CP violation in *b*-baryon two-body decays

Jia-Jie Han(LanZhou University)

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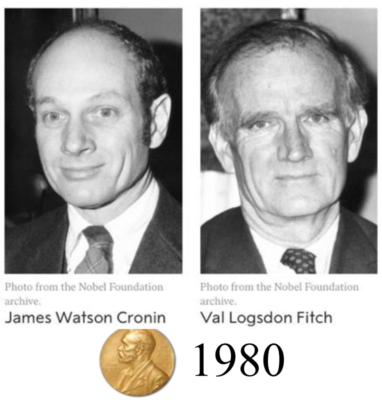
With

Ji-Xin Yu, Ya Li, Jian-Peng Wang, Hsiang-nan Li, Zhen-Jun Xiao & Fu-Sheng Yu

2025·9 HQL2025@Beijing

CP Violations

- Particle physics study symmetry and symmetry breaking.
- Charge-Parity symmetry violation is the key issue of flavor physics.
- CPV relates to most of parameters of SM, is helpful to test SM and search NP.



- 1956, Parity violation in weak interaction;
- 1964, Observation of CPV in Kaon;
- 1973, Kobayashi-Maskawa mechanism
- 2004, Observation of direct CPV in B meson;
- 2019, Observation of direct CPV in D meson.

- CPV in baryon? quite different! Why? What? How?

The first observation of CP asymmetry in baryon decays

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

[LHCb, Nature 2025]

Total CPV $\mathcal{A}_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$ 5.2σ

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 $1.1 < m_{\pi^+K^-} < 1.6$	$(2.7 \pm 0.8 \pm 0.1)\%$
$\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$
$\Lambda_b^0 \to R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.0 \pm 1.2 \pm 0.3)\%$

Regional CPV ($\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$) 6.0σ

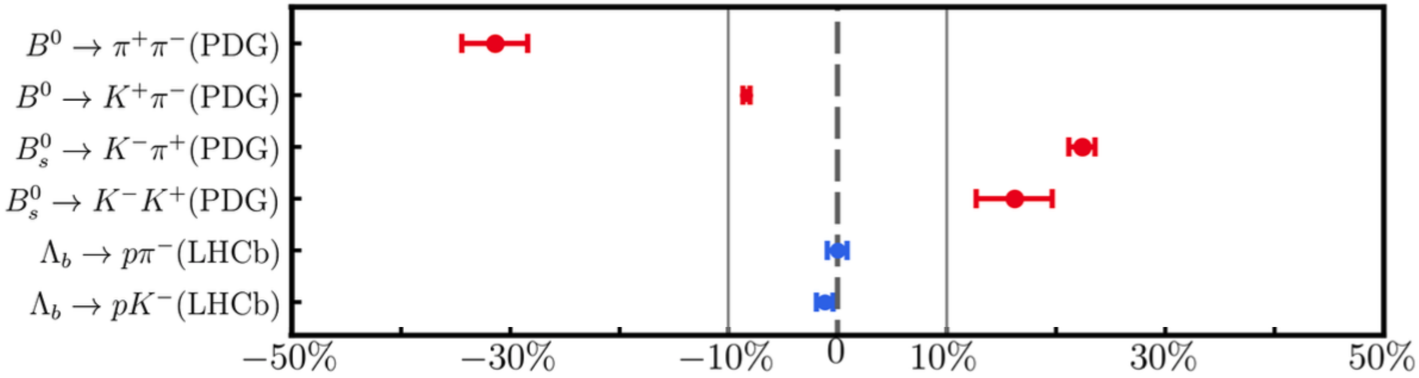
CPVs in baryons

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

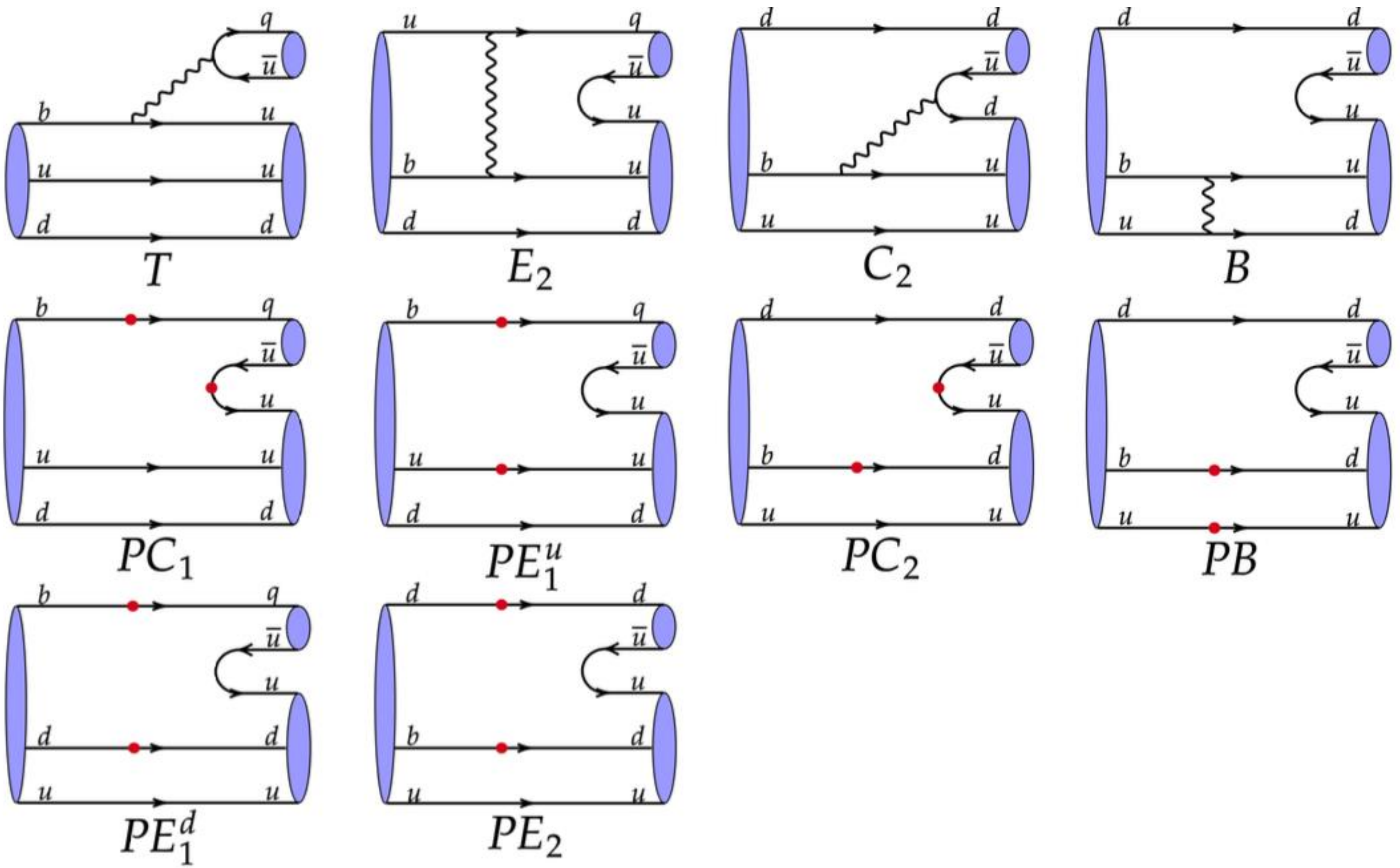
- charm baryon CPV:
  - SM predictions: $\mathcal{O}(10^{-3} \sim 10^{-4})$ [X.G.He, C.W.Liu, 2024] [C.P.Jia, H.Y.Jiang, J.P.Wang, F.S.Yu, 2024]
  - LHCb [JHEP, 2018] $A_{CP}(\Lambda_c \to pK^+K^-/p\pi^+\pi^-) = (3.0 \pm 9.1 \pm 6.1) \times 10^{-3}$

- beauty baryon : SM estimates ~ 10% due to large weak phase difference

$$A_{CP}(B^0 \to K^+\pi^-) = (-8.34 \pm 0.32)\%$$
$$A_{CP}(B_s^0 \to K^-\pi^+) = (22.4 \pm 1.2)\% \text{ [PDG]}$$
$$A_{CP}(\Lambda_b \to p\pi^-) = (0.20 \pm 0.83 \pm 0.37)\%$$
$$A_{CP}(\Lambda_b \to pK^-) = (-1.14 \pm 0.67 \pm 0.36)\% \text{ [LHCb,2024]}$$



Topological diagrams of two-body decays



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

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

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

Tree **Penguin**

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

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

strong phase difference $\Delta\delta_S = \delta^S_{\mathcal{P}} - \delta^S_{\mathcal{T}}$

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

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

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

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

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

weights $\kappa_S \approx \frac{|S|^2}{|S|^2 + \kappa|P|^2}, \qquad \kappa_P \approx \frac{\kappa|P|^2}{|S|^2 + \kappa|P|^2}$

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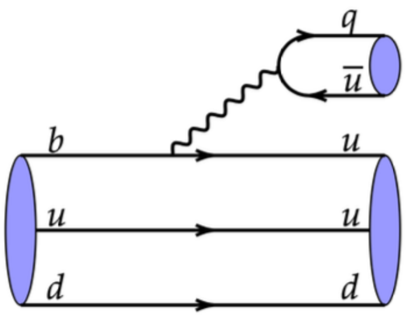
$$S\ wave\quad S = \lambda_{\mathcal{T}}|S_{\mathcal{T}}|e^{i\delta^S_{\mathcal{T}}} + \lambda_{\mathcal{P}}|S_{\mathcal{P}}|e^{i\delta^S_{\mathcal{P}}}$$

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

Tree **Penguin**



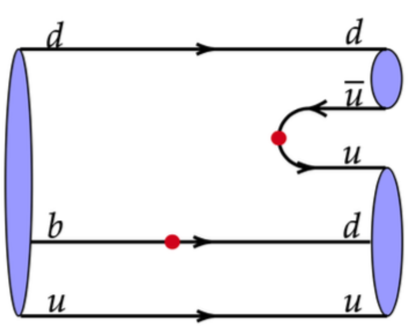
T

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

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

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

different by π



PC_2

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

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

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

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Tree **Penguin**

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

strong phase difference $\Delta\delta_S = \delta^S_{\mathcal{P}} - \delta^S_{\mathcal{T}}$

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

$$A^{\text{dir}}_{CP} \approx \kappa_S A^{S\text{-wave}}_{CP} + \kappa_P A^{P\text{-wave}}_{CP}$$

$$\kappa_S \approx \frac{|S|^2}{|S|^2 + \kappa|P|^2}, \qquad \kappa_P \approx \frac{\kappa|P|^2}{|S|^2 + \kappa|P|^2}$$

- So CPVs of *S*- and *P*-waves can be as large as B mesons, but cancelled with each other.

k_T factorization (PQCD approach)

- The above crude argument needs to be justified by comprehensive 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

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

Partial wave amplitudes of $\Lambda_b \to p\pi^-$ in PQCD

- without the CKM matrix elements, $\times 10^{-9}$

$\Lambda_b \to p\pi^-$	$\|S\|$	$\delta^S(°)$	Real(S)	Imag(S)	$\|P\|$	$\delta^P(°)$	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

Partial wave amplitudes of $\Lambda_b \to pK^-$ in PQCD

- without the CKM matrix elements, $\times 10^{-9}$

$\Lambda_b \to pK^-$	$\|S\|$	$\delta^S(°)$	Real(S)	Imag(S)	$\|P\|$	$\delta^P(°)$	Real(P)	Imag(P)
T^f	865.44	0.00	865.44	0.00	1230.64	0.00	1230.64	0.00
T^{nf}	53.41	-102.81	-11.84	-52.08	343.23	-96.76	-40.43	-340.84
$T^f + T^{nf}$	855.18	-3.49	853.60	-52.08	1238.05	-15.98	1190.21	-340.84
E_2	89.06	-138.10	-66.28	-59.48	94.13	122.31	-50.31	79.56
Tree	795.18	-8.06	787.31	-111.55	1169.46	-12.91	1139.90	-261.28
PC_1^f	76.43	0.00	76.43	0.00	3.30	180.00	-3.30	0.00
PC_1^{nf}	1.14	-134.10	-0.79	-0.82	13.85	-94.36	-1.05	-13.81
$PC_1^f + PC_1^{nf}$	75.64	-0.62	75.64	-0.82	14.48	-107.50	-4.35	-13.81
PE_1^u	11.80	-89.53	0.10	-11.80	11.02	115.62	-4.76	9.93
PE_1^d	7.53	-101.53	-1.50	-7.38	2.67	51.53	1.66	2.09
Penguin	76.88	-15.08	74.23	-20.00	7.66	-166.53	-7.45	-1.79

- SU(3) breaking effect

$$\frac{|T^f(pK)|}{|T^f(p\pi)|} = 1.22, \quad \frac{|T^{nf}(pK)|}{|T^{nf}(p\pi)|} = 1.03, \quad \frac{|E_2(pK)|}{|E_2(p\pi)|} = 1.33 \text{ (S wave)},$$

$$\frac{|T^f(pK)|}{|T^f(p\pi)|} = 1.23, \quad \frac{|T^{nf}(pK)|}{|T^{nf}(p\pi)|} = 1.28, \quad \frac{|E_2(pK)|}{|E_2(p\pi)|} = 1.29 \text{ (P wave)}.$$

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

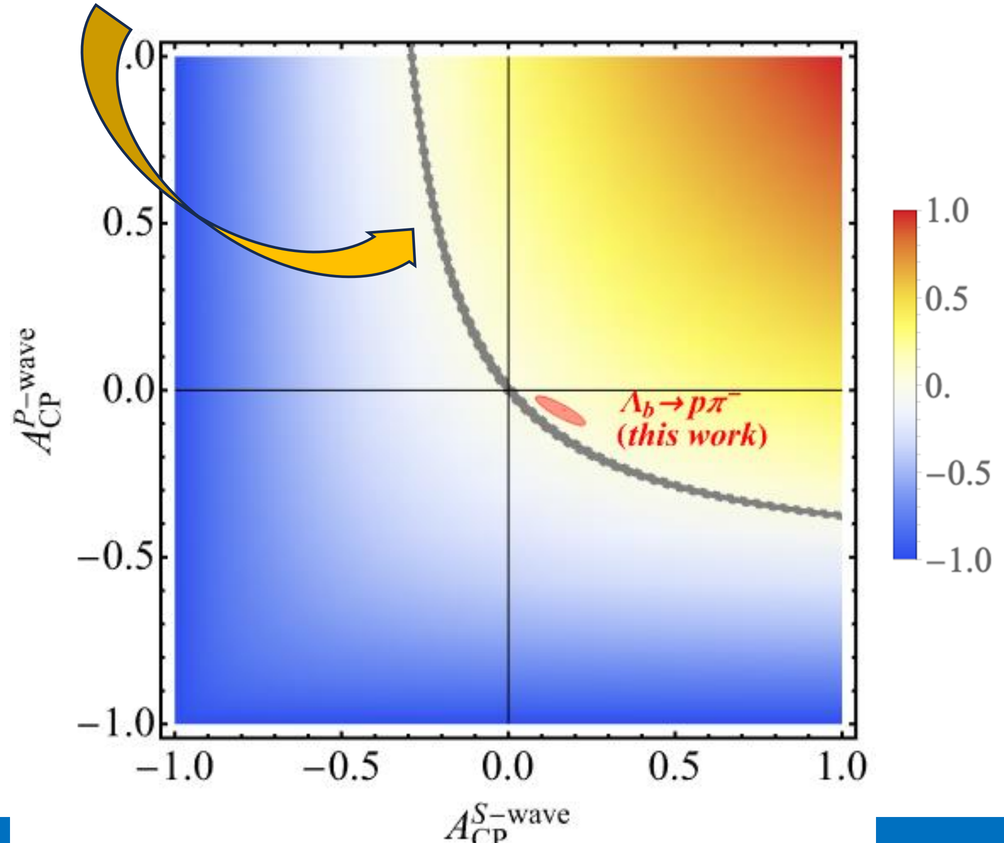
$$A_{CP}^{\mathrm{dir}} \approx \kappa_S A_{CP}^{S\text{-wave}} + \kappa_P A_{CP}^{P\text{-wave}}$$

	$Br(\times 10^{-6})$		
$\Lambda_b \to p\pi^-$	$3.34^{+2.53+1.33+0.10+0.47}_{-1.30-1.10-0.11-0.14}$		
$\Lambda_b \to pK^-$	$2.83^{+2.17+1.17+0.49+2.19}_{-1.05-0.92-0.37-0.66}$		
	A_{CP}^{dir}	$A_{CP}^{S}(\kappa_S)$	$A_{CP}^{P}(\kappa_P)$
$\Lambda_b \to p\pi^-$	$0.05^{+0.00+0.00+0.00+0.02}_{-0.02-0.01-0.02-0.01}$	$0.17^{+0.01+0.01+0.03+0.04}_{-0.04-0.04-0.07-0.04}(49\%)$	$-0.06^{+0.01+0.03+0.02+0.00}_{-0.02-0.03-0.03-0.01}(51\%)$
$\Lambda_b \to pK^-$	$-0.06^{+0.01+0.01+0.02+0.00}_{-0.01-0.01-0.01-0.00}$	$-0.05^{+0.02+0.02+0.04+0.00}_{-0.02-0.01-0.03-0.00}(94\%)$	$-0.21^{+0.07+0.23+0.29+0.04}_{-0.15-0.33-0.27-0.01}(6\%)$
	α	A_{CP}^{α}	$\langle\alpha\rangle$
$\Lambda_b \to p\pi^-$	$-0.94^{+0.00+0.02+0.01+0.03}_{-0.02-0.02-0.02-0.02}$	$0.02^{+0.00+0.01+0.00+0.01}_{-0.01-0.01-0.01-0.01}$	$-0.96^{+0.00+0.01+0.01+0.02}_{-0.00-0.01-0.01-0.01}$
$\Lambda_b \to pK^-$	$0.23^{+0.04+0.02+0.10+0.15}_{-0.03-0.05-0.12-0.07}$	$0.04^{+0.02+0.02+0.01+0.01}_{-0.02-0.03-0.01-0.01}$	$0.20^{+0.02+0.01+0.11+0.14}_{-0.02-0.02-0.12-0.06}$
	β	A_{CP}^{β}	$\langle\beta\rangle$
$\Lambda_b \to p\pi^-$	$0.34^{+0.00+0.05+0.01+0.07}_{-0.06-0.06-0.06-0.05}$	$0.22^{+0.00+0.00+0.03+0.07}_{-0.01-0.01-0.04-0.03}$	$0.12^{+0.00+0.05+0.03+0.00}_{-0.05-0.05-0.04-0.02}$
$\Lambda_b \to pK^-$	$-0.39^{+0.03+0.08+0.08+0.12}_{-0.01-0.04-0.07-0.01}$	$-0.44^{+0.01+0.01+0.02+0.08}_{-0.00-0.00-0.01-0.04}$	$0.05^{+0.03+0.08+0.07+0.04}_{-0.01-0.05-0.07-0.02}$
	γ	A_{CP}^{γ}	$\langle\gamma\rangle$
$\Lambda_b \to p\pi^-$	$0.09^{+0.02+0.04+0.04+0.04}_{-0.04-0.06-0.06-0.01}$	$0.11^{+0.01+0.02+0.03+0.03}_{-0.02-0.03-0.04-0.02}$	$-0.02^{+0.01+0.02+0.01+0.01}_{-0.02-0.04-0.01-0.00}$
$\Lambda_b \to pK^-$	$0.89^{+0.02+0.04+0.04+0.00}_{-0.01-0.02-0.05-0.01}$	$0.02^{+0.02+0.05+0.04+0.00}_{-0.01-0.03-0.04-0.00}$	$0.87^{+0.00+0.01+0.02+0.00}_{-0.00-0.01-0.02-0.01}$

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

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

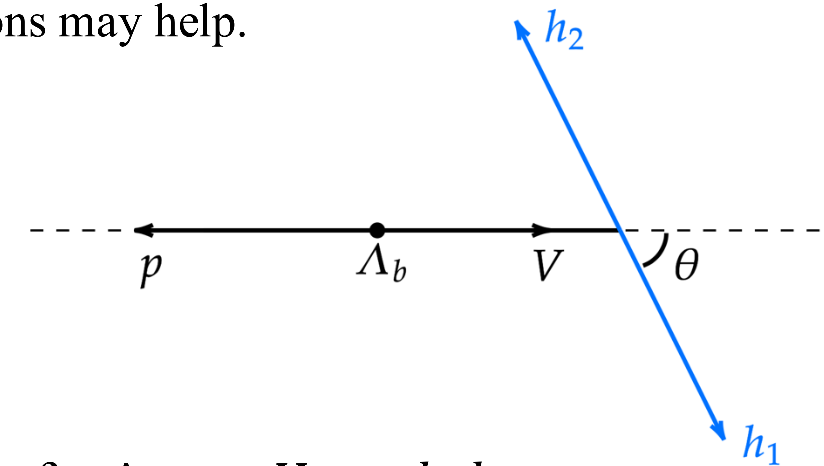
$A_{CP}(\Lambda_b \to p\pi^-) = (0.20 \pm 0.83 \pm 0.37)\%$ [LHCb,2024]



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

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

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



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

$$\frac{d\Gamma}{d\theta} \propto |H_{\frac{1}{2},0}|^2 + |H_{-\frac{1}{2},0}|^2 + |H_{-\frac{1}{2},-1}|^2 + |H_{\frac{1}{2},1}|^2 + (2|H_{\frac{1}{2},0}|^2 + 2|H_{-\frac{1}{2},0}|^2 - |H_{-\frac{1}{2},-1}|^2 - |H_{\frac{1}{2},1}|^2)P_2$$

$$\propto 1 + \frac{2|H_{\frac{1}{2},0}|^2 + 2|H_{-\frac{1}{2},0}|^2 - |H_{-\frac{1}{2},-1}|^2 - |H_{\frac{1}{2},1}|^2}{|H_{\frac{1}{2},0}|^2 + |H_{-\frac{1}{2},0}|^2 + |H_{-\frac{1}{2},-1}|^2 + |H_{\frac{1}{2},1}|^2} P_2$$

$$\propto 1 + \mathcal{J} \cdot P_2$$

- The CP asymmetry and average for $\mathcal{J}$:

$$A_{CP}^{\mathcal{J}} = \frac{\mathcal{J} - \bar{\mathcal{J}}}{2}, \qquad \langle \mathcal{J} \rangle = \frac{\mathcal{J} + \bar{\mathcal{J}}}{2}$$

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

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

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

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

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

	$Br(\times 10^{-6})$	A_{CP}^{dir}	$A_{CP}^{S^T}(\kappa_{S^T})$
$\Lambda_b \to pa_1^-(1260)$	$11.06^{+8.21+3.88+0.91+1.73}_{-4.30-3.32-0.46-0.06}$	$-0.01^{+0.01+0.03+0.02+0.03}_{-0.00-0.01-0.02-0.00}$	$-0.22^{+0.04+0.07+0.05+0.04}_{-0.03-0.07-0.07-0.01}(6\%)$
$\Lambda_b \to pK_1^-(1270)(30^\circ)$	$5.48^{+3.63+1.94+0.27+2.49}_{-1.87-1.55-0.31-1.11}$	$0.09^{+0.03+0.07+0.03+0.01}_{-0.04-0.02-0.02-0.00}$	$0.34^{+0.00+0.01+0.01+0.00}_{-0.02-0.03-0.01-0.05}(8\%)$
$\Lambda_b \to pK_1^-(1400)(30^\circ)$	$1.25^{+0.59+0.33+0.13+0.64}_{-0.39-0.19-0.19-0.31}$	$0.06^{+0.03+0.05+0.03+0.00}_{-0.03-0.09-0.04-0.01}$	$0.71^{+0.05+0.06+0.03+0.03}_{-0.02-0.16-0.04-0.13}(13\%)$
$\Lambda_b \to pK_1^-(1270)(60^\circ)$	$6.28^{+3.97+1.93+0.18+2.79}_{-2.13-1.51-0.41-1.32}$	$0.07^{+0.01+0.03+0.03+0.01}_{-0.04-0.04-0.03-0.00}$	$0.46^{+0.00+0.00+0.02+0.01}_{-0.02-0.04-0.02-0.07}(9\%)$
$\Lambda_b \to pK_1^-(1400)(60^\circ)$	$0.53^{+0.33+0.38+0.09+0.36}_{-0.16-0.19-0.22-0.13}$	$0.08^{+0.11+0.09+0.12+0.00}_{-0.08-0.11-0.04-0.03}$	$0.07^{+0.00+0.41+0.08+0.22}_{-0.12-0.09-0.15-0.10}(3\%)$

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

Results of $\Lambda_b \to pa_1, pK_1$

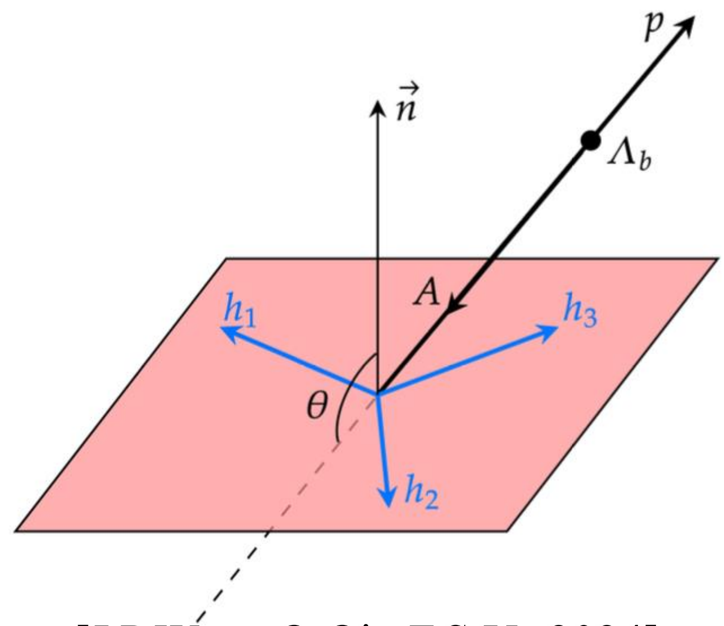
- The angle distribution for $\Lambda_b \to pA \to ph_1h_2h_3$:

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

- up-down asymmetry :

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

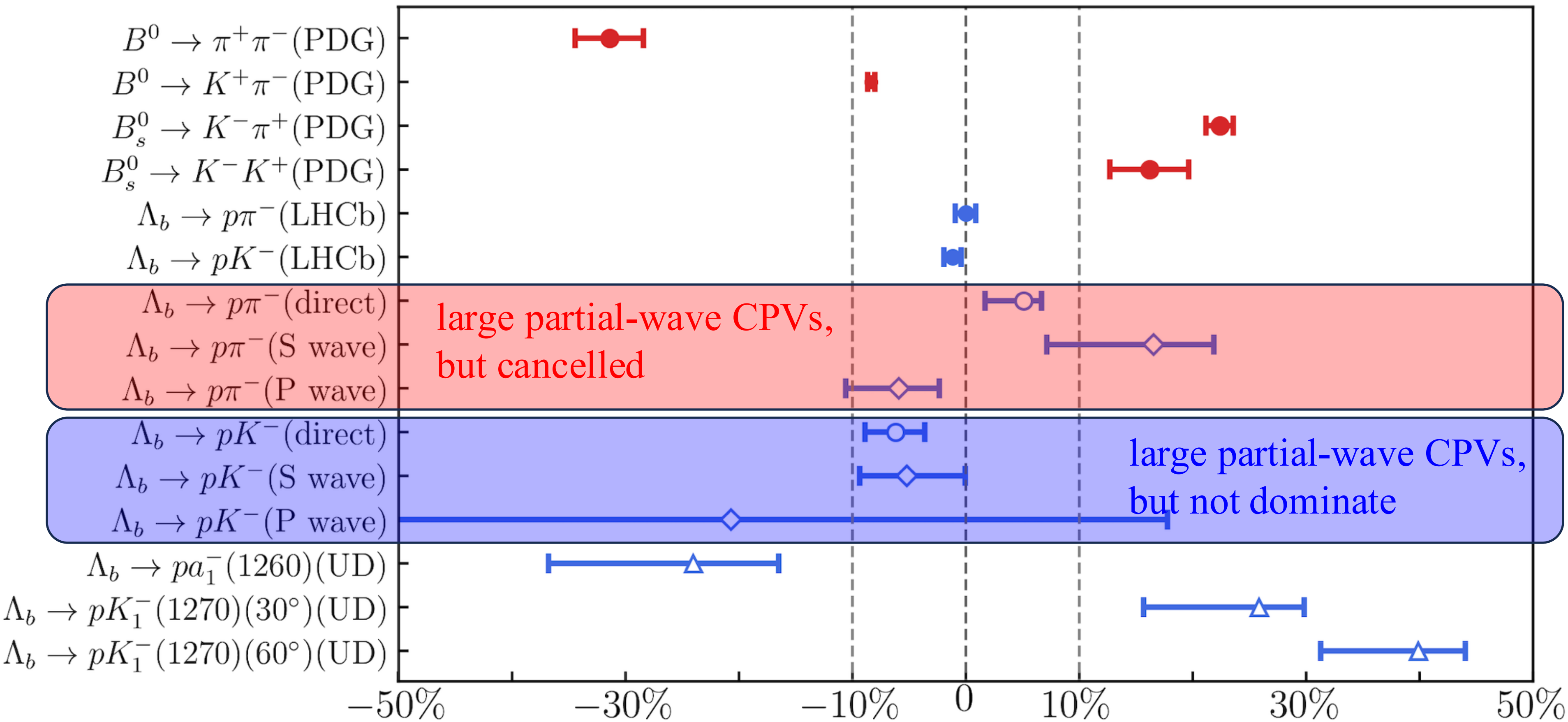
$$A_{CP}^{UD} = \frac{A_{UD}+\bar{A}_{UD}}{A_{UD}-\bar{A}_{UD}}$$



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

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

Summary



$B^0 \to \pi^+\pi^-$(PDG)
$B^0 \to K^+\pi^-$(PDG)
$B_s^0 \to K^-\pi^+$(PDG)
$B_s^0 \to K^-K^+$(PDG)
$\Lambda_b \to p\pi^-$(LHCb)
$\Lambda_b \to pK^-$(LHCb)
$\Lambda_b \to p\pi^-$(direct)
$\Lambda_b \to p\pi^-$(S wave)
$\Lambda_b \to p\pi^-$(P wave)
$\Lambda_b \to pK^-$(direct)
$\Lambda_b \to pK^-$(S wave)
$\Lambda_b \to pK^-$(P wave)
$\Lambda_b \to pa_1^-(1260)$(UD)
$\Lambda_b \to pK_1^-(1270)(30°)$(UD)
$\Lambda_b \to pK_1^-(1270)(60°)$(UD)
large partial-wave CPVs, but cancelled
large partial-wave CPVs, but not dominate
−50%
−30%
−10%
0
10%
30%
50%

Conclusion

First full QCD analysis of b-baryon decays

Find cancellation of partial wave CPVs

Half-integer spin of baryon, different partial wave amplitudes, different dynamics

Small direct CPVs of $\Lambda_b \to p\pi, pK$ are well explained

Our PQCD calculation have No conflict with known measurements

Large CPV observables are proposed and predicted

We suggest to measure the A_{CP}^{UD} and direct CPV in $\Lambda_b \to pK\pi\pi, p\pi\pi\pi$ modes !

Backup

Opportunities and puzzle

- LHCb is a baryon factory !

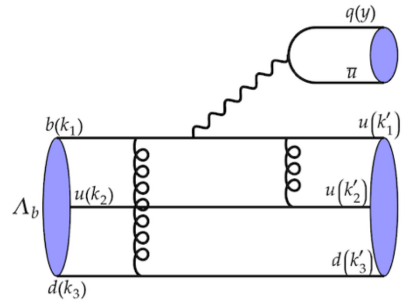
$$\frac{f_{\Lambda_b}}{f_{u,d}} \sim 0.5 \quad \Rightarrow \quad \frac{N_{\Lambda_b}}{N_B^{0,-}} \sim 0.5 \text{ [LHCb, 2012]}$$

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

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

- Why CPVs of $\Lambda_b \to p\pi, pK$ 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

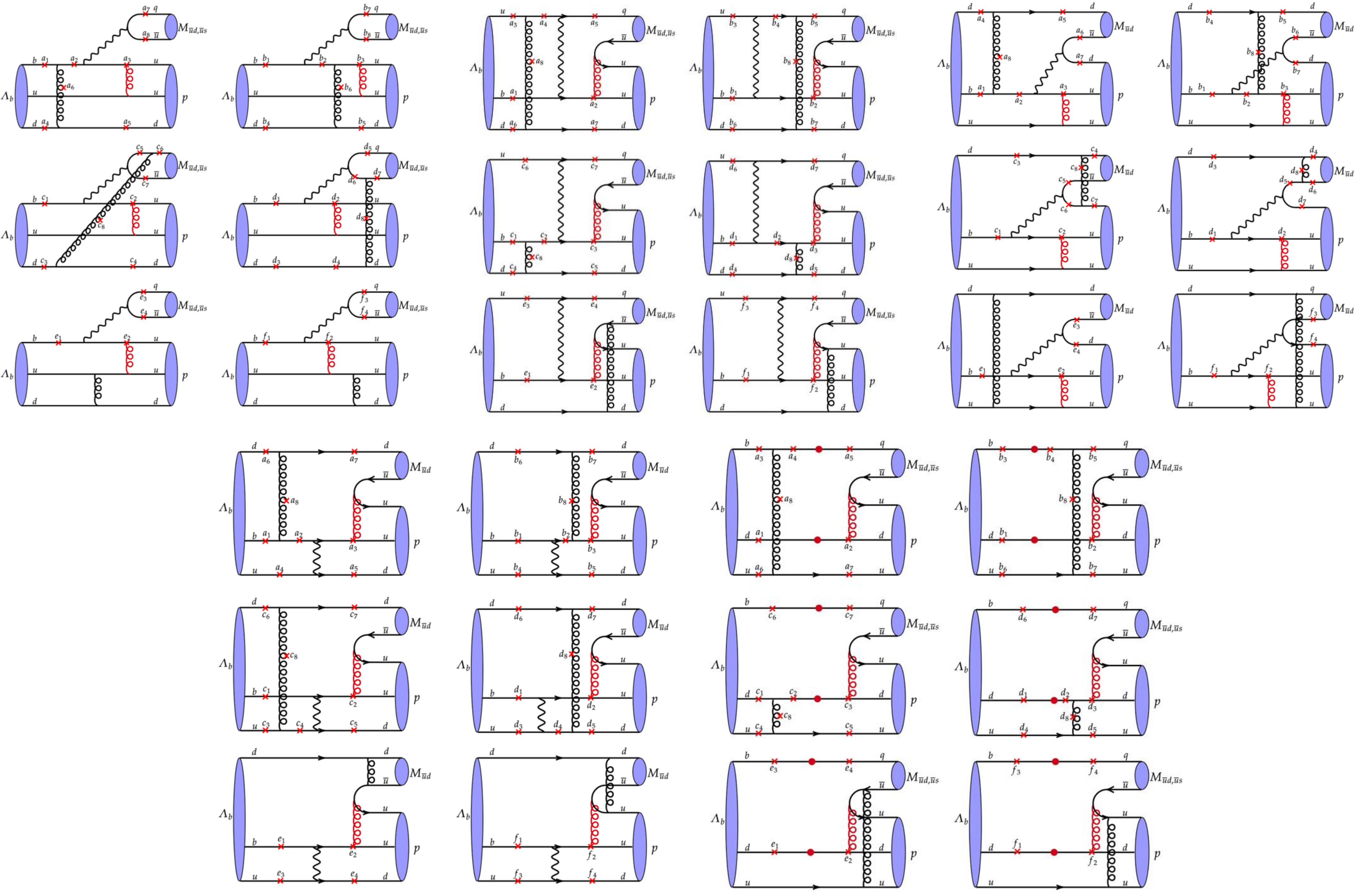


  - SCET: power counting of baryon is different from meson
    - heavy-to-light form factor is factorizable at leading power and no end-point singularity!

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

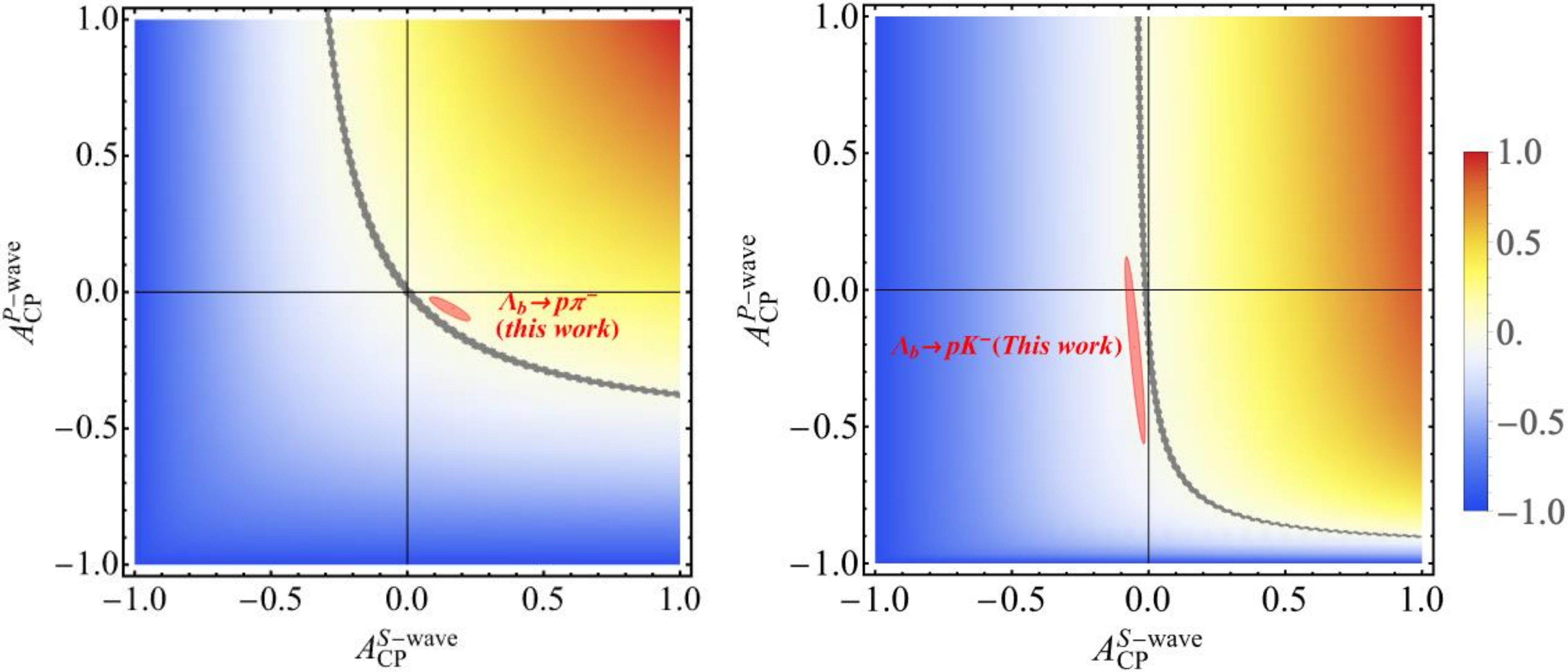
    - leading power: $\xi_{\Lambda_b \to \Lambda}(q^2 = 0) = -0.012$ [W.Wang, 2011]
    - Total form factors: $\xi_{\Lambda_b \to \Lambda}(q^2 = 0) = 0.18$ [Y.L.Shen, Y.M.Wang, 2016]

Feynman diagrams



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

$$\begin{aligned} A_{CP}^{dir} &\equiv \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \\ &= \frac{M_+^2(|S|^2 - |\bar{S}|^2) + M_-^2(|P|^2 - |\bar{P}|^2)}{M_+^2(|S|^2 + |\bar{S}|^2) + M_-^2(|P|^2 + |\bar{P}|^2)} \\ &= \frac{|S|^2}{|S|^2 + \frac{M_-^2}{M_+^2}\frac{1+A_{CP}^{S\text{-wave}}}{1+A_{CP}^{P\text{-wave}}}|P|^2} A_{CP}^{S\text{-wave}} + \frac{\frac{M_-^2}{M_+^2}|P|^2}{\frac{1+A_{CP}^{P\text{-wave}}}{1+A_{CP}^{S\text{-wave}}}|S|^2 + \frac{M_-^2}{M_+^2}|P|^2} A_{CP}^{P\text{-wave}} \\ &= \kappa_S A_{CP}^{S\text{-wave}} + \kappa_P A_{CP}^{P\text{-wave}}, \end{aligned}$$



$\Lambda_b \to p\pi^-$	$\lvert S \rvert$	$\delta^S(^\circ)$	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
$P_f^{C_1}$	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

$$S(P_f^{C_1}) = -\frac{G_F}{\sqrt{2}} f_h V_{tb} V_{td}^* \left(\frac{C_3}{3} + C_4 + \frac{C_9}{3} + C_{10} + R_1^\pi \left(\frac{C_5}{3} + C_6 + \frac{C_7}{3} + C_8\right) \right) \left[F_1(m_h^2)(M_{\Lambda_b} - M_p) + F_3(m_h^2) m_h^2\right]$$

chiral factors $R_1 \approx R_2$

$$P(P_f^{C_1}) = -\frac{G_F}{\sqrt{2}} f_h V_{tb} V_{td}^* \left(\frac{C_3}{3} + C_4 + \frac{C_9}{3} + C_{10} - R_2^\pi \left(\frac{C_5}{3} + C_6 + \frac{C_7}{3} + C_8\right) \right) \left[G_1(m_h^2)(M_{\Lambda_b} + M_p) - G_3(m_h^2) m_h^2\right]$$