Establishing *CP* violation in *b*-baryon

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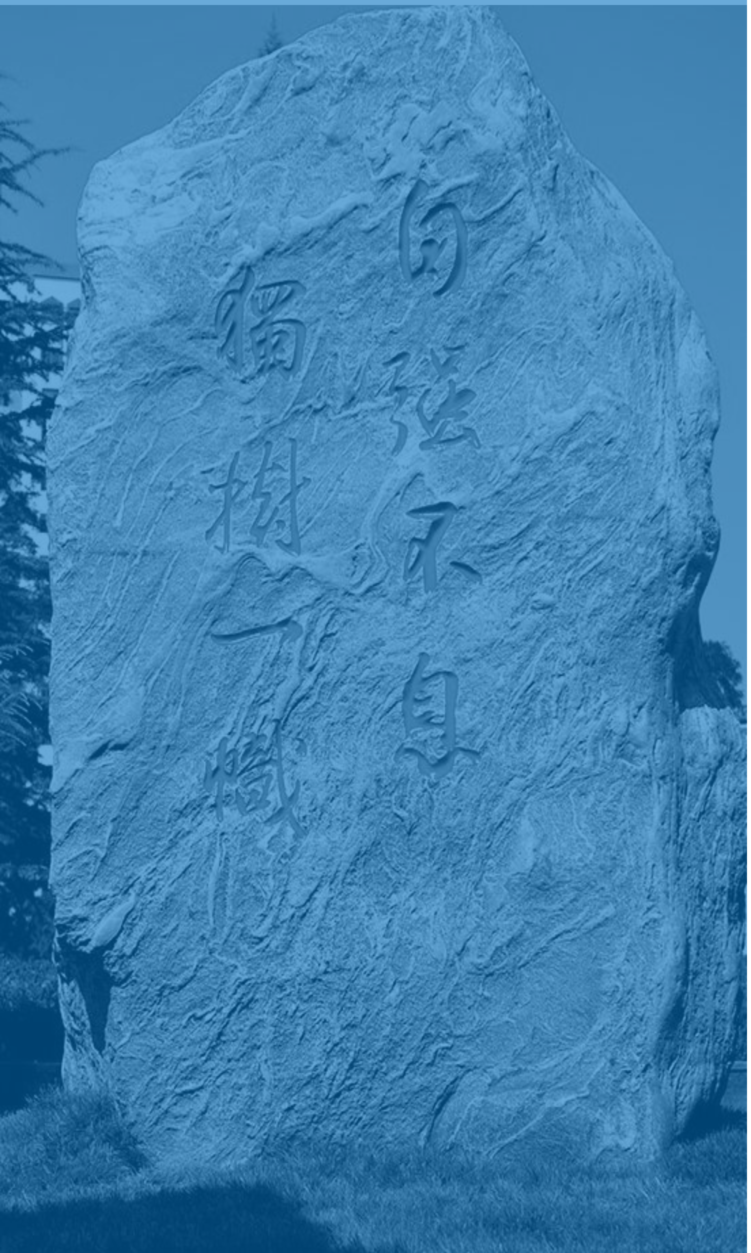
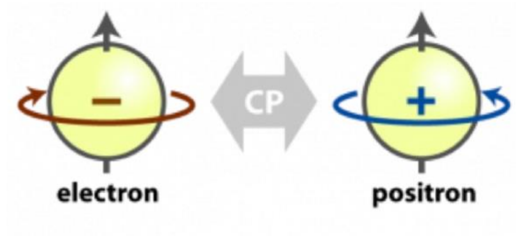


- Introduction
- Direct CP violation
- Asymmetry parameters
- Summary

CP violation

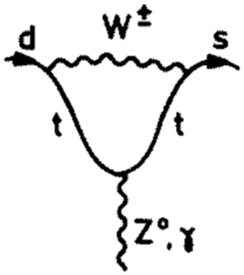
- Matter-antimatter asymmetry in the Universe [Science 109 (2005) 5731]

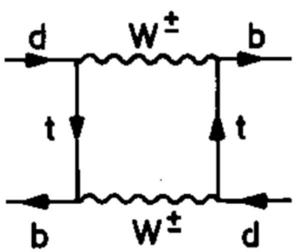
- Three conditions for Matter-antimatter asymmetry: [Sakharov JETP Lett.(1967)]
    - Interaction to violate baryon number;
    - C and CP violation;
    - Deviate thermal equilibrium



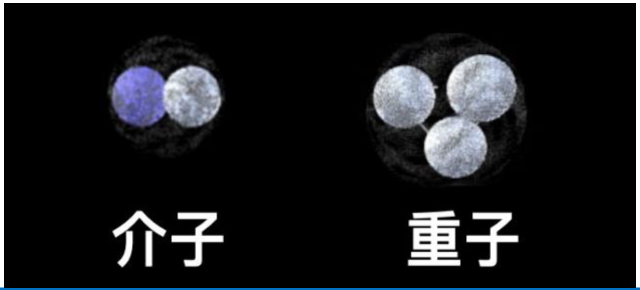
CP: 电荷共轭+宇称变换

- 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.



Baryon CPV

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

$A_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$

[LHCb, Nature 643(2025)8074]

Beauty hadron: SM estimates $\sim$ 10% due to large weak phase difference [PDG]

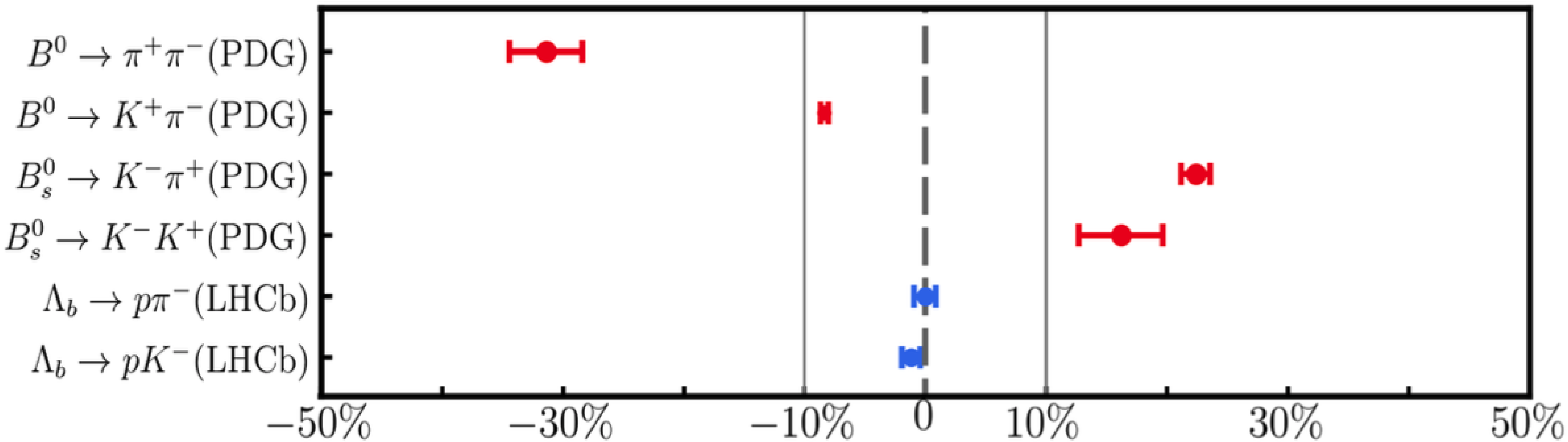
$A_{CP}(B^0 \to K^+\pi^-) = (-8.34 \pm 0.32)\%$ $A_{CP}(B_s^0 \to K^-\pi^+) = (22.4 \pm 1.2)\%$

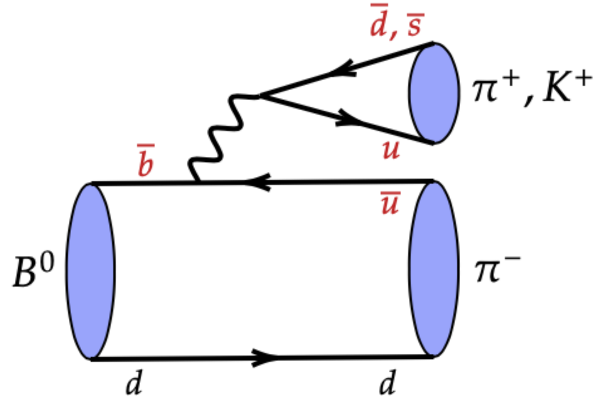
	GFA (Hsiao,Yao,Geng,2017)	QCDF (Zhu,Ke,Wei,2018)	PQCD(hybrid) (Lü,Wang,et.al.,2009)	LFQM (Geng,Liu,Tsai,2021)
$A_{CP}(\Lambda_b \to p\pi^-)\%$	-3.9 ± 0.4	-3.4 ± 0.4	-31^{+42}_{-1}	-3.6 ± 0.20
$A_{CP}(\Lambda_b \to pK^-)\%$	6.7 ± 0.4	10.1 ± 2.0	-5^{+26}_{-5}	6.36 ± 0.28

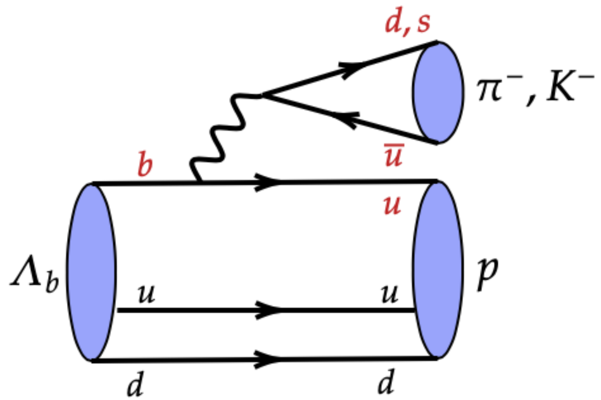
Puzzle of b-baryon CPVs

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

[LHCb, 2018,2025]

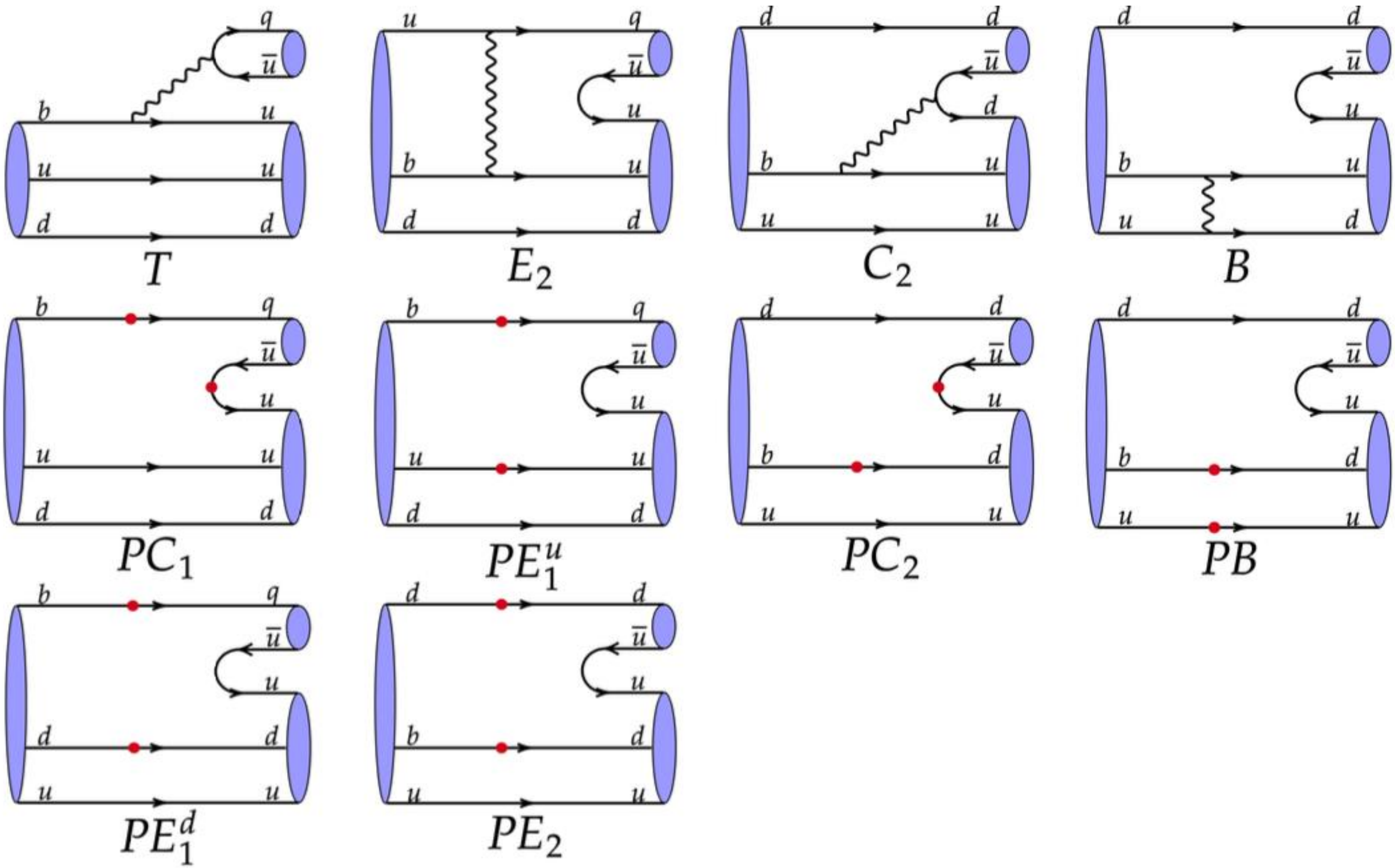






only direct CPV
in baryon decays

Topological diagrams of $\Lambda_b \to p\pi^-, pK^-$



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

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

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

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

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

Tree — Penguin — **strong phase difference**

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

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

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

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

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

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

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

partial-wave CPVs

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

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

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

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

strong phase difference

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

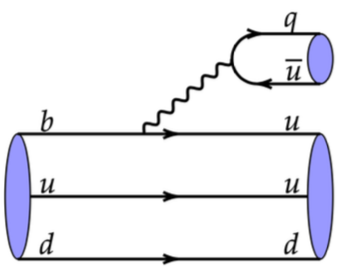
- Baryons have half-integer spin, and thus two partial wave amplitudes.

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

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

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

Tree Penguin



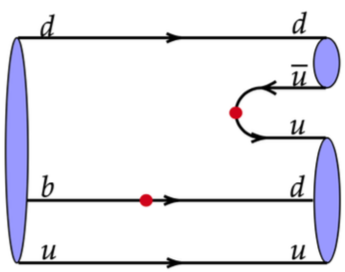
T

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

$$\Delta\delta_{S-wave} = \delta^{S-wave}_{PC_2} - \delta^{S-wave}_{T} \sim 0$$

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

different by π



PC_2

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

Strong phases depending on:

- operators
- diagram
- non-perturbative LCDAs

CPVs in PQCD

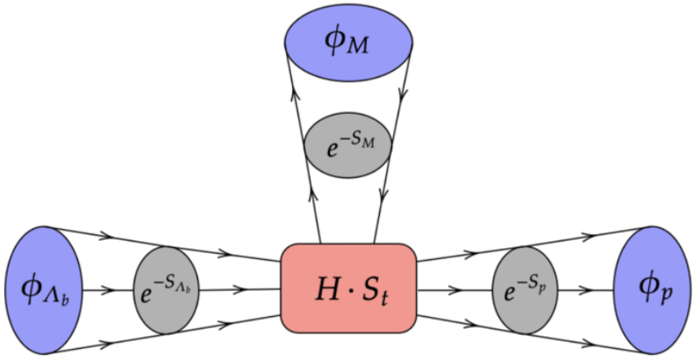
- Strong phases need to be determined by QCD
- Based on k_T factorization, PQCD approach has successfully predicted B meson CPV

$C_{\pi\pi}(B \to \pi^+\pi^-)\%$	$A_{CP}(B \to K^+\pi^-)\%$
~ -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

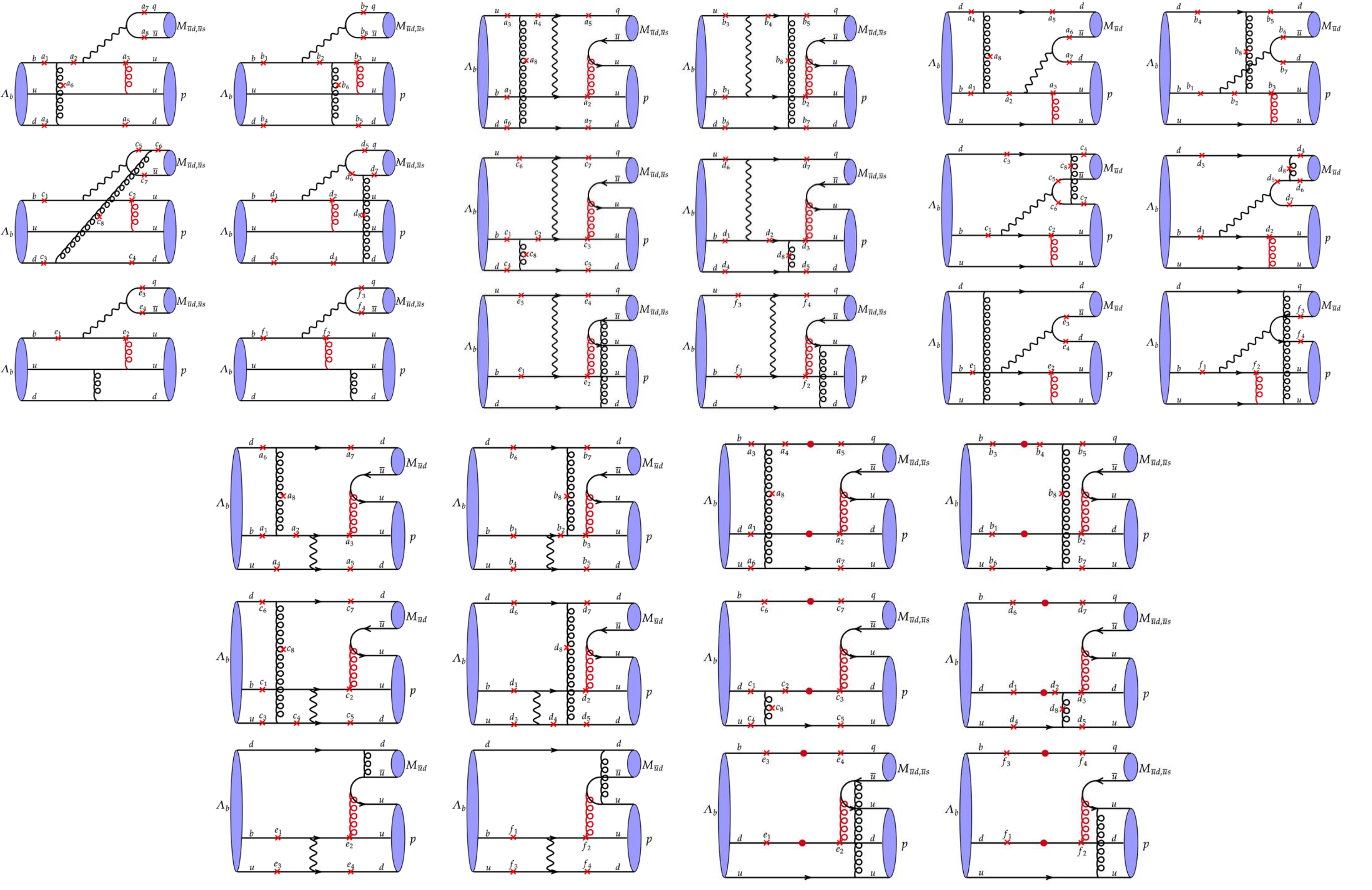
[Sterman,Hsiang-nan Li,1995~2005]

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



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

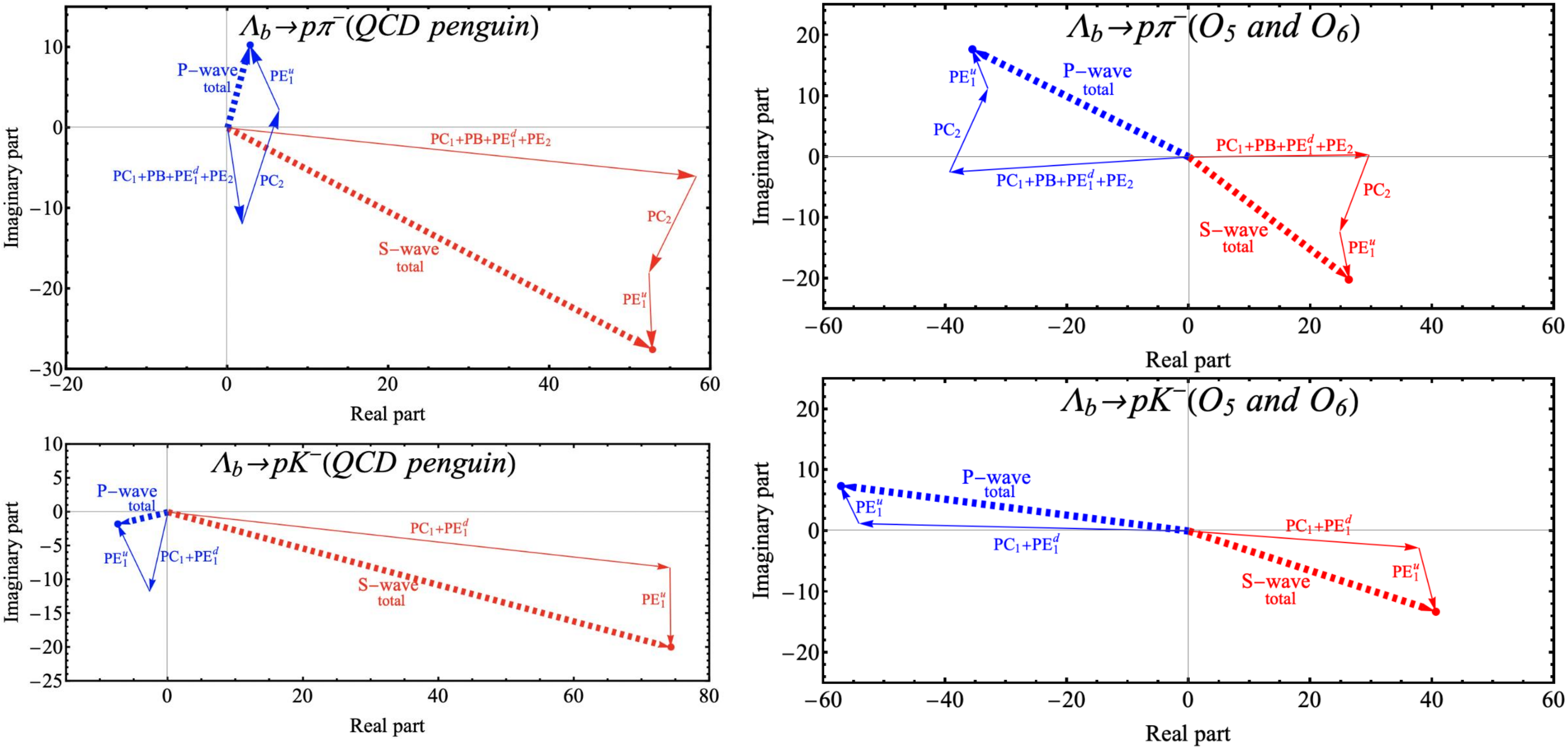
Feynman diagrams



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

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

	$\Lambda_b \to p\pi^-$	$\lvert S\rvert$	$\delta^S(^\circ)$	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
$V-A \otimes V-A$	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
$V-A \otimes V+A$	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


$\Lambda_b \to p\pi^-$ (QCD penguin)
P−wave total
PE_1^u
$PC_1+PB+PE_1^d+PE_2$
PC_2
S−wave total
Imaginary part
Real part
$\Lambda_b \to p\pi^-$ (O_5 and O_6)
$\Lambda_b \to pK^-$ (QCD penguin)
$PC_1+PE_1^d$
$\Lambda_b \to pK^-$ (O_5 and O_6)

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

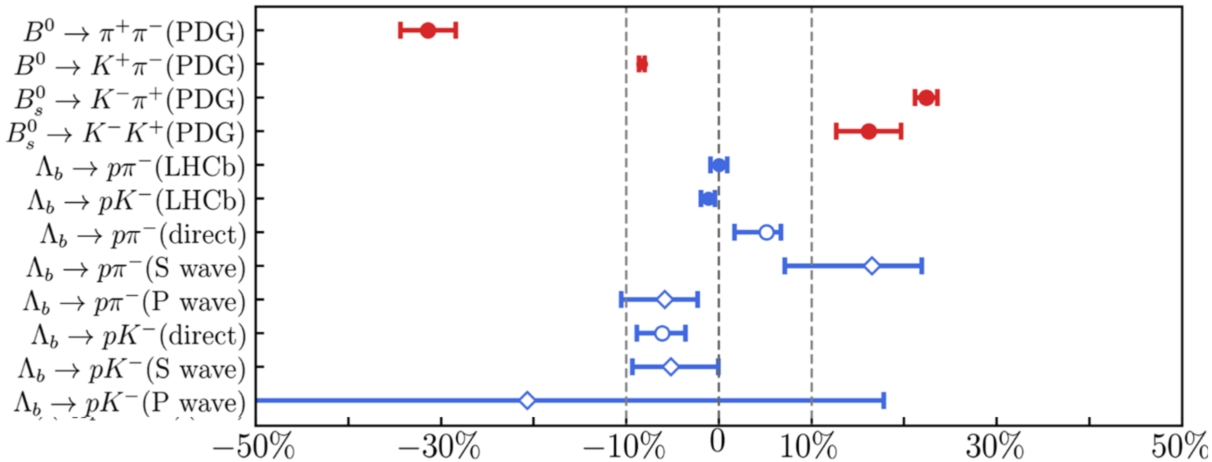
$$A_{CP}^{dir} \approx \frac{|S|^2}{|S|^2+|P|^2} A_{CP}^S + \frac{|P|^2}{|S|^2+|P|^2} A_{CP}^P$$

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

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

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

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



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

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

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

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

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

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

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

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

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

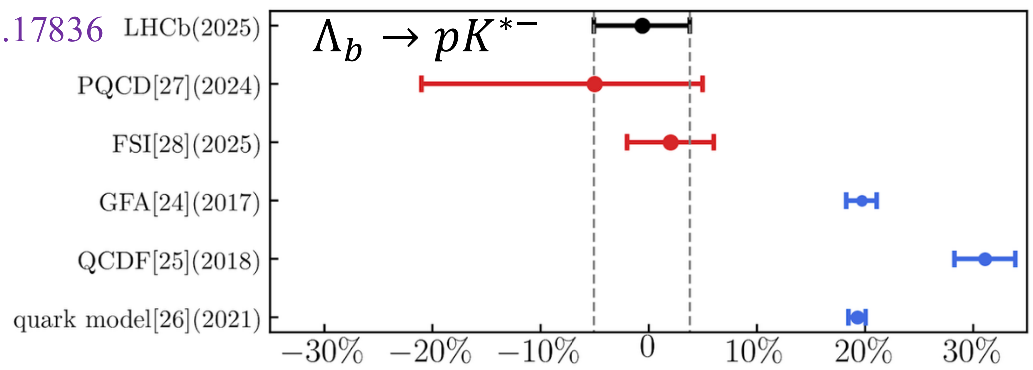
	α	A_{CP}^α	$\langle\alpha\rangle$
$\Lambda_b \to p\pi^-$	$-0.94^{+0.00+0.02+0.01+0.03}_{-0.02-0.02-0.02-0.02}$	$0.02^{+0.00+0.01+0.00+0.01}_{-0.01-0.01-0.01-0.01}$	$-0.96^{+0.00+0.01+0.01+0.02}_{-0.00-0.01-0.01-0.01}$
$\Lambda_b \to pK^-$	$0.23^{+0.04+0.02+0.10+0.15}_{-0.03-0.05-0.12-0.07}$	$0.04^{+0.02+0.02+0.01+0.01}_{-0.02-0.03-0.01-0.01}$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

$\Lambda_b \to p\rho^-, pK^{*-}$

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

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

LHCb, arXiv: 2508.17836



"…… The vanishing CP asymmetry observed for the $\Lambda_b^0 \to pK_S^0\pi^-$ 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.

$\Lambda_b \to pa_1, pK_1(1270), pK_1(1400)$

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

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

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

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

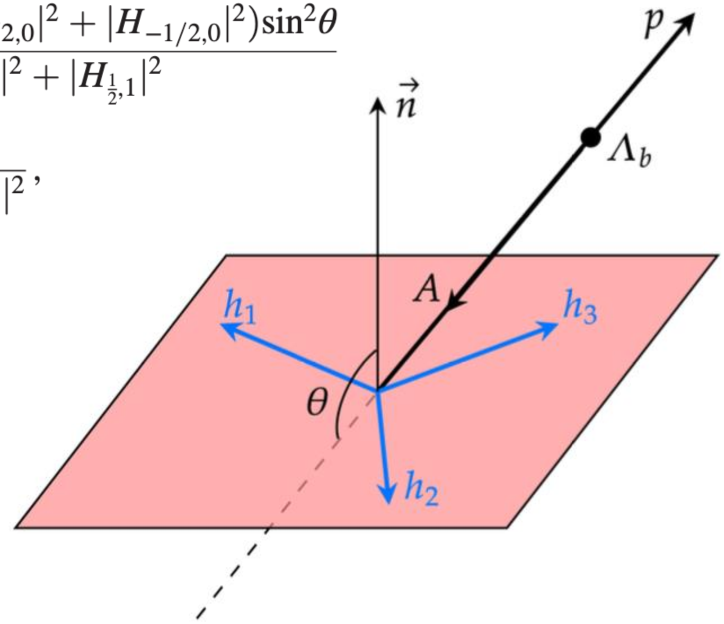
	$A_{CP}^{S^L+D}(\kappa_{S^L+D})$	$A_{CP}^{P_1}(\kappa_{P_1})$	$A_{CP}^{P_2}(\kappa_{P_2})$
$\Lambda_b \to pa_1^-(1260)$	$-0.11^{+0.02+0.01+0.02+0.02}_{-0.00-0.01-0.07-0.03}(46\%)$	$0.18^{+0.03+0.02+0.04+0.09}_{-0.03-0.02-0.03-0.04}(40\%)$	$-0.24^{+0.01+0.05+0.04+0.03}_{-0.02-0.09-0.06-0.06}(8\%)$
$\Lambda_b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

Results of $\Lambda_b \to pa_1, pK_1$

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

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

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



- up-down asymmetry :

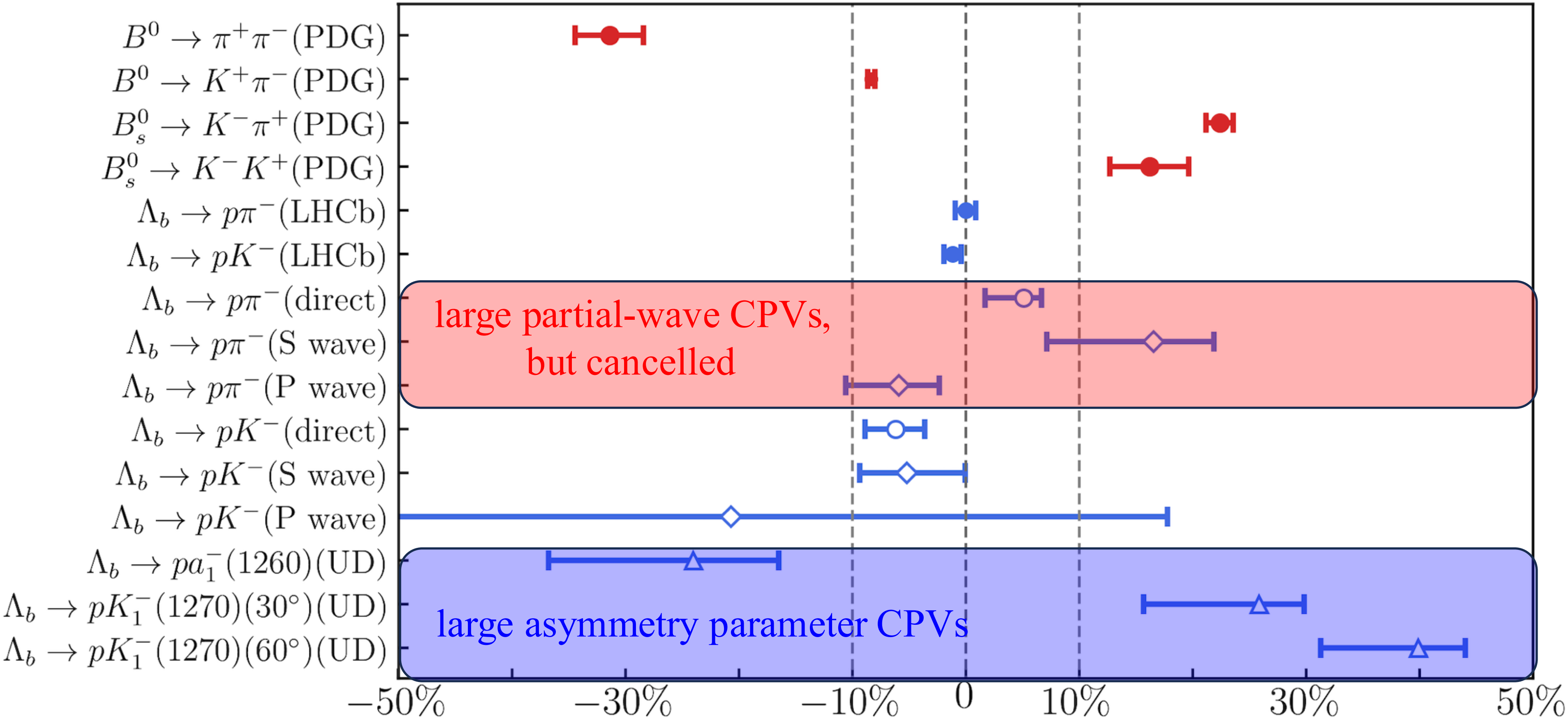
$$A_{UD} \equiv \frac{\Gamma(\cos\theta > 0) - \Gamma(\cos\theta < 0)}{\Gamma(\cos\theta > 0) + \Gamma(\cos\theta < 0)} = R\,\mathcal{R}e(S^T P_2^*)$$

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

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

Summary

First full QCD analysis of baryon decays



Thanks

Backup

Opportunities and puzzle

- LHCb is a baryon factory !

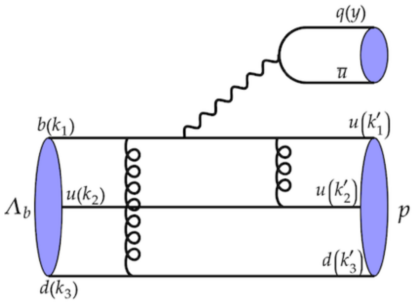
$$\frac{f_{\Lambda_b}}{f_{u,d}} \sim 0.5 \quad \Rightarrow \quad \frac{N_{\Lambda_b}}{N_B^{0,-}} \sim 0.5$$ [LHCb, 2012]

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

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

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

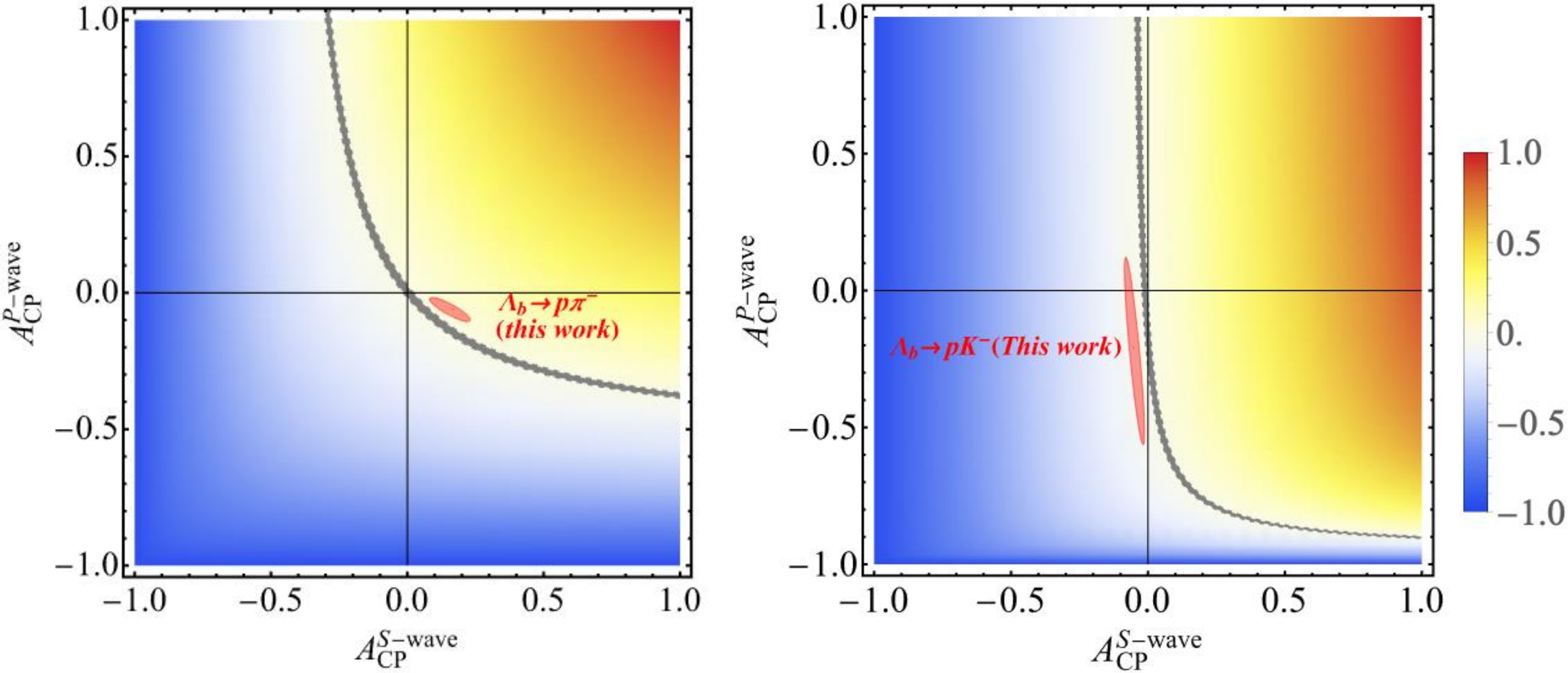
    - leading power: $\xi_{\Lambda_b \to \Lambda}(q^2 = 0) = -0.012$ [W.Wang, 2011]
    - Total form factors: $\xi_{\Lambda_b \to \Lambda}(q^2 = 0) = 0.18$ [Y.L.Shen, Y.M.Wang, 2016]

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

	$Br(\times 10^{-6})$	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}	$\langle\Lambda\rangle$
$\Lambda_b \to p\rho^-$	$-0.96^{+0.05+0.06+0.04+0.05}_{-0.00-0.00-0.00-0.00}$	$0.00^{+0.01+0.02+0.01+0.02}_{-0.00-0.00-0.00-0.00}$	$-0.97^{+0.04+0.04+0.03+0.04}_{-0.00-0.00-0.00-0.00}$
$\Lambda_b \to pK^{*-}$	$-0.91^{+0.06+0.15+0.09+0.00}_{-0.02-0.02-0.00-0.03}$	$-0.01^{+0.03+0.06+0.03+0.01}_{-0.00-0.03-0.00-0.00}$	$-0.90^{+0.05+0.09+0.07+0.00}_{-0.03-0.05-0.01-0.03}$
	$\mathcal{J}$	$A_{CP}^{\mathcal{J}}$	$\langle\mathcal{J}\rangle$
$\Lambda_b \to p\rho^-$	$1.66^{+0.04+0.04+0.02+0.02}_{-0.03-0.03-0.05-0.00}$	$-0.01^{+0.01+0.01+0.01+0.00}_{-0.01-0.01-0.01-0.00}$	$1.67^{+0.03+0.04+0.02+0.02}_{-0.05-0.03-0.05-0.00}$
$\Lambda_b \to pK^{*-}$	$1.67^{+0.02+0.00+0.04+0.00}_{-0.14-0.12-0.08-0.12}$	$0.04^{+0.02+0.05+0.02+0.01}_{-0.06-0.04-0.02-0.03}$	$1.63^{+0.01+0.03+0.04+0.00}_{-0.08-0.15-0.09-0.09}$

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

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



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

Invariant amplitudes

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

$$\mathcal{M}^T\left[B_i(1/2^+) \to B_f(1/2^+) + V\right] = \bar{u}_f(p_f)\epsilon_T^{*\mu}\left[A_1^T\gamma_\mu\gamma_5 + B_1^T\gamma_\mu\right]u_i(p_i).$$

Partial wave amplitudes

$$S^T = -A_1^T,$$

$$S^L = -A_1^L,$$

$$P_1 = -\frac{p_c}{E_V}\left(\frac{m_i + m_f}{E_f + m_f}B_1^L + B_2^L\right),$$

$$P_2 = \frac{p_c}{E_f + m_f}B_1^T,$$

$$D = -\frac{p_c^2}{E_V(E_f + m_f)}\left(A_1^L - A_2^L\right).$$

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

Helicity amplitudes

$$H_{1/2,1} = -M_+A_1^T - M_-B_1^T,$$

$$H_{-1/2,-1} = M_+A_1^T - M_-B_1^T,$$

$$H_{1/2,0} = \frac{1}{\sqrt{2}m_V}\left[M_+(m_i - m_f)A_1^L - M_-p_cA_2^L + M_-(m_i + m_f)B_1^L + M_+p_cB_2^L\right],$$

$$H_{-1/2,0} = \frac{1}{\sqrt{2}m_V}\left[-M_+(m_i - m_f)A_1^L + M_-p_cA_2^L + M_-(m_i + m_f)B_1^L + M_+p_cB_2^L\right].$$

$$\mathcal{B} = \frac{p_c\tau_{\Lambda_b}}{8\pi m_i^2}\left(|H_{1/2,1}|^2 + |H_{-1/2,-1}|^2 + |H_{1/2,0}|^2 + |H_{-1/2,0}|^2\right).$$

[Koener,Kramer,1992]
[Cheng,1996]

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

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

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

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

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

LCDA-mesons

- π/K

$$\Phi_{\pi(K)}(q,y)=\frac{i}{\sqrt{2N_C}}\left[\gamma_5 \not{q}\phi^A_{\pi(K)}(y)+m_0^{\pi(K)}\gamma_5\phi^P_{\pi(K)}(y)+m_0^{\pi(K)}\gamma_5(\not{v}\not{n}-1)\phi^T_{\pi(K)}(y)\right]$$

$$\phi^A_{\pi(K)}(y)=\frac{f_{\pi(K)}}{2\sqrt{2N_c}}6y(1-y)\left[1+a_1^{\pi(K)}C_1^{3/2}(2y-1)+a_2^{\pi(K)}C_2^{3/2}(2y-1)+a_4^{\pi(K)}C_4^{3/2}(2y-1)\right],$$

$$\phi^P_{\pi(K)}(y)=\frac{f_{\pi(K)}}{2\sqrt{2N_c}}\left[1+\left(0.45-\frac{5}{2}\rho^2_{\pi(K)}\right)C_2^{1/2}(2y-1)-3\left(-0.045+\frac{9}{20}\rho^2_{\pi(K)}(1+6a_2^{\pi(K)})\right)C_4^{1/2}(2y-1)\right]$$

$$\phi^T_{\pi(K)}(y)=\frac{f_{\pi(K)}}{2\sqrt{2N_c}}(1-2y)\left[1+6\left(0.0975-\frac{7}{20}\rho^2_{\pi(K)}-\frac{3}{5}\rho^2_{\pi(K)}a_2^{\pi(K)}\right)(1-10y+10y^2)\right], \quad (24)$$

- ρ/K^*

$$\langle P|(\bar{q}q')_{V\mp A}|0\rangle=\pm i f_P p_\mu,$$
$$\langle P|(\bar{q}q')_{S\mp P}|0\rangle=\pm i f_P m_{0P},$$

$$\Phi_V^L(q,\epsilon_L^*,y)=\frac{-1}{\sqrt{2N_c}}\left[m_V\not{\epsilon}_L^*\phi_V(y)+\not{\epsilon}_L^*\not{q}\phi_V^t(y)+m_V\phi_V^s(y)\right]_{\alpha\beta},$$

$$\Phi_V^T(q,\epsilon_T^*,y)=\frac{-1}{\sqrt{2N_c}}\left[m_V\not{\epsilon}_T^*\phi_V^v(y)+\not{\epsilon}_T^*\not{q}\phi_V^T(y)+m_V i\epsilon_{\mu\nu\rho\sigma}\gamma_5\gamma^\mu\epsilon_T^{*\nu}v^\rho n^\sigma\phi_V^a(y)\right]_{\alpha\beta}, \quad (27)$$

$$\phi_V(y)=\frac{3f_V}{\sqrt{2N_c}}y(1-y)\left[1+a_1^{\parallel}C_1^{3/2}(2y-1)+a_2^{\parallel}C_2^{3/2}(2y-1)\right], \quad (28)$$

$$\phi_V^T(y)=\frac{3f_V^T}{\sqrt{2N_c}}y(1-y)\left[1+a_1^{\perp}C_1^{3/2}(2y-1)+a_2^{\perp}C_2^{3/2}(2y-1)\right], \quad (29)$$

$$\phi_V^t(y)=\frac{3f_V^T}{2\sqrt{2N_c}}(2y-1)^2, \quad (30)$$

$$\phi_V^s(y)=\frac{3f_V^T}{2\sqrt{2N_c}}(1-2y), \quad (31)$$

$$\phi_V^v(y)=\frac{3f_V}{8\sqrt{2N_c}}(1+(2y-1)^2), \quad (32)$$

$$\phi_V^a(y)=\frac{3f_V}{4\sqrt{2N_c}}(1-2y), \quad (33)$$

$$\langle V|(\bar{q}q')_{V\mp A}|0\rangle=f_V m_V\epsilon_\mu^*,$$
$$\langle V|(\bar{q}q')_{S\mp P}|0\rangle=0,$$

LCDA-mesons

- a_1/K_1

$$\Phi_A^L(q,\epsilon_L^*,y)=\frac{-i}{\sqrt{2N_c}}\left[m_A\gamma_5\not\epsilon_L^*\phi_A(y)+\not\epsilon_L^*\not q\gamma_5\phi_A^t(y)+m_A\gamma_5\phi_A^s(y)\right]_{\alpha\beta}, \quad (34)$$

$$\Phi_A^T(q,\epsilon_T^*,y)=\frac{-i}{\sqrt{2N_c}}\left[m_A\gamma_5\not\epsilon_T^*\phi_A^v(y)+\not\epsilon_T^*\not q\gamma_5\phi_A^T(y)+m_A i\epsilon_{\mu\nu\rho\sigma}\gamma^\mu\epsilon_T^{*\nu}v^\rho n^\sigma\phi_A^a(y)\right]_{\alpha\beta}, \quad (35)$$

$$\phi_A(y)=\frac{3f_A}{\sqrt{2N_c}}y(1-y)\left[a_{0A}^{\parallel}+3a_{1A}^{\parallel}(2y-1)+\frac{3}{2}a_{2A}^{\parallel}(5(2y-1)^2-1)\right], \quad (36)$$

$$\phi_A^T(y)=\frac{3f_A}{\sqrt{2N_c}}y(1-y)\left[a_{0A}^{\perp}+3a_{1A}^{\perp}(2y-1)+\frac{3}{2}a_{2A}^{\perp}(5(2y-1)^2-1)\right]. \quad (37)$$

$$\phi_A^t(y)=\frac{f_A}{2\sqrt{2N_c}}\left[3a_{0A}^{\perp}(2y-1)^2+\frac{3}{2}a_{1A}^{\perp}(2y-1)(3(2y-1)^2-1)\right], \quad (38)$$

$$\phi_A^s(y)=\frac{3f_A}{2\sqrt{2N_c}}(a_{0A}^{\perp}-a_{1A}^{\perp}-2a_{0A}^{\perp}y+6a_{1A}^{\perp}y-6a_{1A}^{\perp}y^2), \quad (39)$$

$$\phi_A^v(y)=\frac{f_A}{2\sqrt{2N_c}}\left[\frac{3}{4}a_{0A}^{\parallel}(1+(2y-1)^2)+\frac{3}{2}a_{1A}^{\parallel}(2y-1)^3\right], \quad (40)$$

$$\phi_A^a(y)=\frac{3f_A}{4\sqrt{2N_c}}(a_{0A}^{\parallel}-a_{1A}^{\parallel}-2a_{0A}^{\parallel}y+6a_{1A}^{\parallel}y-6a_{1A}^{\parallel}y^2).$$

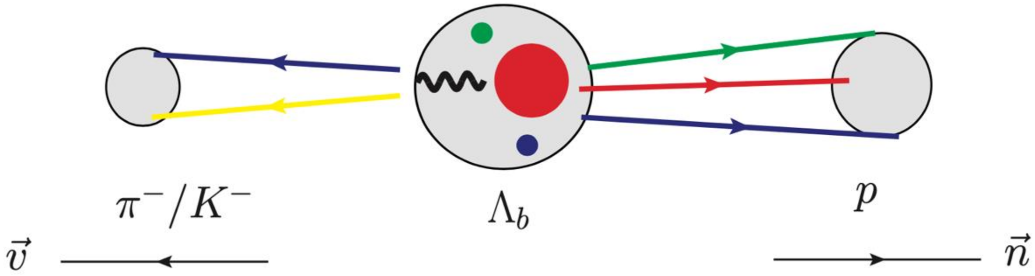
$$\langle A|(\bar{q}q')_{V\mp A}|0\rangle=\mp i f_A m_A\epsilon_\mu^*,$$

$$\langle A|(\bar{q}q')_{S\mp P}|0\rangle=0,$$

- mixing angle $\theta_{K_1}\sim 30^\circ/60^\circ$

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

Kinematics



$$p_i = \frac{m_i}{\sqrt{2}}(1, 1, \mathbf{0}_T),$$
$$p_f = \frac{m_i}{\sqrt{2}}(\eta^+, \eta^-, \mathbf{0}_T),$$
$$q = p_i - p_f = \frac{m_i}{\sqrt{2}}(1-\eta^+, 1-\eta^-, \mathbf{0}_T),$$

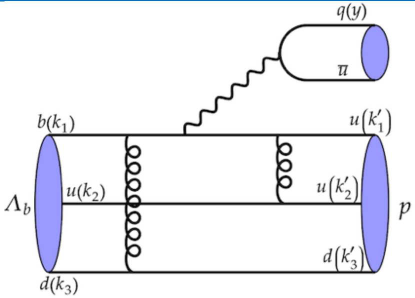
$$k_1 = (\frac{m_i}{\sqrt{2}}, \frac{m_i}{\sqrt{2}}x_1, \boldsymbol{k}_{1T}), \quad k_2 = (0, \frac{m_i}{\sqrt{2}}x_2, \boldsymbol{k}_{2T}), \quad k_3 = (0, \frac{m_i}{\sqrt{2}}x_3, \boldsymbol{k}_{3T}),$$
$$k'_1 = (\frac{m_i}{\sqrt{2}}\eta^+ x'_1, 0, \boldsymbol{k}'_{1T}), \quad k'_2 = (\frac{m_i}{\sqrt{2}}\eta^+ x'_2, 0, \boldsymbol{k}'_{2T}), \quad k'_3 = (\frac{m_i}{\sqrt{2}}\eta^+ x'_3, 0, \boldsymbol{k}'_{3T}),$$
$$q_1 = (0, \frac{m_i}{\sqrt{2}}y(1-\eta^-), \boldsymbol{q}_T), \quad q_2 = (0, \frac{m_i}{\sqrt{2}}(1-y)(1-\eta^-), -\boldsymbol{q}_T),$$

for T, E and P diagrams

$$k_1 = (\frac{m_i}{\sqrt{2}}(1-x3), \frac{m_i}{\sqrt{2}}(1-x2), \boldsymbol{k}_{1T}), \quad k_2 = (0, \frac{m_i}{\sqrt{2}}x_2, \boldsymbol{k}_{2T}), \quad k_3 = (\frac{m_i}{\sqrt{2}}x_3, 0, \boldsymbol{k}_{3T})$$

for B and C' diagrams

High power dominant



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

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

  - 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]

- PQCD: previous results of $\Lambda_b \to p$ form factors show high-twist contributions dominant

	Lattice/exp.	PQCD (Lü,Wang,et.al.,2009)	PQCD (Han,et.al.,2022)
$f_1^{\Lambda_b\to p}(q^2=0)$	~ 0.18	0.002 ± 0.001	0.27 ± 0.12

	twist-3	twist-4	twist-5	twist-6	total
exponential					
twist-2	0.0007	-0.00007	-0.0005	-0.000003	0.0001
twist-3^{+-}	-0.0001	0.002	0.0004	-0.000004	0.002
twist-3^{-+}	-0.0002	0.0060	0.000004	0.00007	0.006
twist-4	0.01	0.00009	0.25	0.0000007	0.26
total	0.01	0.008	0.25	0.00007	$0.27 \pm 0.09 \pm 0.07$

LCDA-Λ_b

$$(Y_{\Lambda_b})_{\alpha\beta\gamma}(x_i,\mu) = \frac{1}{8\sqrt{2}N_c}\left\{f^{(1)}_{\Lambda_b}(\mu)[M_1(x_2,x_3)\gamma_5 C^T]_{\gamma\beta} + f^{(2)}_{\Lambda_b}(\mu)[M_2(x_2,x_3)\gamma_5 C^T]_{\gamma\beta}\right\}[\Lambda_b(p)]_\alpha$$

$$M_1(x_2,x_3) = \frac{\not{n}\not{\bar{n}}}{4}\psi_3^{+-}(x_2,x_3) + \frac{\not{\bar{n}}\not{n}}{4}\psi_3^{-+}(x_2,x_3),$$

$$M_2(x_2,x_3) = \frac{\not{n}}{\sqrt{2}}\psi_2(x_2,x_3) + \frac{\not{\bar{n}}}{\sqrt{2}}\psi_4(x_2,x_3),$$

$$\psi_2(x_2,x_3) = \frac{x_2 x_3}{\omega_0^4} m^4_{\Lambda_b} e^{-(x_2+x_3)m_{\Lambda_b}/\omega_0},$$

$$\psi_3^{+-}(x_2,x_3) = \frac{2x_2}{\omega_0^3} m^3_{\Lambda_b} e^{-(x_2+x_3)m_{\Lambda_b}/\omega_0},$$

$$\psi_3^{-+}(x_2,x_3) = \frac{2x_3}{\omega_0^3} m^3_{\Lambda_b} e^{-(x_2+x_3)m_{\Lambda_b}/\omega_0},$$

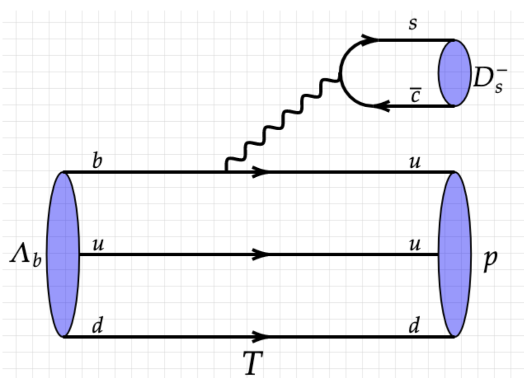
$$\psi_4(x_2,x_3) = \frac{1}{\omega_0^2} m^2_{\Lambda_b} e^{-(x_2+x_3)m_{\Lambda_b}/\omega_0},$$

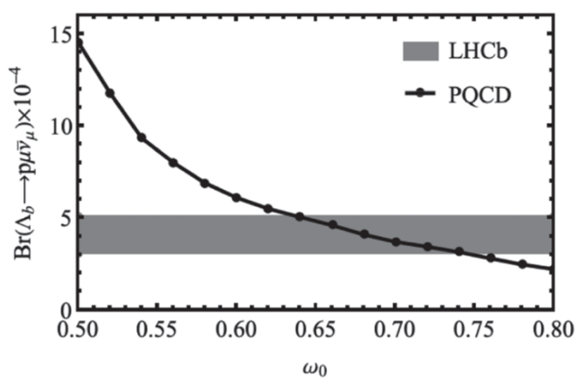
[P.Ball, V.M.Braun, E.Gardi, 2008]
[G.Bell, T.Feldmann, Y.M.Wang, M.W.Y.Yip, 2013]
[Y.M.Wang, Y.L.Shen, 2016]

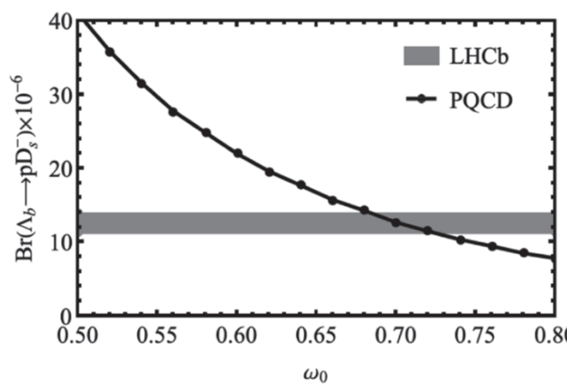
- (LHCb,2212.12574) recently measured the branching fraction:

$$Br(\Lambda_b \to pD_s^-) = (12.6 \pm 1.3)\%$$

- This mode has only W-external emission diagram, used to determine the parameter $\omega_0 = 0.7 \pm 0.1 GeV$







LCDAs-proton

$$(\overline{Y}_P)_{\alpha\beta\gamma}(x_i',\mu) \equiv \frac{1}{2\sqrt{2}N_c}\int\prod_{l=2}^{3}\frac{dz_l^- dz_l}{(2\pi)^3}e^{ik_l\cdot z_l}\epsilon^{i'j'k'}\langle p(p')|T[\bar{u}_\alpha^{i'}(0)\bar{u}_\beta^{j'}(z_2)\bar{d}_\gamma^{k'}(z_3)]|0\rangle$$

$$= \frac{-1}{8\sqrt{2}N_c}\Big\{S_1 m_p C_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma + S_2 m_p C_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma + P_1 m_p (C\gamma_5)_{\beta\alpha}\bar{N}^+_\gamma$$
$$+ P_2 m_p (C\gamma_5)_{\beta\alpha}\bar{N}^-_\gamma + V_1(C\not{P})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma + V_2(C\not{P})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma$$
$$+ V_3\frac{m_p}{2}(C\gamma_\perp)_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma + V_4\frac{m_p}{2}(C\gamma_\perp)_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma + V_5\frac{m_p^2}{2Pz}(C\not{z})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma$$
$$+ V_6\frac{m_p^2}{2Pz}(C\not{z})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma + A_1(C\gamma_5\not{P})_{\beta\alpha}(\bar{N}^+)_\gamma + A_2(C\gamma_5\not{P})_{\beta\alpha}(\bar{N}^-)_\gamma$$
$$+ A_3\frac{m_p}{2}(C\gamma_5\gamma_\perp)_{\beta\alpha}(\bar{N}^+\gamma^\perp)_\gamma + A_4\frac{m_p}{2}(C\gamma_5\gamma_\perp)_{\beta\alpha}(\bar{N}^-\gamma^\perp)_\gamma + A_5\frac{m_p^2}{2Pz}(C\gamma_5\not{z})_{\beta\alpha}(\bar{N}^+)_\gamma$$
$$+ A_6\frac{m_p^2}{2Pz}(C\gamma_5\not{z})_{\beta\alpha}(\bar{N}^-)_\gamma - T_1(iC\sigma_{\perp P})_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma - T_2(iC\sigma_{\perp P})_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma$$
$$- T_3\frac{m_p}{Pz}(iC\sigma_{Pz})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma - T_4\frac{m_p}{Pz}(iC\sigma_{zP})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma - T_5\frac{m_p^2}{2Pz}(iC\sigma_{\perp z})_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma$$
$$- T_6\frac{m_p^2}{2Pz}(iC\sigma_{\perp z})_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma + T_7\frac{m_p}{2}(C\sigma_{\perp\perp'})_{\beta\alpha}(\bar{N}^+\gamma_5\sigma^{\perp\perp'})_\gamma$$
$$+ T_8\frac{m_p}{2}(C\sigma_{\perp\perp'})_{\beta\alpha}(\bar{N}^-\gamma_5\sigma^{\perp\perp'})_\gamma\Big\},$$

[V.Braun, R.J.Fries, N.Mahnke, E.Stein (2000)]
[V.Braun, A.Lenz, M.Wittmann, Phys.Rev.D (2006)]
[RQCD, Eur.Phys.J.A (2019)]

Twist classification of the distribution amplitudes in Eq. (2.9)

	twist-3	twist-4	twist-5	twist-6
Vector	V_1	V_2, V_3	V_4, V_5	V_6
Pseudo-vector	A_1	A_2, A_3	A_4, A_5	A_6
Tensor	T_1	T_2, T_3, T_7	T_4, T_5, T_8	T_6
Scalar		S_1	S_2	
Pseudo-scalar		P_1	P_2	

	$f_N\ (10^{-3})$	$\lambda_1\ (10^{-2})$	$\lambda_2\ (10^{-2})$	V_1^d	A_1^u	f_1^d	f_2^d	f_1^u
QCDSR	5.0 ± 0.5	-2.7 ± 0.9	5.4 ± 1.9	0.23 ± 0.03	0.38 ± 0.15	0.4 ± 0.05	0.22 ± 0.05	0.07 ± 0.05
LQCD	3.67 ± 0.06	-4.02 ± 0.38	8.37 ± 0.43	0.288 ± 0.007	0.096 ± 0.010	...	...	...

- π/K

$$\Phi_{\pi(K)}(q,y)=\frac{i}{\sqrt{2N_C}}\left[\gamma_5 \not{q}\phi^A_{\pi(K)}(y)+m_0^{\pi(K)}\gamma_5\phi^P_{\pi(K)}(y)+m_0^{\pi(K)}\gamma_5(\not{v}\not{n}-1)\phi^T_{\pi(K)}(y)\right]$$

$$\phi^A_{\pi(K)}(y)=\frac{f_{\pi(K)}}{2\sqrt{2N_c}}6y(1-y)\left[1+a_1^{\pi(K)}C_1^{3/2}(2y-1)+a_2^{\pi(K)}C_2^{3/2}(2y-1)+a_4^{\pi(K)}C_4^{3/2}(2y-1)\right],$$

$$\phi^P_{\pi(K)}(y)=\frac{f_{\pi(K)}}{2\sqrt{2N_c}}\left[1+\left(0.45-\frac{5}{2}\rho^2_{\pi(K)}\right)C_2^{1/2}(2y-1)-3\left(-0.045+\frac{9}{20}\rho^2_{\pi(K)}(1+6a_2^{\pi(K)})\right)C_4^{1/2}(2y-1)\right]$$

$$\phi^T_{\pi(K)}(y)=\frac{f_{\pi(K)}}{2\sqrt{2N_c}}(1-2y)\left[1+6\left(0.0975-\frac{7}{20}\rho^2_{\pi(K)}-\frac{3}{5}\rho^2_{\pi(K)}a_2^{\pi(K)}\right)(1-10y+10y^2)\right], \quad (24)$$

$$\langle P|(\bar{q}q')_{V\mp A}|0\rangle=\pm i f_P p_\mu,$$
$$\langle P|(\bar{q}q')_{S\mp P}|0\rangle=\pm i f_P m_{0P},$$

[P.Ball, R.Zwicky, Phys.Rev.D (2005)]
[P.Ball, V.Braun, A.Lenz, JHEP (2006)]

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

$$|T^f| \gg |E_2| \gtrsim |PC_1^f| \gtrsim |T^{nf}| > |C_2| > |PC_2| > |B| \gtrsim |PE_1^u| > |PE_1^d| \sim |PB| \sim |PE_2| \sim |PC_1^{nf}| \quad (S \text{ wave}),$$

$$|T^f| \gg |T^{nf}| \gg |E_2| > |C_2| > |B| > |PC_2| \gtrsim |PC_1^{nf}| \gtrsim |PE_1^u| > |PC_1^f| > |PE_1^d| \sim |P^B| \sim |PE_2| \quad (P \text{ wave}),$$

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}

$\Lambda_b \to p\pi^-$	$\|S\|$	$\delta^S(^\circ)$	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

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

$$\frac{|C_2|}{|T|} = 0.042, \quad \frac{|E_2|}{|T|} = 0.095, \quad \frac{|B|}{|T|} = 0.014 \ \ (S \text{ wave}),$$

$$\frac{|C_2|}{|T|} = 0.041, \quad \frac{|E_2|}{|T|} = 0.072, \quad \frac{|B|}{|T|} = 0.024 \ (P \text{ wave}),$$

Results of $\Lambda_b \to pK^-$

TABLE VII. Same as Table V but for the $\Lambda_b \to pK^-$ decay.

$\Lambda_b \to pK^-$	$\|S\|$	$\delta^S(^\circ)$	Real(S)	Imag(S)	$\|P\|$	$\delta^P(^\circ)$	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

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

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

[H.Y.Cheng, S.Oh, JHEP (2011)]