcal{T}}|S_{\mathcal{T}}|e^{i\delta_{\mathcal{T}}^S}}_{\text{Tree}} + \underbrace{\lambda_{\mathcal{P}}|S_{\mathcal{P}}|e^{i\delta_{\mathcal{P}}^S}}_{\text{Penguin}} \quad \Delta\delta_S = \delta_{\mathcal{P}}^S - \delta_{\mathcal{T}}^S \\
 P \text{ wave} \quad P = \underbrace{\lambda_{\mathcal{T}}|P_{\mathcal{T}}|e^{i\delta_{\mathcal{T}}^P}}_{\text{Tree}} + \underbrace{\lambda_{\mathcal{P}}|P_{\mathcal{P}}|e^{i\delta_{\mathcal{P}}^P}}_{\text{Penguin}} \quad \Delta\delta_P = \delta_{\mathcal{P}}^P - \delta_{\mathcal{T}}^P \\
 \hspace{15em} \text{strong phase difference}
 \end{array}$$

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

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

$$\mathcal{A}(\Lambda_b \rightarrow ph) = i\bar{u}_p(S + P\gamma_5)u_{\Lambda_b}$$

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

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

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

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

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

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

$\Delta\delta_S = \delta_P^S - \delta_T^S$   
 $\Delta\delta_P = \delta_P^P - \delta_T^P$

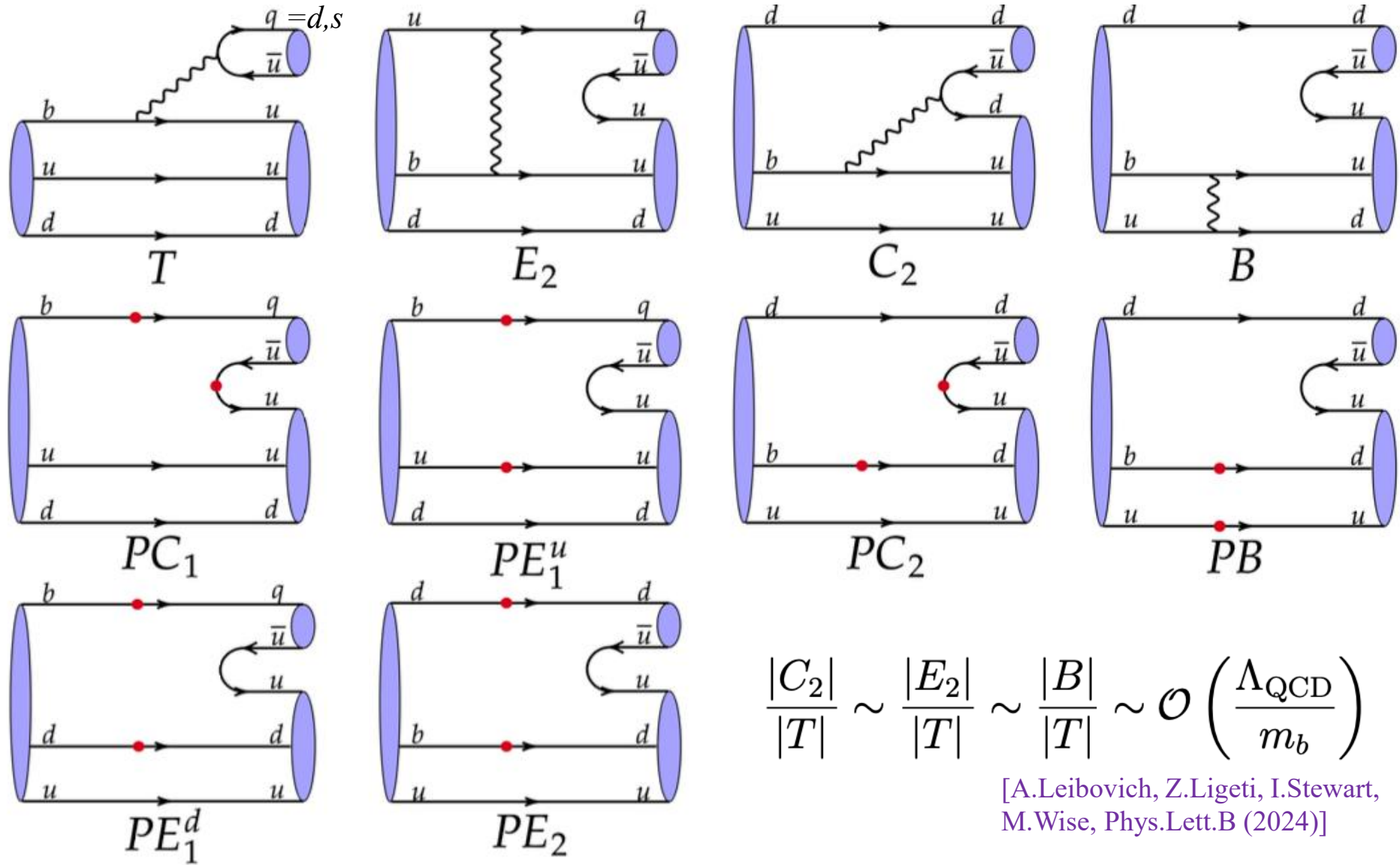
partial-wave CPVs

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# Topological diagrams



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

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

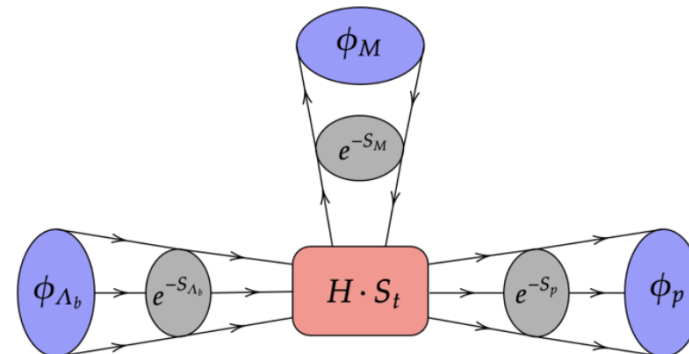
- Strong phases need to be determined by QCD calculations
- Based on  $k_T$  factorization, PQCD approach has successfully predicted  $B$  meson CPV

$C_{\pi\pi}(B \rightarrow \pi^+\pi^-)\%$	$A_{CP}(B \rightarrow K^+\pi^-)\%$
$\sim -40$ [Lü,Ukai,Yang,2000]	$\sim -18$ [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]
$-31.4 \pm 3$ [PDG]	$-8.31 \pm 0.31$ [PDG]

- Amplitudes are expressed as convolution of hard kernels and LCDAs

$$\begin{aligned}
 \mathcal{M} &= \langle pM | H_{eff} | \Lambda_b \rangle && \text{[Sterman,Hsiang-nan Li,1995~2000]} \\
 &\sim \int [d^4k_p][d^4k_M][d^4k_{\Lambda_b}] \Psi_p([k_p], \mu) \Psi_M([k_M], \mu) \Psi_{\Lambda_b}([k_{\Lambda_b}], \mu) \cdot C_i(\mu) H([k_p], [k_M], [k_{\Lambda_b}], \mu) \\
 &\sim \int_0^1 [dx_p][dx_M][dx_{\Lambda_b}] \int [d^2k_p^T][d^2k_M^T][d^2k_{\Lambda_b}^T] \phi_p([x_p], \mu) \phi_M([x_M], \mu) \phi_{\Lambda_b}([x_{\Lambda_b}], \mu) \\
 &\quad \cdot C_i(\mu) H([x_p, k_p^T], [x_M, k_M^T], [x_{\Lambda_b}, k_{\Lambda_b}^T], \mu)
 \end{aligned}$$

- Free of end-point singularity



$$\mathcal{A}(\Lambda_b \rightarrow pM) \sim \int \phi_{\Lambda_b} e^{-S_{\Lambda_b}} \cdot H S_t \cdot \phi_p e^{-S_p} \phi_M S^{-S_M}$$

# Results of $\Lambda_b \rightarrow p\pi^-$

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

$\Lambda_b \rightarrow p\pi^-$	$ S $	$\delta^S(^{\circ})$	Real( $S$ )	Imag( $S$ )	$ P $	$\delta^P(^{\circ})$	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

# Observables of $\Lambda_b \rightarrow p\pi^-, pK^-$

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

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

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

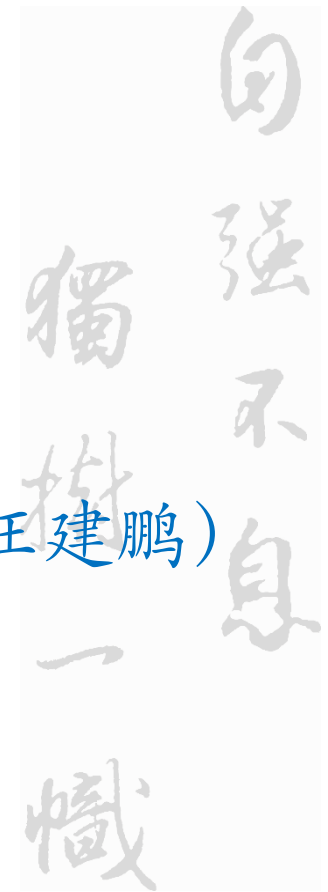
$Br(\times 10^{-6})$		分波CPV符号相反, 相互抵消			
$\Lambda_b \rightarrow p\pi^-$	$3.34_{-1.30-1.10-0.11-0.14}^{+2.53+1.33+0.10+0.47}$				
$\Lambda_b \rightarrow pK^-$	$2.83_{-1.05-0.92-0.37-0.66}^{+2.17+1.17+0.49+2.19}$				
	$A_{CP}^{dir}$	$A_{CP}^S(\kappa_S)$		$A_{CP}^P(\kappa_P)$	
$\Lambda_b \rightarrow p\pi^-$	$0.05_{-0.02-0.01-0.02-0.01}^{+0.00+0.00+0.00+0.02}$	<span style="border: 1px solid red; padding: 2px;">0.17</span>	$+0.01+0.01+0.03+0.04$	<span style="border: 1px solid red; padding: 2px;">-0.06</span>	$+0.01+0.03+0.02+0.00$ (49%) (51%)
$\Lambda_b \rightarrow pK^-$	$-0.06_{-0.01-0.01-0.01-0.00}^{+0.01+0.01+0.02+0.00}$	<span style="border: 1px solid blue; padding: 2px;">-0.05</span>	$+0.02+0.02+0.04+0.00$ (94%)	<span style="border: 1px solid blue; padding: 2px;">-0.21</span>	$+0.07+0.23+0.29+0.04$ (6%)

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

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



### 3. Multi-body decays (汪建鹏)



## ➤ 为什么研究多体衰变CP破坏

- **实验优势**: 统计量高, 可以尝试更多观测量

$$Br[\Lambda_b^0 \rightarrow p\pi^+\pi^-\pi^-] = (2.08 \pm 0.21) \times 10^{-5}$$

$$Br[\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-] = (5 \pm 0.5) \times 10^{-5}$$

$$Br[\Lambda_b^0 \rightarrow pK^-K^+\pi^-] = (4 \pm 0.6) \times 10^{-6}$$

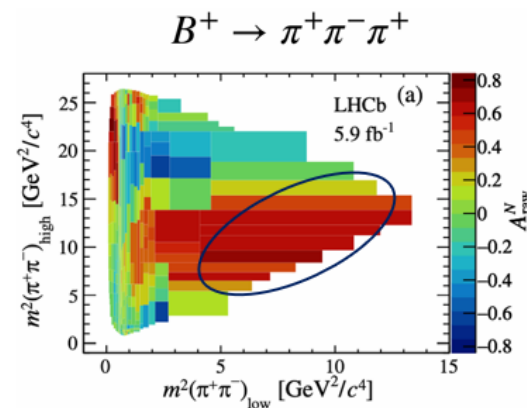
$$Br[\Lambda_b^0 \rightarrow pK^+K^-K^-] = (1.25 \pm 0.13) \times 10^{-5}$$

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

- 多体衰变可能有**很大的局域CP破坏**

$$A_{CP}(B^\pm \rightarrow \pi^\pm\pi^+\pi^-) = +0.080 \pm 0.004$$

[LHCb, [Phys.Rev.D 108 \(2023\)](#)]



- **理论缺乏研究**: 中间共振态多, 理论不确定性变大

# ➤ 理论困难

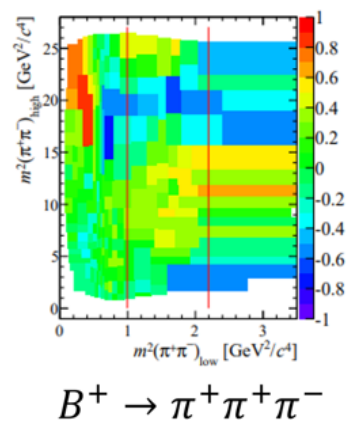
- 多体衰变  $\Lambda_b^0 \rightarrow (p\pi^0)h^-, (p\pi^+\pi^-)h^- (h=\pi, K)$  中存在大量共振态

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

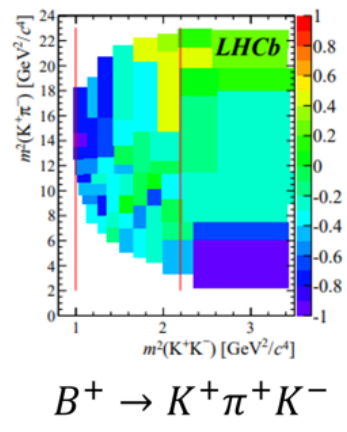
$N(1700)$ BREIT-WIGNER MASS	1650 to 1800 ( $\approx 1720$ ) MeV
$N(1700)$ BREIT-WIGNER WIDTH	100 to 300 ( $\approx 200$ ) MeV
$N(1710)$ BREIT-WIGNER MASS	1680 to 1740 ( $\approx 1710$ ) MeV
$N(1710)$ BREIT-WIGNER WIDTH	80 to 200 ( $\approx 140$ ) MeV
$N(1720)$ BREIT-WIGNER MASS	1680 to 1750 ( $\approx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

- $p\pi, p\pi\pi$  系统共振态太多，彼此靠近!
- 难以确定主导贡献来源，理论无法预言!

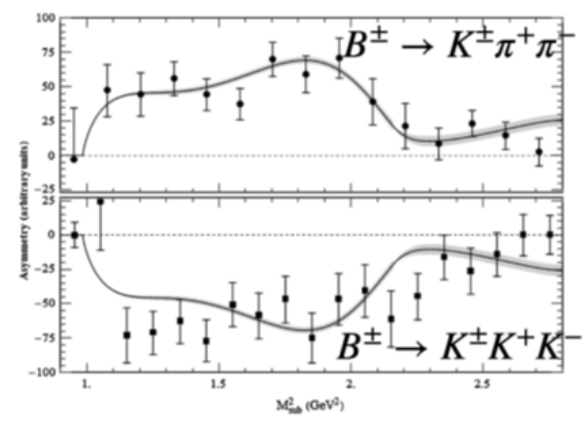
# ► B介子三体衰变的启发



$$\pi^+ \pi^- \leftrightarrow K^+ K^-$$

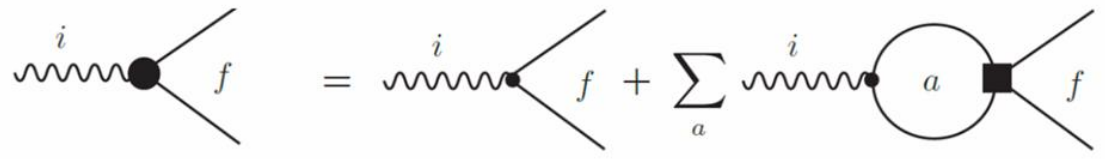


实验理论符合



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

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



# ➤ $N\pi$ 散射

- $N^*$  共振态来源于  $N\pi$  散射分波振幅
- $N\pi$  散射分波振幅有实验数据

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

**INS DAC Services [SAID Program]**

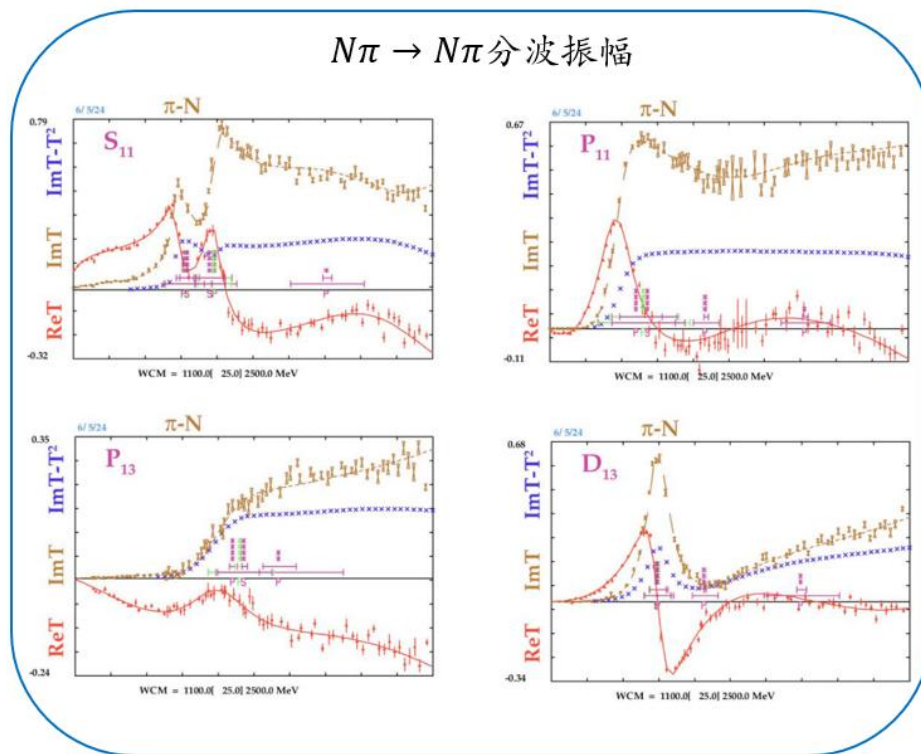
- The SAID Partial-Wave Analysis Facility is based
- New features are being added and will first appear always welcome.

**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 specil mail message).

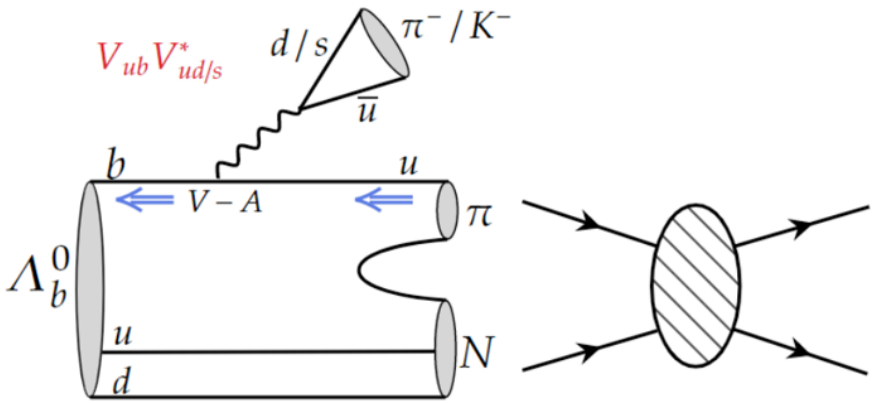
All programs expect energies in MeV units. All of the soluti Some are unstable beyond their upper energy limits. Extrapa **Increments:** The programs will not allow an arbitrary numb



- 散射分波振幅有明显的虚部，提供强相位！
- 避免处理共振态，采用实验数据，**model-independent!**

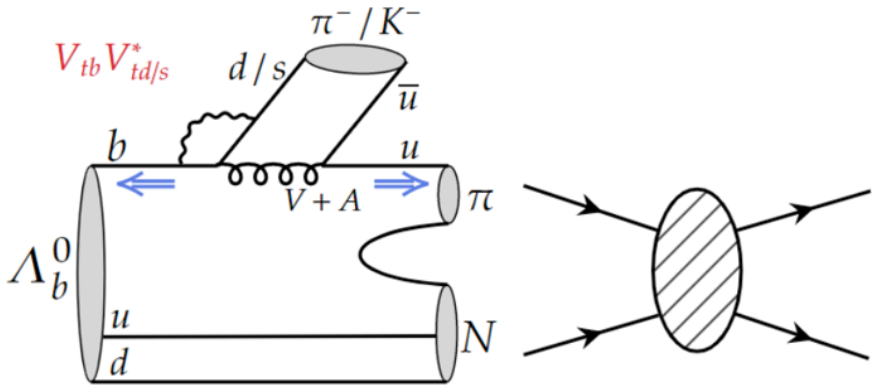
数据驱动

# 多体衰变CP破坏机制



$$O_1^u = (\bar{u}_\alpha b_\alpha)_{V-A} (\bar{q}_\beta u_\beta)_{V-A},$$

$$O_2^u = (\bar{u}_\alpha b_\beta)_{V-A} (\bar{q}_\beta u_\alpha)_{V-A},$$



手征不同 → 分波不同 → 树振幅和企鹅振幅有不同的重散射贡献

$$O_5 = (\bar{q}_\alpha b_\alpha)_{V-A} \sum_{q'} (\bar{q}'_\beta q'_\beta)_{V+A},$$

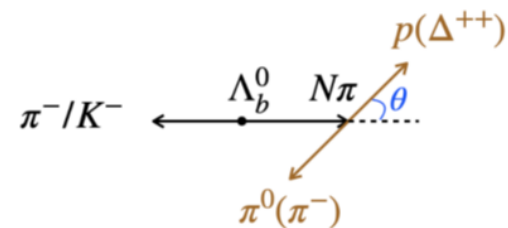
$$O_6 = (\bar{q}_\beta b_\alpha)_{V-A} \sum_{q'} (\bar{q}'_\alpha q'_\beta)_{V+A},$$

弱相位CKM机制

强相位  $N\pi \rightarrow N\pi, N\pi\pi$

[J.P.Wang, F.S.Yu, Chin.Phys.C 48 (2024)]

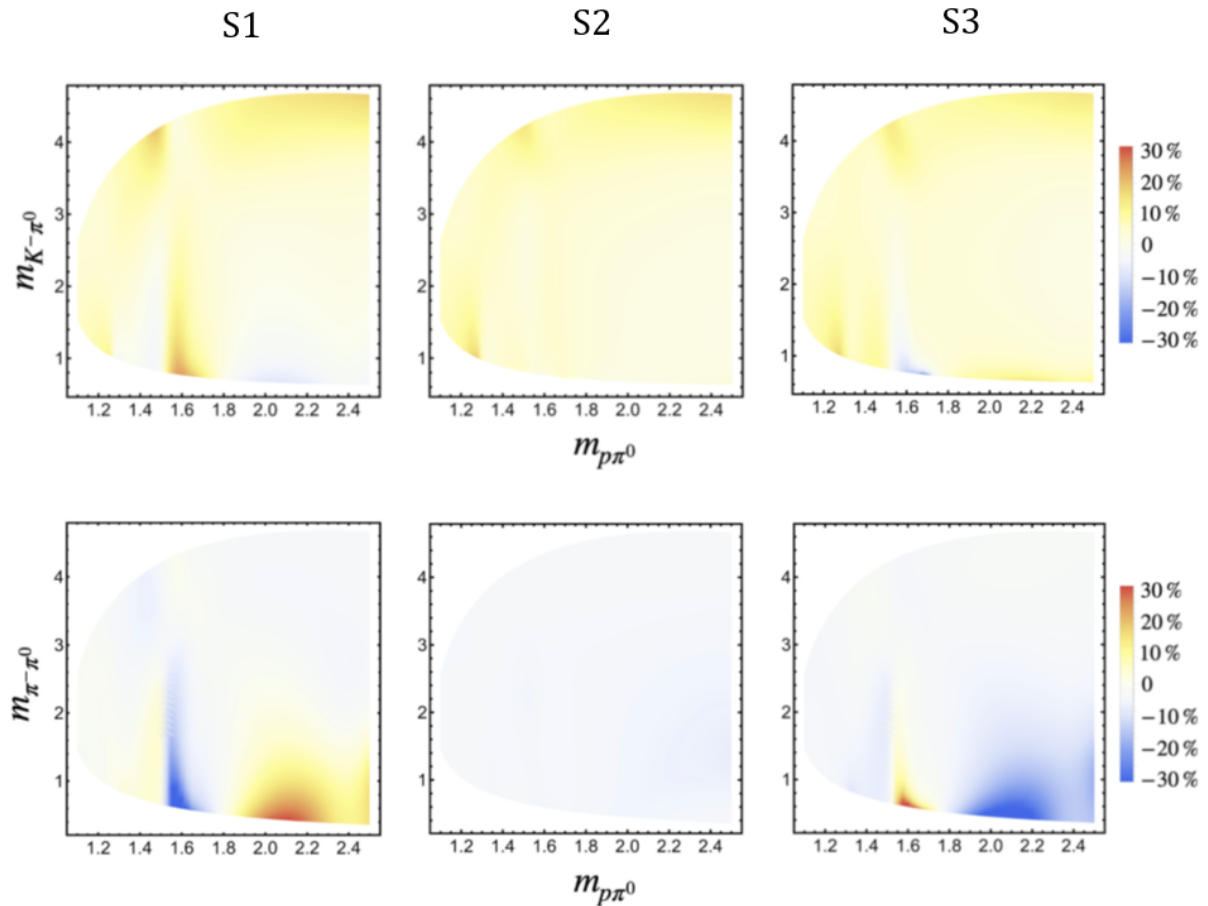
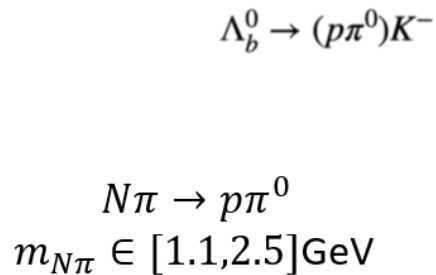
➤ 多体衰变CP破坏数值结果：总CP破坏



decay processes	Scenarios	global CPV	CPV of $\cos \theta < 0$	CPV of $\cos \theta > 0$
$N\pi \rightarrow \Delta^{++}\pi^-$ $m_{N\pi} \in [1.3, 1.9]\text{GeV}$	S1	5.9%	8.0%	3.6%
	S2	5.8%	6.3%	5.3%
	S3	5.6%	4.3%	7.0%
$\Lambda_b^0 \rightarrow (\Delta^{++}\pi^-)K^-$ $\rightarrow (p\pi^+\pi^-)K^-$	S1	-4.1%	-5.4%	-2.4%
	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%
	S2	5.8%	8.0%	3.0%
	S3	5.8%	7.8%	3.3%
$\Lambda_b^0 \rightarrow (p\pi^0)K^-$	S1	-3.9%	-3.9%	-3.7%
	S2	-3.9%	-3.8%	-4.3%
	S3	-3.8%	-3.6%	-4.8%

# 更多预言：Dalitz分布

(S1:  $f_1 = 1.1, g_1 = 0.9$ , S2:  $f_1 = g_1 = 1.0$ , S3:  $f_1 = 0.9, g_1 = 1.1$ )



- Dalitz分布包含了所有信息，将来实验进一步验证！
- 发现很大的局域CP破坏 (20%到30%)，和B介子CP破坏在相同量级



## 4. Summary and outlook

白強不息  
獨樹一幟

Baryon CPV is a new horizon of heavy flavor physics.

We do first full QCD analysis of b-baryon two-body decays

We propose a new CPV mechanism from  $N\pi$  scatterings

Thanks

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

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

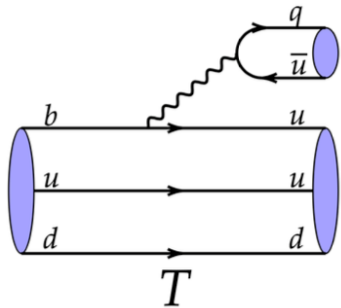
$$\mathcal{A}(\Lambda_b \rightarrow ph) = i\bar{u}_p(S + P\gamma_5)u_{\Lambda_b}$$

$$S \text{ wave } S = \lambda_{\mathcal{T}}|S_{\mathcal{T}}|e^{i\delta_{\mathcal{T}}^S} + \lambda_{\mathcal{P}}|S_{\mathcal{P}}|e^{i\delta_{\mathcal{P}}^S}$$

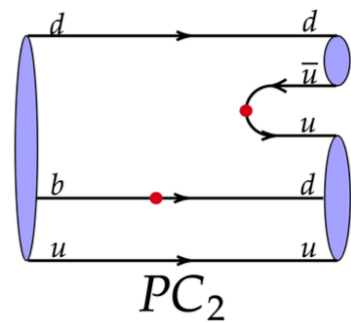
$$P \text{ wave } P = \lambda_{\mathcal{T}}|P_{\mathcal{T}}|e^{i\delta_{\mathcal{T}}^P} + \lambda_{\mathcal{P}}|P_{\mathcal{P}}|e^{i\delta_{\mathcal{P}}^P}$$

**Tree**

**Penguin**



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



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

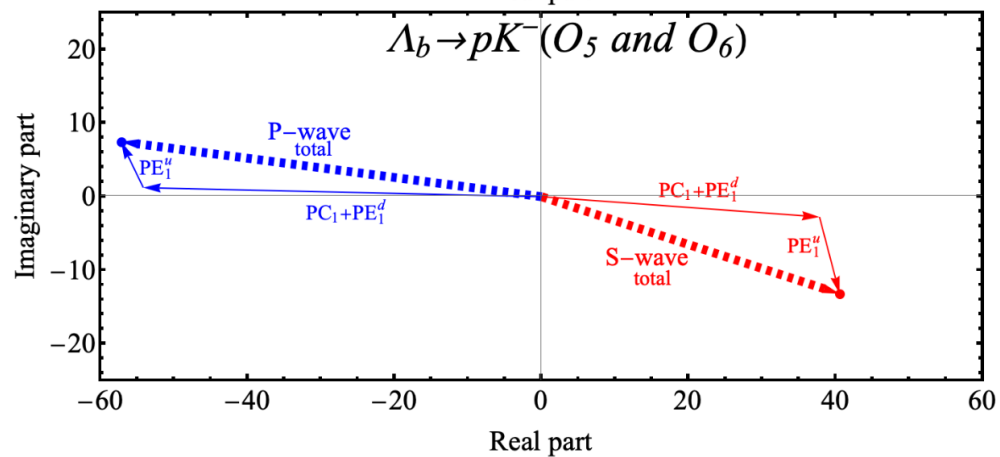
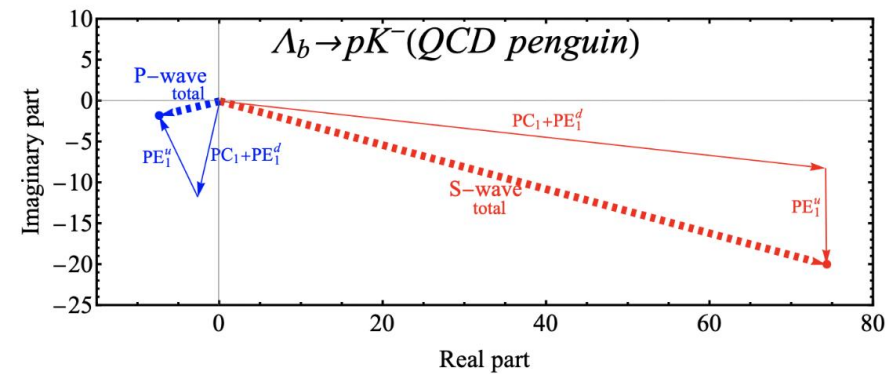
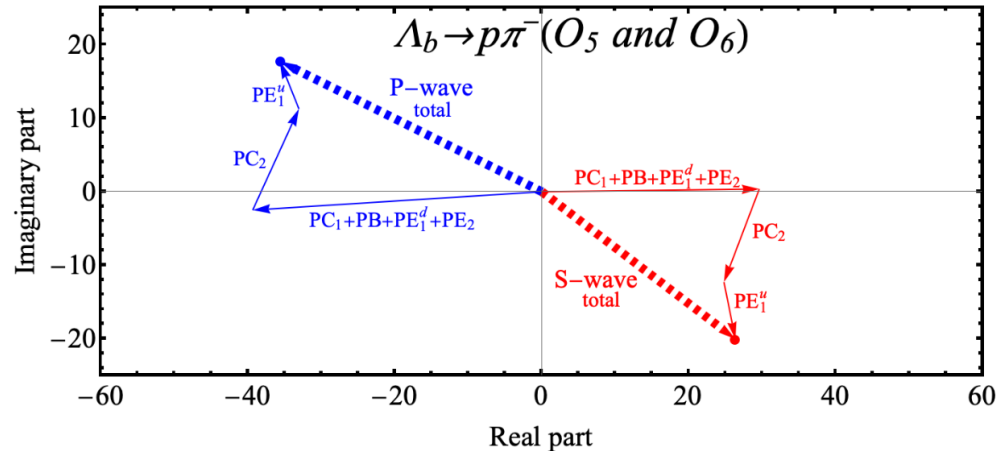
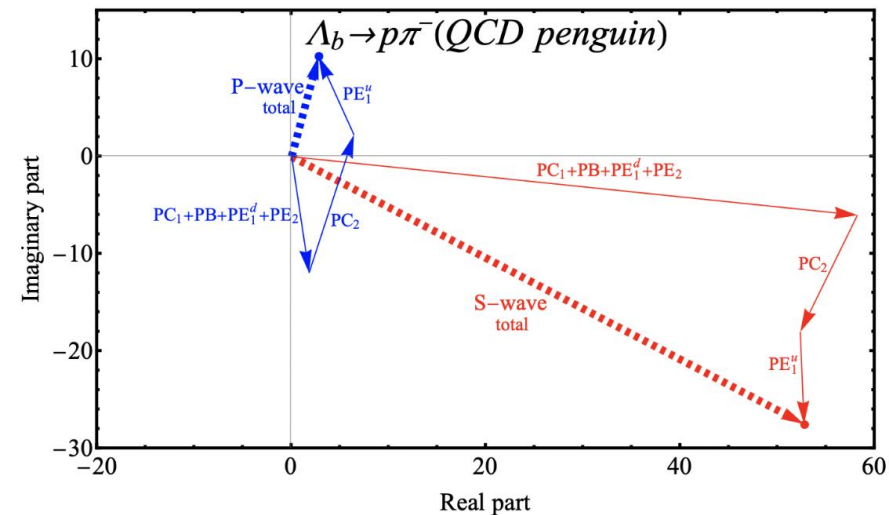
$$\Delta\delta_{S\text{-wave}} = \delta_{PC_2}^{S\text{-wave}} - \delta_T^{S\text{-wave}} \sim 0$$

$$\Delta\delta_{P\text{-wave}} = \delta_{PC_2}^{P\text{-wave}} - \delta_T^{P\text{-wave}} \sim \pi$$

different by  $\pi$

Strong phases depending on:

- operators
- diagram
- non-perturbative LCDAs



$\Lambda_b \rightarrow p\pi^-$		$ S $	$\delta^S(^{\circ})$	$\text{Re}(S)$	$\text{Im}(S)$	$ P $	$\delta^P(^{\circ})$	$\text{Re}(P)$	$\text{Im}(P)$
Tree	$T$	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
	total	619.26	-6.26	615.57	-67.49	904.75	-14.21	877.08	-222.06
QCD Penguin	$PC_1$	59.36	-1.62	59.34	-1.68	13.41	-81.85	1.90	-13.27
	$PC_2$	13.95	-114.84	-5.86	-12.66	13.89	69.92	4.77	13.05
	$PE_1^u$	8.52	-93.30	-0.49	-8.51	10.23	112.10	-3.85	9.48
	$PB$	1.44	-39.65	1.11	-0.92	1.40	-162.08	-1.33	-0.43
	$PE_1^d + PE_2$	3.98	-101.17	-0.77	-3.90	1.35	7.65	1.34	0.18
	total	60.07	-27.41	53.33	-27.65	9.44	72.56	2.83	9.01
$O_{3,4}$	$PC_1$	30.41	-4.26	30.32	-2.26	43.11	-16.55	41.32	-12.28
	$PC_2$	1.05	179.78	-1.05	0.00	1.68	-154.82	-1.52	-0.71
	$PE_1^u$	2.18	-159.87	-2.05	-0.75	3.28	112.54	-1.26	3.03
	$PB$	0.36	103.90	-0.09	0.35	0.38	-114.38	-0.16	-0.35
	$PE_1^d + PE_2$	2.42	-93.34	-0.14	-2.42	1.61	86.32	0.10	1.60
	total	27.47	-10.64	27.00	-5.07	39.46	-12.75	38.49	-8.71
$O_{5,6}$	$PC_1$	29.02	1.15	29.02	0.58	39.44	-178.56	-39.42	-0.99
	$PC_2$	13.54	-110.82	-4.81	-12.66	15.13	65.45	6.29	13.76
	$PE_1^u$	7.92	-78.61	1.56	-7.76	6.95	111.88	-2.59	6.45
	$PB$	1.74	-46.52	1.20	-1.27	1.17	-176.00	-1.17	-0.08
	$PE_1^d + PE_2$	1.61	-113.22	-0.63	-1.48	1.89	-48.96	1.24	-1.42
	total	34.69	-40.61	26.33	-22.58	39.82	153.58	-35.66	17.72

# Observables of $\Lambda_b \rightarrow p\pi^-, pK^-$

$$\alpha = -\frac{2\kappa_c \text{Re}(S^*P)}{|S|^2 + \kappa_c^2|P|^2}, \quad \beta = -\frac{2\kappa_c \text{Im}(S^*P)}{|S|^2 + \kappa_c^2|P|^2}, \quad \gamma = \frac{|S|^2 - \kappa_c^2|P|^2}{|S|^2 + \kappa_c^2|P|^2},$$

$$A_{CP}^\alpha = \frac{\alpha + \bar{\alpha}}{2}, \quad A_{CP}^\beta = \frac{\beta + \bar{\beta}}{2}, \quad A_{CP}^\gamma = \frac{\gamma - \bar{\gamma}}{2},$$

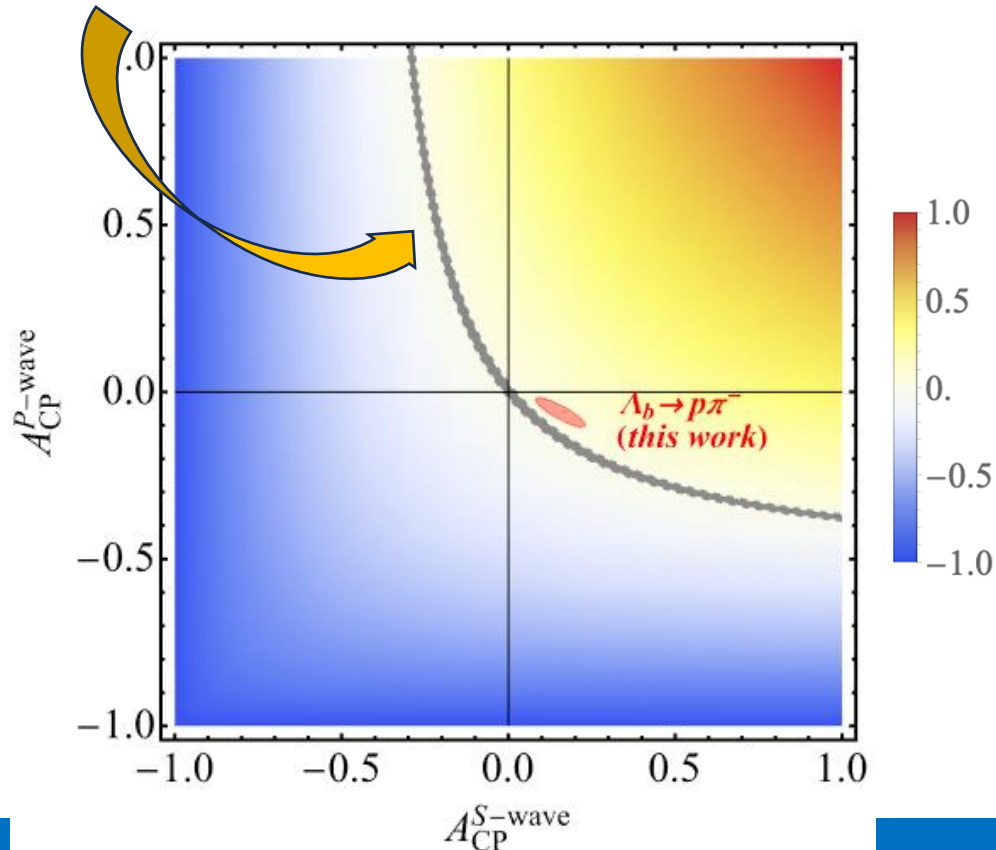
$$\langle \alpha \rangle = \frac{\alpha - \bar{\alpha}}{2}, \quad \langle \beta \rangle = \frac{\beta - \bar{\beta}}{2}, \quad \langle \gamma \rangle = \frac{\gamma + \bar{\gamma}}{2}.$$

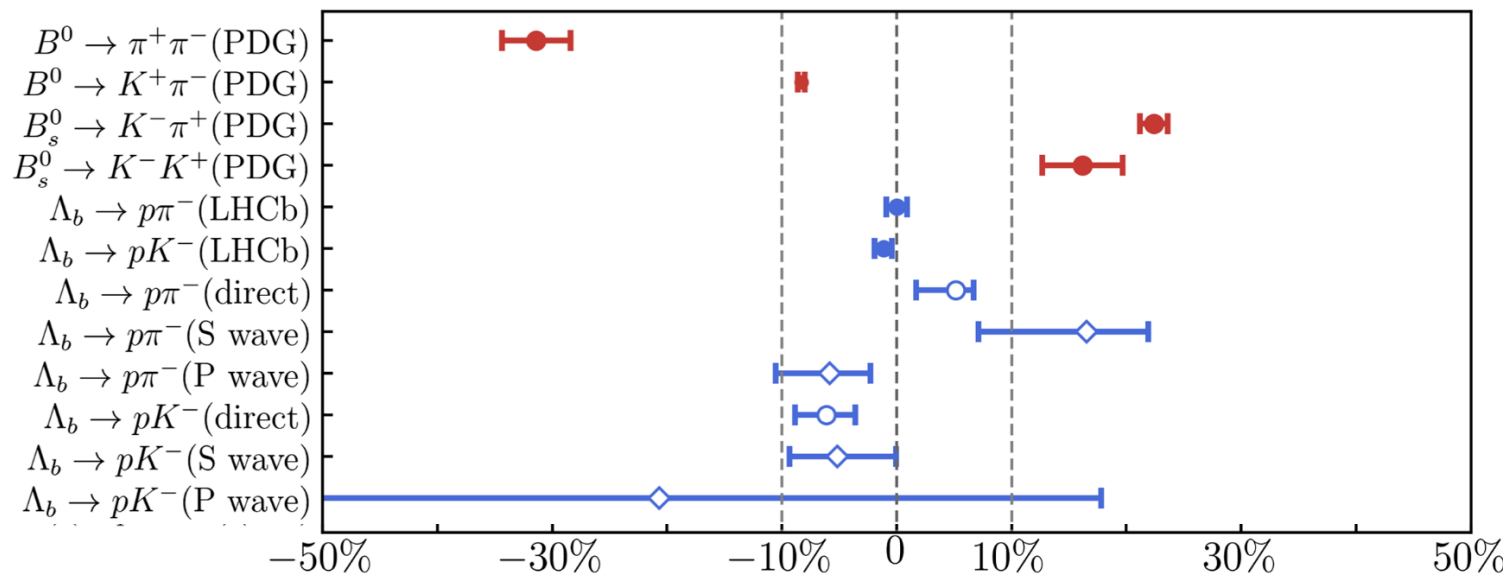
	$\alpha$	$A_{CP}^\alpha$	$\langle \alpha \rangle$
$\Lambda_b \rightarrow p\pi^-$	$-0.94^{+0.00+0.02+0.01+0.03}_{-0.02-0.02-0.02-0.02}$	$0.02^{+0.00+0.01+0.00+0.01}_{-0.01-0.01-0.01-0.01}$	$-0.96^{+0.00+0.01+0.01+0.02}_{-0.00-0.01-0.01-0.01}$
$\Lambda_b \rightarrow pK^-$	$0.23^{+0.04+0.02+0.10+0.15}_{-0.03-0.05-0.12-0.07}$	$0.04^{+0.02+0.02+0.01+0.01}_{-0.02-0.03-0.01-0.01}$	$0.20^{+0.02+0.01+0.11+0.14}_{-0.02-0.02-0.12-0.06}$
	$\beta$	$A_{CP}^\beta$	$\langle \beta \rangle$
$\Lambda_b \rightarrow p\pi^-$	$0.34^{+0.00+0.05+0.01+0.07}_{-0.06-0.06-0.06-0.05}$	$0.22^{+0.00+0.00+0.03+0.07}_{-0.01-0.01-0.04-0.03}$	$0.12^{+0.00+0.05+0.03+0.00}_{-0.05-0.05-0.04-0.02}$
$\Lambda_b \rightarrow pK^-$	$-0.39^{+0.03+0.08+0.08+0.12}_{-0.01-0.04-0.07-0.01}$	$-0.44^{+0.01+0.01+0.02+0.08}_{-0.00-0.00-0.01-0.04}$	$0.05^{+0.03+0.08+0.07+0.04}_{-0.01-0.05-0.07-0.02}$
	$\gamma$	$A_{CP}^\gamma$	$\langle \gamma \rangle$
$\Lambda_b \rightarrow p\pi^-$	$0.09^{+0.02+0.04+0.04+0.04}_{-0.04-0.06-0.06-0.01}$	$0.11^{+0.01+0.02+0.03+0.03}_{-0.02-0.03-0.04-0.02}$	$-0.02^{+0.01+0.02+0.01+0.01}_{-0.02-0.04-0.01-0.00}$
$\Lambda_b \rightarrow pK^-$	$0.89^{+0.02+0.04+0.04+0.00}_{-0.01-0.02-0.05-0.01}$	$0.02^{+0.02+0.05+0.04+0.00}_{-0.01-0.03-0.04-0.00}$	$0.87^{+0.00+0.01+0.02+0.00}_{-0.00-0.01-0.02-0.01}$

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

$\Lambda_b \rightarrow p\pi^-$  is tree-dominant, so taking  $\frac{|S|^2}{|P|^2} = \frac{|619|^2}{|905|^2}$

$A_{CP}(\Lambda_b \rightarrow p\pi^-) = (0.20 \pm 0.83 \pm 0.37)\%$  [LHCb,2024]





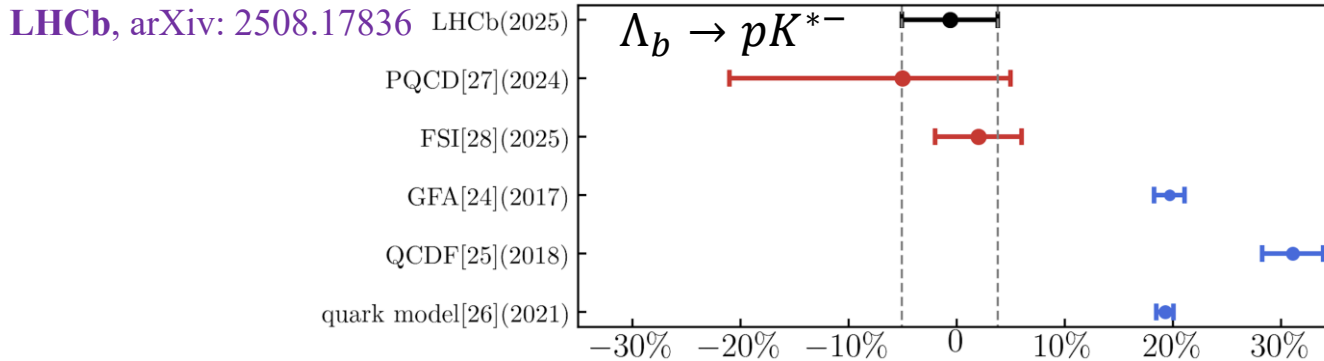
[LHCb, Nature (2025)]

“..... 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 <sup>38</sup> .....”

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

$$A_{CP}^{dir} \approx \kappa_{ST} A_{CP}^{ST} + \kappa_{P_2} A_{CP}^{P_2} + \kappa_{D+SL} A_{CP}^{D+SL} + \kappa_{P_1} A_{CP}^{P_1}$$

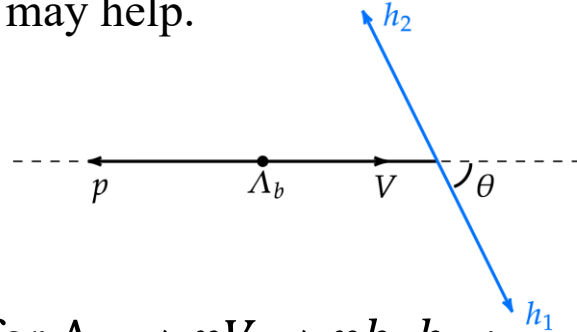
	Br( $\times 10^{-6}$ )	$A_{CP}^{dir}$	$A_{CP}^{ST}(\kappa_{ST})$
$\Lambda_b \rightarrow p\rho^-$	$9.66^{+6.23+3.23+0.21+1.89}_{-3.50-3.03-1.20-0.75}$	$0.03^{+0.02+0.01+0.00+0.02}_{-0.02-0.03-0.03-0.02}$	$0.01^{+0.00+0.00+0.00+0.00}_{-0.01-0.02-0.02-0.02}$ (7%)
$\Lambda_b \rightarrow pK^{*-}$	$2.83^{+1.77+0.46+0.37+0.63}_{-1.29-1.23-0.53-0.66}$	$-0.05^{+0.04+0.07+0.01+0.05}_{-0.11-0.07-0.06-0.08}$	$-0.15^{+0.06+0.09+0.02+0.05}_{-0.00-0.04-0.05-0.00}$ (6%)
	$A_{CP}^{SL+D}(\kappa_{SL+D})$	$A_{CP}^{P_1}(\kappa_{P_1})$	$A_{CP}^{P_2}(\kappa_{P_2})$
$\Lambda_b \rightarrow p\rho^-$	$0.02^{+0.03+0.04+0.02+0.05}_{-0.02-0.02-0.00-0.00}$ (44%)	$0.03^{+0.04+0.00+0.00+0.00}_{-0.05-0.04-0.10-0.05}$ (45%)	$0.17^{+0.00+0.00+0.01+0.03}_{-0.02-0.03-0.03-0.04}$ (4%)
$\Lambda_b \rightarrow pK^{*-}$	$0.27^{+0.02+0.06+0.05+0.03}_{-0.17-0.11-0.02-0.18}$ (33%)	$-0.23^{+0.05+0.07+0.02+0.05}_{-0.11-0.11-0.09-0.03}$ (55%)	$-0.14^{+0.01+0.00+0.02+0.01}_{-0.04-0.09-0.02-0.03}$ (6%)



“..... The vanishing CP asymmetry observed for the  $\Lambda_b^0 \rightarrow pK_S^0\pi^-$  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](https://arxiv.org/abs/2409.02821).

- How to measure the large partial-wave CPV?
- The angular distributions may help.



- The angle distribution for  $\Lambda_b \rightarrow pV \rightarrow ph_1h_2$  :

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

$$\begin{aligned} \frac{d\Gamma}{d\theta} &\propto |H_{\frac{1}{2},0}|^2 + |H_{-\frac{1}{2},0}|^2 + |H_{-\frac{1}{2},-1}|^2 + |H_{\frac{1}{2},1}|^2 + (2|H_{\frac{1}{2},0}|^2 + 2|H_{-\frac{1}{2},0}|^2 - |H_{-\frac{1}{2},-1}|^2 - |H_{\frac{1}{2},1}|^2)P_2 \\ &\propto 1 + \frac{2|H_{\frac{1}{2},0}|^2 + 2|H_{-\frac{1}{2},0}|^2 - |H_{-\frac{1}{2},-1}|^2 - |H_{\frac{1}{2},1}|^2}{|H_{\frac{1}{2},0}|^2 + |H_{-\frac{1}{2},0}|^2 + |H_{-\frac{1}{2},-1}|^2 + |H_{\frac{1}{2},1}|^2} P_2 \\ &\propto 1 + \mathcal{J} \cdot P_2 \quad P_2 = (3 \cos^2 \theta - 1)/2 \end{aligned}$$

- The CP asymmetry and average for  $\mathcal{J}$  :  $A_{CP}^{\mathcal{J}} = \frac{\mathcal{J} - \bar{\mathcal{J}}}{2}$ ,  $\langle \mathcal{J} \rangle = \frac{\mathcal{J} + \bar{\mathcal{J}}}{2}$

	$\mathcal{J}$	$A_{CP}^{\mathcal{J}}$	$\langle \mathcal{J} \rangle$
$\Lambda_b \rightarrow p\rho^-$	$1.66^{+0.04+0.04+0.02+0.02}_{-0.03-0.03-0.05-0.00}$	$-0.01^{+0.01+0.01+0.01+0.00}_{-0.01-0.01-0.01-0.00}$	$1.67^{+0.03+0.04+0.02+0.02}_{-0.05-0.03-0.05-0.00}$
$\Lambda_b \rightarrow pK^{*-}$	$1.67^{+0.02+0.00+0.04+0.00}_{-0.14-0.12-0.08-0.12}$	$0.04^{+0.02+0.05+0.02+0.01}_{-0.06-0.04-0.02-0.03}$	$1.63^{+0.01+0.03+0.04+0.00}_{-0.08-0.15-0.09-0.09}$

# Predict CPVs of $\Lambda_b \rightarrow pa_1, pK_1(1270), pK_1(1400)$

$$A_{CP}^{dir} \approx \kappa_{ST} A_{CP}^{ST} + \kappa_{P_2} A_{CP}^{P_2} + \kappa_{D+S^L} A_{CP}^{D+S^L} + \kappa_{P_1} A_{CP}^{P_1}$$

$$\begin{pmatrix} |K_1(1270)\rangle \\ |K_1(1400)\rangle \end{pmatrix} = \begin{pmatrix} \sin\theta_{K_1} & \cos\theta_{K_1} \\ \cos\theta_{K_1} & -\sin\theta_{K_1} \end{pmatrix} \begin{pmatrix} |K_{1A}\rangle \\ |K_{1B}\rangle \end{pmatrix}$$

$$\theta_K \sim 30^\circ/60^\circ$$

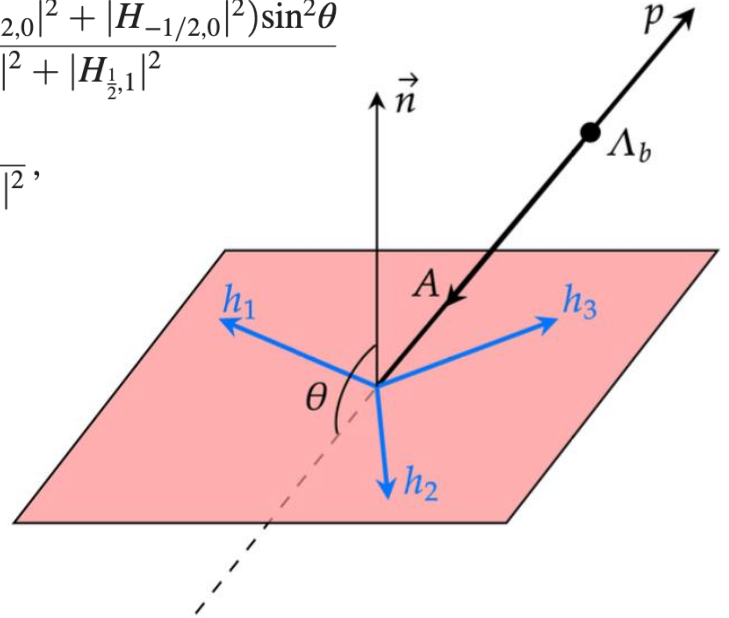
	$Br(\times 10^{-6})$	$A_{CP}^{dir}$	$A_{CP}^{ST}(\kappa_{ST})$
$\Lambda_b \rightarrow pa_1^-(1260)$	$11.06_{-4.30-3.32-0.46-0.06}^{+8.21+3.88+0.91+1.73}$	$-0.01_{-0.00-0.01-0.02-0.00}^{+0.01+0.03+0.02+0.03}$	$-0.22_{-0.03-0.07-0.07-0.01}^{+0.04+0.07+0.05+0.04}$ (6%)
$\Lambda_b \rightarrow pK_1^-(1270)(30^\circ)$	$5.48_{-1.87-1.55-0.31-1.11}^{+3.63+1.94+0.27+2.49}$	$0.09_{-0.04-0.02-0.02-0.00}^{+0.03+0.07+0.03+0.01}$	$0.34_{-0.02-0.03-0.01-0.05}^{+0.00+0.01+0.01+0.00}$ (8%)
$\Lambda_b \rightarrow pK_1^-(1400)(30^\circ)$	$1.25_{-0.39-0.19-0.19-0.31}^{+0.59+0.33+0.13+0.64}$	$0.06_{-0.03-0.09-0.04-0.01}^{+0.03+0.05+0.03+0.00}$	$0.71_{-0.02-0.16-0.04-0.13}^{+0.05+0.06+0.03+0.03}$ (13%)
$\Lambda_b \rightarrow pK_1^-(1270)(60^\circ)$	$6.28_{-2.13-1.51-0.41-1.32}^{+3.97+1.93+0.18+2.79}$	$0.07_{-0.04-0.04-0.03-0.00}^{+0.01+0.03+0.03+0.01}$	$0.46_{-0.02-0.04-0.02-0.07}^{+0.00+0.00+0.02+0.01}$ (9%)
$\Lambda_b \rightarrow pK_1^-(1400)(60^\circ)$	$0.53_{-0.16-0.19-0.22-0.13}^{+0.33+0.38+0.09+0.36}$	$0.08_{-0.08-0.11-0.04-0.03}^{+0.11+0.09+0.12+0.00}$	$0.07_{-0.12-0.09-0.15-0.10}^{+0.00+0.41+0.08+0.22}$ (3%)
	$A_{CP}^{S^L+D}(\kappa_{S^L+D})$	$A_{CP}^{P_1}(\kappa_{P_1})$	$A_{CP}^{P_2}(\kappa_{P_2})$
$\Lambda_b \rightarrow pa_1^-(1260)$	$-0.11_{-0.00-0.01-0.07-0.03}^{+0.02+0.01+0.02+0.02}$ (46%)	$0.18_{-0.03-0.02-0.03-0.04}^{+0.03+0.02+0.04+0.09}$ (40%)	$-0.24_{-0.02-0.09-0.06-0.06}^{+0.01+0.05+0.04+0.03}$ (8%)
$\Lambda_b \rightarrow pK_1^-(1270)(30^\circ)$	$-0.11_{-0.04-0.06-0.03-0.00}^{+0.01+0.08+0.08+0.03}$ (42%)	$0.19_{-0.06-0.09-0.11-0.01}^{+0.10+0.13+0.05+0.02}$ (42%)	$0.33_{-0.02-0.03-0.02-0.03}^{+0.00+0.04+0.02+0.00}$ (8%)
$\Lambda_b \rightarrow pK_1^-(1400)(30^\circ)$	$0.81_{-0.12-0.14-0.11-0.00}^{+0.09+0.17+0.07+0.04}$ (17%)	$-0.41_{-0.07-0.05-0.11-0.04}^{+0.04+0.05+0.08+0.03}$ (60%)	$0.78_{-0.06-0.20-0.04-0.10}^{+0.04+0.11+0.09+0.05}$ (10%)
$\Lambda_b \rightarrow pK_1^-(1270)(60^\circ)$	$0.06_{-0.03-0.07-0.04-0.00}^{+0.01+0.08+0.07+0.03}$ (37%)	$-0.07_{-0.06-0.05-0.05-0.02}^{+0.05+0.06+0.04+0.01}$ (45%)	$0.46_{-0.01-0.03-0.02-0.06}^{+0.00+0.04+0.04+0.02}$ (9%)
$\Lambda_b \rightarrow pK_1^-(1400)(60^\circ)$	$-0.82_{-0.07-0.09-0.07-0.02}^{+0.14+0.19+0.12+0.21}$ (30%)	$0.52_{-0.01-0.14-0.03-0.07}^{+0.06+0.12+0.37+0.00}$ (64%)	$-0.28_{-0.07-0.36-0.25-0.16}^{+0.27+0.04+0.03+0.03}$ (3%)

# Results of $\Lambda_b \rightarrow pa_1, pK_1$

- The angle distribution for  $\Lambda_b \rightarrow pA \rightarrow ph_1h_2h_3$  : [J.P.Wang,Q.Qin,F.S.Yu,2024]

$$\frac{d\Gamma}{d\cos\theta} \propto \frac{(|H_{1/2,1}|^2 + |H_{-1/2,-1}|^2) \frac{1+\cos^2\theta}{2} + (|H_{1/2,0}|^2 + |H_{-1/2,0}|^2) \sin^2\theta}{|H_{\frac{1}{2},0}|^2 + |H_{-\frac{1}{2},0}|^2 + |H_{-\frac{1}{2},-1}|^2 + |H_{\frac{1}{2},1}|^2} + \frac{R(|H_{1/2,1}|^2 - |H_{-1/2,-1}|^2) \cos\theta}{|H_{\frac{1}{2},0}|^2 + |H_{-\frac{1}{2},0}|^2 + |H_{-\frac{1}{2},-1}|^2 + |H_{\frac{1}{2},1}|^2},$$


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



- up-down asymmetry :

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

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

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

# Opportunities and puzzle

- LHCb is a baryon factory !

$$\frac{f_{\Lambda_b}}{f_{u,d}} \sim 0.5 \quad \longrightarrow \quad \frac{N_{\Lambda_b}}{N_B^{0,-}} \sim 0.5 \quad [\text{LHCb, 2012}]$$

- Precision of b-baryon CPV measurement reached the order of 1%

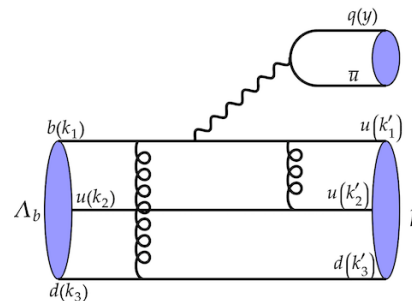
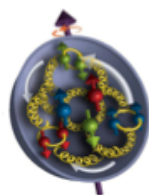
$$A_{CP}(\Lambda_b \rightarrow p\pi^-) = (0.20 \pm 0.83 \pm 0.37)\%$$

$$A_{CP}(\Lambda_b \rightarrow pK^-) = (-1.14 \pm 0.67 \pm 0.36)\% \quad [\text{LHCb, 2024}]$$

- Why CPVs of  $\Lambda_b \rightarrow p\pi, pK$  are small ? What difference of dynamics?

- Baryons are very different from mesons!

- non-zero spin/polarization, more information from polarizations and partial waves
- three valence quarks, need at least two hard gluons



- SCET: power counting of baryon is different from meson
  - heavy-to-light form factor is **factorizable at leading power** and **no end-point singularity!**

$$\xi_{\Lambda_b \rightarrow \Lambda} = f_{\Lambda_b} \Phi_{\Lambda_b}(x_i) \otimes J(x_i, y_i) \otimes f_{\Lambda} \Phi_{\Lambda}(y_i)$$

- leading power:  $\xi_{\Lambda_b \rightarrow \Lambda}(q^2 = 0) = -0.012$  [W.Wang, 2011]
- Total form factors:  $\xi_{\Lambda_b \rightarrow \Lambda}(q^2 = 0) = 0.18$  [Y.L.Shen, Y.M.Wang, 2016]

$$A_{CP}^{dir} \approx \kappa_{ST} A_{CP}^{ST} + \kappa_{P_2} A_{CP}^{P_2} + \kappa_{D+SL} A_{CP}^{D+SL} + \kappa_{P_1} A_{CP}^{P_1}$$

	$Br(\times 10^{-6})$	$A_{CP}^{dir}$	$A_{CP}^{ST}(\kappa_{ST})$
$\Lambda_b \rightarrow p\rho^-$	$9.66^{+6.23+3.23+0.21+1.89}_{-3.50-3.03-1.20-0.75}$	$0.03^{+0.02+0.01+0.00+0.02}_{-0.02-0.03-0.03-0.02}$	$0.01^{+0.00+0.00+0.00+0.00}_{-0.01-0.02-0.02-0.02}$ (7%)
$\Lambda_b \rightarrow pK^{*-}$	$2.83^{+1.77+0.46+0.37+0.63}_{-1.29-1.23-0.53-0.66}$	$-0.05^{+0.04+0.07+0.01+0.05}_{-0.11-0.07-0.06-0.08}$	$-0.15^{+0.06+0.09+0.02+0.05}_{-0.00-0.04-0.05-0.00}$ (6%)
	$A_{CP}^{SL+D}(\kappa_{SL+D})$	$A_{CP}^{P_1}(\kappa_{P_1})$	$A_{CP}^{P_2}(\kappa_{P_2})$
$\Lambda_b \rightarrow p\rho^-$	$0.02^{+0.03+0.04+0.02+0.05}_{-0.02-0.02-0.00-0.00}$ (44%)	$0.03^{+0.04+0.00+0.00+0.00}_{-0.05-0.04-0.10-0.05}$ (45%)	$0.17^{+0.00+0.00+0.01+0.03}_{-0.02-0.03-0.03-0.04}$ (4%)
$\Lambda_b \rightarrow pK^{*-}$	$0.27^{+0.02+0.06+0.05+0.03}_{-0.17-0.11-0.02-0.18}$ (33%)	$-0.23^{+0.05+0.07+0.02+0.05}_{-0.11-0.11-0.09-0.03}$ (55%)	$-0.14^{+0.01+0.00+0.02+0.01}_{-0.04-0.09-0.02-0.03}$ (6%)
	$\alpha$	$A_{CP}^\alpha$	$\langle \alpha \rangle$
$\Lambda_b \rightarrow p\rho^-$	$-0.83^{+0.02+0.01+0.00+0.00}_{-0.02-0.05-0.04-0.01}$	$-0.01^{+0.01+0.01+0.01+0.00}_{-0.00-0.00-0.01-0.00}$	$-0.83^{+0.01+0.01+0.01+0.00}_{-0.02-0.05-0.04-0.01}$
$\Lambda_b \rightarrow pK^{*-}$	$-1.00^{+0.01+0.01+0.00+0.01}_{-0.00-0.00-0.00-0.00}$	$-0.00^{+0.00+0.00+0.00+0.00}_{-0.00-0.00-0.00-0.00}$	$-1.00^{+0.00+0.01+0.00+0.00}_{-0.00-0.00-0.00-0.00}$
	$\beta$	$A_{CP}^\beta$	$\langle \beta \rangle$
$\Lambda_b \rightarrow p\rho^-$	$-0.98^{+0.05+0.07+0.05+0.06}_{-0.00-0.00-0.00-0.00}$	$0.00^{+0.01+0.02+0.01+0.02}_{-0.00-0.00-0.00-0.00}$	$-0.99^{+0.04+0.05+0.04+0.04}_{-0.00-0.00-0.00-0.00}$
$\Lambda_b \rightarrow pK^{*-}$	$-0.90^{+0.07+0.17+0.11+0.00}_{-0.03-0.03-0.00-0.03}$	$-0.02^{+0.04+0.06+0.04+0.01}_{-0.00-0.04-0.00-0.00}$	$-0.88^{+0.06+0.11+0.08+0.00}_{-0.03-0.06-0.00-0.04}$
	$\gamma$	$A_{CP}^\gamma$	$\langle \gamma \rangle$
$\Lambda_b \rightarrow p\rho^-$	$-0.11^{+0.01+0.01+0.01+0.01}_{-0.01-0.01-0.02-0.00}$	$-0.01^{+0.00+0.00+0.00+0.00}_{-0.00-0.00-0.00-0.00}$	$-0.10^{+0.01+0.01+0.01+0.00}_{-0.01-0.01-0.02-0.00}$
$\Lambda_b \rightarrow pK^{*-}$	$-0.12^{+0.01+0.00+0.02+0.00}_{-0.06-0.05-0.03-0.05}$	$0.02^{+0.01+0.03+0.01+0.01}_{-0.02-0.02-0.01-0.01}$	$-0.14^{+0.01+0.01+0.02+0.00}_{-0.04-0.07-0.04-0.04}$
	$\Lambda$	$A_{CP}^\Lambda$	$\langle \Lambda \rangle$
$\Lambda_b \rightarrow p\rho^-$	$-0.96^{+0.05+0.06+0.04+0.05}_{-0.00-0.00-0.00-0.00}$	$0.00^{+0.01+0.02+0.01+0.02}_{-0.00-0.00-0.00-0.00}$	$-0.97^{+0.04+0.04+0.03+0.04}_{-0.00-0.00-0.00-0.00}$
$\Lambda_b \rightarrow pK^{*-}$	$-0.91^{+0.06+0.15+0.09+0.00}_{-0.02-0.02-0.00-0.03}$	$-0.01^{+0.03+0.06+0.03+0.01}_{-0.00-0.03-0.00-0.00}$	$-0.90^{+0.05+0.09+0.07+0.00}_{-0.03-0.05-0.01-0.03}$
	$\mathcal{J}$	$A_{CP}^\mathcal{J}$	$\langle \mathcal{J} \rangle$
$\Lambda_b \rightarrow p\rho^-$	$1.66^{+0.04+0.04+0.02+0.02}_{-0.03-0.03-0.05-0.00}$	$-0.01^{+0.01+0.01+0.01+0.00}_{-0.01-0.01-0.01-0.00}$	$1.67^{+0.03+0.04+0.02+0.02}_{-0.05-0.03-0.05-0.00}$
$\Lambda_b \rightarrow pK^{*-}$	$1.67^{+0.02+0.00+0.04+0.00}_{-0.14-0.12-0.08-0.12}$	$0.04^{+0.02+0.05+0.02+0.01}_{-0.06-0.04-0.02-0.03}$	$1.63^{+0.01+0.03+0.04+0.00}_{-0.08-0.15-0.09-0.09}$

$$A_{CP}(\Lambda_b \rightarrow p\pi^-) = (0.20 \pm 0.83 \pm 0.37)\%$$

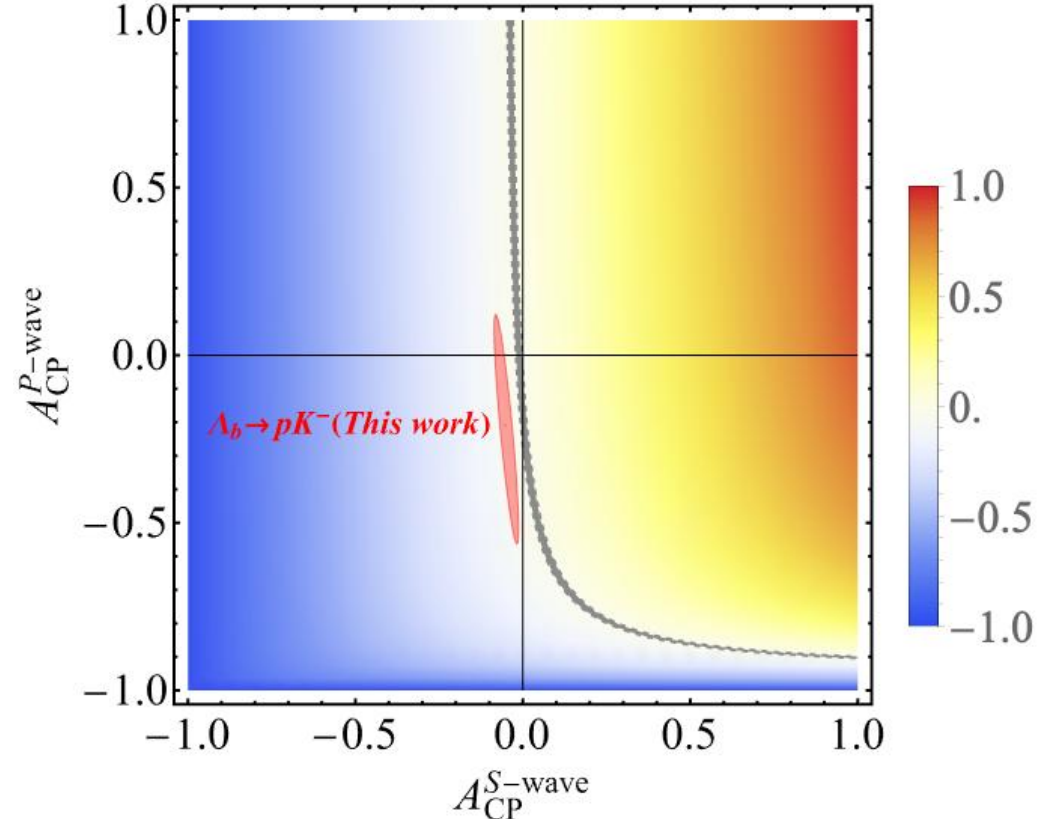
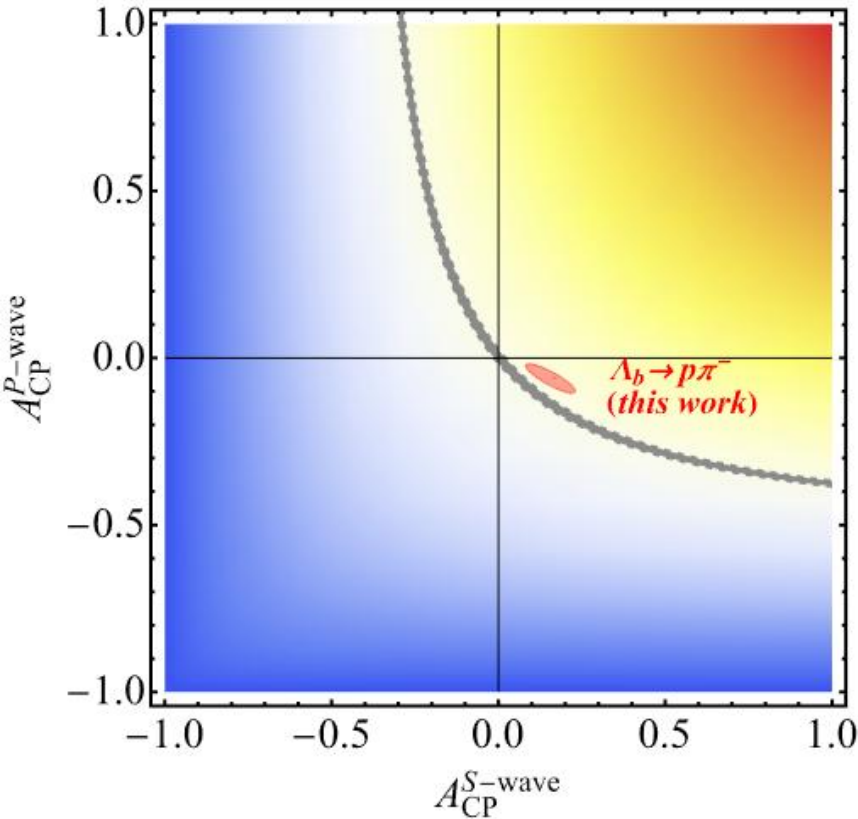
$$A_{CP}(\Lambda_b \rightarrow pK^-) = (-1.14 \pm 0.67 \pm 0.36)\% \text{ [LHCb,2024]}$$

$$A_{CP}^{dir} \equiv \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$$

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

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

$$= \kappa_S A_{CP}^{S\text{-wave}} + \kappa_P A_{CP}^{P\text{-wave}},$$



# Predict CPVs of $\Lambda_b \rightarrow p\rho^-, pK^{*-}$

Invariant amplitudes

$$\left\{ \begin{aligned} \mathcal{M}^L [B_i(1/2^+) \rightarrow B_f(1/2^+) + V] &= \bar{u}_f(p_f) \epsilon_L^{*\mu} \left[ A_1^L \gamma_\mu \gamma_5 + A_2^L \frac{(p_f)_\mu}{m_i} \gamma_5 + B_1^L \gamma_\mu + B_2^L \frac{(p_f)_\mu}{m_i} \right] u_i(p_i), \\ \mathcal{M}^T [B_i(1/2^+) \rightarrow B_f(1/2^+) + V] &= \bar{u}_f(p_f) \epsilon_T^{*\mu} [A_1^T \gamma_\mu \gamma_5 + B_1^T \gamma_\mu] u_i(p_i). \end{aligned} \right.$$

Partial wave amplitudes

$$\left\{ \begin{aligned} S^T &= -A_1^T, \\ S^L &= -A_1^L, \\ P_1 &= -\frac{p_c}{E_V} \left( \frac{m_i + m_f}{E_f + m_f} B_1^L + B_2^L \right), \\ P_2 &= \frac{p_c}{E_f + m_f} B_1^T, \\ D &= -\frac{p_c^2}{E_V(E_f + m_f)} (A_1^L - A_2^L). \end{aligned} \right.$$

$$\Gamma(1/2^+ \rightarrow 1/2^+ + V) = \frac{p_c}{4\pi} \frac{E_f + m_f}{m_i} \left\{ 2(|S|^2 + |P_2|^2) + \frac{E_V^2}{m_V^2} (|S + D|^2 + |P_1|^2) \right\}$$

Helicity amplitudes

$$\left\{ \begin{aligned} H_{1/2,1} &= -M_+ A_1^T - M_- B_1^T, \\ H_{-1/2,-1} &= M_+ A_1^T - M_- B_1^T, \\ H_{1/2,0} &= \frac{1}{\sqrt{2}m_V} [M_+(m_i - m_f)A_1^L - M_- p_c A_2^L + M_-(m_i + m_f)B_1^L + M_+ p_c B_2^L], \\ H_{-1/2,0} &= \frac{1}{\sqrt{2}m_V} [-M_+(m_i - m_f)A_1^L + M_- p_c A_2^L + M_-(m_i + m_f)B_1^L + M_+ p_c B_2^L]. \end{aligned} \right.$$

$$\mathcal{B} = \frac{p_c \tau_{\Lambda_b}}{8\pi m_i^2} (|H_{1/2,1}|^2 + |H_{-1/2,-1}|^2 + |H_{1/2,0}|^2 + |H_{-1/2,0}|^2). \quad [\text{Koener, Kramer, 1992}]$$

[Cheng, 1996]

$\Lambda_b \rightarrow p\pi^-$	$ S $	$\delta^S(^{\circ})$	Real( $S$ )	Imag( $S$ )	$ P $	$\delta^P(^{\circ})$	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
$P_f^{C_1}$	58.44	0.00	58.44	0.00	2.90	0.00	2.90	0.00
$P_{nf}^{C_1}$	1.24	-115.38	-0.53	-1.12	11.16	-95.25	-1.02	-11.11
$P_f^{C_1} + P_{nf}^{C_1}$	57.91	-1.11	57.90	-1.12	11.27	-80.38	1.88	-11.11
$P^{C_2}$	13.36	-116.10	-5.88	-12.00	14.93	71.96	4.62	14.20
$P^{E_1^u}$	9.48	-87.62	0.39	-9.47	8.83	114.44	-3.65	8.04
$P^B$	1.36	-51.30	0.85	-1.06	1.55	-159.86	-1.46	-0.53
$P^{E_1^d} + P^{E_2}$	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

$$S(P_f^{C_1}) = -\frac{G_F}{\sqrt{2}} f_h V_{tb} V_{td}^* \left( \frac{C_3}{3} + C_4 + \frac{C_9}{3} + C_{10} + R_1^{\pi} \left( \frac{C_5}{3} + C_6 + \frac{C_7}{3} + C_8 \right) \right)$$

$$\left[ F_1(m_h^2)(M_{\Lambda_b} - M_p) + F_3(m_h^2)m_h^2 \right]$$

$$R_1^{\pi} \equiv \frac{2m_{\pi}^2}{(m_b - m_u)(m_u + m_d)}$$

$$P(P_f^{C_1}) = -\frac{G_F}{\sqrt{2}} f_h V_{tb} V_{td}^* \left( \frac{C_3}{3} + C_4 + \frac{C_9}{3} + C_{10} - R_2^{\pi} \left( \frac{C_5}{3} + C_6 + \frac{C_7}{3} + C_8 \right) \right)$$

$$\left[ G_1(m_h^2)(M_{\Lambda_b} + M_p) - G_3(m_h^2)m_h^2 \right]$$

$$R_2^{\pi} \equiv \frac{2m_{\pi}^2}{(m_b + m_u)(m_u + m_d)}$$