Establish CP violation in b-baryon decays

$\Lambda_b \to p$ form factors
$\Lambda_b \to p\pi^-, pK^-, p\rho^-, pK^{*-}, pa_1(1260), pK_1(1270), pK_1(1400)$

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With

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2024·12 LanZhou University

Observation of charge-parity symmetry breaking in baryon decays

LHCb collaboration†

Abstract

The Standard Model of particle physics, the theory of particles and interactions at the smallest scale, predicts that matter and antimatter interact differently due to violation of the combined symmetry of charge conjugation (C) and parity (P). Charge conjugation transforms particles into their antimatter particles, while the parity transformation inverts spatial coordinates. This prediction applies to both mesons, which consist of a quark and an antiquark, and baryons, which are composed of three quarks. However, despite having been discovered in various meson decays, CP violation has yet to be observed in baryons, the type of matter that makes up the observable Universe. This article reports a study of the decay of the beauty baryon Λ_b^0 to the $pK^-\pi^+\pi^-$ final state and its CP-conjugated process, using data collected by the LHCb (Large Hadron Collider beauty) experiment at CERN. The results reveal significant asymmetries between the decay rates of the Λ_b^0 baryon and its CP-conjugated antibaryon, marking the first observation of CP violation in baryon decays, thus demonstrating the different behaviour of baryons and antibaryons. In the Standard Model, CP violation arises from the Cabibbo–Kobayashi–Maskawa mechanism, while new forces or particles beyond the Standard Model could provide additional contributions. This discovery opens a new path to search for physics beyond the Standard Model.

Submitted to Nature

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

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

CPV with $N\pi$ scatterings

$N\pi \to \Delta^{++}\pi^-$

$m_{N\pi} \in [1.2, 1.9]$GeV

decay processes	Scenarios	global CPV	CPV of $\cos\theta < 0$	CPV of $\cos\theta > 0$
	S1	5.9%	8.0%	3.6%
$\Lambda_b^0 \to (\Delta^{++}\pi^-)K^-$	S2	5.8%	6.3%	5.3%
	S3	5.6%	4.3%	7.0%

J.P.Wang, **FSY**, 2407.04110 (CPC2024)

LHCb: $(5.4 \pm 0.9 \pm 0.1)\,\%$

•LHCb:

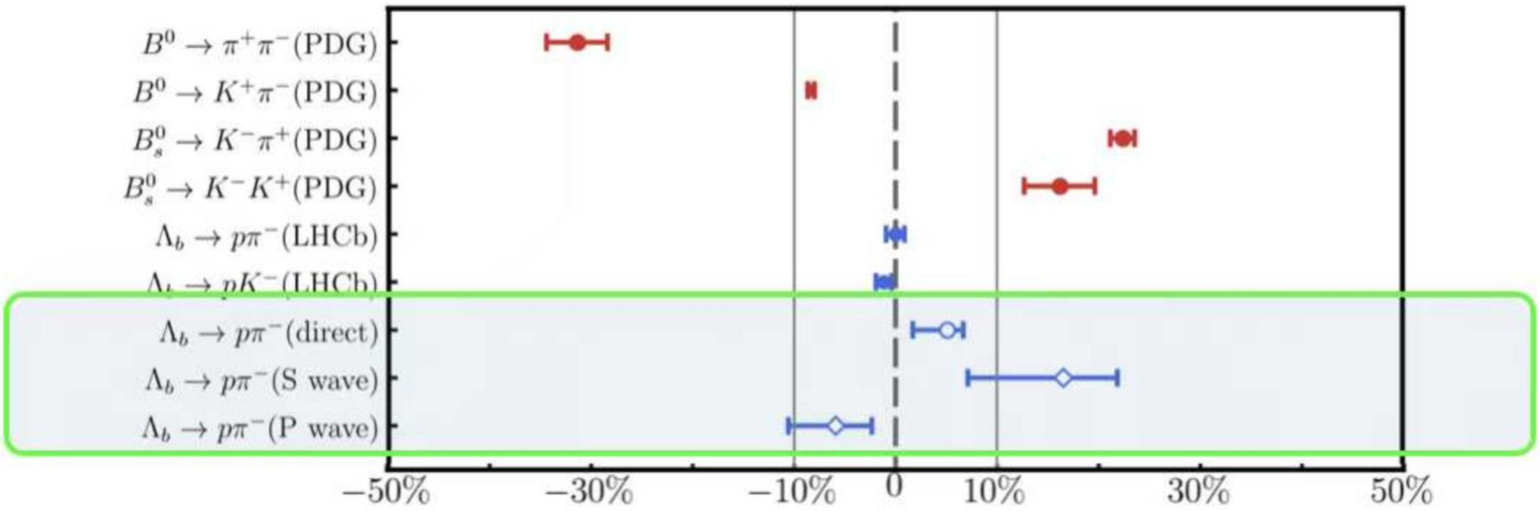
2503.16954

a model-independent investigation of angular distributions [36] or utilising scattering data to extract the hadronic amplitude [28]. Applying this method using $\pi^+ n \to p\pi^+\pi^-$ scattering data [37], an estimate of the *CP* asymmetry in $\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$ decays aligns with the measurement in this work.

[28] J.-P. Wang and F.-S. Yu, *CP violation of baryon decays with $N\pi$ rescatterings*, Chin. Phys. **C48** (2024) 101002, arXiv:2407.04110.

[Slide from Prof.Yu]

S- and P-wave CPV are large but cancelled



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•LHCb:
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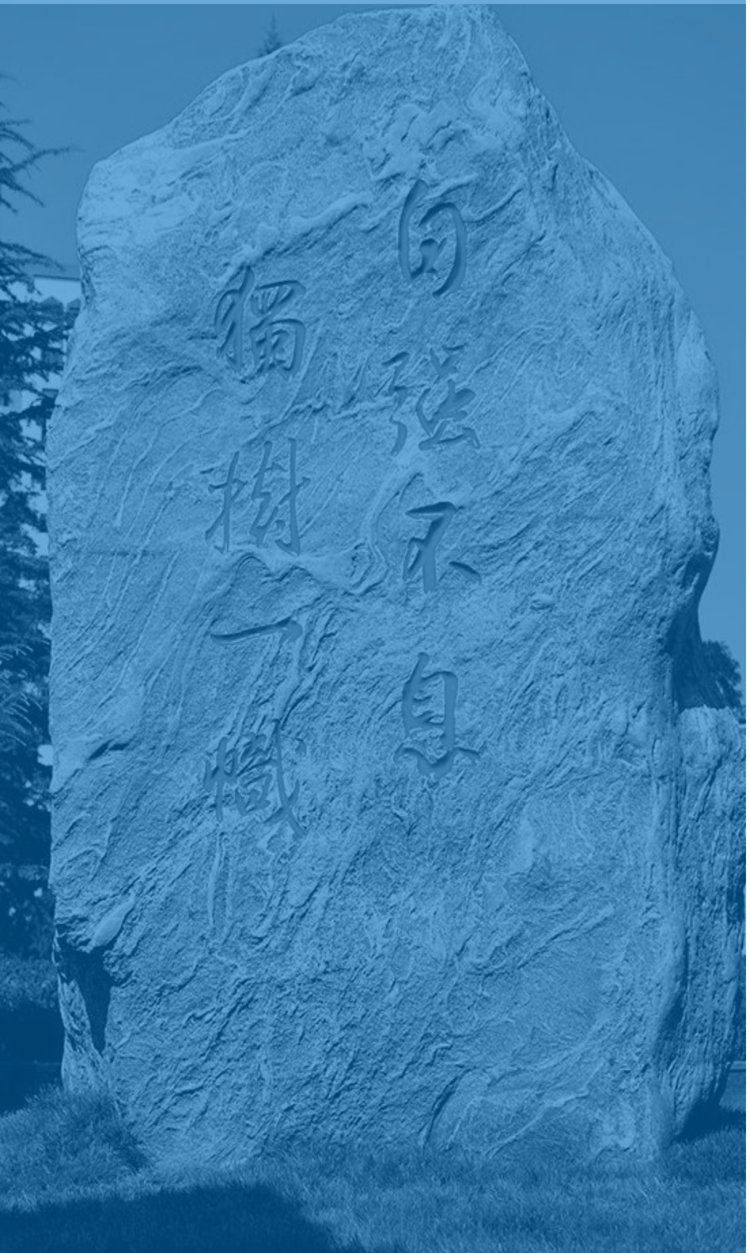
Furthermore, the generally small *CP* asymmetries in beauty-baryon decays imply that the dynamics in baryon decays are more complicated than in meson decays. For instance, the *CP* asymmetries for various angular-momentum amplitudes of the same resonance may cancel [38]. This discovery of baryon decay asymmetry paves the way for further

[38] J.-X. Yu *et al.*, *Establishing CP violation in b-baryon decays*, arXiv:2409.02821.



Why baryon CPVs?

PQCD approach

$\Lambda_b \to p$

Establish CPVs

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

Predict CPVs

$\Lambda_b \to p\rho^-, pK^{*-}, pa_1^-, pK_1^-$

Summary & Outlook

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.

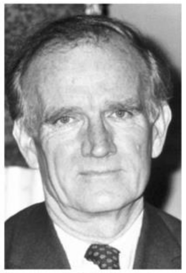
- 1956, Parity violation in weak interaction;
- 1964, Observation of CPV in Kaon;
- 1973, Kobayashi-Maskawa mechanism
- 2004, Observation of direct CPV in B meson;
- 2019, Observation of direct CPV in D meson.


Photo from the Nobel Foundation archive.
Chen Ning Yang


Photo from the Nobel Foundation archive.
Tsung-Dao (T.D.) Lee


1957


Photo from the Nobel Foundation archive.
James Watson Cronin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Val Logsdon Fitch


1980


© The Nobel Foundation Photo: U. Montan
Makoto Kobayashi


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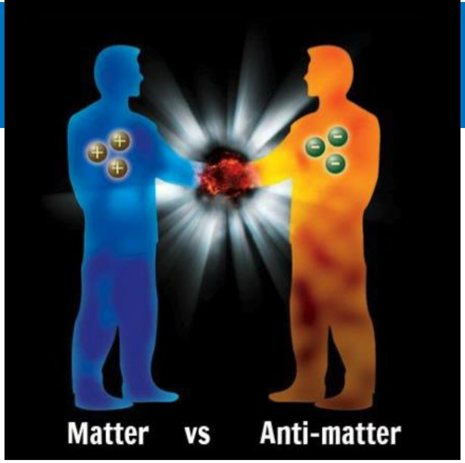
Toshihide Maskawa


2008

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

Why baryon CPVs

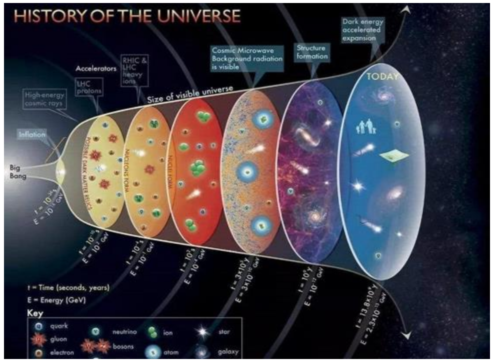


- CPVs relate to matter-antimatter asymmetry of the Universe
  - Sakharov conditions for Baryogenesis:

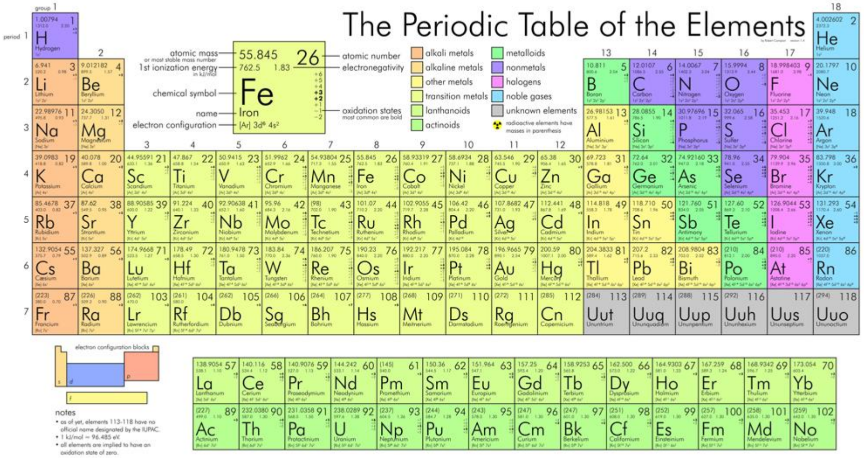
    1). baryon number violation

    2). C and CP violation

    3). out of thermal equilibrium



- The visible universe is mainly made of baryons.
- It is of great significance to search for baryon CPV.



Three types of CP violation in Mesons

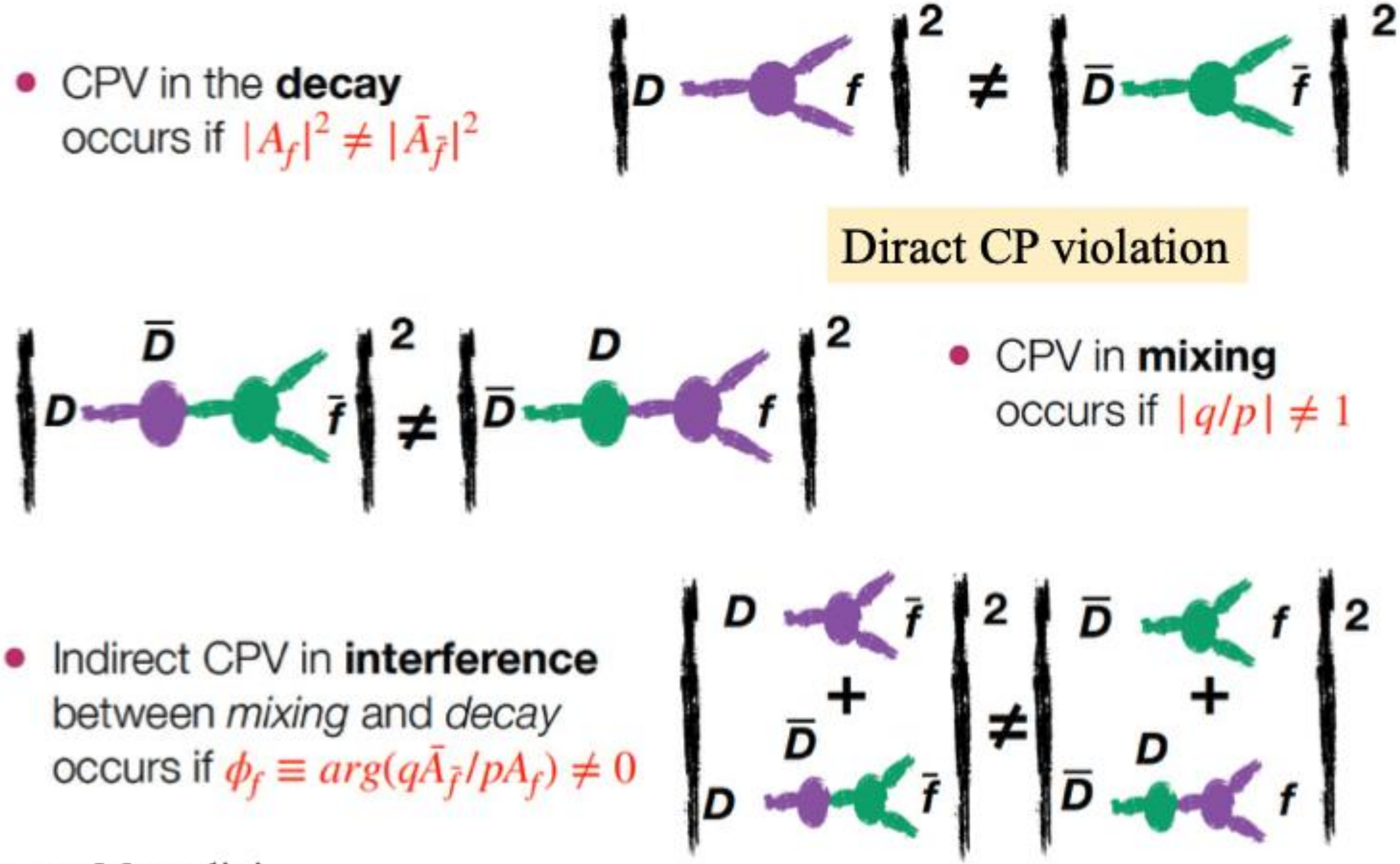


Figure by Serena Maccolini

[Slide from Yan-Xi Zhang]

- Baryons do not exhibit mixing, due to baryon number conservation, thus only direct CPVs can be observed

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] $A_{CP}(\Lambda_c \to pK^+K^-/p\pi^+\pi^-) = (3.0 \pm 9.1 \pm 6.1) \times 10^{-3}$

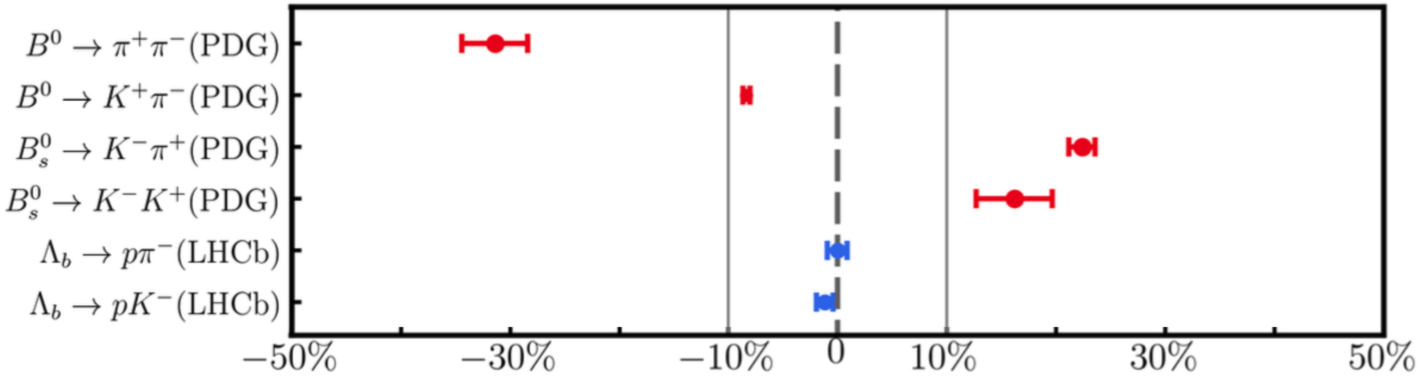
- beauty baryon : SM estimates $\sim 10\%$ due to large weak phase difference

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

$$A_{CP}(B_s^0 \to K^-\pi^+) = (22.4 \pm 1.2)\% \text{ [PDG]}$$

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

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



- LHCb is a baryon factory !

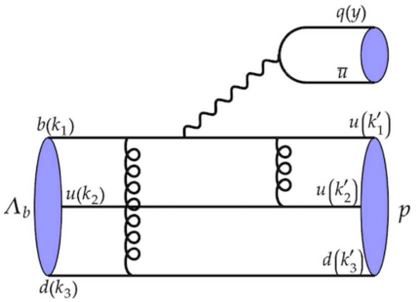
$$\frac{f_{\Lambda_b}}{f_{u,d}} \sim 0.5 \quad \Rightarrow \quad \frac{N_{\Lambda_b}}{N_B^{0,-}} \sim 0.5 \text{ [LHCb, 2012]}$$

- 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!

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

    - 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 approach

- 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]

- PQCD for b-baryon in 2009 [Lü,Wang,Zou,Ali,Kramer,2009]
  - form factor $\langle N(p',s')|\bar{u}\gamma_\mu b|\Lambda_b(p,s)\rangle = \bar{N}(p',s')\left(g_1\gamma_\mu + ig_2\sigma_{\mu\nu}q^\nu + g_3 q_\mu\right)\Lambda_b(p,s)$

	NRQM [19]	LCSR (full QCD)[23]	pQCD [14]	pQCD (this work)
g_1	0.043	0.018	2.3×10^{-3}	$2.2^{+0.8}_{-0.5} \times 10^{-3}$

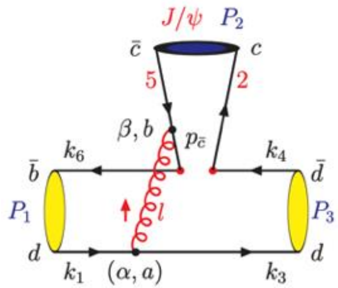
  - W-external emission diagram (T topology)

	factorizable	non-factorizable
$f_1(\Lambda_b \to p\pi)$	$1.47 \times 10^{-11} - i1.97 \times 10^{-11}$	$-2.43 \times 10^{-9} - i2.05 \times 10^{-9}$
$f_2(\Lambda_b \to p\pi)$	$1.26 \times 10^{-11} - i1.94 \times 10^{-11}$	$-1.75 \times 10^{-9} - i1.20 \times 10^{-9}$
$f_1(\Lambda_b \to pK)$	$-1.52 \times 10^{-11} - i0.62 \times 10^{-11}$	$-0.88 \times 10^{-9} + i0.54 \times 10^{-10}$
$f_2(\Lambda_b \to pK)$	$0.17 \times 10^{-11} - i0.60 \times 10^{-11}$	$-1.06 \times 10^{-9} + i1.67 \times 10^{-9}$

PQCD approach

Factorization hypothesis:

$$\mathcal{A} = \langle M_2 M_3 | \mathcal{H} | B \rangle$$
$$\sim \int \frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4}\frac{d^4k_3}{(2\pi)^4}\Psi_B(k_1,\mu)\Psi_2(k_2,\mu)\Psi_3(k_3,\mu)\cdot H(k_1,k_2,k_3,\mu)C_i(\mu)$$



- Collinear factorization, transverse momentum k_T is ignored
  - endpoint singularity, propagator $\sim \frac{1}{x_i(1-x_j)Q^2} \xrightarrow{x_{i,j}\to 0,1} \infty$

$$\mathcal{A} \sim \int_0^1 dx_1 dx_2 dx_3 \phi_1(x_1,\mu)\phi_2(x_2,\mu)\phi_3(x_3,\mu) H\left(x_1,x_2,x_3,\mu,\alpha_s(x_i,\mu)\right) C_i(\mu)$$

- PQCD approach, based on k_T factorization, retain transverse momentum k_T
  - propagators $\sim \frac{1}{x_i(1-x_i)Q^2+|k_{iT}|^2}$

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

  - After resummation, Sudakov factors to suppress contribution from small k_T

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

LCDAs of hadrons

Λ_b

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

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

[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]

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

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

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

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

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

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

LCDAs of hadrons

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]

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	

$\Lambda_b \to p$ form factors

$$\langle N(p',s')|\bar{u}\gamma_\mu(1-\gamma_5)b|\Lambda_b(p,s)\rangle = \bar{N}(p',s')\left(f_1\gamma_\mu - if_2\sigma_{\mu\nu}q^\nu + f_3q_\mu\right)\Lambda_\mathrm{b}(\mathrm{p,s})$$
$$-\bar{N}(p',s')\left(g_1\gamma_\mu - ig_2\sigma_{\mu\nu}q^\nu + g_3q_\mu\right)\gamma_5\Lambda_\mathrm{b}(\mathrm{p,s})$$

f_1	*proton* Twist-3	*proton* Twist-4	*proton* Twist-5	*proton* Twist-6	Total
Exponential					
Twist-2 Λ_b	0.0007	−0.00007	−0.0005	− 0.000003	0.0001
Twist-3^{+-} Λ_b	− 0.0001	0.002	0.0004	− 0.000004	0.002
Twist-3^{-+} Λ_b	− 0.0002	0.0060	0.000004	0.00007	0.006
Twist-4 Λ_b	0.01	0.00009	0.25	0.0000007	0.26
Total	0.01	0.008	0.25	0.00007	0.27±0.09±0.07

[**J.J.Han**,Y.Li,Y.L.Shen,H.n.Li,Z.J.Xiao,F.S.Yu, Eur.Phys.J.C 82(2022)8,686]

- consider high-twist LCDAs, FFs are consistent with LatticeQCD

	Lattice/exp	PQCD(2009)	PQCD(2022)
$f_1^{\Lambda_b\to p}(0)$	0.22 ± 0.08	0.002 ± 0.001	0.27 ± 0.12

$\Lambda_b \to p$ form factors

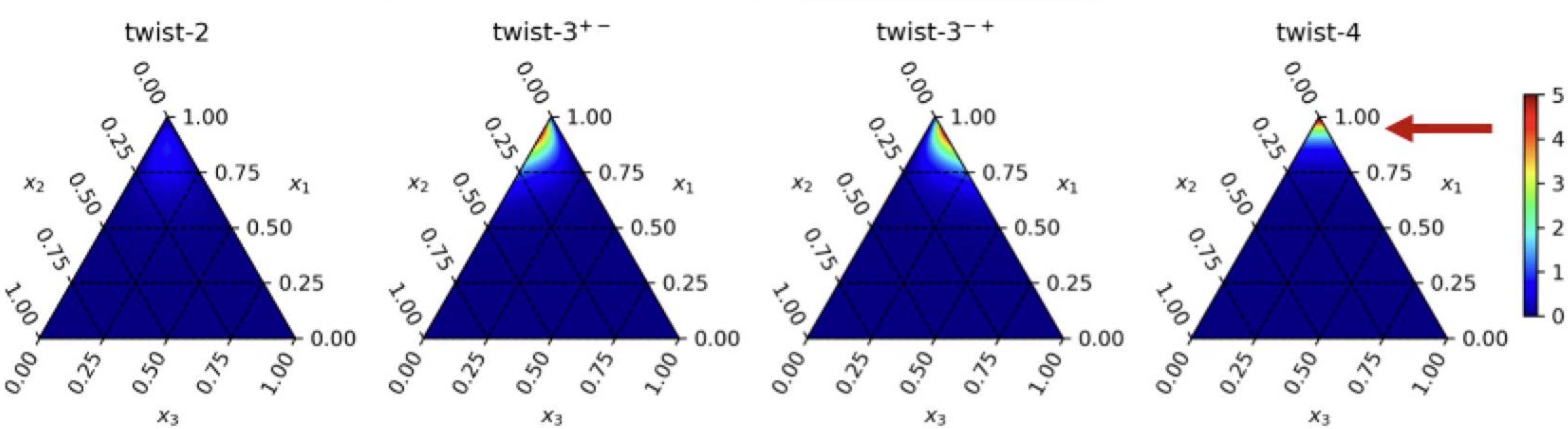
[**J.J.Han**,Y.Li,Y.L.Shen,H.n.Li,Z.J.Xiao,F.S.Yu, Eur.Phys.J.C 82(2022)8,686]

$$\langle N(p',s')|\bar{u}\gamma_\mu(1-\gamma_5)b|\Lambda_b(p,s)\rangle = \bar{N}(p',s')\left(f_1\gamma_\mu - if_2\sigma_{\mu\nu}q^\nu + f_3q_\mu\right)\Lambda_b(p,s) -\bar{N}(p',s')\left(g_1\gamma_\mu - ig_2\sigma_{\mu\nu}q^\nu + g_3q_\mu\right)\gamma_5\Lambda_b(p,s)$$

f_1	*proton* Twist-3	*proton* Twist-4	*proton* Twist-5	*proton* Twist-6	Total
Exponential					
Twist-2 Λ_b	0.0007	−0.00007	−0.0005	− 0.000003	0.0001
Twist-3^{+-} Λ_b	− 0.0001	0.002	0.0004	− 0.000004	0.002
Twist-3^{-+} Λ_b	− 0.0002	0.0060	0.000004	0.00007	0.006
Twist-4 Λ_b	0.01	0.00009	0.25	0.0000007	0.26
Total	0.01	0.008	0.25	0.00007	0.27±0.09±0.07

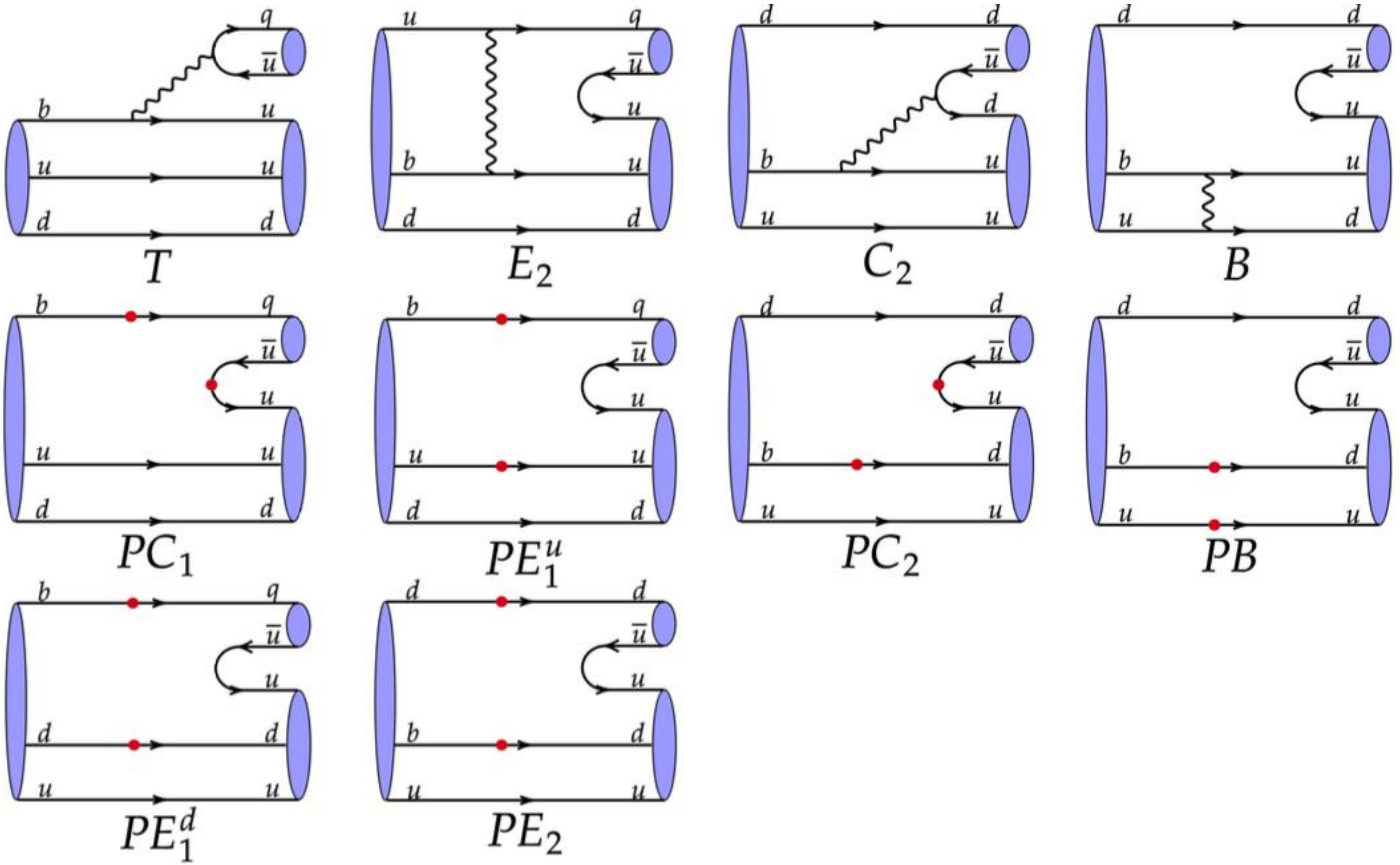
D_7	twist-3	twist-4	twist-5	twist-6
twist-2	~ 0	$r\cdot 2\sqrt{2}(1-x_1)x_3$	$r^2\cdot 2\sqrt{2}x_3$	$r^3\cdot 4\sqrt{2}(1-x_1)(1-x_2')$
twist-3^{+-}	$x_3(1-x_1)$	$r\cdot x_3$	$r^2\cdot(1-x_1)(1-x_2')$	~ 0
twist-3^{-+}	~ 0	$r\cdot x_3$	$r^2\cdot(1-x_1)(1-x_2')$	$r^3\cdot(1-x_2')$
twist-4	$4\sqrt{2}x_3$	$r\cdot 2\sqrt{2}(1-x_1)(1-x_2')$	$r^2\cdot 2\sqrt{2}(1-x_2')$	~ 0

$$r = \frac{m_p}{M_{\Lambda_b}}$$

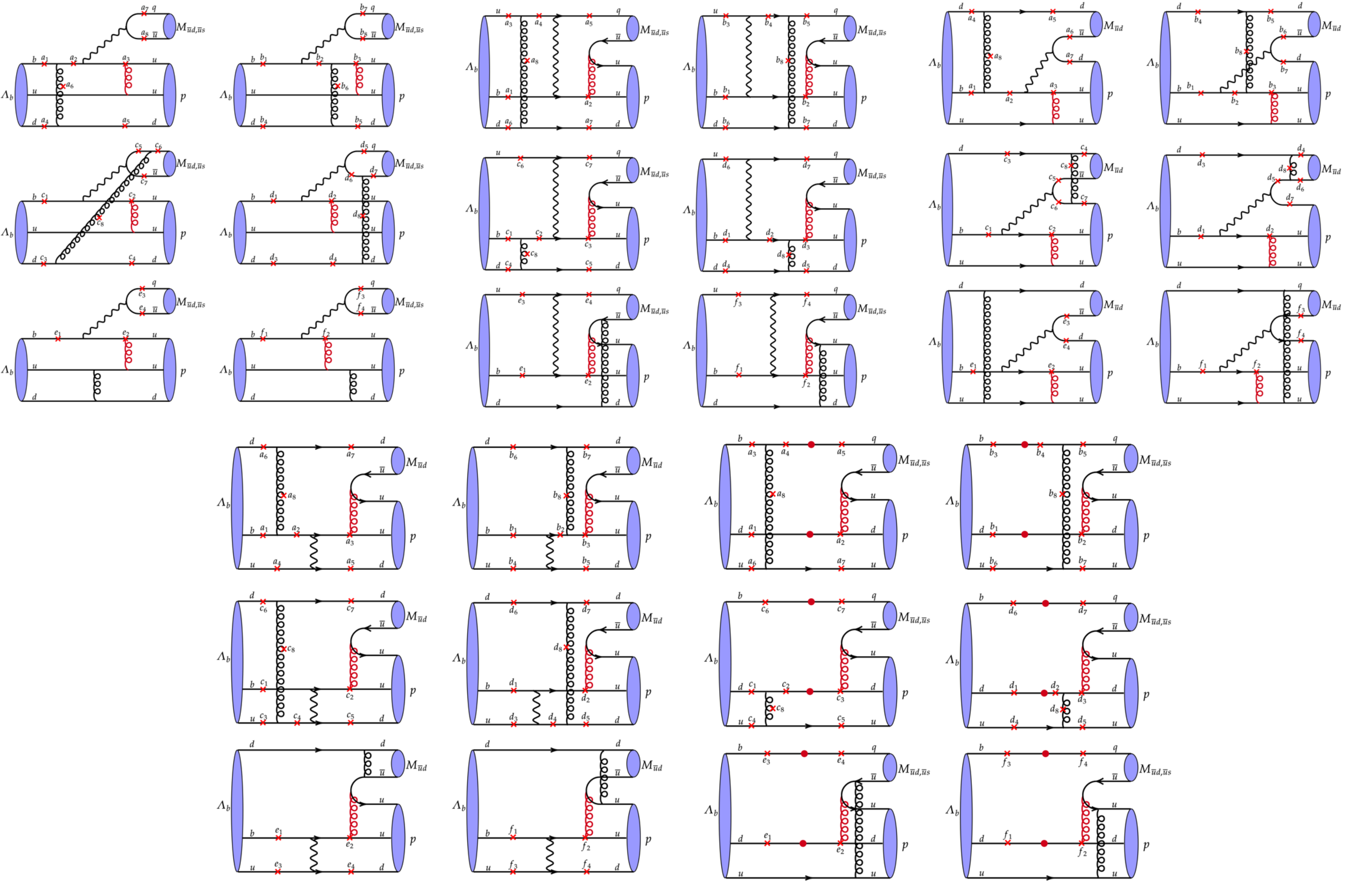


Λ_b LCDA

Topological diagrams of two-body decays



Feynman diagrams



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**

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

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

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

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

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

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

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

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

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

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

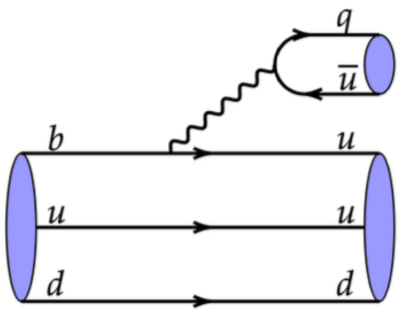
- Baryons have half-integer spin, and thus two partial wave amplitudes.

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

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

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

Tree **Penguin**



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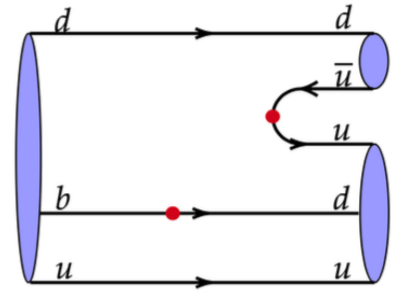

PC_2

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

$$S_{\mathcal{T}} \approx P_{\mathcal{T}}$$

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

$$S_{PC_2} \approx -P_{PC_2}$$

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

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

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

$\Lambda_b \to p\pi^-$	$\|S\|$	$\delta^S(^\circ)$	Real(S)	Imag(S)	$\|P\|$	$\delta^P(^\circ)$	Real(P)	Imag(P)
T_f	707.17	0.00	707.17	0.00	1004.44	0.00	1004.44	0.00
T_{nf}	51.72	-96.64	-5.98	-51.38	267.72	-97.92	-36.90	-265.17
$T_f + T_{nf}$	703.07	-4.19	701.19	-51.38	1003.22	-15.33	967.54	-265.17
C_2	29.37	154.96	-26.61	12.43	41.51	179.80	-41.51	0.14
E_2	66.94	-145.26	-55.01	-38.14	72.58	119.94	-36.23	62.89
B	10.40	112.64	-4.00	9.60	23.65	-122.56	-12.73	-19.93
Tree	619.26	-6.26	615.57	-67.49	904.75	-14.21	877.08	-222.06
$P_f^{C_1}$	58.44	0.00	58.44	0.00	2.90	0.00	2.90	0.00
$P_{nf}^{C_1}$	1.24	-115.38	-0.53	-1.12	11.16	-95.25	-1.02	-11.11
$P_f^{C_1} + P_{nf}^{C_1}$	57.91	-1.11	57.90	-1.12	11.27	-80.38	1.88	-11.11
P^{C_2}	13.36	-116.10	-5.88	-12.00	14.93	71.96	4.62	14.20
$P^{E_1^u}$	9.48	-87.62	0.39	-9.47	8.83	114.44	-3.65	8.04
P^B	1.36	-51.30	0.85	-1.06	1.55	-159.86	-1.46	-0.53
$P^{E_1^d} + P^{E_2}$	3.87	-98.18	-0.55	-3.83	1.41	-12.55	1.37	-0.31
Penguin	59.45	-27.54	52.71	-27.49	10.65	74.93	2.77	10.28

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

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

$\Lambda_b \to p\pi^-$	$\lvert S \rvert$	$\delta^S(^\circ)$	Real(S)	Imag(S)	$\lvert P \rvert$	$\delta^P(^\circ)$	Real(P)	Imag(P)
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T_{nf}	51.72	-96.64	-5.98	-51.38	267.72	-97.92	-36.90	-265.17
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E_2	66.94	-145.26	-55.01	-38.14	72.58	119.94	-36.23	62.89
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$P_f^{C_1}$	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
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$P^{E_1^d} + P^{E_2}$	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

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

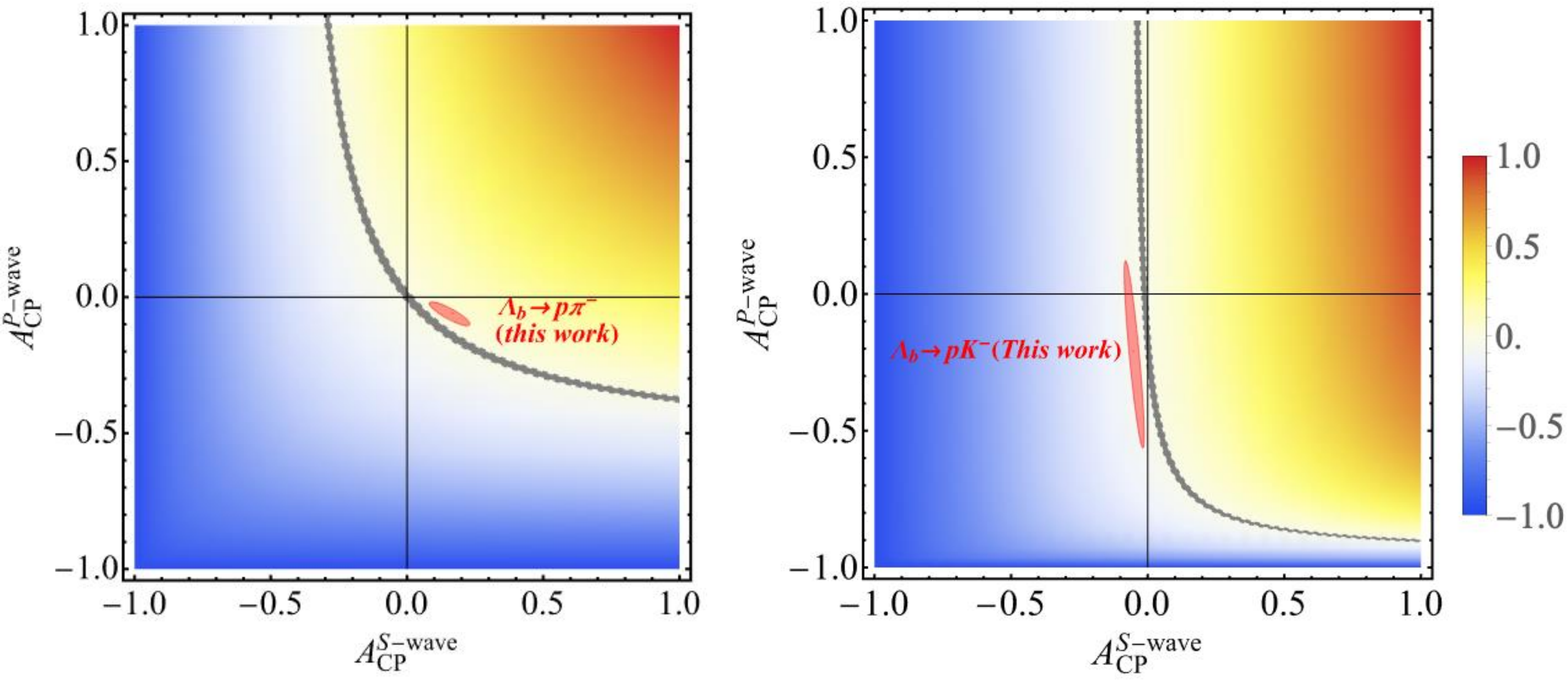
chiral factors $R_1 \approx R_2$

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

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

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

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



1.0
0.5
0.0
−0.5
−1.0
−1.0
−0.5
0.0
0.5
1.0
A_{CP}^{P-wave}
A_{CP}^{S-wave}
$\Lambda_b \to p\pi^-$
(this work)
$\Lambda_b \to pK^-$(This work)
1.0
0.5
0.
−0.5
−1.0

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

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

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

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

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

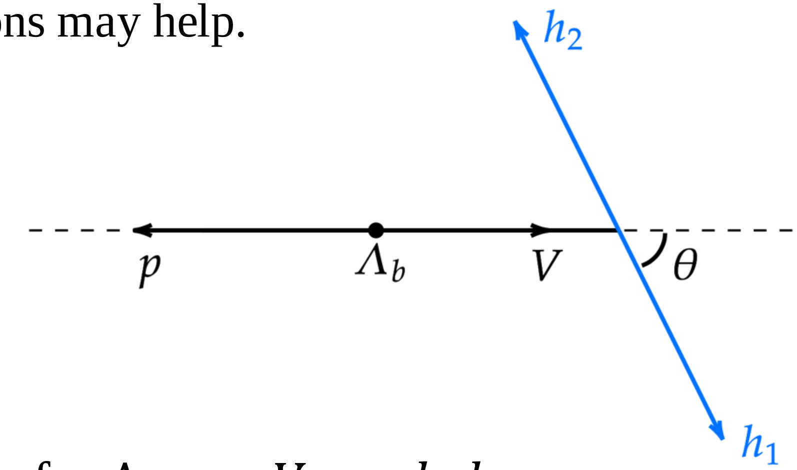
$$\mathcal{B} = \frac{p_c\tau_{\Lambda_b}}{8\pi m_i^2}(|H_{1/2,1}|^2 + |H_{-1/2,-1}|^2 + |H_{1/2,0}|^2 + |H_{-1/2,0}|^2).$$

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

- 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 $\Lambda_b \to pa_1, pK_1$

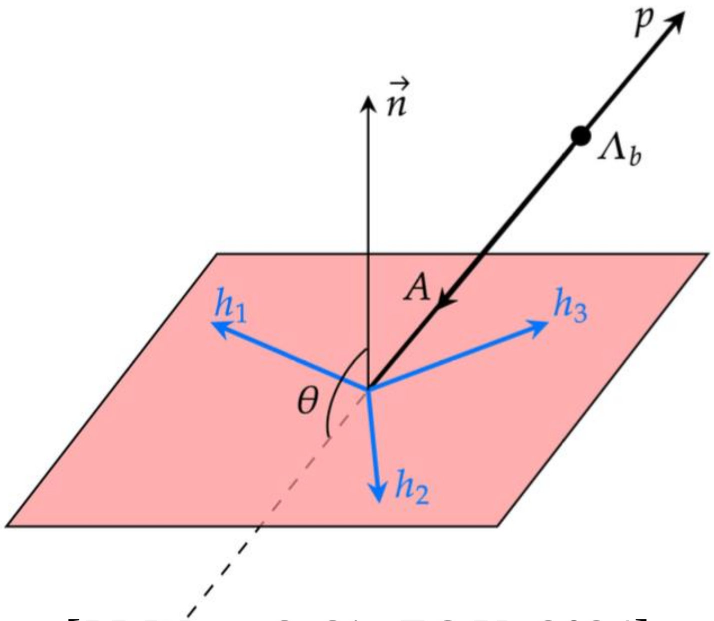
- The angle distribution for $\Lambda_b \to pA \to ph_1h_2h_3$:

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

- up-down asymmetry :

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

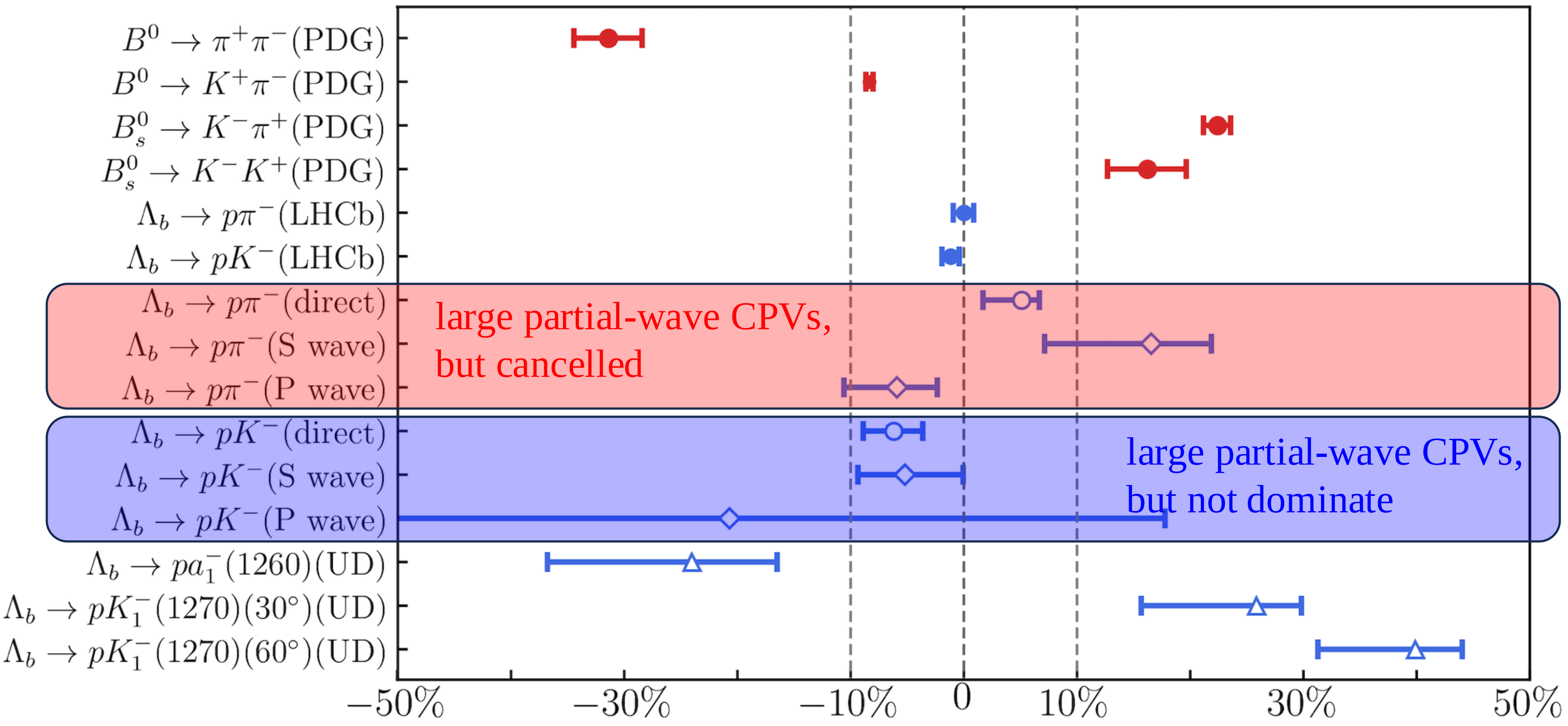
$$A_{CP}^{UD} = \frac{A_{UD} + \bar{A}_{UD}}{A_{UD} - \bar{A}_{UD}}$$



[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)
$\Lambda_b \to pK_1^-(1270)(30^\circ)$(UD)
$\Lambda_b \to pK_1^-(1270)(60^\circ)$(UD)
-50%
-30%
-10%
0
10%
30%
50%
large partial-wave CPVs,
but cancelled
large partial-wave CPVs,
but not dominate

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

	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

LCDA-Λ_b

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

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

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

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

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

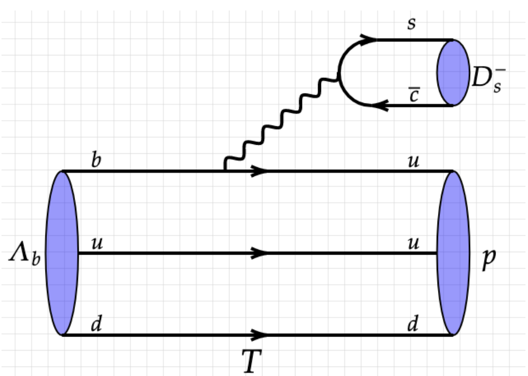
$$\psi_3^{-+}(x_2,x_3) = \frac{2x_3}{\omega_0^3}m^3_{\Lambda_b}e^{-(x_2+x_3)m_{\Lambda_b}/\omega_0},$$

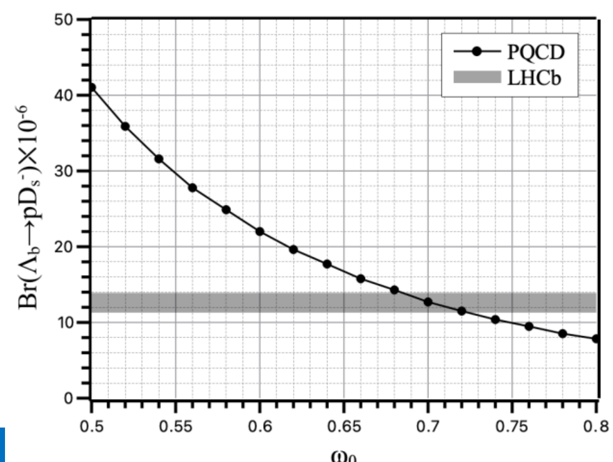
$$\psi_4(x_2,x_3) = \frac{1}{\omega_0^2}m^2_{\Lambda_b}e^{-(x_2+x_3)m_{\Lambda_b}/\omega_0},$$

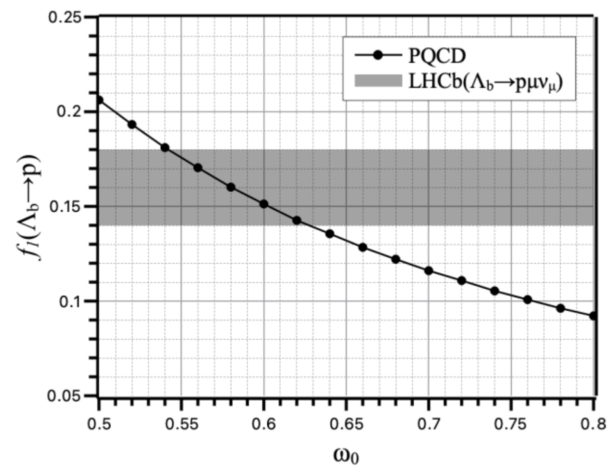
- (LHCb,2212.12574) recently measured the branching fraction:

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

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







LCDA-proton

$$
\begin{aligned}
(\bar{Y}_P)_{\alpha\beta\gamma}(x_i',\mu) = \frac{-1}{8\sqrt{2}N_c}\Big\{ & S_1 m_p C_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma + S_2 m_p C_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma + P_1 m_p (C\gamma_5)_{\beta\alpha}\bar{N}^+_\gamma \\
& + P_2 m_p (C\gamma_5)_{\beta\alpha}\bar{N}^-_\gamma + V_1(C\not{P})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma + V_2(C\not{P})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma \\
& + V_3\frac{m_p}{2}(C\gamma_\perp)_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma + V_4\frac{m_p}{2}(C\gamma_\perp)_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma + V_5\frac{m_p^2}{2Pz}(C\not{z})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma \\
& + V_6\frac{m_p^2}{2Pz}(C\not{z})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma + A_1(C\gamma_5\not{P})_{\beta\alpha}(\bar{N}^+)_\gamma + A_2(C\gamma_5\not{P})_{\beta\alpha}(\bar{N}^-)_\gamma \\
& + A_3\frac{m_p}{2}(C\gamma_5\gamma_\perp)_{\beta\alpha}(\bar{N}^+\gamma^\perp)_\gamma + A_4\frac{m_p}{2}(C\gamma_5\gamma_\perp)_{\beta\alpha}(\bar{N}^-\gamma^\perp)_\gamma + A_5\frac{m_p^2}{2Pz}(C\gamma_5\not{z})_{\beta\alpha}(\bar{N}^+)_\gamma \\
& + A_6\frac{m_p^2}{2Pz}(C\gamma_5\not{z})_{\beta\alpha}(\bar{N}^-)_\gamma - T_1(iC\sigma_{\perp P})_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma - T_2(iC\sigma_{\perp P})_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma \\
& - T_3\frac{m_p}{Pz}(iC\sigma_{Pz})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma - T_4\frac{m_p}{Pz}(iC\sigma_{zP})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma - T_5\frac{m_p^2}{2Pz}(iC\sigma_{\perp z})_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma \\
& - T_6\frac{m_p^2}{2Pz}(iC\sigma_{\perp z})_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma + T_7\frac{m_p}{2}(C\sigma_{\perp\perp'})_{\beta\alpha}(\bar{N}^+\gamma_5\sigma^{\perp\perp'})_\gamma \\
& + T_8\frac{m_p}{2}(C\sigma_{\perp\perp'})_{\beta\alpha}(\bar{N}^-\gamma_5\sigma^{\perp\perp'})_\gamma\Big\}, \qquad (16)
\end{aligned}
$$

	$f_N(GeV^2)$	$\lambda_1(GeV^2)$	$\lambda_2(GeV^2)$	V_1^d
QCDSR(2001)[58]	$(5.3\pm0.5)\times10^{-3}$	$-(2.7\pm0.9)\times10^{-2}$	$(5.1\pm1.9)\times10^{-2}$	0.23 ± 0.03
QCDSR(2006)[59]	$(5.0\pm0.5)\times10^{-3}$	$-(2.7\pm0.9)\times10^{-2}$	$(5.4\pm1.9)\times10^{-2}$	0.23 ± 0.03
LQCD(2019)[51]	$(3.54\pm0.06)\times10^{-3}$	$-(4.49\pm0.42)\times10^{-2}$	$(9.34\pm0.48)\times10^{-2}$	0.19 ± 0.22
	A_1^u	f_1^d	f_2^d	f_1^u
QCDSR(2001)[58]	0.38 ± 0.15	0.6 ± 0.2	0.15 ± 0.06	0.22 ± 0.15
QCDSR(2006)[59]	0.38 ± 0.15	0.4 ± 0.05	0.22 ± 0.05	0.07 ± 0.05
LQCD(2019)[51]	0.30 ± 0.32	...	...	...

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^*

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

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

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

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

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

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

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

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

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

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

- a_1/K_1

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

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

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

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

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

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

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

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

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

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

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

Λ_b two-body decays

$\Lambda_b \to p M_{\bar{u}q} (q = d, s)$

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \left\{ V_{ub} V_{uq}^* \left[C_1(\mu) O_1^u(\mu) + C_2(\mu) O_2^u(\mu) \right] - V_{tb} V_{tq}^* \left[\sum_{i=3}^{10} C_i(\mu) O_i(\mu) \right] \right\}$$

$$O_1^u = (\bar{u}_\alpha b_\beta)_{V-A} (\bar{q}_\beta u_\alpha)_{V-A}, \qquad O_2^u = (\bar{u}_\alpha b_\alpha)_{V-A} (\bar{q}_\beta u_\beta)_{V-A},$$

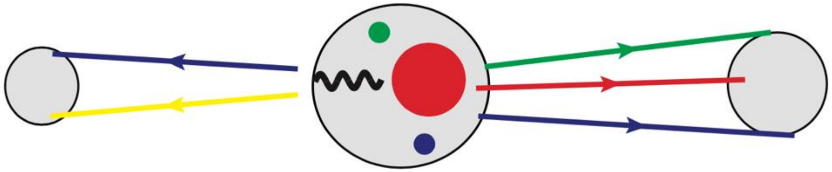
$$O_3 = (\bar{q}_\alpha b_\alpha)_{V-A} \sum_{q'} (\bar{q}'_\beta q'_\beta)_{V-A}, \qquad O_4 = (\bar{q}_\beta b_\alpha)_{V-A} \sum_{q'} (\bar{q}'_\alpha q'_\beta)_{V-A},$$

$$O_5 = (\bar{q}_\alpha b_\alpha)_{V-A} \sum_{q'} (\bar{q}'_\beta q'_\beta)_{V+A}, \qquad O_6 = (\bar{q}_\beta b_\alpha)_{V-A} \sum_{q'} (\bar{q}'_\alpha q'_\beta)_{V+A},$$

$$O_7 = \frac{3}{2} (\bar{q}_\alpha b_\alpha)_{V-A} \sum_{q'} e_{q'} (\bar{q}'_\beta q'_\beta)_{V+A}, \qquad O_8 = \frac{3}{2} (\bar{q}_\beta b_\alpha)_{V-A} \sum_{q'} e_{q'} (\bar{q}'_\alpha q'_\beta)_{V+A},$$

$$O_9 = \frac{3}{2} (\bar{q}_\alpha b_\alpha)_{V-A} \sum_{q'} e_{q'} (\bar{q}'_\beta q'_\beta)_{V-A}, \qquad O_{10} = \frac{3}{2} (\bar{q}_\beta b_\alpha)_{V-A} \sum_{q'} e_{q'} (\bar{q}'_\alpha q'_\beta)_{V-A},$$

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