Studies of baryonic *b* decays in PQCD

$\Lambda_b \to pM$ & $B \to \mathcal{B}_c \overline{\mathcal{B}}'_c$

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Why baryon physics?

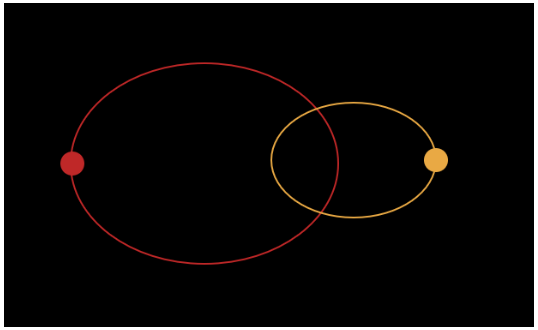
CPV of $\Lambda_b \to pM$

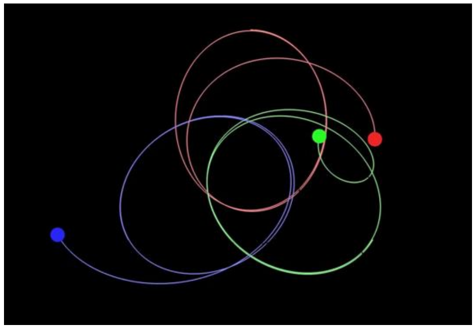
Discussions of $B \to \boldsymbol{\mathcal{B}}_c \overline{\boldsymbol{\mathcal{B}}}'_c$

Summary

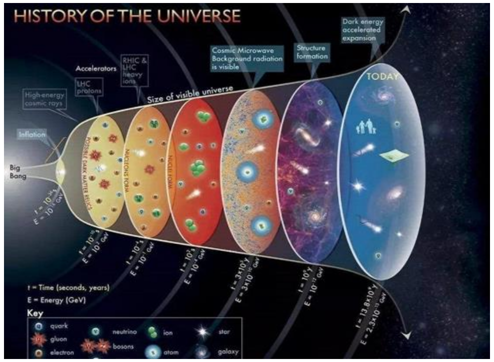
- CP violation for Universal evolution
  - Sakharov conditions for Baryogenesis:

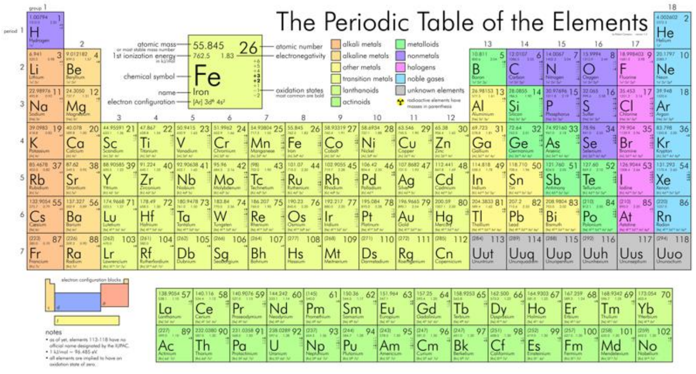
baryon number violation | C and CP violation | out of thermal equilibrium





  - CPV relates to most of parameters of SM, is helpful to test SM and search NP;
  - CPV has been established for *K*, *B* and *D* meson decays, CKM mechanism has been established for CPV in B meson decays;
  - The visible universe is mainly made of baryons. It is of great significance to search for baryon CPV !





Opportunities

- Hyperon CPV:

  $A_{CP}^{\alpha}(\Lambda \to p\pi^-) = 0.0025 \pm 0.0048$ [BESIII,2022] v.s. $\mathcal{O}(10^{-5} \sim 10^{-4})$ [theory]

- charm baryon CPV:

  $A_{CP}(\Lambda_c \to pK^+K^-/p\pi^+\pi^-) = 0.003 \pm 0.0091 \pm 0.0061$[LHCb,2018] v.s. $\mathcal{O}(10^{-3})$ [theory]

- beauty hadron ~ 10% due to large weak phase difference

  $A_{CP}(B^0 \to K^+\pi^-) = (-8.34 \pm 0.32)\%$ $A_{CP}(B_s^0 \to K^-\pi^+) = (22.4 \pm 1.2)\%$ [PDG2022]

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

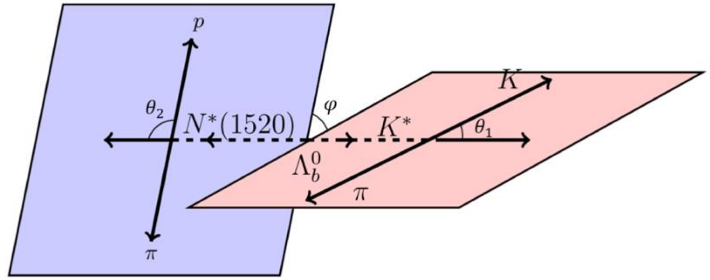
  $A_{CP}(\Lambda_b \to p\pi^-) = (0.2 \pm 0.8 \pm 0.4)\%$

  $A_{CP}(\Lambda_b \to pK^-) = (-1.1 \pm 0.7 \pm 0.4)\%$ [LHCb,2018,2024]

  $A_{CP}(\Lambda_b \to pK^-\pi^+\pi^-) = (2.45 \pm 0.46 \pm 0.10)\%$ **5.2σ** [LHCb,2025]

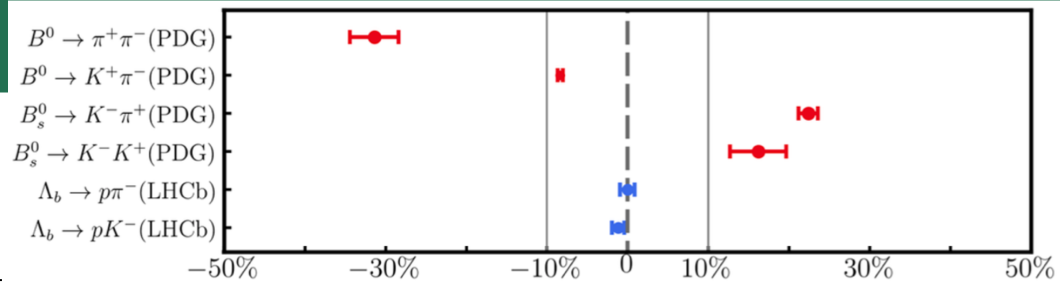
- LHCb is a baryon factory ! $\frac{N_{\Lambda_b}}{N_B^{0,-}} \sim 0.5$ $N_{\Lambda_b} \sim 10^{12}$ [LHCb,2012]

- non-zero polarization, more observables

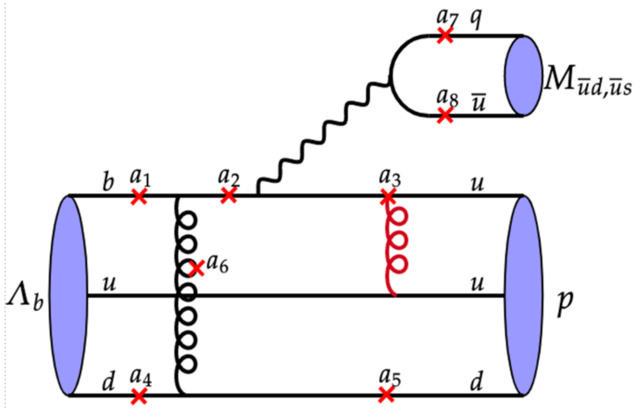


Challenges

- why CPVs of $\Lambda_b \to p\pi, pK$ are small ?



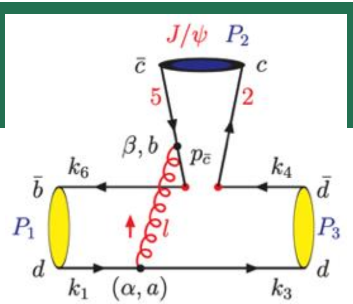
- QCD dynamics for baryon are different
  - non-zero spin/polarization
  - one more energetic quark, one more hard gluon
  - power counting of baryon is different from meson



- QCD studies on baryon are listed
  - GFA (Hsiao,Yao,Geng,2017; Liu,Geng,2021)
  - QCDF (Zhu,Ke,Wei,2016,2018)
  - PQCD (Lü,Wang,Zou,Ali,Kramer,2009; Zhou,et.al.,2022~2023)
  - quark model(Geng,Liu,Tsai,et.al.,2019~2022)
  - Light-cone Sum rule (Jiang,Cheng,Khodjamirian,Yu, in progress)

	Exp.	GFA (Hsiao,Yao,Geng, 2017)	QCDF (Zhu,Ke,Wei, 2018)	PQCD(hybrid) (Lü,Wang,et.al., 2009)	LFQM (Geng,Liu,Tsai, 2021)	LCSR (Jiang,et.al., 2022)
$A_{CP}(\Lambda_b \to p\pi^-)\%$	0.20 ± 0.89	-3.9 ± 0.4	-3.4 ± 0.4	-31^{+42}_{-1}	-3.6 ± 0.20	-1.8
$A_{CP}(\Lambda_b \to pK^-)\%$	-1.1 ± 0.81	6.7 ± 0.4	10.1 ± 2.0	-5^{+26}_{-5}	6.36 ± 0.28	-0.1

PQCD approach



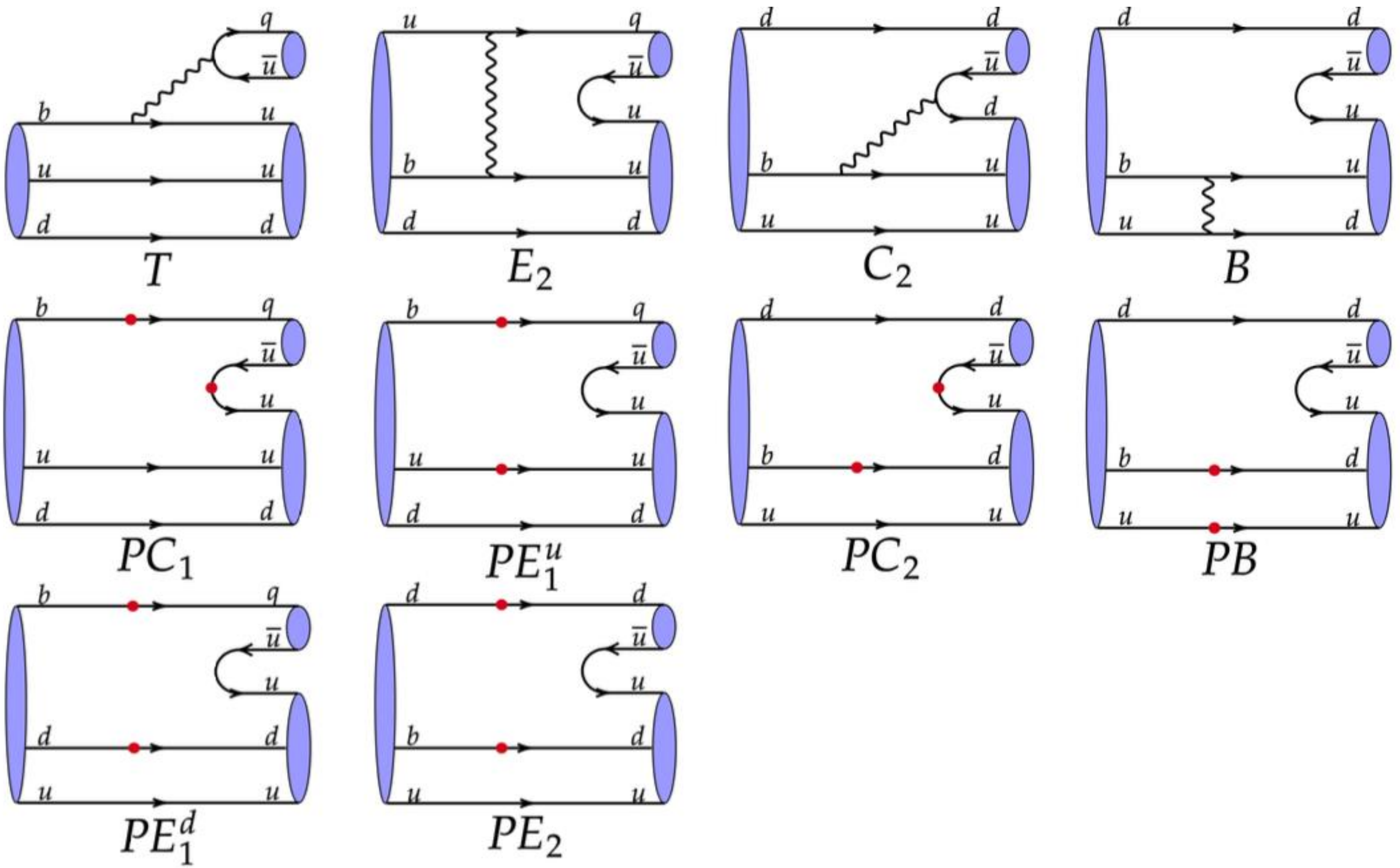
- Collinear factorization, transverse momentum k_T is ignored
  - endpoint singularity, $\frac{1}{x_i(1-x_j)Q^2} \xrightarrow{x_{i,j}\to 0,1} \infty$
- PQCD approach, based on k_T factorization, retain transverse momentum k_T
  - propagators $\sim \frac{1}{x_i(1-x_j)Q^2+|k_{iT}|^2}$ [Sterman,Hsiang-nan Li,1995~2000]
  - After resummation, Sudakov factors to suppress contribution from small k_T

$$\mathcal{A} = \langle M_2 M_3 | \mathscr{H} | B \rangle$$
$$\sim \int \frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4}\frac{d^4k_3}{(2\pi)^4}\Psi_B(k_1,\mu)\Psi_2(k_2,\mu)\Psi_3(k_3,\mu)\cdot H(k_1,k_2,k_3,\mu)C_i(\mu)$$
$$\sim \int_0^1 dx_2 dx_2 dx_3 \int \frac{d^2k_{1T}}{(2\pi)^2}\frac{d^2k_{2T}}{(2\pi)^2}\frac{d^2k_{3T}}{(2\pi)^2}\phi_B(x_1,k_{1T},\mu)\phi_2(x_2,k_{2T},\mu)\phi_3(x_3,k_{3T},\mu)\cdot H(x_1,x_2,x_3,k_{1T},k_{2T},k_{3T},\mu)C_i(\mu)$$

- PQCD 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]

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

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

Tree **Penguin**

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

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

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

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

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

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

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

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

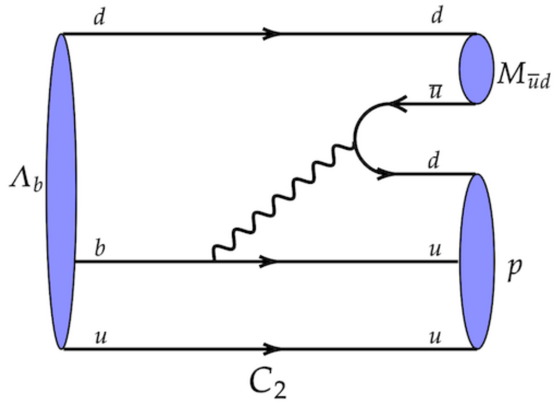
weights $\quad \kappa_S \approx \frac{|S|^2}{|S|^2 + \kappa|P|^2}, \qquad \kappa_P \approx \frac{\kappa|P|^2}{|S|^2 + \kappa|P|^2}$

Signs between S- and P-wave

- PQCD approach

$$\mathscr{A} = \langle M_2 M_3 | \mathscr{H} | B \rangle$$
$$\sim \int \frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4}\frac{d^4k_3}{(2\pi)^4}\Psi_B(k_1,\mu)\Psi_2(k_2,\mu)\Psi_3(k_3,\mu)\cdot H(k_1,k_2,k_3,\mu)C_i(\mu)$$
$$\sim \int_0^1 dx_2 dx_2 dx_3 \int \frac{d^2k_{1T}}{(2\pi)^2}\frac{d^2k_{2T}}{(2\pi)^2}\frac{d^2k_{3T}}{(2\pi)^2}\phi_B(x_1,k_{1T},\mu)\phi_2(x_2,k_{2T},\mu)\phi_3(x_3,k_{3T},\mu)\cdot H(x_1,x_2,x_3,k_{1T},k_{2T},k_{3T},\mu)C_i(\mu)$$

- Signs of S- and P-wave depend on interaction and wave functions



$$\mathcal{A} \sim \bar{N}\gamma_\mu(1-\gamma_5)\phi_\pi\phi_{\Lambda_b}\phi_p\gamma^\mu(1-\gamma_5)\Lambda_b$$
$$\xrightarrow{\phi_\pi=\gamma_5\not{q},\qquad \phi_{\Lambda_b}=\not{n}\gamma_5,\qquad \phi_p=\not{p}'}$$
$$\sim \bar{N}(\not{p}-\not{p}')(1-\gamma_5)\Lambda_b$$
$$\sim \bar{N}\left[(M_{\Lambda_b}-m_p)+(M_{\Lambda_b}+m_p)\gamma_5\right]\Lambda_b$$

$$\mathcal{A} \sim \bar{N}(1+\gamma_5)\phi_\pi\phi_{\Lambda_b}\phi_p(1-\gamma_5)\Lambda_b$$
$$\xrightarrow{\phi_\pi=\gamma_5\not{q},\qquad \phi_{\Lambda_b}=\gamma_5\not{v},\qquad \phi_p=\not{p}'}$$
$$\sim \bar{N}\not{p}'(1-\gamma_5)\Lambda_b$$
$$\sim \bar{N}[m_p - m_p\gamma_5]\Lambda_b$$

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

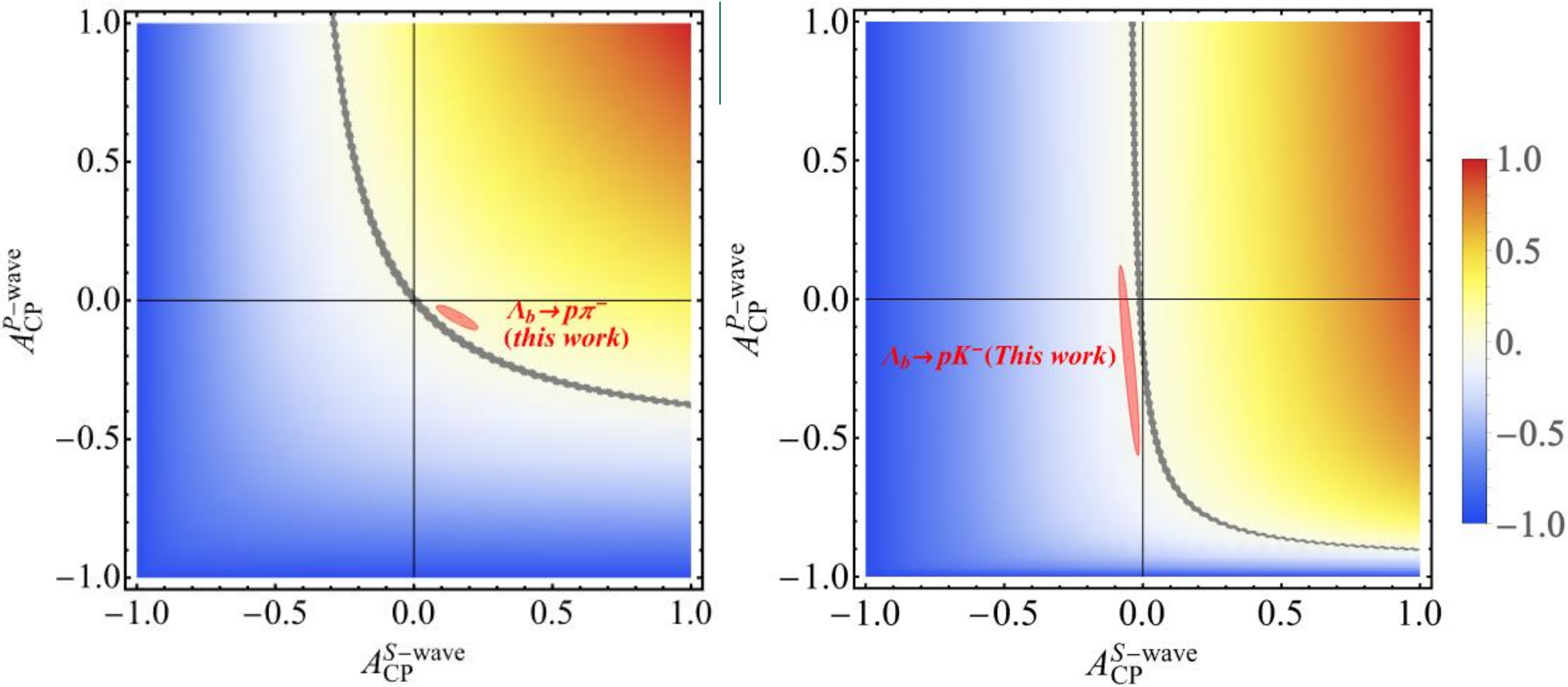
- The above crude argument needs to be justified by comprehensive QCD calculations

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

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

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

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



	LHCb	LO	$+QL$
$A_{CP}^{dir}(\Lambda_b \to p\pi^-)$	$0.002 \pm 0.008 \pm 0.004$	0.05	0.0013
$A_{CP}^{S-wave}(\Lambda_b \to p\pi^-)$		0.17	0.081
$A_{CP}^{P-wave}(\Lambda_b \to p\pi^-)$		−0.06	−0.077
$A_{CP}^{dir}(\Lambda_b \to pK^-)$	$-0.011 \pm 0.007 \pm 0.004$	−0.06	−0.0025
$A_{CP}^{S-wave}(\Lambda_b \to pK^-)$		−0.05	0.0001
$A_{CP}^{P-wave}(\Lambda_b \to pK^-)$		−0.21	−0.045

Quark loop: complex Wilson coefficients.
[A.Ali, G.Kramer, C.D.Lü]

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

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

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

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

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

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

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

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

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

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 $\Lambda_b \to p a_1, pK_1$

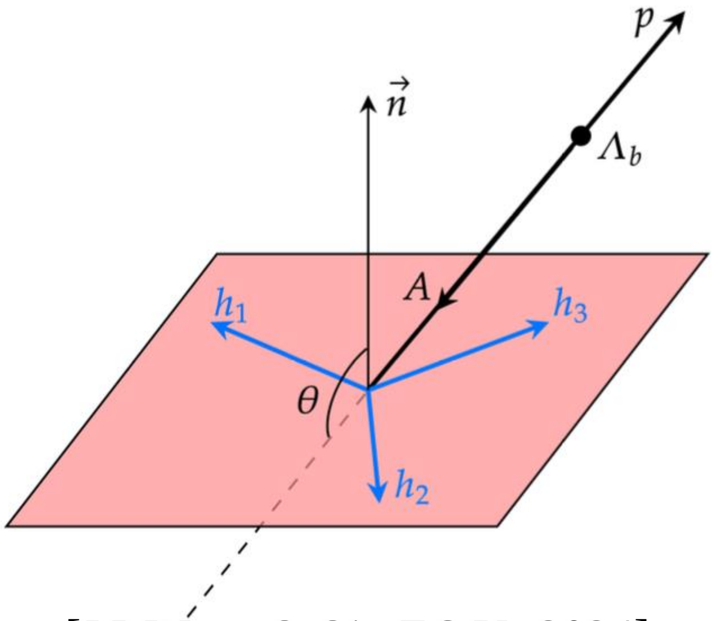
- The angle distribution for $\Lambda_b \to pA \to p h_1 h_2 h_3$:

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

- up-down asymmetry :

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

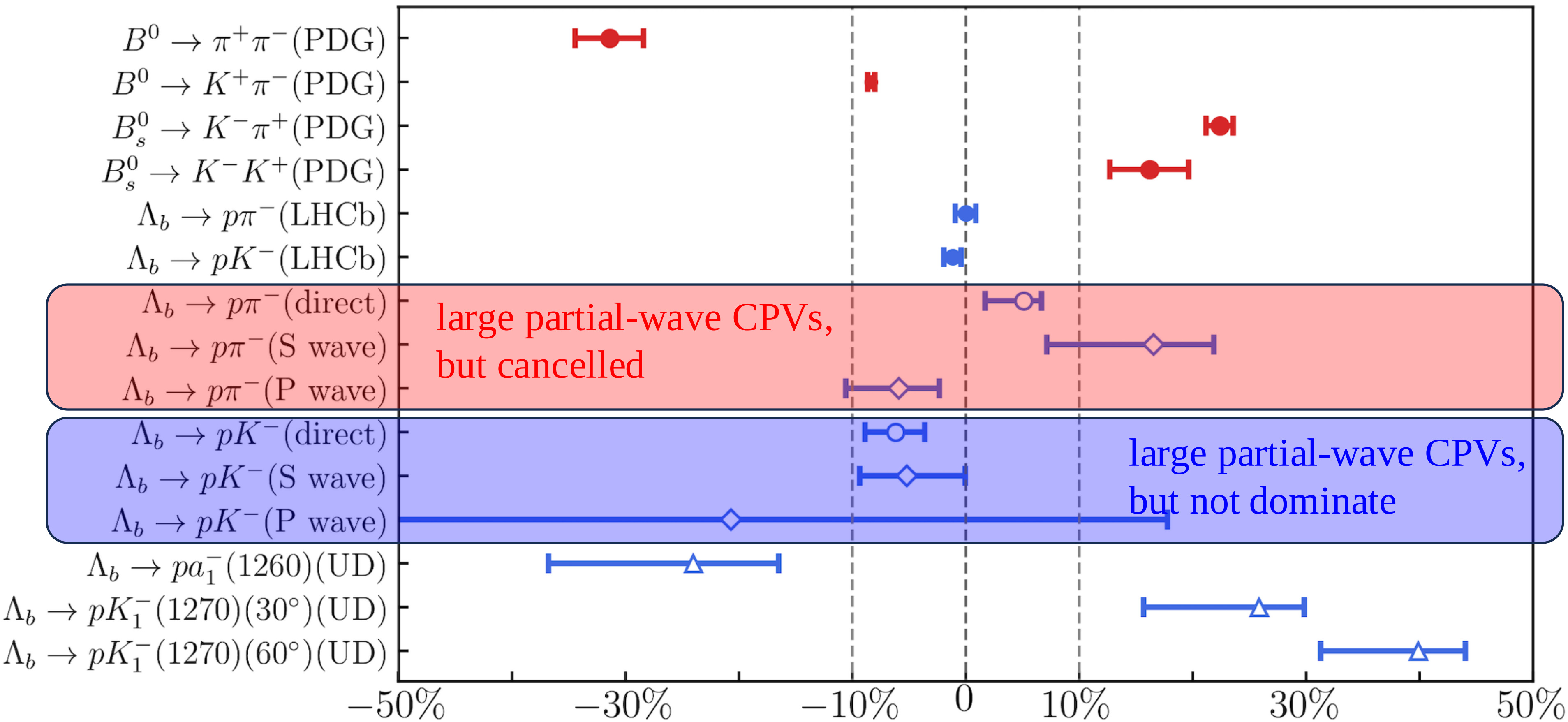
$$A_{CP}^{UD} = \frac{A_{UD} + \bar{A}_{UD}}{A_{UD} - \bar{A}_{UD}}$$



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

	a_{UD}	A_{CP}^{UD}
$\Lambda_b \to p a_1^-(1260)$	$-0.09^{+0.00+0.01+0.02+0.00}_{-0.01-0.01-0.01-0.01}$	$-0.24^{+0.03+0.05+0.05+0.03}_{-0.03-0.09-0.06-0.06}$
$\Lambda_b \to p K_1^-(1270)(30^\circ)$	$-0.19^{+0.03+0.02+0.01+0.01}_{-0.02-0.02-0.01-0.02}$	$0.26^{+0.02+0.03+0.01+0.00}_{-0.03-0.08-0.04-0.04}$
$\Lambda_b \to p K_1^-(1400)(30^\circ)$	$-0.38^{+0.06+0.10+0.05+0.00}_{-0.06-0.09-0.07-0.03}$	$0.72^{+0.05+0.13+0.07+0.05}_{-0.05-0.23-0.03-0.12}$
$\Lambda_b \to p K_1^-(1270)(60^\circ)$	$-0.24^{+0.04+0.04+0.01+0.00}_{-0.02-0.03-0.02-0.03}$	$0.40^{+0.02+0.03+0.02+0.01}_{-0.01-0.04-0.03-0.07}$
$\Lambda_b \to p K_1^-(1400)(60^\circ)$	$-0.04^{+0.02+0.02+0.01+0.02}_{-0.01-0.05-0.03-0.01}$	$-0.19^{+0.12+0.14+0.00+0.06}_{-0.18-0.19-0.20-0.00}$

Summary



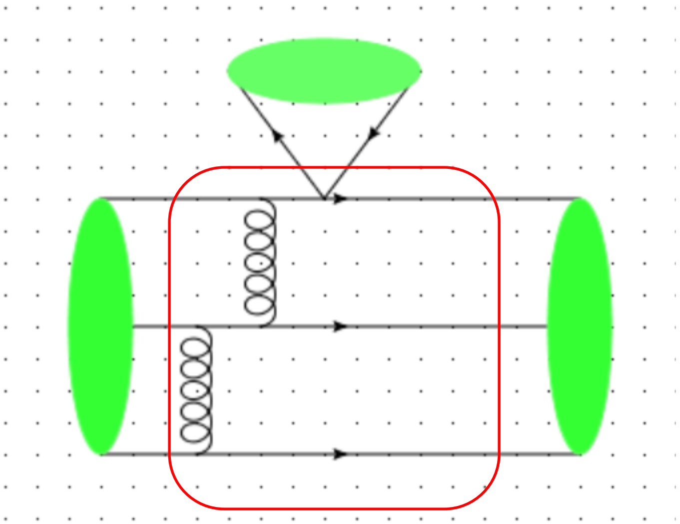
$B^0 \to \pi^+\pi^-$(PDG)
$B^0 \to K^+\pi^-$(PDG)
$B_s^0 \to K^-\pi^+$(PDG)
$B_s^0 \to K^-K^+$(PDG)
$\Lambda_b \to p\pi^-$(LHCb)
$\Lambda_b \to pK^-$(LHCb)
$\Lambda_b \to p\pi^-$(direct)
$\Lambda_b \to p\pi^-$(S wave)
$\Lambda_b \to p\pi^-$(P wave)
$\Lambda_b \to pK^-$(direct)
$\Lambda_b \to pK^-$(S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

Discussions of $B \to \boldsymbol{\mathcal{B}}_c \bar{\boldsymbol{\mathcal{B}}}'_c$

Higher twist corrections to doubly-charmed baryonic B decays

Zhou Rui, Zhi-Tian Zou and Ying Li

BASED ON JHEP 12 (2024) 159



$$M \propto \psi_{\mathrm{B}} \otimes H \otimes \psi_{\overline{B_c}} \otimes \psi_{B_c}$$

- The hard amplitude involves eight external on shell quarks, four of which correspond to the four-fermion operators and four of which are the spectator quarks in the final states.
- The hard kernels start at α_s^2 in the PQCD approach.
- Hadronic LCDAs are the necessary inputs in PQCD calculations.

Invariant amplitudes $\mathcal{M} = \langle \mathcal{B}_c \bar{\mathcal{B}}_c | \mathcal{H}_{eff} | B \rangle = \bar{u}[H_S + H_P \gamma_5] v$

- B-meson LCDAs: [Phys. Rev. D 74 (2006) 014027]

$$\Phi_B = -\frac{i}{\sqrt{2N_c}} (\not{q} + M)\gamma_5 \left(\phi_B^- + \frac{\not{n}_+}{\sqrt{2}} (\phi_B^- - \phi_B^+) \right)$$

Mode	Type	Amplitude	ϕ_B	$\bar{\phi}_B$	$\phi_B + \bar{\phi}_B$
		H_S	$1.2 \times 10^{-7} + i8.3 \times 10^{-9}$	$2.0 \times 10^{-8} + i3.2 \times 10^{-8}$	$1.4 \times 10^{-7} + i4.0 \times 10^{-8}$
$B^- \to \Xi_c^0 \bar{\Lambda}_c^-$	C	H_P	$-7.8 \times 10^{-9} + i4.9 \times 10^{-8}$	$-1.0 \times 10^{-8} + i1.5 \times 10^{-8}$	$-1.8 \times 10^{-8} + i6.4 \times 10^{-8}$
		$\lvert\mathcal{M}\rvert$(GeV)	3.7×10^{-7}	1.3×10^{-7}	4.8×10^{-7}
		H_S	$4.8 \times 10^{-9} - i1.1 \times 10^{-8}$	$5.0 \times 10^{-9} + i8.6 \times 10^{-9}$	$9.8 \times 10^{-9} - i2.4 \times 10^{-9}$
$\bar{B}_s^0 \to \Lambda_c^+ \bar{\Lambda}_c^-$	E	H_P	$-9.6 \times 10^{-10} + i1.9 \times 10^{-8}$	$5.8 \times 10^{-9} - i3.0 \times 10^{-9}$	$4.8 \times 10^{-9} + i1.6 \times 10^{-8}$
		$\lvert\mathcal{M}\rvert$(GeV)	1.1×10^{-7}	4.5×10^{-8}	9.5×10^{-8}
		H_S	$7.8 \times 10^{-9} + i6.1 \times 10^{-9}$	$1.0 \times 10^{-10} + i1.7 \times 10^{-9}$	$7.9 \times 10^{-9} + i7.8 \times 10^{-9}$
$\bar{B}^0 \to \Lambda_c^+ \bar{\Lambda}_c^-$	$C + E$	H_P	$-2.5 \times 10^{-9} + i1.5 \times 10^{-9}$	$-2.8 \times 10^{-9} + i2.3 \times 10^{-9}$	$-5.3 \times 10^{-9} + i3.8 \times 10^{-9}$
		$\lvert\mathcal{M}\rvert$(GeV)	3.0×10^{-8}	2.0×10^{-8}	4.5×10^{-8}

- The subleading contributions can reach as much as (30−70)% of leading ones.
- The interference patterns for C and E amplitudes differ, with the former being constructive and the latter destructive.
- The inclusion of subleading correction can obviously enhance or reduce the total amplitudes.

➢ Magnitude of amplitude(GeV) from various twist combinations of the baryon and antibaryon LCDAs.

$$\epsilon^{ijk}\langle 0|q^i_{1\alpha}(t_1)q^j_{2\beta}(t_2)c^k_\gamma(0)|\mathcal{B}_c\rangle = \frac{f^{(1)}}{8}\Big[(\bar{\not{n}}\gamma_5 C)_{\alpha\beta}\phi_2(t_1,t_2) + (\not{n}\gamma_5 C)_{\alpha\beta}\phi_4(t_1,t_2)\Big]u_\gamma + \frac{f^{(2)}}{4}\Big[(\gamma_5 C)_{\alpha\beta}\phi_3^s(t_1,t_2) - \frac{i}{2}(\sigma_{\bar{n}n}\gamma_5 C)_{\alpha\beta}\phi_3^a(t_1,t_2)\Big]u_\gamma$$

	Twist-2	Twist-3	Twist-4
$B^-\to\Xi_c^0\bar{\Lambda}_c^-$			
Twist-2	3.5×10^{-8}	1.7×10^{-7}	9.6×10^{-8}
Twist-3	1.4×10^{-7}	1.9×10^{-7}	1.4×10^{-7}
Twist-4	1.1×10^{-7}	2.0×10^{-7}	1.6×10^{-7}
$\bar{B}_s^0\to\Lambda_c^+\bar{\Lambda}_c^-$			
Twist-2	3.2×10^{-9}	0	1.5×10^{-7}
Twist-3	0	1.5×10^{-7}	0
Twist-4	5.8×10^{-8}	0	1.5×10^{-8}
$\bar{B}^0\to\Lambda_c^+\bar{\Lambda}_c^-$			
Twist-2	5.0×10^{-9}	2.6×10^{-8}	4.1×10^{-8}
Twist-3	2.1×10^{-8}	5.0×10^{-8}	1.5×10^{-8}
Twist-4	2.4×10^{-8}	3.0×10^{-8}	2.4×10^{-8}

- The contributions of the twist-4-twist-4 combination are less than the dominant twist-3-twist-3 combination, indicating the reliability of twist expansion of the baryon LCDAs.

Branching ratios

$$\mathcal{B} = \frac{P_c \tau_B}{8\pi M^2}|\mathcal{M}|^2 = \frac{P_c \tau_B}{8\pi M^2}(|H_S|^2 Q_+ + |H_P|^2 Q_-), \quad Q_\pm = M^2 - (m \pm \bar{m})^2$$

Mode	PQCD	SU(3)	Data
$B^- \to \Xi_c^0 \overline{\Lambda_c^-}$	$9.5^{+3.0+2.6+1.7+1.2}_{-2.3-3.5-1.4-1.1} \times 10^{-4}$	$7.8^{+2.3}_{-2.0} \times 10^{-4}$	$(9.5 \pm 2.3) \times 10^{-4}$
$\overline{B^0} \to \Xi_c^+ \overline{\Lambda_c^-}$	$8.8^{+2.7+2.6+1.5+1.1}_{-2.1-3.1-1.2-1.0} \times 10^{-4}$	$7.2^{+2.1}_{-1.9} \times 10^{-4}$	$(12 \pm 8) \times 10^{-4}$
$\bar{B}_s^0 \to \Lambda_c^+ \overline{\Lambda_c^-}$	$4.0^{+0.7+0.2+0.9+1.0}_{-0.3-0.1-0.7-0.8} \times 10^{-5}$	$8.1^{+1.7}_{-1.5} \times 10^{-5}$	$< 9.9 \times 10^{-5}$
$\overline{B^0} \to \Lambda_c^+ \overline{\Lambda_c^-}$	$8.8^{+4.4+3.5+1.1+1.0}_{-2.8-3.6-0.9-0.6} \times 10^{-6}$	$2.1^{+1.0}_{-0.8} \times 10^{-5}$	$< 1.6 \times 10^{-5}$

- Theoretical uncertainties: B meson LCDAs, charmed baryon LCDAs, the scale dependence, and the Sudakov resummation.
- The branching ratios suffer large theoretical uncertainties from the nonperturbative hadronic parameters.
- The PQCD predictions for the first two modes agree with the SU(3) and PDG data, while those of the last two modes reach half of the measured upper limits.

Asymmetry parameters

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

$$H_\pm = \frac{1}{\sqrt{2}}(\sqrt{Q_+}H_S \mp \sqrt{Q_-}H_P)$$

Mode	α	β	γ
$B^- \to \Xi_c^0 \bar{\Lambda}_c^-$	$-0.01^{+0.10+0.12+0.05+0.01}_{-0.10-0.29-0.14-0.01}$	$-0.99^{+0.01+0.09+0.00+0.00}_{-0.00-0.01-0.00-0.00}$	$-0.07^{+0.07+0.38+0.04+0.07}_{-0.06-0.13-0.05-0.08}$
$\bar{B}_s^0 \to \Lambda_c^+ \bar{\Lambda}_c^-$	$-0.03^{+0.05+0.03+0.05+0.01}_{-0.04-0.04-0.03-0.00}$	$-0.57^{+0.02+0.02+0.00+0.05}_{-0.03-0.02-0.02-0.05}$	$-0.82^{+0.03+0.02+0.01+0.04}_{-0.01-0.01-0.00-0.03}$
$\bar{B}^0 \to \Lambda_c^+ \bar{\Lambda}_c^-$	$0.17^{+0.08+0.08+0.03+0.02}_{-0.08-0.05-0.18-0.01}$	$-0.97^{+0.04+0.06+0.02+0.02}_{-0.03-0.00-0.02-0.01}$	$-0.15^{+0.17+0.54+0.14+0.09}_{-0.14-0.16-0.11-0.11}$

- The most important source of the theoretical errors is the charmed baryon LCDAs.

- FSIs gives $\gamma(\bar{B}_s^0 \to \Lambda_c^+ \overline{\Lambda_c^-}) > 0.8$ by considering the LD contributions. (arXiv:2409.11374)

- Future experiments will tell us whether this process is dominated by the SD or LD contributions.

Conclusion

First full QCD analysis of b-baryon decays and two-body doubly charmed baryonic B 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

Thank you!

Backup

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

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

chiral factors $R_1 \approx R_2$

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

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

Signs between S- and P-wave hard kernels

"+" means S- and P-wave have same signs
"-" means S- and P-wave have opposite signs

Pion twist2	proton			
	twist3	twist4	twist5	twist6
Λ_b twist2	+	-	+	-
Λ_b twist3	-	+	-	+
Λ_b twist4	+	-	+	-

Pion twist3	proton			
	twist3	twist4	twist5	twist6
Λ_b twist2	-	+	-	+
Λ_b twist3	+	-	+	-
Λ_b twist4	-	+	-	+

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

$$\frac{|T^f(pK)|}{|T^f(p\pi)|} = 1.22, \quad \frac{|T^{nf}(pK)|}{|T^{nf}(p\pi)|} = 1.03, \quad \frac{|E_2(pK)|}{|E_2(p\pi)|} = 1.33 \text{ (S wave)},$$
$$\frac{|T^f(pK)|}{|T^f(p\pi)|} = 1.23, \quad \frac{|T^{nf}(pK)|}{|T^{nf}(p\pi)|} = 1.28, \quad \frac{|E_2(pK)|}{|E_2(p\pi)|} = 1.29 \text{ (P wave)}.$$

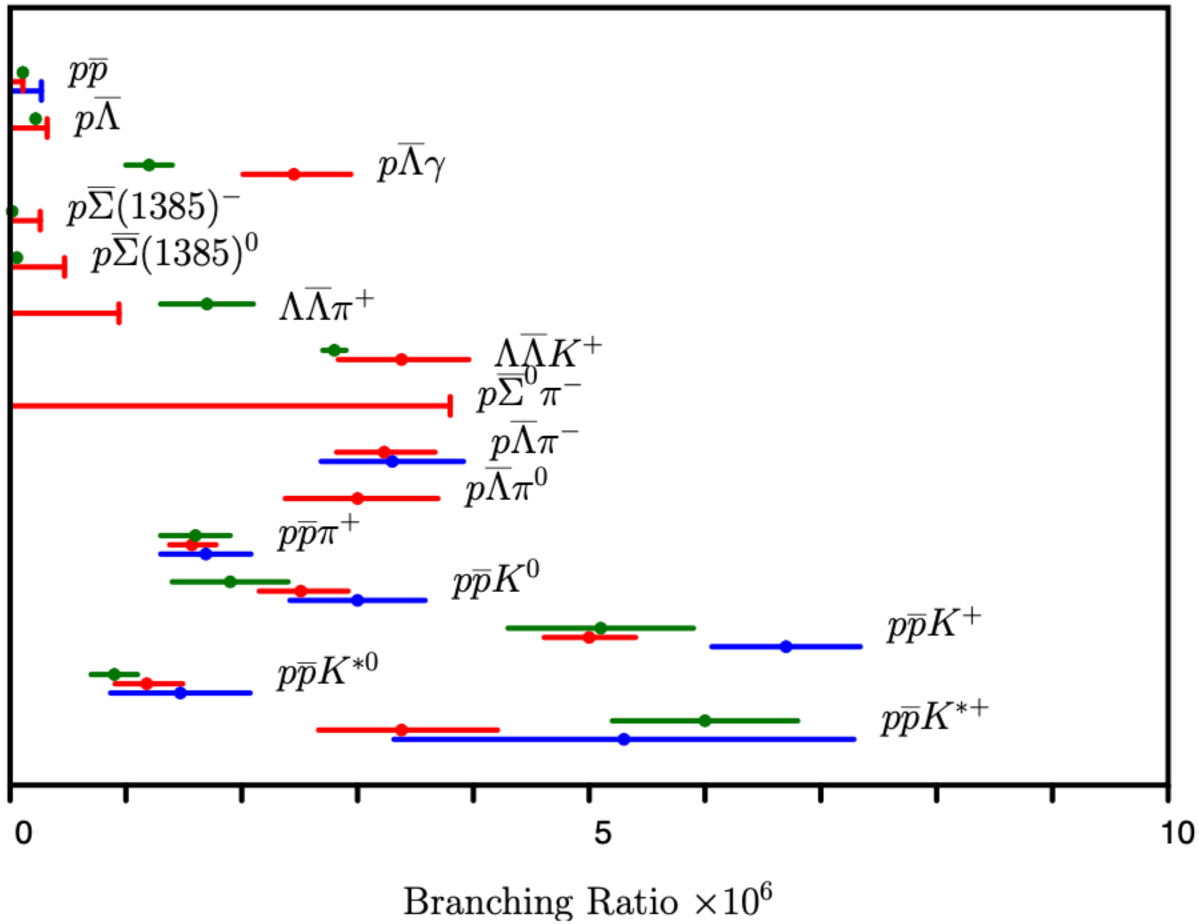


Figure 10: Experimental results for decays with baryons from BABAR (blue) (141, 142, 143, 144) and Belle (red) (145, 146, 147, 148, 149, 150) and theoretical predictions (green) (151, 152).

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Λ_b

$$(Y_{\Lambda_b})_{\alpha\beta\gamma}(x_i,\mu) \equiv \frac{1}{2\sqrt{2}N_c}\int\prod_{l=2}^{3}\frac{dz_l^- d\boldsymbol{z}_l}{(2\pi)^3}e^{ik_l\cdot z_l}\epsilon^{ijk}\langle 0|T[b_\alpha^i(0)u_\beta^j(z_2)d_\gamma^k(z_3)]|\Lambda_b\rangle$$

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

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

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

$$\psi_2(x_2,x_3) = \frac{x_2x_3}{\omega_0^4}m_{\Lambda_b}^4 e^{-(x_2+x_3)m_{\Lambda_b}/\omega_0},$$

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

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

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

[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]

$\Lambda_b \to p$ form factors

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proton

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

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

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	

[V.Braun, R.J.Fries, N.Mahnke, E.Stein, 2000]