CPV in baryon decays

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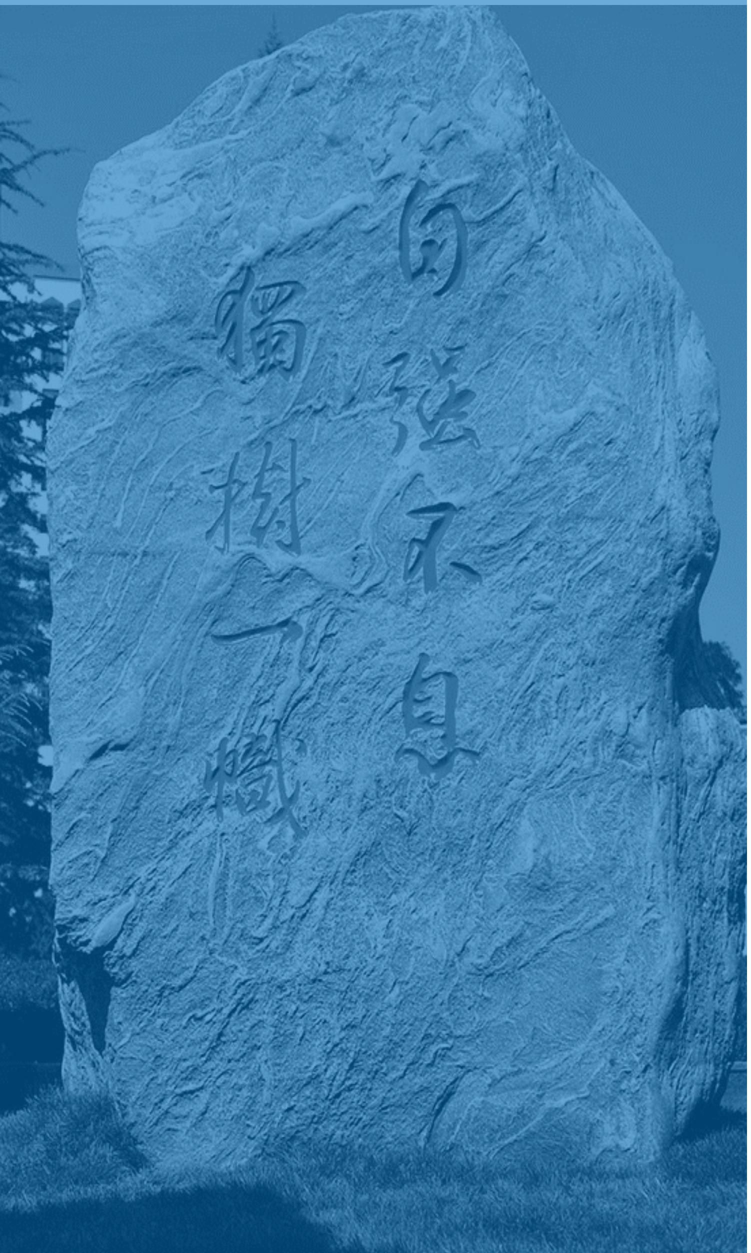
第6届LHCb前沿研讨会@广州

2026.5



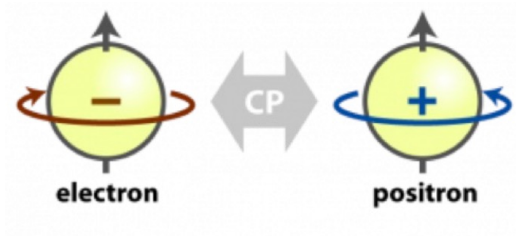
Introduction

Theoretical Progress

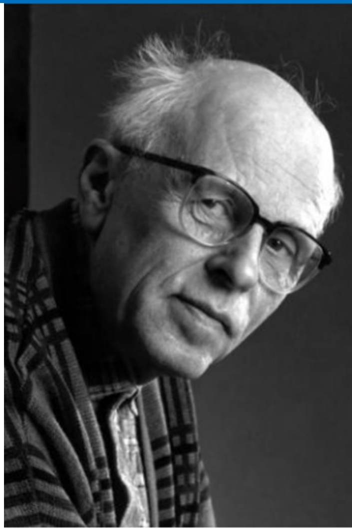
Summary and Outlook

CP violation

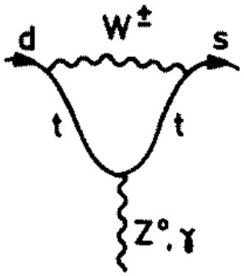
- Matter-antimatter asymmetry in the Universe [Science 109 (2005) 5731]
- Three conditions for Matter-antimatter asymmetry: [Sakharov JETP Lett.(1967)]
  - Interaction to violate baryon number;
  - C and CP violation;
  - Deviate thermal equilibrium

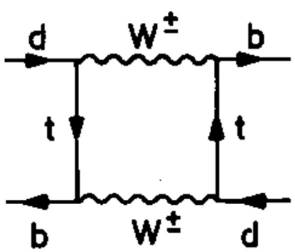


CP: 电荷共轭+宇称变换

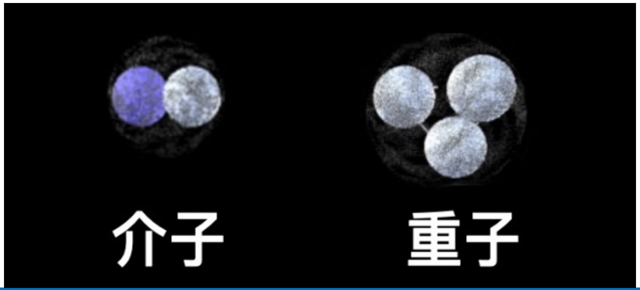


- Moreover, CPV relates to parameters in SM, is helpful to search NP indirectly.

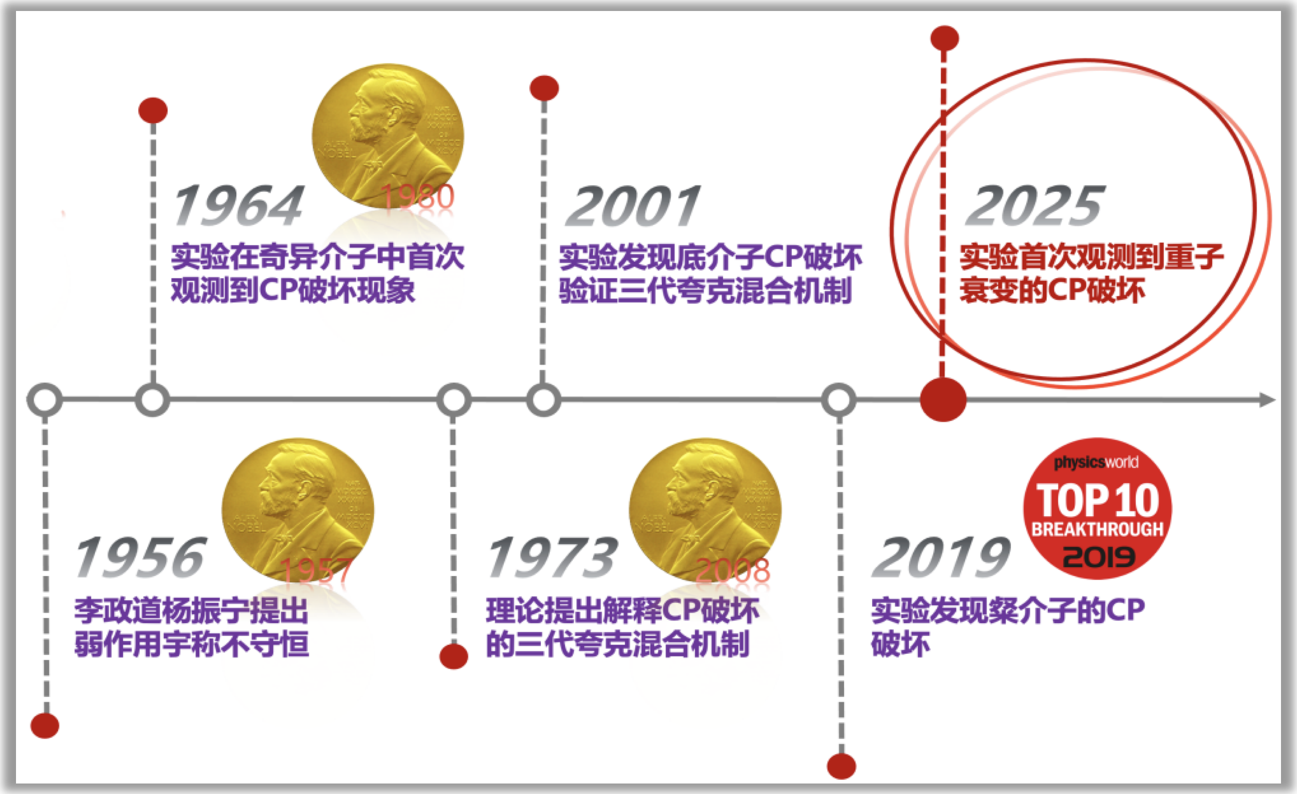




- Baryon CPV is more crucial, as visible matter in Universe is made of baryons.



First observation of baryon CP violation

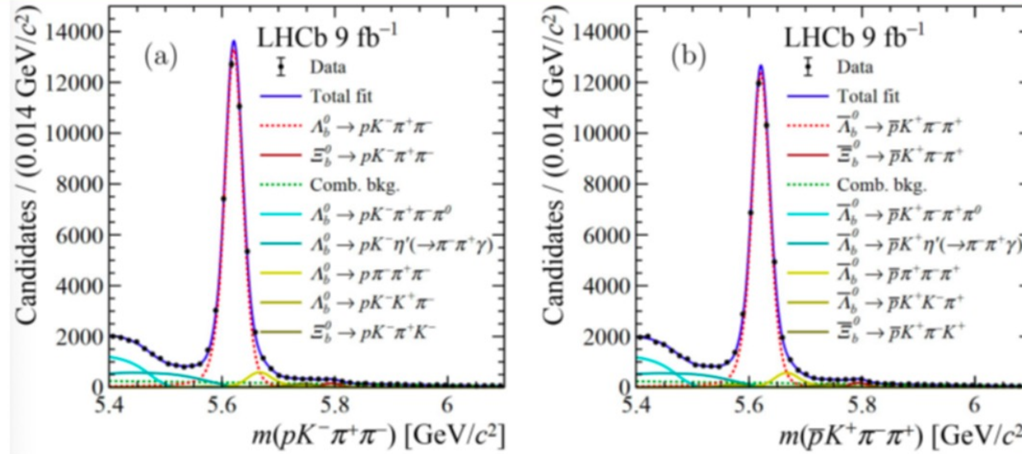


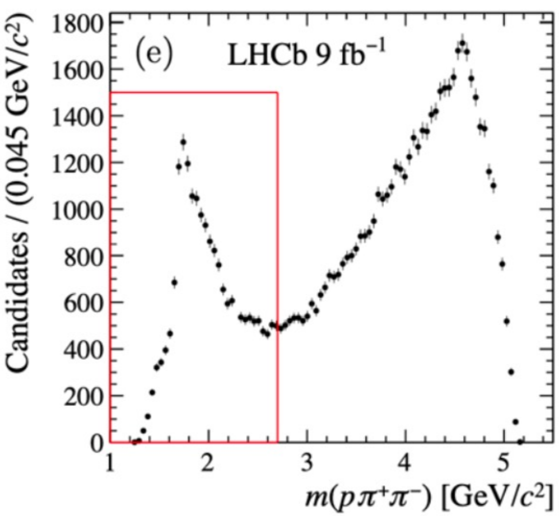
First observation of baryon CP violation

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

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

5.2σ





[LHCb Nature(2025)]

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

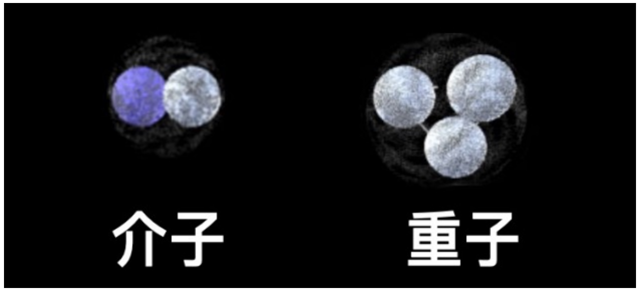
6.0σ

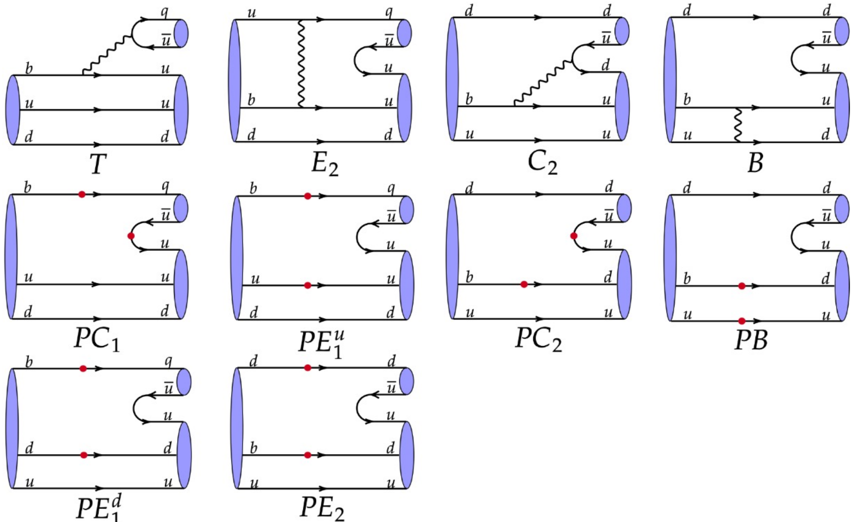
What should theory do?

- **Observables**: Study new CP-violating observables to increase the likelihood of discovering CP violation in baryon decays.
  [Zhen-Hua Zhang, et,al.]
  [Jian-Peng Wang, Qin Qin, Fu-Sheng Yu]

- **Dynamics**: Develop dynamical methods to predict CP violation in baryon decays
  [PQCD: HJJ, Ji-Xin Yu, Rui Zhou Ya Li, Lei ang, et,al.]
  [FSI: Cai-Ping Jia, Jian-Peng Wang, Xiao-Hui Hu, Zhu-Ding Duan, et,al.]
  [Topological: Fan-Rong Xu, Zhi-Peng Xing, et,al.]
  [quark model]: Chia-Wei Liu, Yu-Kuo Hsiao Chao-Qiang Geng, et,al.]
  [……]

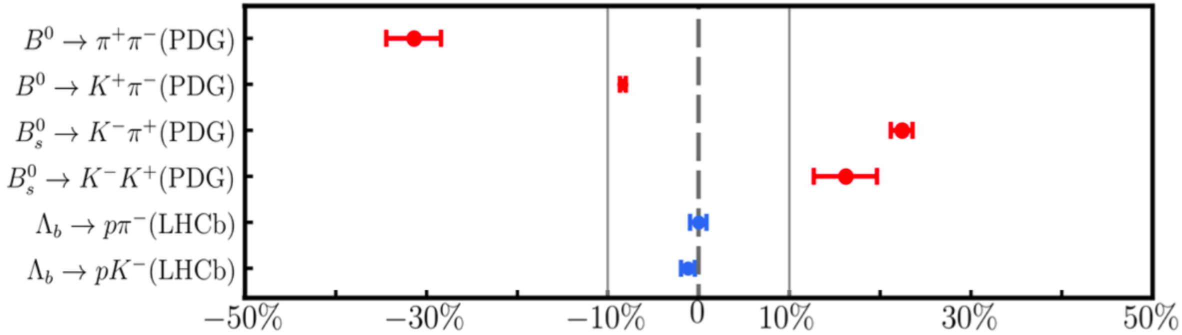
- Theoretical studies of baryons are challenging





Progress in PQCD

$A_{CP}(\Lambda_b \to p\pi^-) = (0.20 \pm 0.83 \pm 0.37)\%$ ➢ LHCb, 2024
$A_{CP}(\Lambda_b \to pK^-) = (-1.14 \pm 0.67 \pm 0.36)\%$



$$A_{CP}^{dir}(\Lambda_b \to p\pi, pK) = \kappa_S A_{CP}^S + \kappa_P A_{CP}^P$$

	A_{CP}^{dir}	$A_{CP}^S(\kappa_S)$	$A_{CP}^P(\kappa_P)$
$\Lambda_b \to p\pi^-$	$0.05^{+0.00+0.00+0.00+0.02}_{-0.02-0.01-0.02-0.01}$	$0.17^{+0.01+0.01+0.03+0.04}_{-0.04-0.04-0.07-0.04}(49\%)$	$-0.06^{+0.01+0.03+0.02+0.00}_{-0.02-0.03-0.03-0.01}(51\%)$
$\Lambda_b \to pK^-$	$-0.06^{+0.01+0.01+0.02+0.00}_{-0.01-0.01-0.01-0.00}$	$-0.05^{+0.02+0.02+0.04+0.00}_{-0.02-0.01-0.03-0.00}(94\%)$	$-0.21^{+0.07+0.23+0.29+0.04}_{-0.15-0.33-0.27-0.01}(6\%)$

$$A_{CP}^{dir}(\Lambda_b \to p\rho, pK^*) = \kappa_S A_{CP}^S + \kappa_{P_1} A_{CP}^{P_1} + \kappa_{P_2} A_{CP}^{P_2} + \kappa_D A_{CP}^D$$

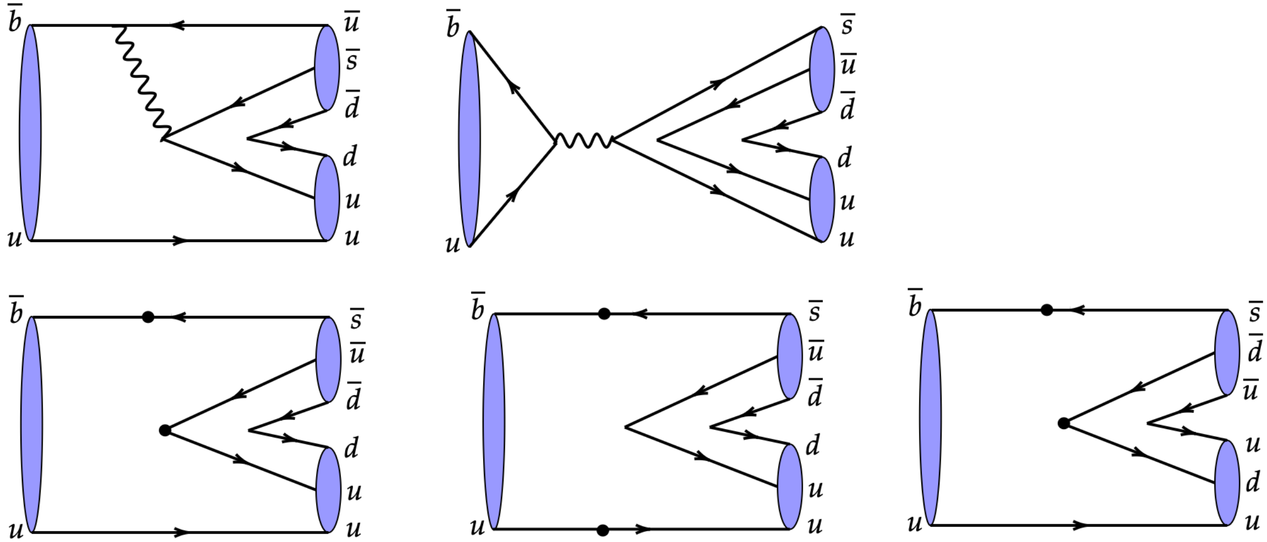
	$A_{CP}^{S^L+D}(\kappa_{S^L+D})$	$A_{CP}^{P_1}(\kappa_{P_1})$	$A_{CP}^{P_2}(\kappa_{P_2})$	$A_{CP}^{S^T}(\kappa_{S^T})$
$\Lambda_b \to p\rho^-$	$0.02^{+0.03+0.04+0.02+0.05}_{-0.02-0.02-0.00-0.00}(44\%)$	$0.03^{+0.04+0.00+0.00+0.00}_{-0.05-0.04-0.10-0.05}(45\%)$	$0.17^{+0.00+0.00+0.01+0.03}_{-0.02-0.03-0.03-0.04}(4\%)$	$0.01^{+0.00+0.00+0.00+0.00}_{-0.01-0.02-0.02-0.02}(7\%)$
$\Lambda_b \to pK^{*-}$	$0.27^{+0.02+0.06+0.05+0.03}_{-0.17-0.11-0.02-0.18}(33\%)$	$-0.23^{+0.05+0.07+0.02+0.05}_{-0.11-0.11-0.09-0.03}(55\%)$	$-0.14^{+0.01+0.00+0.02+0.01}_{-0.04-0.09-0.02-0.03}(6\%)$	$-0.15^{+0.06+0.09+0.02+0.05}_{-0.00-0.04-0.05-0.00}(6\%)$

	$A_{CP}^{S^L+D}(\kappa_{S^L+D})$	$A_{CP}^{P_1}(\kappa_{P_1})$	$A_{CP}^{P_2}(\kappa_{P_2})$	$A_{CP}^{S^T}(\kappa_{S^T})$
$\Lambda_b \to pa_1^-(1260)$	$-0.11^{+0.02+0.01+0.02+0.02}_{-0.00-0.01-0.07-0.03}(46\%)$	$0.18^{+0.03+0.02+0.04+0.09}_{-0.03-0.02-0.03-0.04}(40\%)$	$-0.24^{+0.01+0.05+0.04+0.03}_{-0.02-0.09-0.06-0.06}(8\%)$	$-0.22^{+0.04+0.07+0.05+0.04}_{-0.03-0.07-0.07-0.01}(6\%)$
$\Lambda_b \to pK_1^-(1270)(30^\circ)$	$-0.11^{+0.01+0.08+0.08+0.03}_{-0.04-0.06-0.03-0.00}(42\%)$	$0.19^{+0.10+0.13+0.05+0.02}_{-0.06-0.09-0.11-0.01}(42\%)$	$0.33^{+0.00+0.04+0.02+0.00}_{-0.02-0.03-0.02-0.03}(8\%)$	$0.34^{+0.00+0.01+0.01+0.00}_{-0.02-0.03-0.01-0.05}(8\%)$
$\Lambda_b \to pK_1^-(1400)(30^\circ)$	$0.81^{+0.09+0.17+0.07+0.04}_{-0.12-0.14-0.11-0.00}(17\%)$	$-0.41^{+0.04+0.05+0.08+0.03}_{-0.07-0.05-0.11-0.04}(60\%)$	$0.78^{+0.04+0.11+0.09+0.05}_{-0.06-0.20-0.04-0.10}(10\%)$	$0.71^{+0.05+0.06+0.03+0.03}_{-0.02-0.16-0.04-0.13}(13\%)$
$\Lambda_b \to pK_1^-(1270)(60^\circ)$	$0.06^{+0.01+0.08+0.07+0.03}_{-0.03-0.07-0.04-0.00}(37\%)$	$-0.07^{+0.05+0.06+0.04+0.01}_{-0.06-0.05-0.05-0.02}(45\%)$	$0.46^{+0.00+0.04+0.04+0.02}_{-0.01-0.03-0.02-0.06}(9\%)$	$0.46^{+0.00+0.00+0.02+0.01}_{-0.02-0.04-0.02-0.07}(9\%)$
$\Lambda_b \to pK_1^-(1400)(60^\circ)$	$-0.82^{+0.14+0.19+0.12+0.21}_{-0.07-0.09-0.07-0.02}(30\%)$	$0.52^{+0.06+0.12+0.37+0.00}_{-0.01-0.14-0.03-0.07}(64\%)$	$-0.28^{+0.27+0.04+0.03+0.03}_{-0.07-0.36-0.25-0.16}(3\%)$	$0.07^{+0.00+0.41+0.08+0.22}_{-0.12-0.09-0.15-0.10}(3\%)$

PQCD: $B^+ \to p\overline{\Lambda}$

$$\mathcal{B}(B^+ \to p\bar{\Lambda}) = (1.24 \pm 0.17 \pm 0.05 \pm 0.03) \times 10^{-7}\,,$$
$$\alpha_B = 0.87^{+0.26}_{-0.29} \pm 0.09,$$

[LHCb, PRL 2026]



$$\mathcal{A} = i\bar{u}_p(p_p)(S + P\gamma_5)v_{\bar{\Lambda}}(p_{\bar{\Lambda}})$$

$$A_{CP}^{dir} = \frac{M_+^2(|S|^2 - |\bar{S}|^2) + M_-^2(|P|^2 - |\bar{P}|^2)}{M_+^2(|S|^2 + |\bar{S}|^2) + M_-^2(|P|^2 + |\bar{P}|^2)} = \kappa_S A_{CP}^S + \kappa_P A_{CP}^P$$

$$\alpha = \frac{|H_{1/2,1/2}|^2 - |H_{-1/2,-1/2}|^2}{|H_{1/2,1/2}|^2 + |H_{-1/2,-1/2}|^2}, \quad \beta = \frac{2\mathrm{Im}(H_{1/2,1/2}H^*_{-1/2,-1/2})}{|H_{1/2,1/2}|^2 + |H_{-1/2,-1/2}|^2}, \quad \gamma = \frac{2\mathrm{Re}(H_{1/2,1/2}H^*_{-1/2,-1/2})}{|H_{1/2,1/2}|^2 + |H_{-1/2,-1/2}|^2}.$$

PQCD: $B^+ \to p\overline{\Lambda}$

$$\mathcal{A} = i\bar{u}_p(p_p)(S + P\gamma_5)v_{\bar{\Lambda}}(p_{\bar{\Lambda}})$$

Amplitudes	$\|S\|$	$\delta^S(^\circ)$	Re(S)	Im(S)	$\|P\|$	$\delta^P(^\circ)$	Re(P)	Im(P)
C	54.33	41.34	40.79	35.89	10.98	49.45	7.13	8.34
A	20.21	-109.76	-6.83	-19.02	41.61	-178.56	-41.60	-1.04
Tree	37.92	26.42	33.96	16.87	35.23	168.05	-34.46	7.30
PC^u	3.62	128.74	-2.27	2.82	5.79	-32.90	4.86	-3.14
P^d	6.04	-157.01	-5.56	-2.36	4.92	-44.13	3.53	-3.42
PA	5.60	-54.74	3.23	-4.57	9.10	74.00	2.51	8.74
Penguin	6.16	-138.20	-4.59	-4.11	11.11	11.29	10.90	2.18

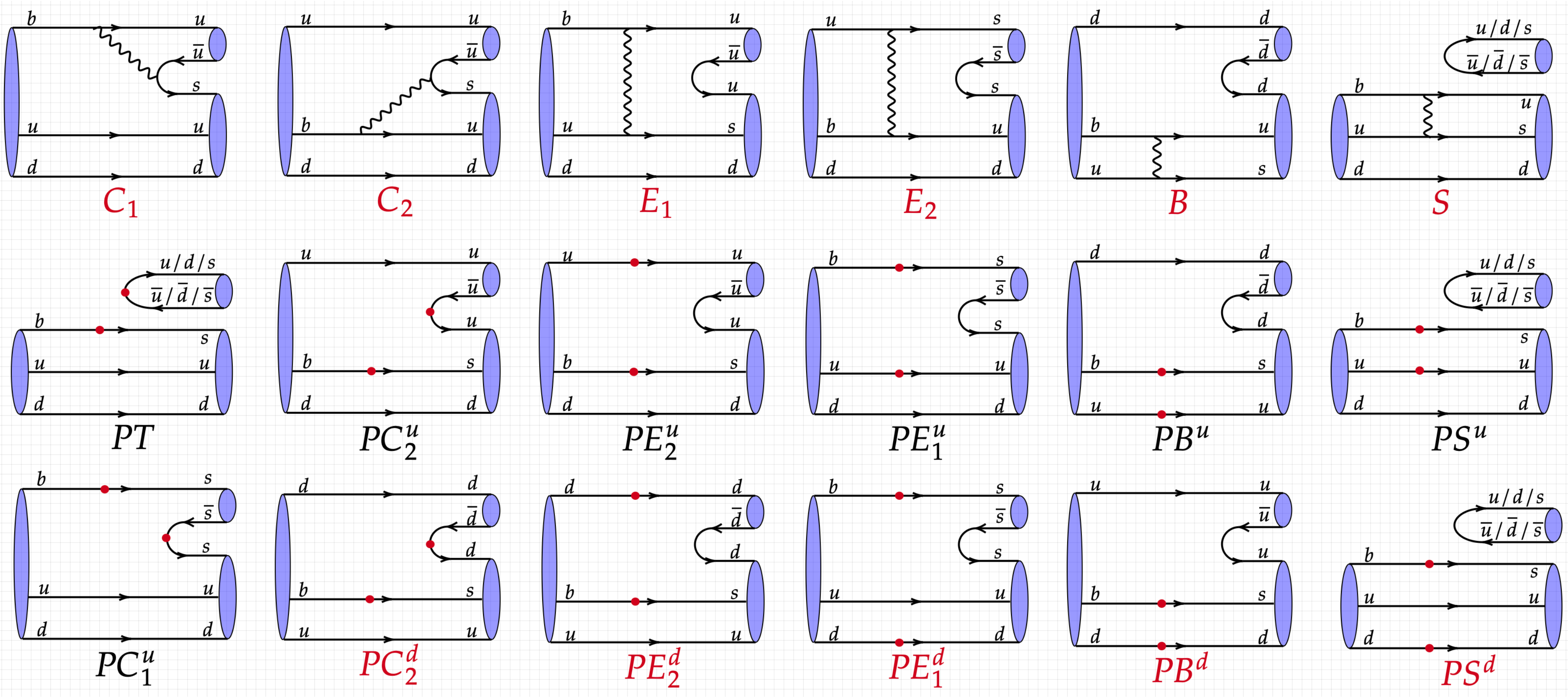
$$BR = 1.36 \times 10^{-7}$$

[See Ya Li's report]

A_{CP}^{dir}	$A_{CP}^{S\text{-wave}}(\kappa_S)$	$A_{CP}^{P\text{-wave}}(\kappa_P)$	α	A_{CP}^{α}	β	A_{CP}^{β}	γ	A_{CP}^{γ}
0.05	0.05(21.56%)	0.04(78.44%)	0.69	-0.019	0.45	0.04	0.56	0.00

PQCD: $\Lambda_b^0 \to \Lambda^0 + meson$

[Lei Yang, HJJ, et,al., in progress]



➤ 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

$$Br\left[\Lambda_b^0 \to p\pi^+\pi^-\pi^-\right] = (2.08 \pm 0.21) \times 10^{-5}$$
$$Br\left[\Lambda_b^0 \to pK^-\pi^+\pi^-\right] = (5 \pm 0.5) \times 10^{-5}$$
$$Br\left[\Lambda_b^0 \to pK^-K^+\pi^-\right] = (4 \pm 0.6) \times 10^{-6}$$
$$Br\left[\Lambda_b^0 \to pK^+K^-K^-\right] = (1.25 \pm 0.13) \times 10^{-5}$$

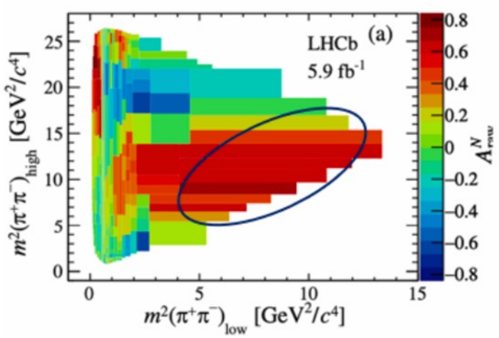
Decay mode	Signal yields	
	X_b^0	$\overline{X}_b^0$
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	2335 ± 56	2264 ± 55
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	6807 ± 92	6232 ± 89
$\Lambda_b^0 \to pK^-K^+\pi^-$	555 ± 38	630 ± 38
$\Lambda_b^0 \to pK^-K^+K^-$	2312 ± 54	2248 ± 54

- 多体衰变可能有很大的局域CP破坏

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

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

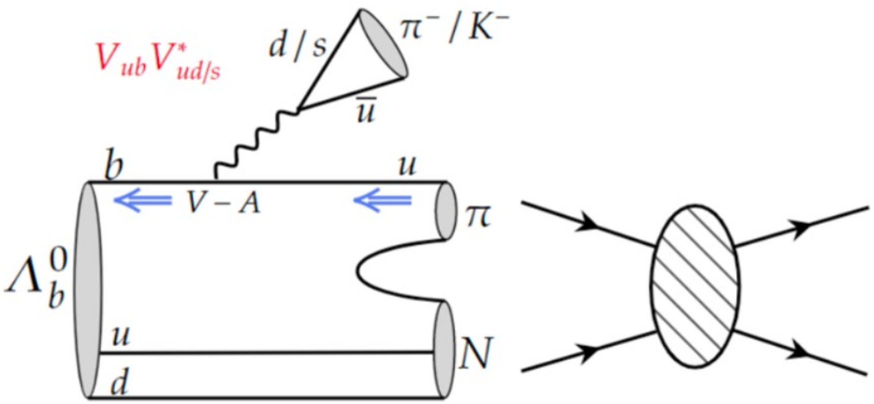
$B^+ \to \pi^+\pi^-\pi^+$



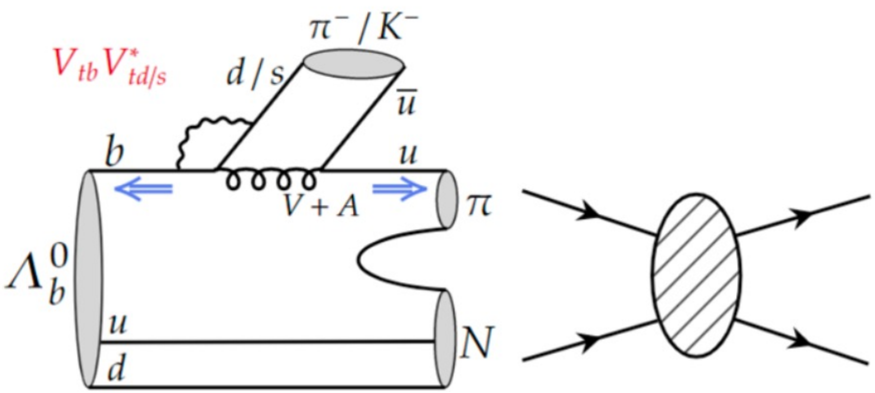
- 理论缺乏研究：中间共振态多，理论不确定性变大

FSI: multi-body decay

- 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$N\pi \to N\pi, N\pi\pi$

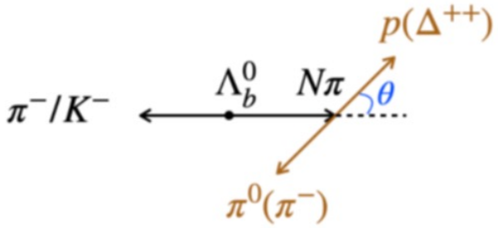
Weak decay: Form factors　　Rescatter: From data

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

FSI: multi-body decay

➢ 多体衰变CP破坏数值结果：总CP破坏

[Jian-Peng Wang, Fu-Sheng Yu, CPC 2024]



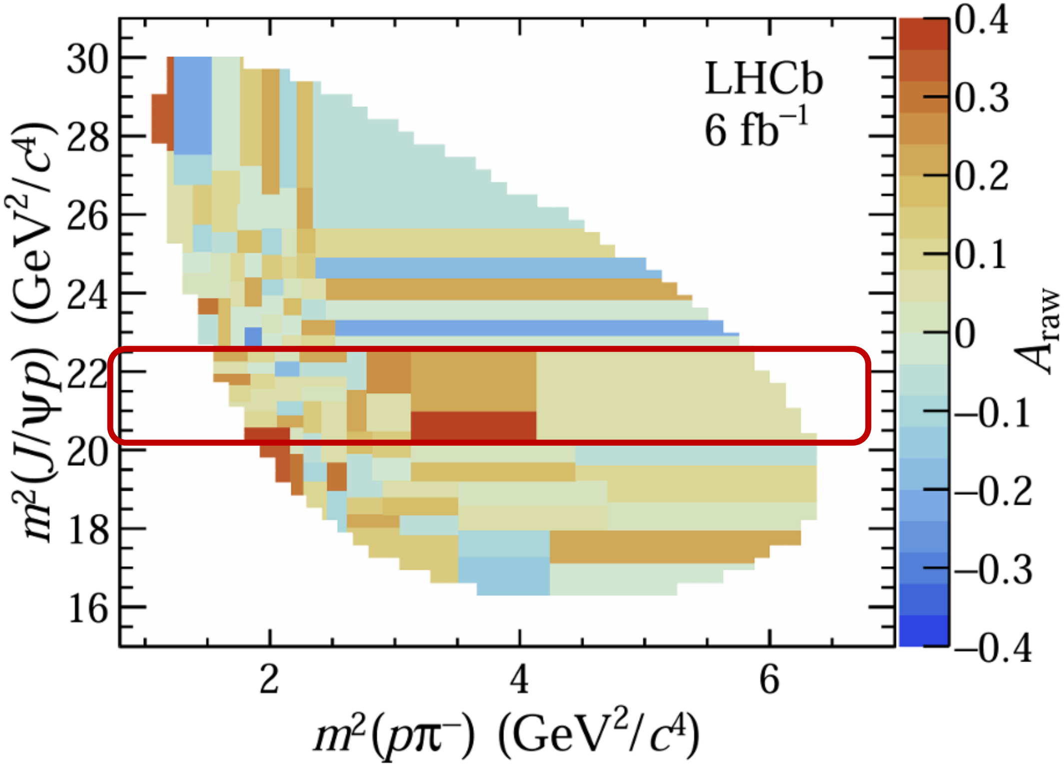
	decay processes	Scenarios	global CPV	CPV of $\cos\theta < 0$	CPV of $\cos\theta > 0$
$N\pi \to \Delta^{++}\pi^-$, $m_{N\pi} \in [1.3,1.9]$GeV	$\Lambda_b^0 \to (\Delta^{++}\pi^-)K^- \to (p\pi^+\pi^-)K^-$	S1	5.9%	8.0%	3.6%
		S2	5.8%	6.3%	5.3%
		S3	5.6%	4.3%	7.0%
	$\Lambda_b^0 \to (\Delta^{++}\pi^-)\pi^-$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

FSI: decay involving exotic state

$$\Delta A_{CP} = A_{CP}(\Lambda_b^0 \to J/\psi p\pi) - A_{CP}(\Lambda_b^0 \to J/\psi\, pK)$$
$$= (4.31 \pm 1.06 \pm 0.28)\%$$

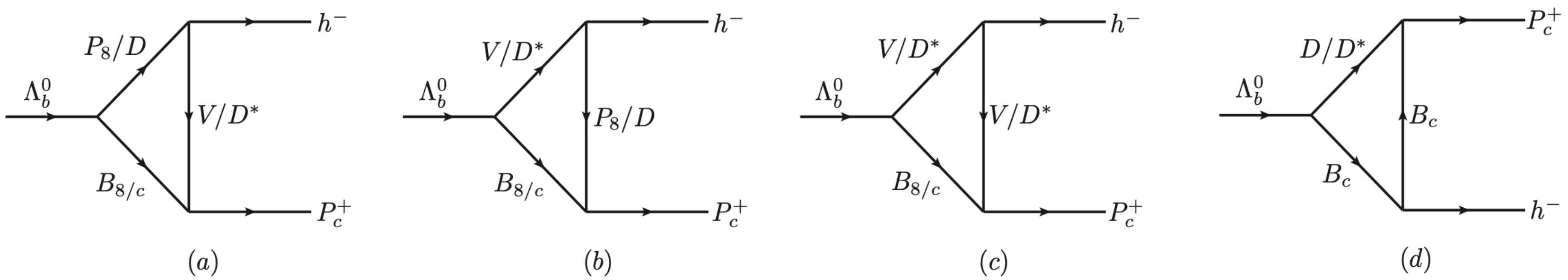
[LHCb, Sci.Bull. 2025]

$P_c(4312)^+$,
$P_c(4440)^+$,
$P_c(4457)^+$



(a) Raw asymmetry

FSI: decay involving exotic state



改进计算方法：圈积分

$$\frac{1}{k^2-m^2+i\epsilon} \to \frac{1}{k^2-m^2+i\epsilon} + \sum_i \frac{a_i}{k^2-\Lambda_i^2+i\epsilon}$$

$$\Rightarrow \frac{1}{k^2-m^2+i\epsilon} + \frac{-1}{k^2-\Lambda_1^2+i\epsilon}$$

$$\to \frac{m^2-\Lambda_1^2}{(k^2-m^2)(k^2-\Lambda_1^2)} = \frac{1}{k^2-m^2}\boxed{\frac{m^2-\Lambda_1^2}{k^2-\Lambda_1^2}}$$

与传统方法中形状因子形式一致

$\boldsymbol{\Lambda = m + \eta\Lambda_{QCD}}$

- 完整计算重散射机制下的振幅可以提供强相位，以计算不对称参数和CP破坏

[Cai-Ping Jia, Hua-Yu Jiang, Jian-Peng Wang, Fu-Sheng Yu, JHEP 2024]

FSI: decay involving exotic state

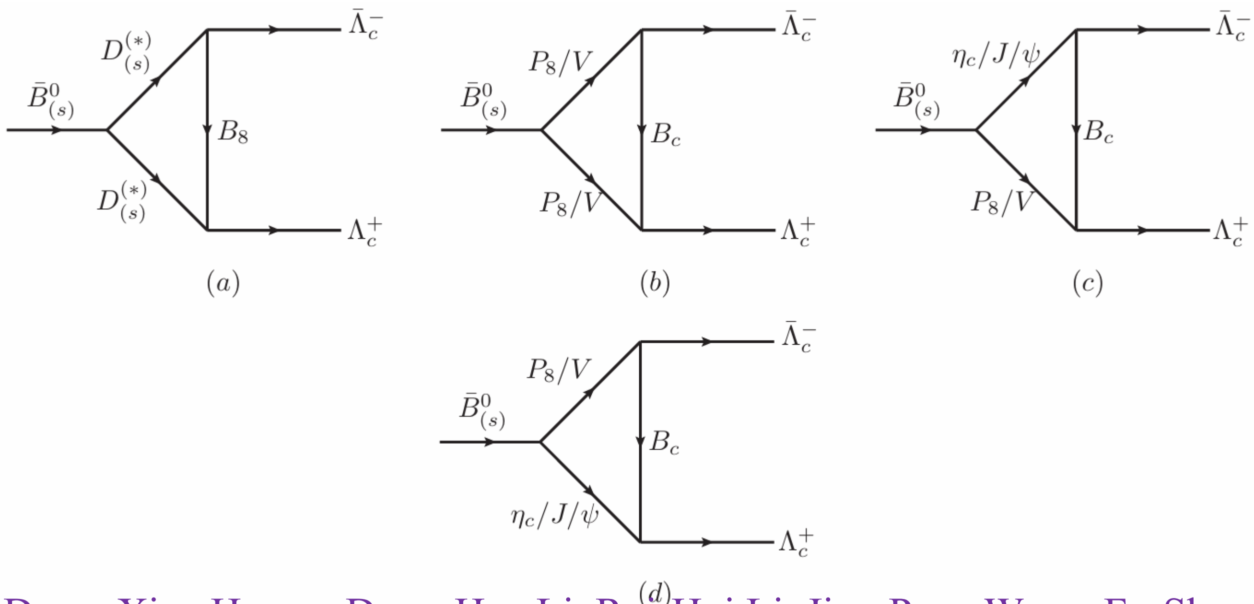
decay modes	BR(10^{-6})	Direct CP(10^{-2})
$\Lambda_b^0 \to P_c^{1/2^-}(4312)\pi^-$	$4.27^{+1.13}_{-0.98}$	$0.13^{+0.08}_{-0.09}$
$\Lambda_b^0 \to P_c^{1/2^-}(4440)\pi^-$	$1.12^{+0.19}_{-0.14}$	$-1.69^{+0.44}_{-0.28}$
$\Lambda_b^0 \to P_c^{3/2^-}(4440)\pi^-$	$1.44^{+0.73}_{-0.49}$	$0.72^{+0.43}_{-0.34}$
$\Lambda_b^0 \to P_c^{1/2^-}(4457)\pi^-$	$0.94^{+0.13}_{-0.10}$	$-1.18^{+0.26}_{-0.18}$
$\Lambda_b^0 \to P_c^{3/2^-}(4457)\pi^-$	$1.21^{+0.57}_{-0.38}$	$0.58^{+0.37}_{-0.30}$

BR Ratio	Value
$\mathrm{BR}(\Lambda_b^0 \to P_c^{1/2}(4312)\pi^-)/\mathrm{BR}(\Lambda_b^0 \to P_c^{1/2}(4312)K^-)$	$0.083^{+0.002}_{-0.002}$
$\mathrm{BR}(\Lambda_b^0 \to P_c^{1/2}(4440)\pi^-)/\mathrm{BR}(\Lambda_b^0 \to P_c^{1/2}(4440)K^-)$	$0.039^{+0.002}_{-0.001}$
$\mathrm{BR}(\Lambda_b^0 \to P_c^{3/2}(4440)\pi^-)/\mathrm{BR}(\Lambda_b^0 \to P_c^{3/2}(4440)K^-)$	$0.406^{+0.151}_{-0.109}$
$\mathrm{BR}(\Lambda_b^0 \to P_c^{1/2}(4457)\pi^-)/\mathrm{BR}(\Lambda_b^0 \to P_c^{1/2}(4457)K^-)$	$0.040^{+0.001}_{-0.001}$
$\mathrm{BR}(\Lambda_b^0 \to P_c^{3/2}(4457)\pi^-)/\mathrm{BR}(\Lambda_b^0 \to P_c^{3/2}(4457)K^-)$	$0.355^{+0.125}_{-0.089}$

[Zhu-Ding Duan, Tian-Liang Feng, Rui-Hui Li, Jian-Peng Wang, Fu-Sheng Yu, arXiv:2602.03661]

FSI: $B \to \Lambda_c \overline{\Lambda_c}$

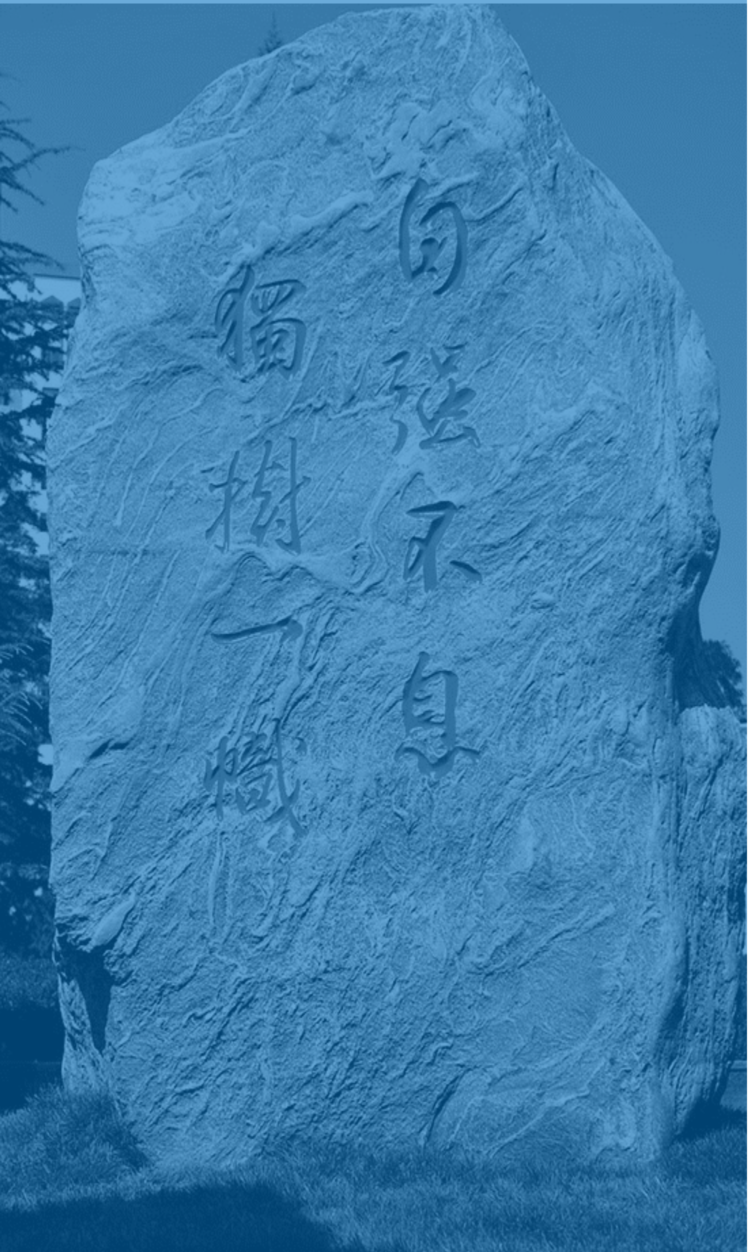
Decay mode	Source	$\mathcal{BR}$	A_{CP}^{dir}
$\bar{B}^0 \to \Lambda_c^+ \bar{\Lambda}_c^-$	FSI	$0.67^{+0.57}_{-0.34} \times 10^{-5}$	$1.13^{+1.17}_{-1.00} \times 10^{-3}$
	Experiment [LHCb, PRL 2026]	$\left(1.01^{+0.27}_{-0.28} \pm 0.08 \pm 0.15\right) \times 10^{-5}$ [1]	—
$\bar{B}_s^0 \to \Lambda_c^+ \bar{\Lambda}_c^-$	FSI	$3.43^{+3.10}_{-1.80} \times 10^{-5}$	$-6.61^{+4.47}_{-1.15} \times 10^{-4}$
	Experiment [LHCb, PRL 2026]	$(5.0 \pm 1.3 \pm 0.5 \pm 0.8) \times 10^{-5}$ [1]	—



[Zhu-Ding Duan, Xiao Huang, Dong-Hao Li, Rui-Hui Li, Jian-Peng Wang, Fu-Sheng Yu, arXiv:2602.03661]

Baryon CPV is a new horizon of heavy flavor physics.

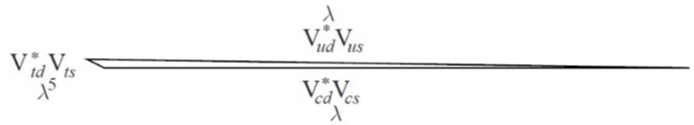
Theoretical studies of baryons are challenging.



Backup

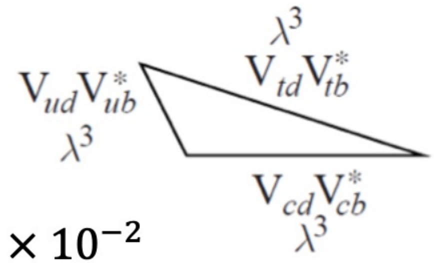
Baryon CPV

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

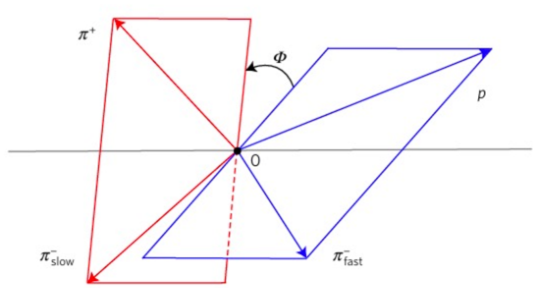


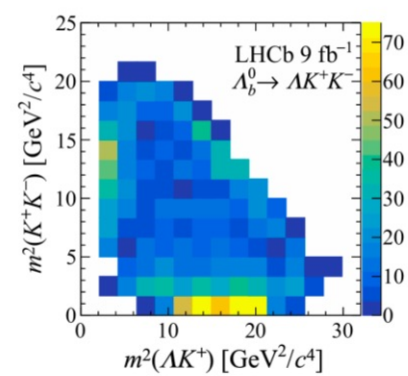
- 粲重子
  - SM: $\mathcal{O}(10^{-3} \sim 10^{-4})$ [X.G.He, C.W.Liu, 2024] [C.P.Jia, H.Y.Jiang, J.P.Wang, F.S.Yu, 2024]
  - LHCb [JHEP, 2018] $A_{CP}(\Lambda_c \to pK^+K^-/p\pi^+\pi^-) = (3.0 \pm 9.1 \pm 6.1) \times 10^{-3}$

- 底重子
  - SM estimates ~10% due to large weak phase difference



  - 两体衰变直接CP破坏 $A_{CP}(\Lambda_b^0 \to pK^-) = (-1.1 \pm 0.7 \pm 0.4) \times 10^{-2}$
    $A_{CP}(\Lambda_b^0 \to p\pi^-) = (-0.2 \pm 0.8 \pm 0.4) \times 10^{-2}$
  - 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)]

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

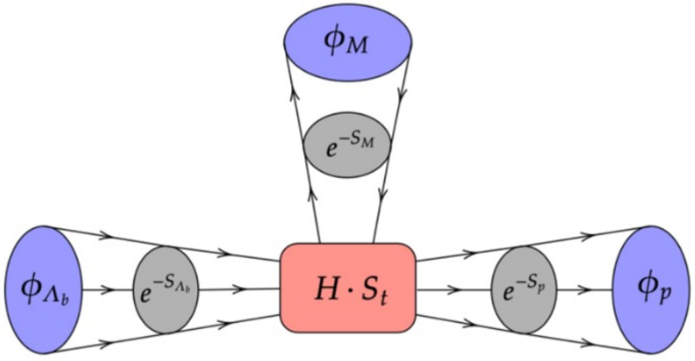
$C_{\pi\pi}(B \to \pi^+\pi^-)\%$	$A_{CP}(B \to K^+\pi^-)\%$
~ -40 [Lü,Ukai,Yang,2000]	~ -18 [Keum,Li,Sanda,2000]
$-30 \pm 25 \pm 4$ [BaBar,2002]	$-19 \pm 10 \pm 3$ [BaBar,2001]
$-12.8^{+3.48}_{-3.29}$ [Chai,Cheng,Ju,Yan, Lü,Xiao,2022]	$-5.43^{+2.25}_{-2.34}$ [Chai,Cheng,Ju,Yan, Lü,Xiao,2022]
-31.4 ±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

- Amplitudes are expressed as convolution of hard kernels and LCDAs

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

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

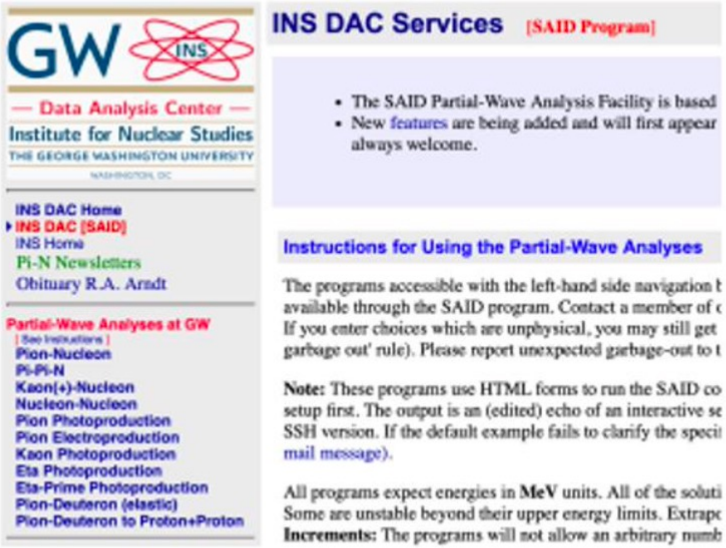
- Free of end-point singularity



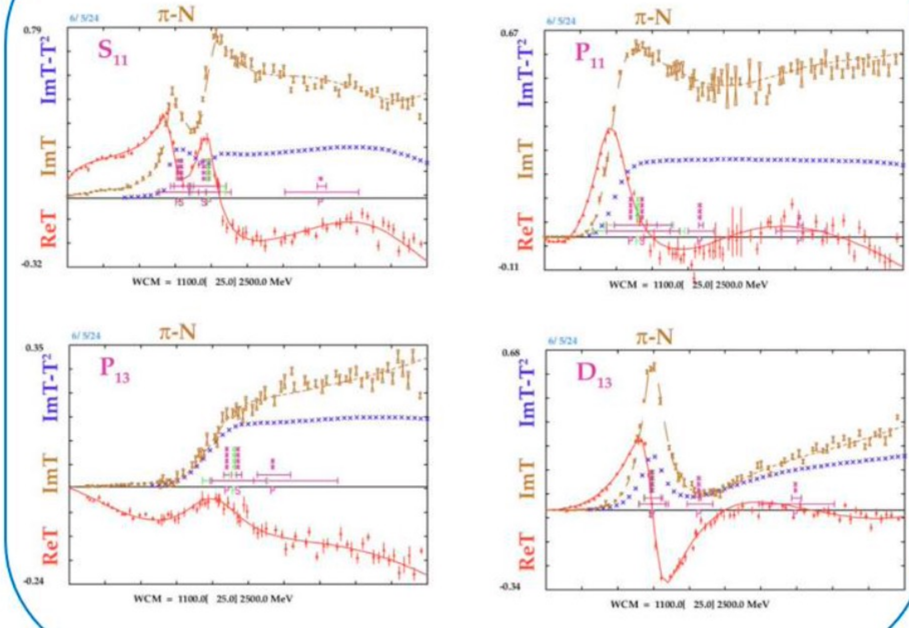
➤ $N\pi$散射

- 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



$N\pi \to N\pi$分波振幅



数据驱动

- 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！

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

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

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

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

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

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

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

弱相位

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

强相位

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

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

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

partial-wave CPVs

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

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

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

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

	$Br(\times 10^{-6})$
$\Lambda_b \to p\pi^-$	$3.34^{+2.53+1.33+0.10+0.47}_{-1.30-1.10-0.11-0.14}$
$\Lambda_b \to pK^-$	$2.83^{+2.17+1.17+0.49+2.19}_{-1.05-0.92-0.37-0.66}$

分波CPV符号相反，相互抵消

	A_{CP}^{dir}	$A_{CP}^S(\kappa_S)$	$A_{CP}^P(\kappa_P)$
$\Lambda_b \to p\pi^-$	$0.05^{+0.00+0.00+0.00+0.02}_{-0.02-0.01-0.02-0.01}$	$0.17^{+0.01+0.01+0.03+0.04}_{-0.04-0.04-0.07-0.04}(49\%)$	$-0.06^{+0.01+0.03+0.02+0.00}_{-0.02-0.03-0.03-0.01}(51\%)$
$\Lambda_b \to pK^-$	$-0.06^{+0.01+0.01+0.02+0.00}_{-0.01-0.01-0.01-0.00}$	$-0.05^{+0.02+0.02+0.04+0.00}_{-0.02-0.01-0.03-0.00}(94\%)$	$-0.21^{+0.07+0.23+0.29+0.04}_{-0.15-0.33-0.27-0.01}(6\%)$

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

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

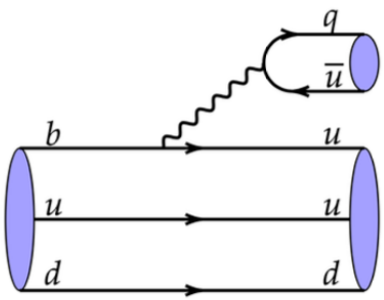
- Baryons have half-integer spin, and thus two partial wave amplitudes.

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

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

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

Tree **Penguin**



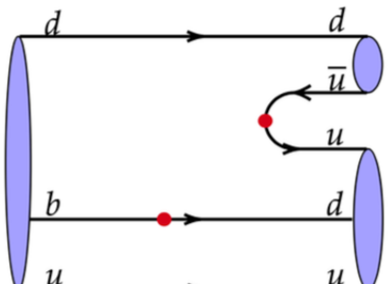
T

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

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

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

different by π



PC_2

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

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