CP violation of Λ_b decays in PQCD

$\Lambda_b \to p$ form factors

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

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Based on

Eur.Phys.J.C 82(2022)8,686, arXiv:2409.02821 & 2411.xxxxx

With

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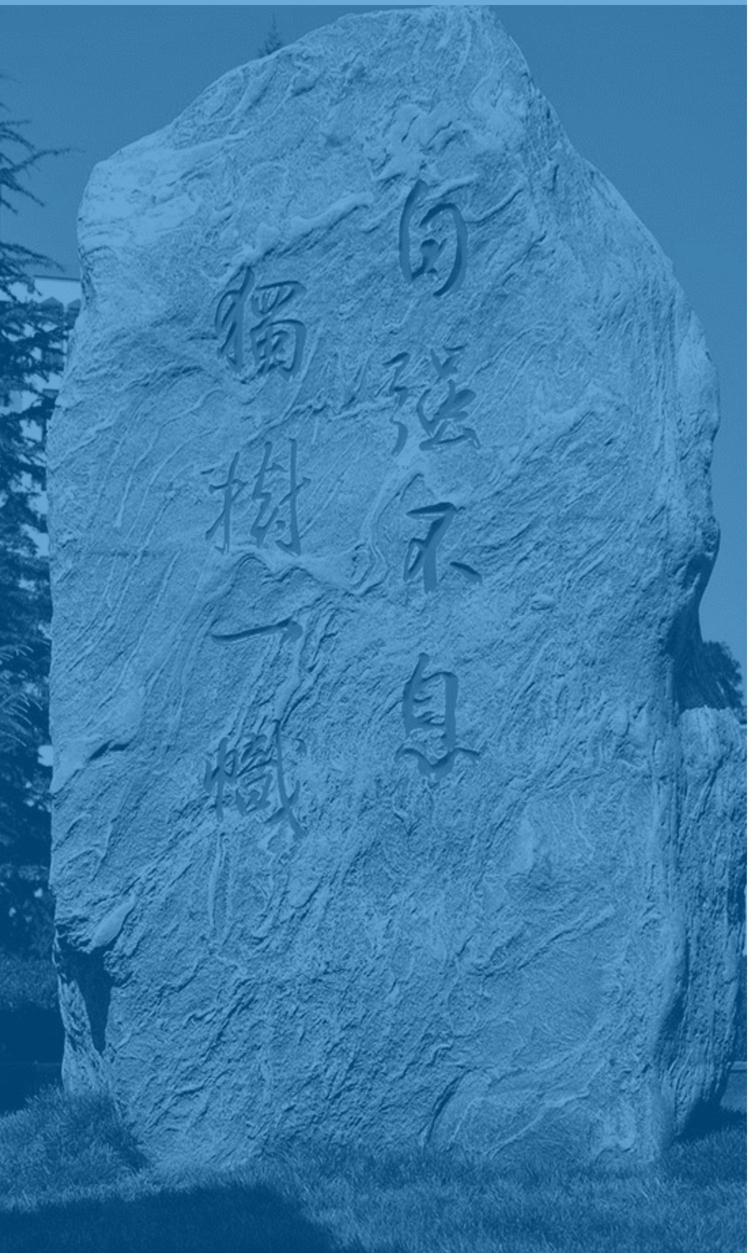
HFCPV2024，湖南・衡阳



Why baryon physics?

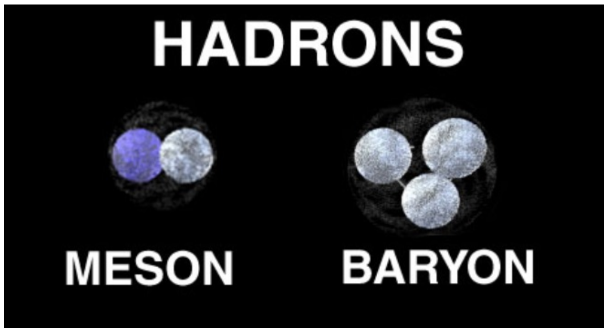
Form factors of $\Lambda_b \to p$

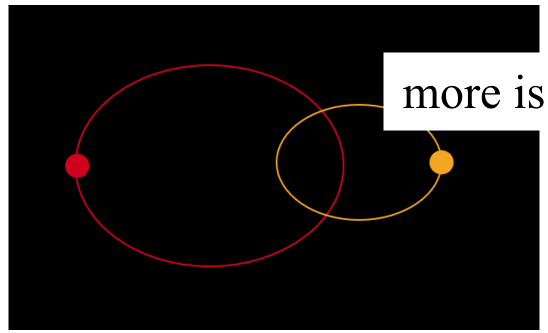
Establish CPV of Λ_b decays

Summary

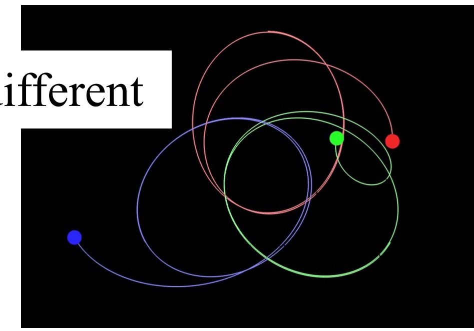
Why baryon physics

- Heavy flavor physics
  - heavy flavor physics has achieved great progress in heavy meson systems,
  - CKM mechanism has been established for CPV in B meson decays,
  - however, studies on heavy flavor baryon are limited.



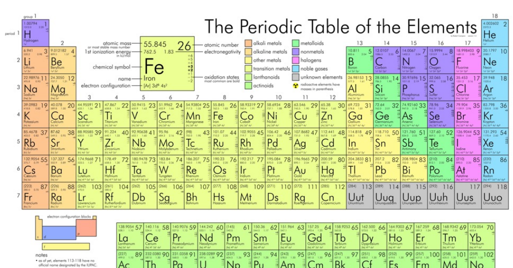


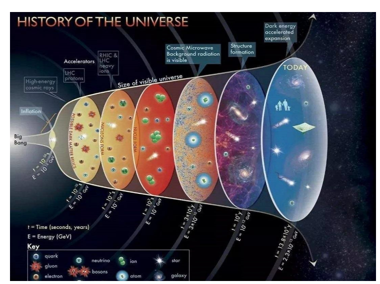
more is different



- CP violation in baryon
  - Sakharov conditions for Baryogenesis:

    baryon number violation   C and CP violation   out of thermal equilibrium
  - CPV well established in K, B and D mesons, but CPV never established in baryon,
  - comparison between prediction and measurement is helpful to test SM and search NP.





Opportunities

- Hyperon CPV:

  $A^{\alpha}_{CP}(\Lambda \to p\pi^-) = -0.002 \pm 0.004$(BESIII,2019) v.s. $\mathcal{O}(10^{-5} \sim 10^{-4})$(theory)
- charm baryon CPV:

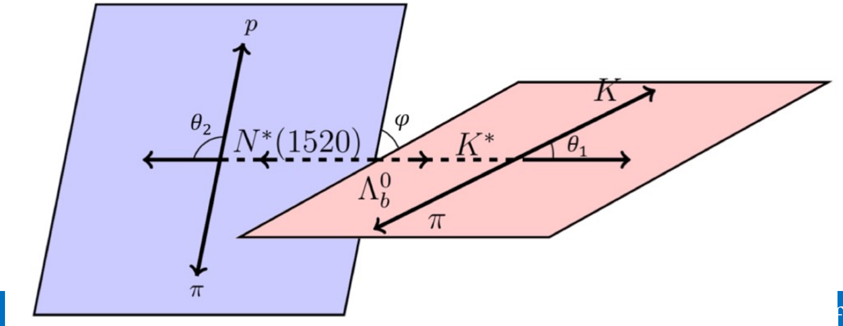
  $A_{CP}(\Lambda_c \to pK^+K^-/p\pi^+\pi^-) = 0.003 \pm 0.011$(LHCb,2018) v.s. $\mathcal{O}(10^{-3})$(theory)
- beauty hadron ~ 10% due to large weak phase difference

  $A_{CP}(B^0 \to K^+\pi^-) = (-8.34 \pm 0.32)\%$ $A_{CP}(B_s^0 \to K^-\pi^+) = (22.4 \pm 1.2)\%$(PDG2022)
- LHCb is a baryon factory ! $\frac{N_{\Lambda_b}}{N_B^{0,-}} \sim 0.5$ $N_{\Lambda_b} \sim 10^{12}$(LHCb,2012)
- Precision of b-baryon CPV measurement reached of order 1%

$$A_{CP}(\Lambda_b \to p\pi^-) = (-3.5 \pm 1.7 \pm 2.0)\%$$

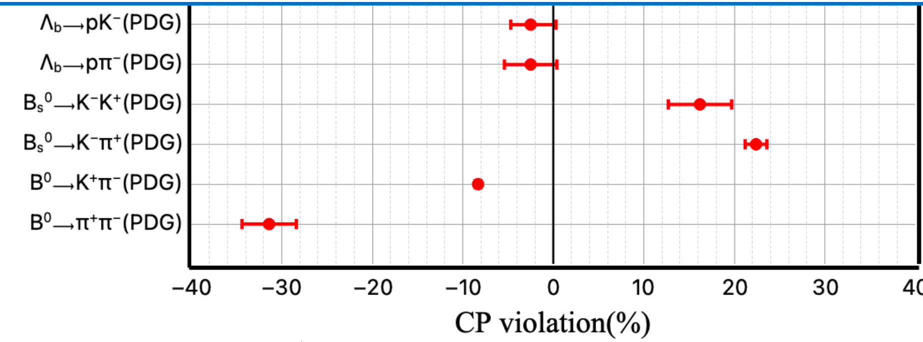
$$A_{CP}(\Lambda_b \to pK^-) = (-2.0 \pm 1.3 \pm 1.0)\%\text{(LHCb,2018)}$$

- non-zero polarization, more observables



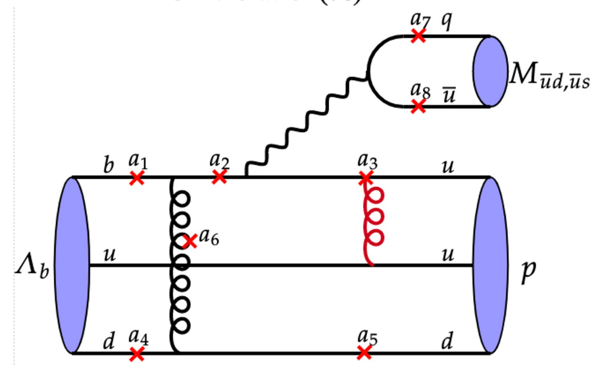
evidence for CPV at 3.3σ is found in $\Lambda_b \to p\pi^-\pi^+\pi^-$ at LHCb,2017

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 limited
  - 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)
$Br(\Lambda \to p\pi^-)\times 10^{-6}$	4.5 ± 0.8	$4.25^{+1.40}_{-1.05}$	$4.3^{+0.27}_{-0.19}$	$5.21^{+2.47}_{-1.93}$	4.18 ± 0.34	5.94
$Br(\Lambda \to pK^-)\times 10^{-6}$	5.4 ± 1.0	$4.49^{+1.06}_{-0.75}$	$2.17^{+0.98}_{-0.47}$	$2.02^{+0.96}_{-1.25}$	5.76 ± 0.91	6.50
$A_{CP}(\Lambda_b \to p\pi^-)\%$	-2.5 ± 2.9	-3.9 ± 0.4	-3.4 ± 0.4	-31^{+42}_{-1}	-3.6 ± 0.20	−1.8
$A_{CP}(\Lambda_b \to pK^-)\%$	-2.5 ± 2.2	6.7 ± 0.4	10.1 ± 2.0	-5^{+26}_{-5}	6.36 ± 0.28	−0.1

PQCD approach

- 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)
$-12.8^{+3.48}_{-3.29}$(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 CPV
  - Lü,Wang,Zou,Ali,Kramer,2009
    - W-external emission diagram (T)

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

    - form factor $\langle N(p',s')|\bar{u}\gamma_\mu b|\Lambda_b(p,s)\rangle = \bar{N}(p',s')(g_1\gamma_\mu + ig_2\sigma_{\mu\nu}q^\nu + g_3 q_\mu)\Lambda_b(p,s)$

	NRQM [19]	LCSR (full QCD)[23]	pQCD [14]	Lü,Wang,Zou,Ali,Kramer,2009
g_1	0.043	0.018	2.3×10^{-3}	$2.2^{+0.8}_{-0.5} \times 10^{-3}$

$\Lambda_b \to p$ form factors

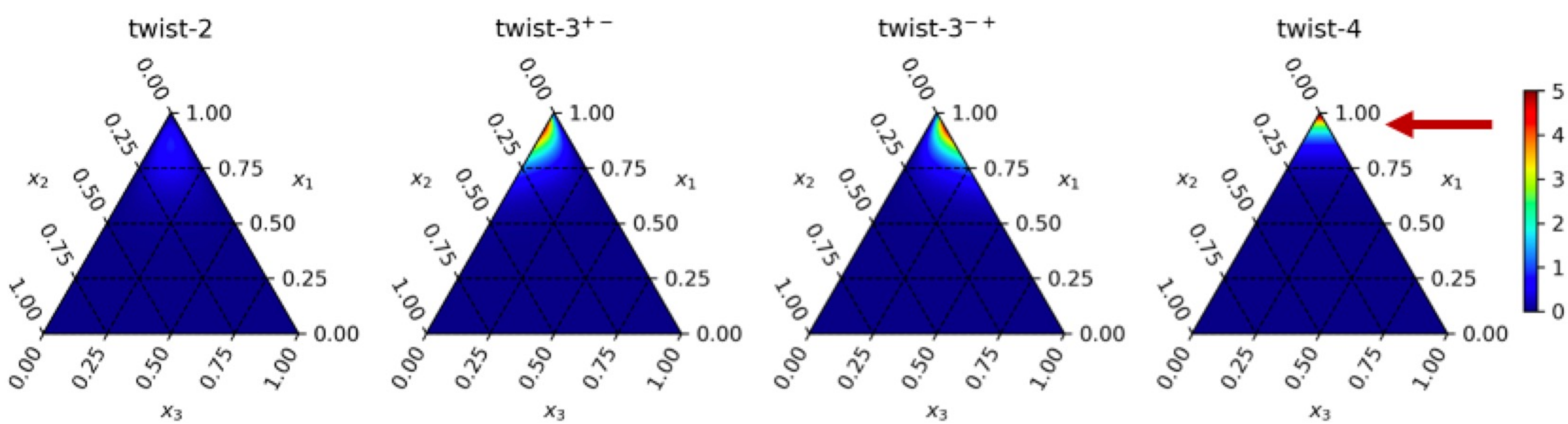
J.J.Han,Y.Li,Y.L.Shen,H.n.Li,Z.J.Xiao,F.S.Yu, Eur.Phys.J.C 82(2022)8,686

$$\langle N(p',s')|\bar{u}\gamma_\mu(1-\gamma_5)b|\Lambda_b(p,s)\rangle = \bar{N}(p',s')\big(f_1\gamma_\mu - if_2\sigma_{\mu\nu}q^\nu + f_3 q_\mu\big)\Lambda_b(p,s) - \bar{N}(p',s')\big(g_1\gamma_\mu - ig_2\sigma_{\mu\nu}q^\nu + g_3 q_\mu\big)\gamma_5\Lambda_b(p,s)$$

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

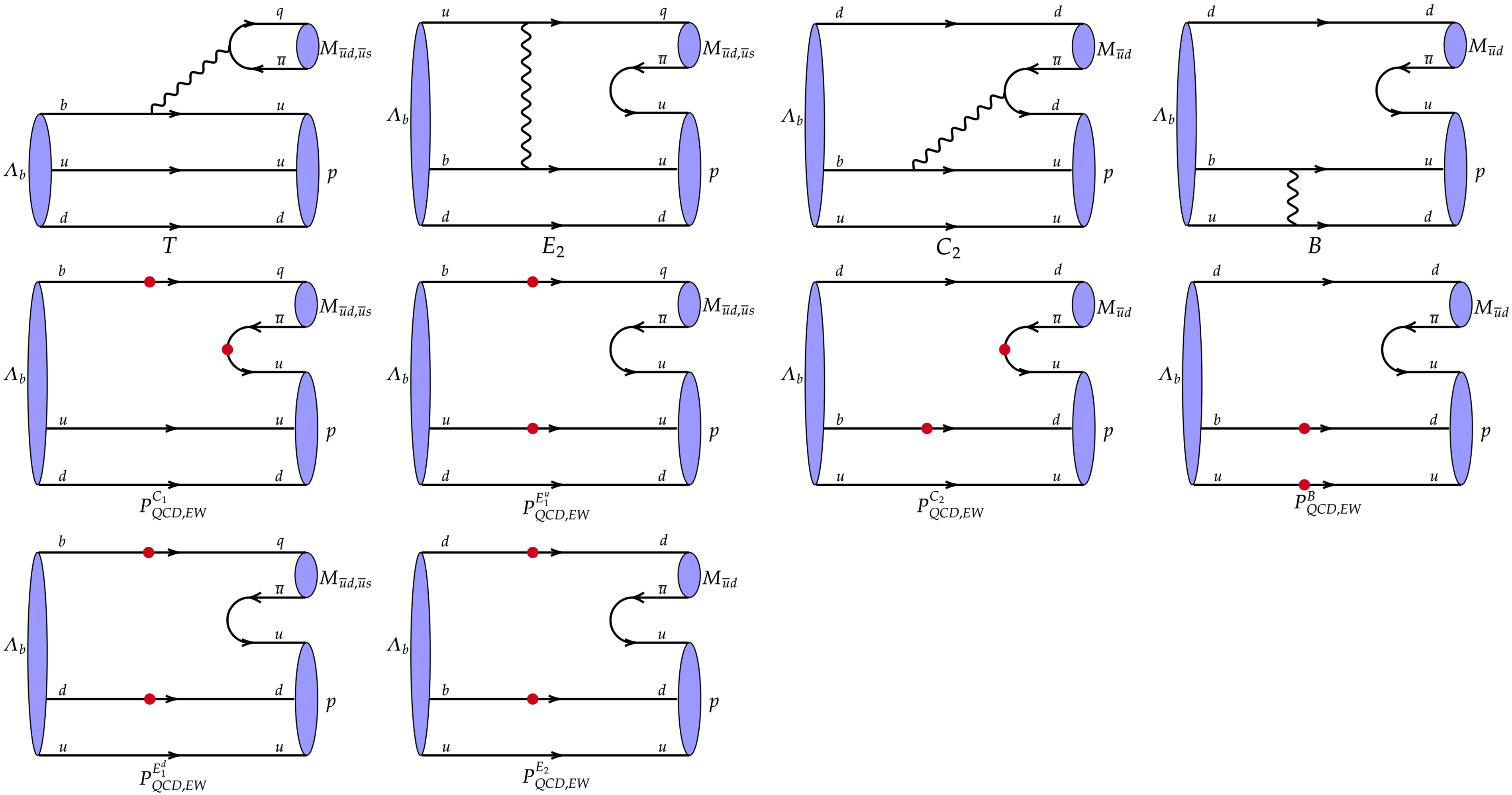
D_7	twist-3	twist-4	twist-5	twist-6
twist-2	~ 0	$r\cdot 2\sqrt{2}(1-x_1)x_3$	$r^2\cdot 2\sqrt{2}x_3$	$r^3\cdot 4\sqrt{2}(1-x_1)(1-x_2')$
twist-3^{+-}	$x_3(1-x_1)$	$r\cdot x_3$	$r^2\cdot(1-x_1)(1-x_2')$	~ 0
twist-3^{-+}	~ 0	$r\cdot x_3$	$r^2\cdot(1-x_1)(1-x_2')$	$r^3\cdot(1-x_2')$
twist-4	$4\sqrt{2}x_3$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

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

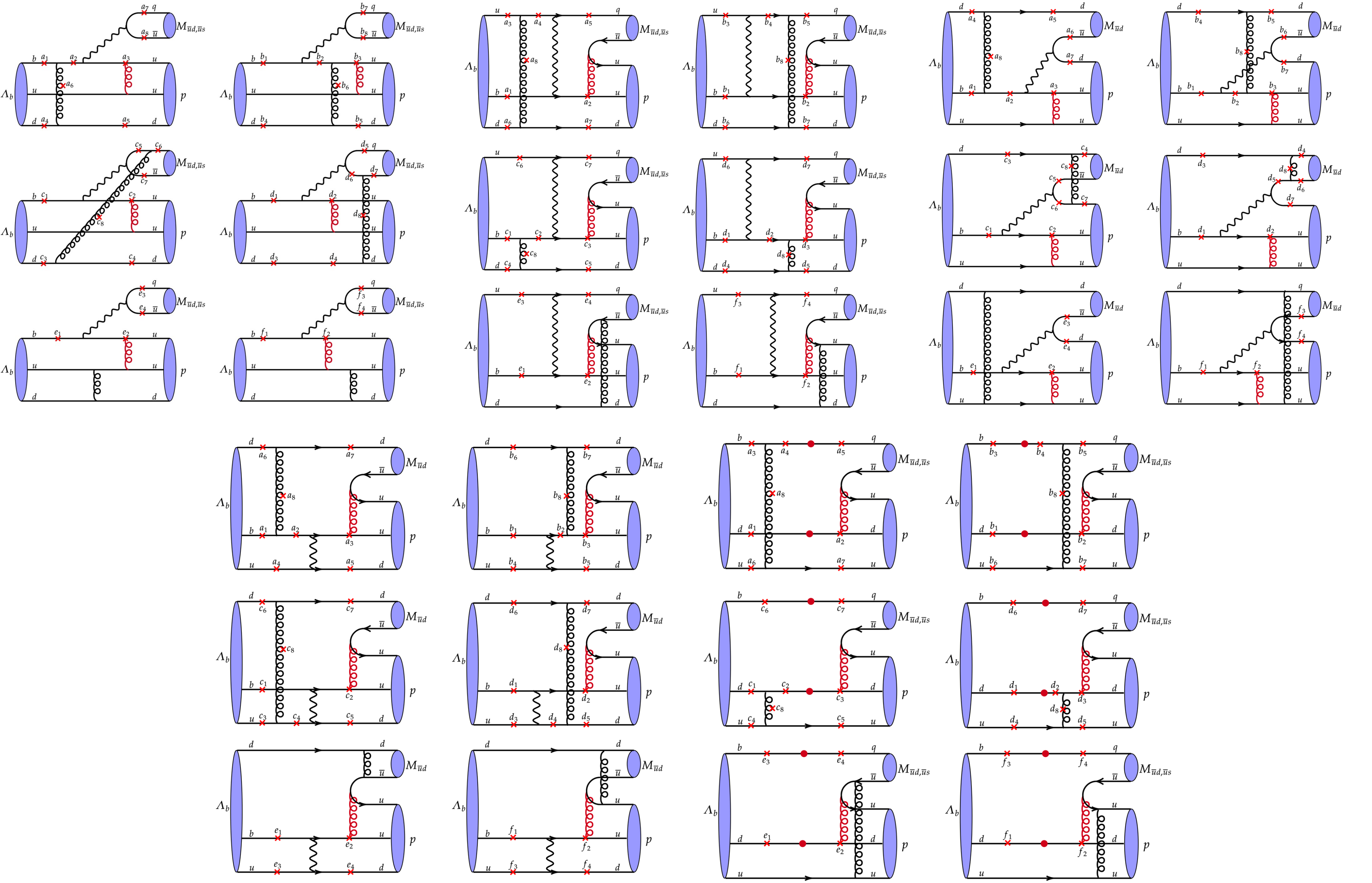


Λ_b LCDA

Topological diagrams



Feynman diagrams



LCDA-Λ_b

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

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

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

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

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

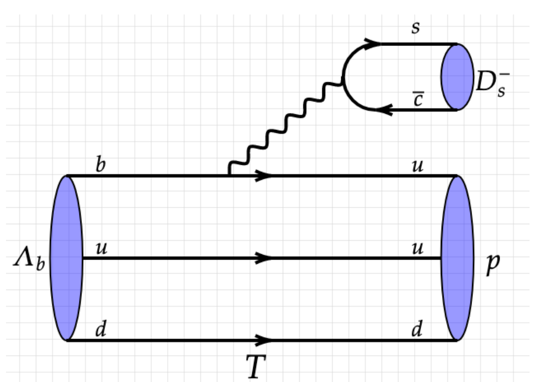
$$\psi_3^{-+}(x_2,x_3) = \frac{2x_3}{\omega_0^3}m^3_{\Lambda_b}e^{-(x_2+x_3)m_{\Lambda_b}/\omega_0},$$

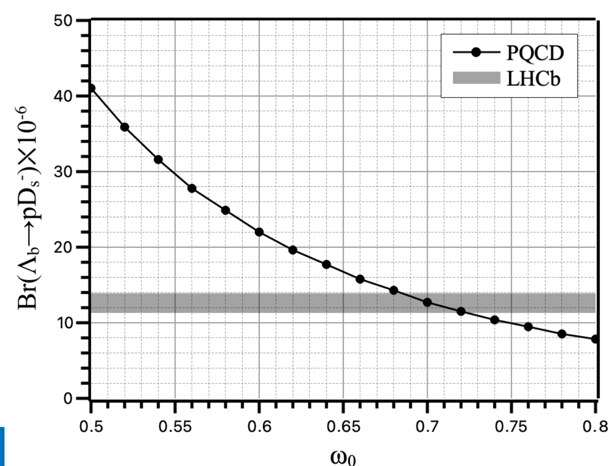
$$\psi_4(x_2,x_3) = \frac{1}{\omega_0^2}m^2_{\Lambda_b}e^{-(x_2+x_3)m_{\Lambda_b}/\omega_0},$$

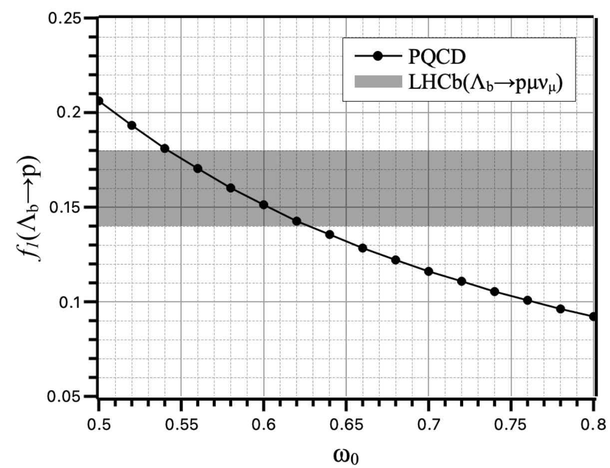
- (LHCb,2212.12574) recently measured the branching fraction:

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

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







LCDA-proton

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

	$f_N(GeV^2)$	$\lambda_1(GeV^2)$	$\lambda_2(GeV^2)$	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^*

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

$$\Phi^L_V(q,\epsilon^*_L,y)=\frac{-1}{\sqrt{2N_c}}\left[m_V\not{\epsilon}^*_L\phi_V(y)+\not{\epsilon}^*_L\not{q}\phi^t_V(y)+m_V\phi^s_V(y)\right]_{\alpha\beta},$$

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

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

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

$$\phi^t_V(y)=\frac{3f^T_V}{2\sqrt{2N_c}}(2y-1)^2, \quad (30)$$

$$\phi^s_V(y)=\frac{3f^T_V}{2\sqrt{2N_c}}(1-2y), \quad (31)$$

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

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

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

LCDA-mesons

- a_1/K_1

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

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

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

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

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

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

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

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

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

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

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

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

$$\mathcal{M}\left[B_i(1/2^+) \to B_f(1/2^+) + P\right] = i\bar{u}_f(p_f)(f_1 + f_2\gamma_5)u_i(p_i)$$
$$= i\bar{u}_f(p_f)\sum_{T,P} \lambda^{T,P}_{CKM}(S^{T,P} + P^{T,P}\gamma_5)u_i(p_i),$$

$\Lambda_b \to p\pi^-$	$\|S\|$	$\phi(S)^\circ$	Real(S)	Imag(S)	$\|P\|$	$\phi(P)^\circ$	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	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^{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

TABLE VI: Results of the $\Lambda_b \to p\pi^-$ decay.

$$\mathcal{M}\left[B_i(1/2^+) \to B_f(1/2^+) + P\right] = i\bar{u}_f(p_f)(f_1 + f_2\gamma_5)u_i(p_i)$$
$$= i\bar{u}_f(p_f)\sum_{T,P}\lambda_{CKM}^{T,P}(S^{T,P} + P^{T,P}\gamma_5)u_i(p_i),$$

$\Lambda_b \to p\pi^-$	$\lvert S\rvert$	$\phi(S)^\circ$	Real(S)	Imag(S)	$\lvert P\rvert$	$\phi(P)^\circ$	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	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
$P_f^{C_1}$	76.43	0.00	76.43	0.00	3.30	180.00	-3.30	0.00
$P_{nf}^{C_1}$	1.14	-134.10	-0.79	-0.82	13.85	-94.36	-1.05	-13.81
P^{C_1}	75.64	-0.62	75.64	-0.82	14.48	-107.50	-4.35	-13.81
$P^{E_1^u}$	11.80	-89.53	0.10	-11.80	11.02	115.62	-4.76	9.93
$P^{E_1^d}$	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

TABLE VIII: Results of the $\Lambda_b \to pK^-$ decay.

$$f_1(P_f^{C_1}) = -\frac{G_F}{\sqrt{2}}f_h V_{tb}V_{td}^*(\frac{C_3}{3} + C_4 + \frac{C_9}{3} + C_{10} + R_1^h(\frac{C_5}{3} + C_6 + \frac{C_7}{3} + C_8))\left[F_1(m_h^2)(M_{\Lambda_b} - M_p) + F_3(m_h^2)m_h^2\right]$$

$$f_2(P_f^{C_1}) = -\frac{G_F}{\sqrt{2}}f_h V_{tb}V_{td}^*(\frac{C_3}{3} + C_4 + \frac{C_9}{3} + C_{10} - R_2^h(\frac{C_5}{3} + C_6 + \frac{C_7}{3} + C_8))\left[G_1(m_h^2)(M_{\Lambda_b} + M_p) - G_3(m_h^2)m_h^2\right]$$

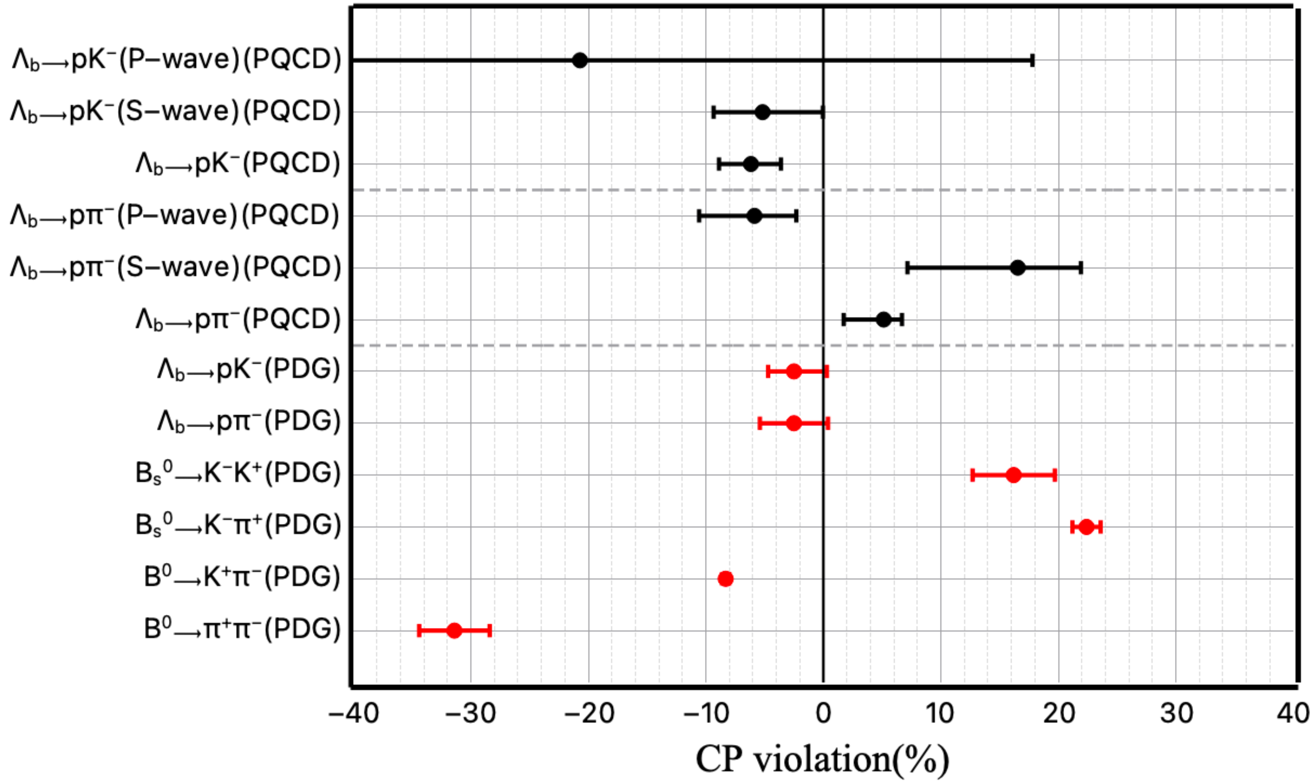
CPV of $\Lambda_b \to p\pi^-, pK^-$

$$A_{CP}^{dir} = \frac{-2A|f_1^T|^2 r_1 sin\Delta\phi sin\Delta\delta_1 - 2B|f_2^T|^2 r_2 sin\Delta\phi sin\Delta\delta_2}{A|f_1^T|^2(1+r_1^2+2r_1 cos\Delta\phi cos\Delta\delta_1) + B|f_2^T|^2(1+r_2^2+2r_2 cos\Delta\phi cos\Delta\delta_2)}$$

	$Br(\times 10^{-6})$	A_{CP}^{dir}	A_{CP}^{S}	A_{CP}^{P}		
$\Lambda_b \to p\pi^-$	$3.34^{+2.89}_{-1.71}$	$0.0514^{+0.0155}_{-0.0341}$	0.1655	-0.0586		
$\Lambda_b \to pK^-$	$2.83^{+3.33}_{-1.59}$	$-0.0616^{+0.0255}_{-0.0207}$	-0.0517	-0.2071		
	α	β	γ			
$\Lambda_b \to p\pi^-$	-0.9378	0.3351	0.0905			
$\Lambda_b \to pK^-$	0.2348	-0.3850	0.8926			
	a_{CP}^{α}	a_{CP}^{β}	a_{CP}^{γ}	$\langle\alpha\rangle$	$\langle\beta\rangle$	$\langle\gamma\rangle$
$\Lambda_b \to p\pi^-$	0.0241	0.2166	0.1123	-0.9620	0.1185	-0.0219
$\Lambda_b \to pK^-$	0.0382	-0.4391	0.0186	0.1966	0.0541	0.8740

TABLE X: Observables for the $\Lambda_b \to p\pi^-, pK^-$ decays.

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



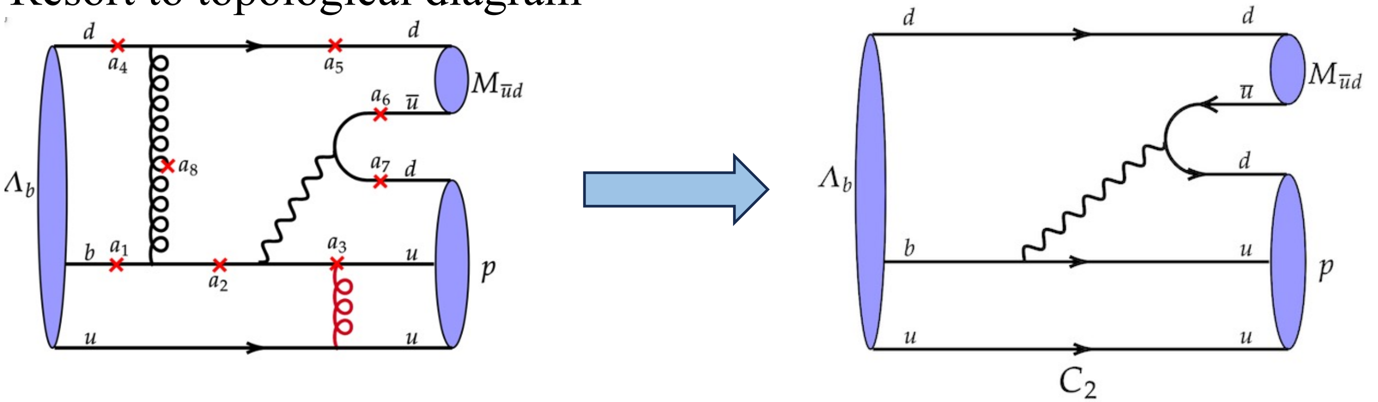
	PDG	GFA (Hsiao,Yao,Geng, 2017)	QCDF (Zhu,Ke,Wei, 2018)	PQCD(hybrid) (Lü,Wang,et.al., 2009)	LFQM (Geng,Liu,Tsai, 2021)	LCSR (Jiang,et.al., 2022)
$Br(\Lambda \to p\pi^-)\times 10^{-6}$	4.5 ± 0.8	$4.25^{+1.40}_{-1.05}$	$4.3^{+0.27}_{-0.19}$	$5.21^{+2.47}_{-1.93}$	4.18 ± 0.34	5.94
$Br(\Lambda \to pK^-)\times 10^{-6}$	5.4 ± 1.0	$4.49^{+1.06}_{-0.75}$	$2.17^{+0.98}_{-0.47}$	$2.02^{+0.96}_{-1.25}$	5.76 ± 0.91	6.50
$A_{CP}(\Lambda_b \to p\pi^-)\%$	-2.5 ± 2.9	-3.9 ± 0.4	-3.4 ± 0.4	-31^{+42}_{-1}	-3.6 ± 0.20	-1.8
$A_{CP}(\Lambda_b \to pK^-)\%$	-2.5 ± 2.2	6.7 ± 0.4	10.1 ± 2.0	-5^{+26}_{-5}	6.36 ± 0.28	-0.1

Signs between S- and P-wave

- PQCD approach

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

- Resort to topological diagram



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

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	-	+	-	+

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

Results 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

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

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

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

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

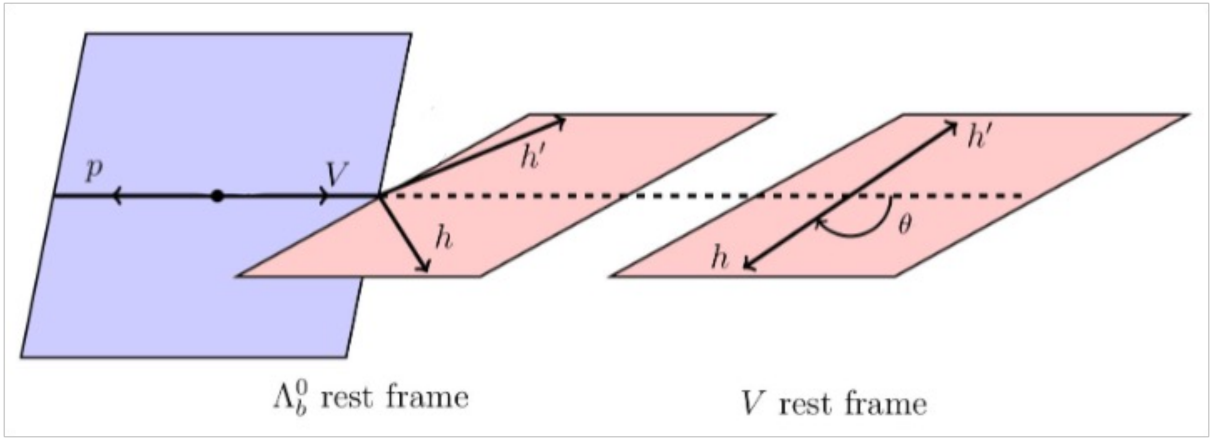
$$\mathcal{B} = \frac{p_c\tau_{\Lambda_b}}{8\pi m_i^2}(|H_{1/2,1}|^2 + |H_{-1/2,-1}|^2 + |H_{1/2,0}|^2 + |H_{-1/2,0}|^2).$$

Koener,Kramer,1992
Cheng,1996

	Real(A_1^L)	Imag(A_1^L)	Real(B_1^L)	Imag(B_1^L)	Real(A_2^L)	Imag(A_2^L)	Real(B_2^L)	Imag(B_2^L)	Real(A_1^T)	Imag(A_1^T)	Real(B_1^T)	Imag(B_1^T)
T_f	-162.20	0.00	222.31	0.00	58.98	0.00	-64.57	0.00	-162.20	0.00	222.31	0.00
T_{nf}	5.05	8.83	0.64	-17.28	-15.58	-172.86	-6.32	-25.32	1.52	-6.01	4.19	1.28
T	-157.15	8.83	222.95	-17.28	43.40	-172.86	-70.90	-25.32	-160.68	-6.01	226.51	1.28
C'	91.63	58.69	118.67	115.65	206.61	163.16	-209.59	-180.04	25.15	73.11	19.06	128.59
E_2	-23.49	197.98	41.40	-284.37	-67.94	529.91	-74.14	486.93	-29.91	182.78	44.33	-251.50
B	-4.74	-2.65	-13.35	9.86	-12.43	-4.05	13.59	-21.22	-5.47	-8.45	-10.04	-4.43
Tree	-93.75	262.86	369.67	-176.14	169.64	516.17	-341.04	260.36	-170.92	241.42	279.86	-126.06
$P_f^{C_1}$	-6.80	0.00	9.33	0.00	2.45	0.00	-2.66	0.00	-6.80	0.00	9.33	0.00
$P_{nf}^{C_1}$	0.19	0.63	0.42	-1.04	-0.45	-4.76	-0.57	-0.21	-0.71	-3.67	1.27	5.27
P^{C_1}	-6.61	0.63	9.74	-1.04	2.00	-4.76	-3.23	-0.21	-7.50	-3.67	10.60	5.27
P^{C_2}	4.55	-1.89	2.37	8.63	7.32	-9.69	-2.56	-9.65	1.32	2.65	-0.20	2.89
$P^{E_1^u}$	0.27	11.50	-0.99	-16.74	1.04	31.64	0.93	24.60	-0.85	8.45	0.64	-12.45
P^B	-1.46	0.22	-0.39	-0.24	-4.45	0.09	0.87	-0.02	-1.24	-0.48	0.45	-0.71
$P^{E_1^d}+P^{E_2}$	0.46	5.02	1.75	-23.57	1.97	14.30	-3.22	38.37	0.71	5.17	0.23	-12.35
Penguin	-2.80	15.47	12.49	-32.96	7.89	31.59	-7.22	53.08	-7.57	12.12	11.71	-17.36

	$\|A_1^L\|$	$\phi(A_1^L)^\circ$	$\|B_1^L\|$	$\phi(B_1^L)^\circ$	$\|A_2^L\|$	$\phi(A_2^L)^\circ$	$\|B_2^L\|$	$\phi(B_2^L)^\circ$	$\|A_1^T\|$	$\phi(A_1^T)^\circ$	$\|B_1^T\|$	$\phi(B_1^T)^\circ$
T_f	162.20	180.00	222.31	0.00	58.98	0.00	64.57	180.00	162.20	180.00	222.31	0.00
T_{nf}	10.18	60.24	17.29	-87.87	173.56	-95.15	26.10	-104.03	6.20	-75.84	4.38	16.92
T	157.39	176.78	223.62	-4.43	178.22	-75.91	75.28	-160.35	160.79	-177.86	226.51	0.32
C'	108.81	32.64	165.70	44.26	263.27	38.30	276.30	-139.34	77.31	71.02	130.00	81.57
E_2	199.37	96.77	287.37	-81.72	534.25	97.31	492.54	98.66	185.21	99.29	255.38	-80.00
B	5.43	-150.82	16.60	143.55	13.07	-161.96	25.19	-57.36	10.07	-122.92	10.97	-156.19
Tree	279.08	109.63	409.49	-25.48	543.33	71.81	429.06	142.64	295.80	125.30	306.95	-24.25
$P_f^{C_1}$	6.80	180.00	9.33	0.00	2.45	0.00	2.66	180.00	6.80	180.00	9.33	0.00
$P_{nf}^{C_1}$	0.66	73.47	1.12	-68.10	4.78	-95.43	0.61	-159.74	3.74	-100.92	5.42	76.46
P^{C_1}	6.64	174.56	9.80	-6.06	5.16	-67.20	3.24	-176.28	8.35	-153.95	11.83	26.43
P^{C_2}	4.92	-22.61	8.95	74.64	12.14	-52.92	9.99	-104.88	2.96	63.52	2.89	93.99
$P^{E_1^u}$	11.51	88.68	16.77	-93.38	31.66	88.11	24.61	87.84	8.49	95.75	12.47	-87.06
P^B	1.48	171.53	0.45	-148.68	4.45	178.88	0.87	-1.16	1.33	-158.77	0.84	-57.76
$P^{E_1^d}+P^{E_2}$	5.04	84.78	23.64	-85.75	14.44	82.15	38.51	94.79	5.22	82.23	12.35	-88.94
Penguin	15.72	100.26	35.25	-69.24	32.56	75.97	53.57	97.74	14.29	122.00	20.94	-55.99

TABLE XIII: Invariant amplitudes of the $\Lambda_b \to p\rho^-$ decay.



$$\mathcal{W}(\theta) \propto |H_{\frac{1}{2},0}|^2 + |H_{-\frac{1}{2},0}|^2 + |H_{-\frac{1}{2},-1}|^2 + |H_{\frac{1}{2},1}|^2 + (2|H_{\frac{1}{2},0}|^2 + 2|H_{-\frac{1}{2},0}|^2 - |H_{-\frac{1}{2},-1}|^2 - |H_{\frac{1}{2},1}|^2)P_2$$
$$\propto 1 + \frac{2|H_{\frac{1}{2},0}|^2 + 2|H_{-\frac{1}{2},0}|^2 - |H_{-\frac{1}{2},-1}|^2 - |H_{\frac{1}{2},1}|^2}{|H_{\frac{1}{2},0}|^2 + |H_{-\frac{1}{2},0}|^2 + |H_{-\frac{1}{2},-1}|^2 + |H_{\frac{1}{2},1}|^2} P_2$$
$$\propto 1 + \mathcal{J} \cdot P_2 \tag{83}$$

where $P_2 = (3cos^2\theta - 1)/2$ is the Legendre polynomial.

$$a_{CP}^{\mathcal{J}} = \frac{\mathcal{J} - \bar{\mathcal{J}}}{2} \tag{84}$$

$$\langle \mathcal{J} \rangle = \frac{\mathcal{J} + \bar{\mathcal{J}}}{2} \tag{85}$$

Wang,Qin,Yu,in progress

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

	$Br(\times 10^{-6})$	A_{CP}^{dir}			
$\Lambda_b \to p\rho^-$	$9.66^{+7.28}_{-4.85}$	$0.0305^{+0.0271}_{-0.0540}$			
$\Lambda_b \to pK^{*-}$	$2.82^{+1.97}_{-1.97}$	$-0.0513^{+0.0963}_{-0.1631}$			
	$A_{CP}^{S^T}$	$A_{CP}^{S^L+D}$	$A_{CP}^{P_1}$	$A_{CP}^{P_2}$	
$\Lambda_b \to p\rho^-$	0.0137	0.0190	0.0319	0.1747	
$\Lambda_b \to pK^{*-}$	−0.1524	0.2732	−0.2261	−0.1422	
	α	β	γ	Λ	$\mathcal{J}$
$\Lambda_b \to p\rho^-$	−0.8332	−0.9809	−0.1069	−0.9641	$1.6588^{+0.0616}_{-0.0720}$
$\Lambda_b \to pK^{*-}$	−1.0000	−0.8981	−0.1245	−0.9093	$1.6679^{+0.0439}_{-0.2302}$
	a_{CP}^{α}	a_{CP}^{β}	a_{CP}^{γ}	a_{CP}^{Λ}	$a_{CP}^{\mathcal{J}}$
$\Lambda_b \to p\rho^-$	−0.0081	0.0046	−0.1013	0.0039	$-0.0132^{+0.0141}_{-0.0152}$
$\Lambda_b \to pK^{*-}$	−0.0002	−0.0159	−0.1398	−0.0126	$0.0356^{+0.0603}_{-0.0772}$
	$\langle\alpha\rangle$	$\langle\beta\rangle$	$\langle\gamma\rangle$	$\langle\Lambda\rangle$	$\langle\mathcal{J}\rangle$
$\Lambda_b \to p\rho^-$	−0.8251	−0.9855	−0.0056	−0.9680	$1.6720^{+0.0589}_{-0.0714}$
$\Lambda_b \to pK^{*-}$	−0.9997	−0.8821	0.0154	−0.8967	$1.6323^{+0.0519}_{-0.2133}$

TABLE XI: Observables for the $\Lambda_b \to p\rho^-, pK^{*-}$ decays.

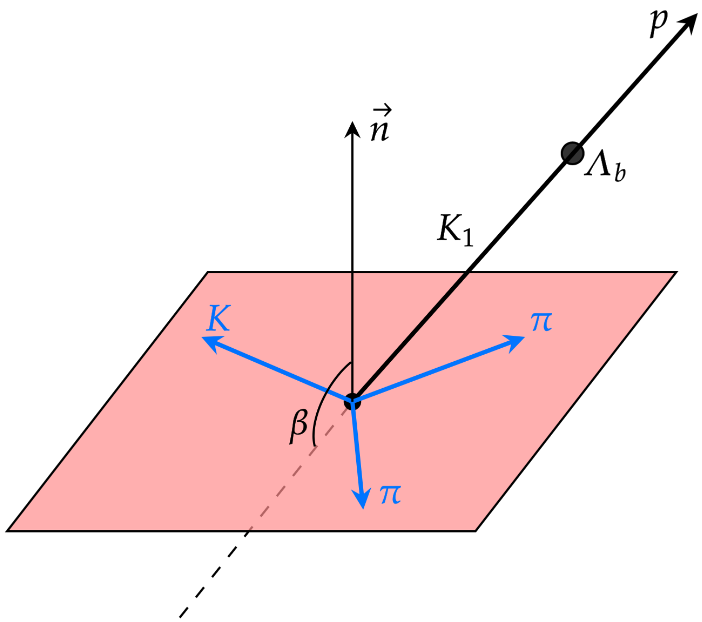
Results and CPVs of $\Lambda_b \to p a_1, p K_1(1270), p K_1(1400)$

Results of $\Lambda_b \to p a_1, p K_1$

$$\frac{dN}{d\Omega} \propto \frac{3}{4}\frac{\left(|H_{1/2,1}|^2+|H_{-1/2,-1}|^2\right)\frac{1+cos^2\beta}{2}+\left(|H_{1/2,0}|^2+|H_{-1/2,0}|^2\right)sin^2\beta}{|H_{\frac{1}{2},0}|^2+|H_{-\frac{1}{2},0}|^2+|H_{-\frac{1}{2},-1}|^2+|H_{\frac{1}{2},1}|^2} + \frac{3R_1^-}{4R_1^+}\frac{\left(|H_{1/2,1}|^2-|H_{-1/2,-1}|^2\right)cos\beta}{|H_{\frac{1}{2},0}|^2+|H_{-\frac{1}{2},0}|^2+|H_{-\frac{1}{2},-1}|^2+|H_{\frac{1}{2},1}|^2}$$

$$A_{UD} = \frac{\Gamma(cos\beta>0)-\Gamma(cos\beta<0)}{\Gamma(cos\beta>0)+\Gamma(cos\beta<0)} = \frac{3R_1^-}{4R_1^+}\frac{\left(|H_{1/2,1}|^2-|H_{-1/2,-1}|^2\right)}{\left(|H_{1/2,1}|^2+|H_{-1/2,-1}|^2+|H_{1/2,0}|^2+|H_{-1/2,0}|^2\right)} = \frac{3R_1^-}{4R_1^+}\cdot a_{UD}$$

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



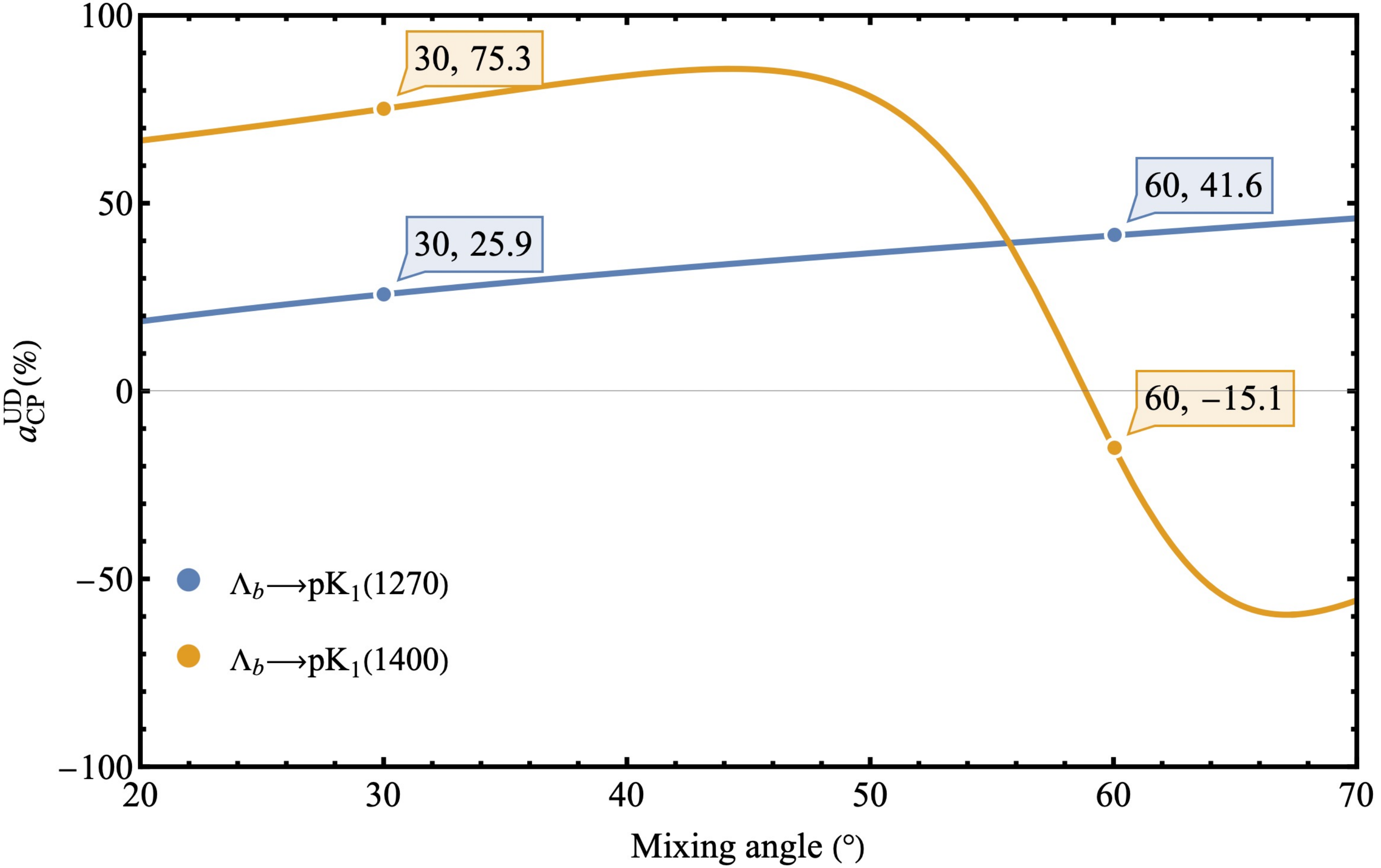
Wang,Qin,Yu,in progress

	$Br(\times 10^{-6})$	A_{CP}^{dir}			
$\Lambda_b \to p a_1^-(1260)$	$11.06^{+9.30}_{-5.45}$	$-0.0099^{+0.0443}_{-0.0260}$			
$\Lambda_b \to p K_1^-(1270)(\theta_K = 30^\circ)$	$5.48^{+4.82}_{-2.69}$	$0.0870^{+0.0801}_{-0.0511}$			
$\Lambda_b \to p K_1^-(1400)(\theta_K = 30^\circ)$	$1.25^{+0.94}_{-0.57}$	$0.0554^{+0.0701}_{-0.1050}$			
$\Lambda_b \to p K_1^-(1270)(\theta_K = 60^\circ)$	$6.28^{+5.22}_{-2.96}$	$0.0736^{+0.0466}_{-0.0614}$			
$\Lambda_b \to p K_1^-(1400)(\theta_K = 60^\circ)$	$0.53^{+0.62}_{-0.40}$	$0.0822^{+0.1892}_{-0.1456}$			
	$A_{CP}^{S^T}$	$A_{CP}^{S^L+D}$	$A_{CP}^{P_1}$	$A_{CP}^{P_2}$	
$\Lambda_b \to p a_1^-(1260)$	-0.2209	-0.1081	0.1820	-0.2399	
$\Lambda_b \to p K_1^-(1270)(\theta_K = 30^\circ)$	0.3447	-0.1078	0.1874	0.3320	
$\Lambda_b \to p K_1^-(1400)(\theta_K = 30^\circ)$	0.7103	0.8134	-0.4147	0.7796	
$\Lambda_b \to p K_1^-(1270)(\theta_K = 60^\circ)$	0.4567	0.0604	-0.0669	0.4621	
$\Lambda_b \to p K_1^-(1400)(\theta_K = 60^\circ)$	0.0687	-0.8204	0.5230	-0.2789	
	α	β	γ	Λ	a_{UD}
$\Lambda_b \to p a_1^-(1260)$	-0.8638	-0.9784	-0.1040	-0.9661	$-0.0928^{+0.0218}_{-0.0222}$
$\Lambda_b \to p K_1^-(1270)(\theta_K = 30^\circ)$	-0.9999	-0.9870	-0.2376	-0.9895	$-0.1920^{+0.0358}_{-0.0362}$
$\Lambda_b \to p K_1^-(1400)(\theta_K = 30^\circ)$	-0.9965	-0.1489	-0.6115	-0.4712	$-0.3790^{+0.1284}_{-0.1296}$
$\Lambda_b \to p K_1^-(1270)(\theta_K = 60^\circ)$	-0.9996	-0.9452	-0.3178	-0.9583	$-0.2411^{+0.0537}_{-0.0543}$
$\Lambda_b \to p K_1^-(1400)(\theta_K = 60^\circ)$	-0.9599	-0.0137	-0.0459	-0.0568	$-0.0438^{+0.0300}_{-0.0593}$
	a_{CP}^{α}	a_{CP}^{β}	a_{CP}^{γ}	a_{CP}^{Λ}	a_{CP}^{UD}
$\Lambda_b \to p a_1^-(1260)$	0.0164	-0.0060	-0.1432	-0.0057	$-0.2402^{+0.0753}_{-0.1277}$
$\Lambda_b \to p K_1^-(1270)(\theta_K = 30^\circ)$	-0.0000	-0.0034	-0.1825	-0.0035	$0.2589^{+0.0395}_{-0.1017}$
$\Lambda_b \to p K_1^-(1400)(\theta_K = 30^\circ)$	-0.0119	0.0667	-0.3385	-0.0727	$0.7213^{+0.1612}_{-0.2606}$
$\Lambda_b \to p K_1^-(1270)(\theta_K = 60^\circ)$	-0.0001	0.0032	-0.2166	-0.0009	$0.3993^{+0.0415}_{-0.0862}$
$\Lambda_b \to p K_1^-(1400)(\theta_K = 60^\circ)$	-0.0045	-0.2614	-0.0572	-0.2338	$-0.1878^{+0.1981}_{-0.3277}$

★ ★★

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

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



100
50
0
−50
−100
20
30
40
50
60
70
Mixing angle (°)
a_{CP}^{UD}(%)
30, 75.3
60, 41.6
30, 25.9
60, −15.1
$\Lambda_b \longrightarrow pK_1(1270)$
$\Lambda_b \longrightarrow pK_1(1400)$

Conclusion

PQCD applied to baryon decays well

High power contributions are important in baryon

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

Cancellation of partial wave CPV is found, and tested in Λ_b decays

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

Our PQCD calculation have No conflict with known measurements

CPVs and asymmetry observables of Λ_b decays are proposed and predicted

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

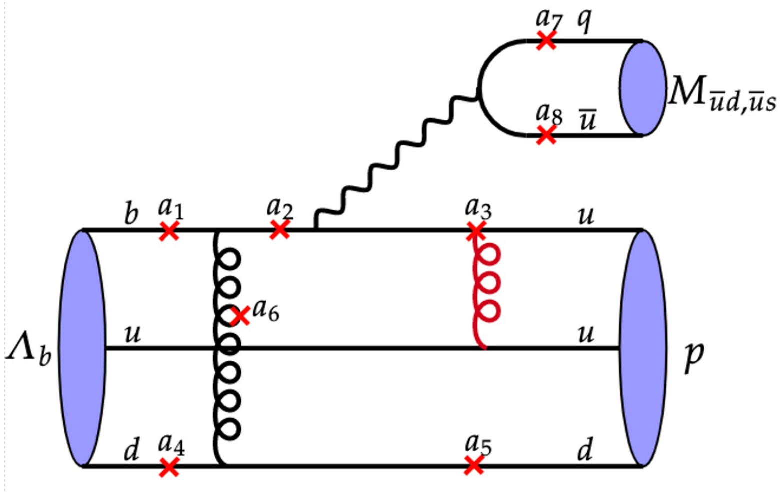
Backup

Progresses

- Baryon is different !
- Factorization: heavy-to-light form factor is factorizable at leading power in SCET and no end-point singularity appears! (Wang,2011)

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

- However, the leading-power results is one order smaller
  - Leading-power: $\xi_{\Lambda_b\to\Lambda}(0) = -0.012$(Wang,2011)
  - Total form factor: $\xi_{\Lambda_b\to\Lambda}(0) = 0.18$(Shen,Wang,2016)
- Two hard gluons suppressed by α_s^2 at leading power, compared to the soft contribution in the power correction



Λ_b two-body decays

$\Lambda_b \to pM_{\overline{u}q}(q = d, s)$

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

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

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

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

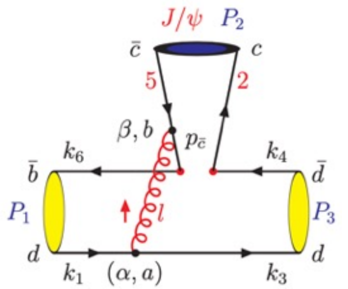
$$O_7 = \frac{3}{2}(\bar{q}_\alpha b_\alpha)_{V-A}\sum_{q'} e_{q'}(\bar{q}'_\beta q'_\beta)_{V+A}, \qquad O_8 = \frac{3}{2}(\bar{q}_\beta b_\alpha)_{V-A}\sum_{q'} e_{q'}(\bar{q}'_\alpha q'_\beta)_{V+A},$$

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

PQCD approach

Factorization hypothesis:

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



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

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

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

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

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

Sterman,Hsiang-nan Li,1995~2000

$\Lambda_b \to p$ form factors

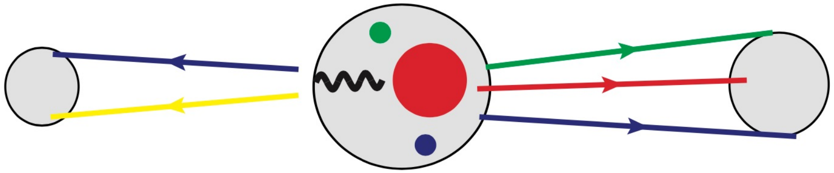
J.J.Han,Y.Li,Y.L.Shen,H.n.Li,Z.J.Xiao,F.S.Yu, Eur.Phys.J.C 82(2022)8,686

$$\langle N(p',s')|\bar{u}\gamma_\mu(1-\gamma_5)b|\Lambda_b(p,s)\rangle = \bar{N}(p',s')\left(f_1\gamma_\mu - if_2\sigma_{\mu\nu}q^\nu + f_3 q_\mu\right)\Lambda_b(p,s) - \bar{N}(p',s')\left(g_1\gamma_\mu - ig_2\sigma_{\mu\nu}q^\nu + g_3 q_\mu\right)\gamma_5\Lambda_b(p,s)$$

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

	$f_1(0)$	$f_2(0)$	$g_1(0)$	$g_2(0)$
NRQM [78]	0.043			
Heavy-LCSR [50]	$0.023^{+0.006}_{-0.005}$		$0.023^{+0.006}_{-0.005}$	
Light-LCSR-$\mathcal{A}$ [79]	$0.14^{+0.03}_{-0.03}$	$-0.054^{+0.016}_{-0.013}$	$0.14^{+0.03}_{-0.03}$	$-0.028^{+0.012}_{-0.009}$
Light-LCSR-$\mathcal{P}$ [79]	$0.12^{+0.03}_{-0.04}$	$-0.047^{+0.015}_{-0.013}$	$0.12^{+0.03}_{-0.03}$	$-0.016^{+0.007}_{-0.005}$
QCD-light-LCSR [80]	0.018	−0.028	0.018	−0.028
HQET-light-LCSR [80]	−0.002	−0.015		
Relativistic quark model [81]	0.169	0.009	0.196	−0.00004
3-point QSR [49]	0.22	0.0071		
Lattice [47]	0.22±0.08	0.04±0.12	0.12±0.14	0.04±0.31
PQCD [31]	$2.2^{+0.8}_{-0.5}\times 10^{-3}$			
This work (exponential)	0.27±0.12	0.008±0.005	0.31±0.16	0.014±0.008
This work (free parton)	0.24±0.10	0.007±0.004	0.27±0.13	0.014±0.010

Kinematics



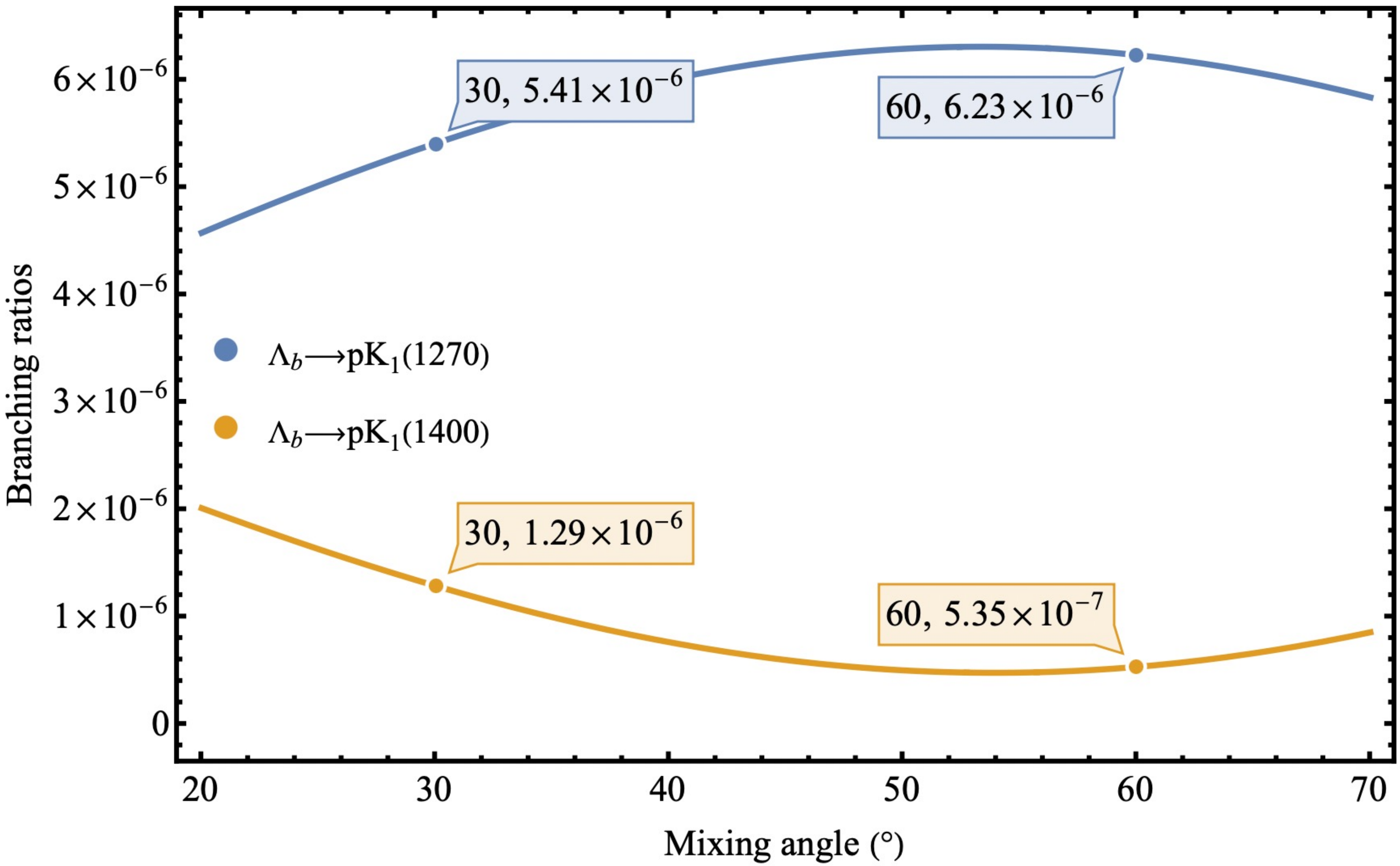
$$p_i = \frac{m_i}{\sqrt{2}}(1, 1, \mathbf{0}_T),$$
$$p_f = \frac{m_i}{\sqrt{2}}(\eta^+, \eta^-, \mathbf{0}_T),$$
$$q = p_i - p_f = \frac{m_i}{\sqrt{2}}(1-\eta^+, 1-\eta^-, \mathbf{0}_T),$$

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

for T, E and P diagrams

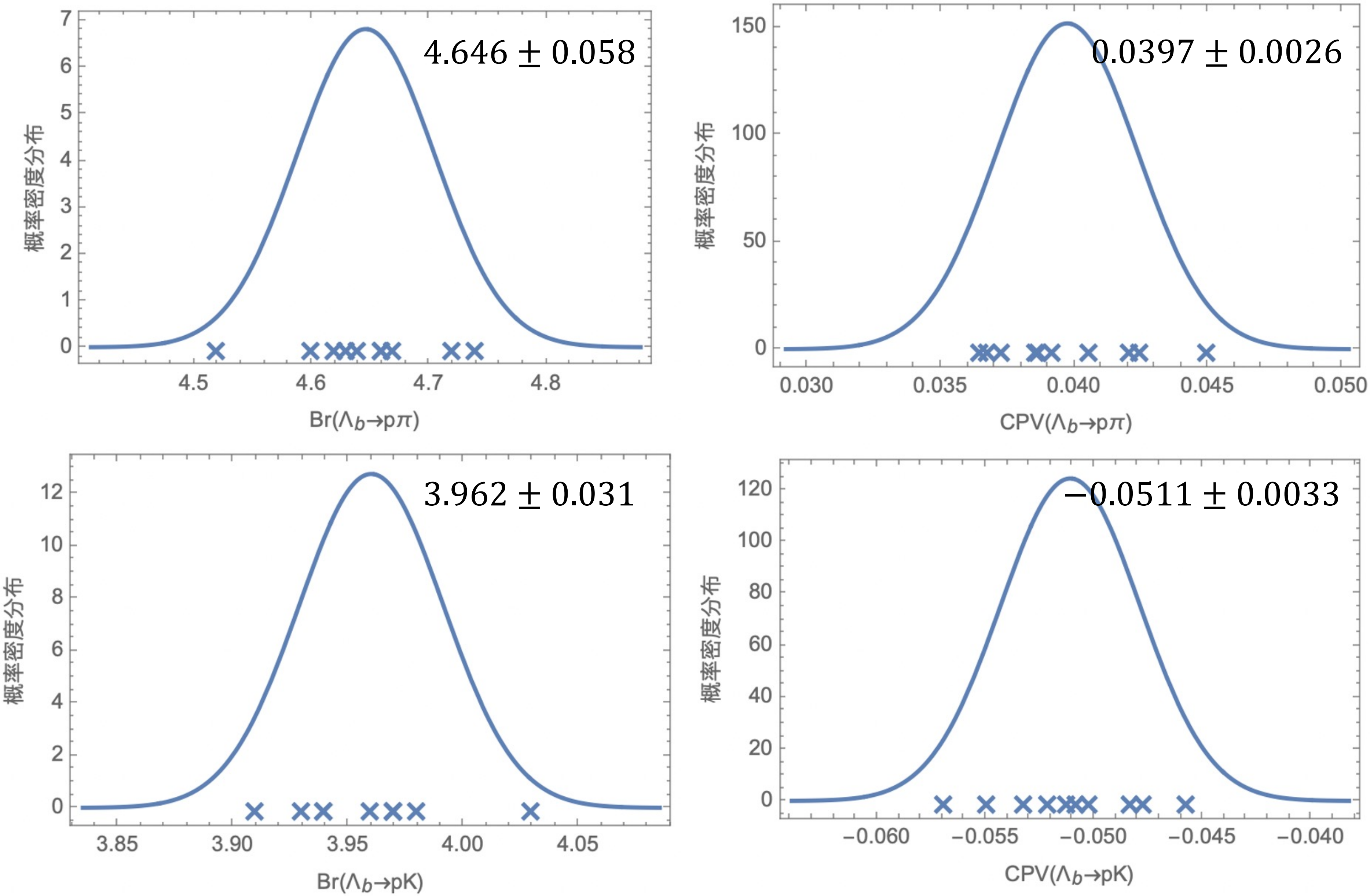
$$k_1 = (\frac{m_i}{\sqrt{2}}(1-x3), \frac{m_i}{\sqrt{2}}(1-x2), \boldsymbol{k}_{1T}), \quad k_2 = (0, \frac{m_i}{\sqrt{2}}x_2, \boldsymbol{k}_{2T}), \quad k_3 = (\frac{m_i}{\sqrt{2}}x_3, 0, \boldsymbol{k}_{3T})$$

for B and C' diagrams



Branching ratios
Mixing angle (°)
$\Lambda_b \longrightarrow pK_1(1270)$
$\Lambda_b \longrightarrow pK_1(1400)$
30, 5.41×10^{-6}
60, 6.23×10^{-6}
30, 1.29×10^{-6}
60, 5.35×10^{-7}
6×10^{-6}
5×10^{-6}
4×10^{-6}
3×10^{-6}
2×10^{-6}
1×10^{-6}
0
20
30
40
50
60
70

Error from MC integration



$\Lambda_b \to p\pi^-$	$\lvert S\rvert$	$\phi(S)^\circ$	Real(S)	Imag(S)	$\lvert P\rvert$	$\phi(P)^\circ$	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
C'	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^{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

$\Lambda_b \to p\pi^-$	$\lvert S\rvert$	$\phi(S)^\circ$	Real(S)	Imag(S)	$\lvert P\rvert$	$\phi(P)^\circ$	Real(P)	Imag(P)
T_f	1.98	0.00	1.98	0.00	2.77	0.00	2.77	0.00
T_{nf}	139.36	-93.94	-9.58	-139.03	192.66	-95.45	-18.31	-191.79
T	139.24	-93.13	-7.61	-139.03	192.42	-94.63	-15.55	-191.79
C'	1.44	-72.64	0.43	-1.37	1.92	-55.22	1.09	-1.58
E_2	7.35	-146.72	-6.14	-4.03	11.27	-15.07	10.88	-2.93
B	0.21	105.17	-0.06	0.21	0.29	98.41	-0.04	0.29
Tree	144.85	-95.30	-13.38	-144.23	196.04	-91.06	-3.61	-196.01
$P_f^{C_1}$	0.10	0.00	0.10	0.00	0.02	0.00	0.02	0.00
$P_{nf}^{C_1}$	3.84	-97.84	-0.52	-3.80	8.02	-93.91	-0.55	-8.00
P^{C_1}	3.83	-96.40	-0.43	-3.80	8.02	-93.74	-0.52	-8.00
P^{C_2}	2.28	-89.80	0.01	-2.28	3.32	87.14	0.17	3.32
$P^{E_1^u}$	0.80	24.57	0.73	0.33	1.27	-140.22	-0.98	-0.81
P^B	0.16	-45.07	0.11	-0.11	0.32	141.89	-0.25	0.20
$P^{E_1^d}+P^{E_2}$	0.16	-129.45	-0.10	-0.12	0.29	-55.86	0.16	-0.24
Penguin	6.00	-86.94	0.32	-5.99	5.71	-104.46	-1.43	-5.53

TABLE XI: Results of the $\Lambda_b \to p\pi^-$ decay.

only use proton and Λ_b leading twist LCDA

$\Lambda_b \to p\pi^-$	$\|S\|$	$\phi(S)^\circ$	Real(S)	Imag(S)	$\|P\|$	$\phi(P)^\circ$	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
C'	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^{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

TABLE VI: Results of the $\Lambda_b \to p\pi^-$ decay.

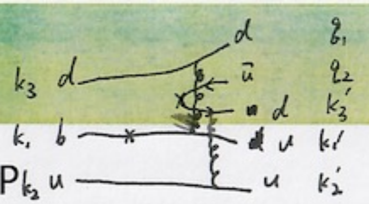
$\Lambda_b \to p\pi^-$	$\|S\|$	$\phi(S)^\circ$	Real(S)	Imag(S)	$\|P\|$	$\phi(P)^\circ$	Real(P)	Imag(P)
T_f	839.84	0.00	839.84	-0.00	850.10	0.00	850.10	-0.00
T_{nf}	62.83	-100.16	-11.08	-61.84	240.42	-97.09	-29.69	-238.58
C'	35.65	162.64	-34.02	10.64	32.99	-176.98	-32.95	-1.74
E_2	84.36	-141.20	-65.75	-52.86	51.84	128.88	-32.54	40.35
B	17.54	104.24	-4.32	17.00	13.74	-124.50	-7.78	-11.32
Tree	729.88	-6.85	724.66	-87.06	776.44	-15.79	747.14	-211.29
$P_f^{C_1}$	67.66	0.00	67.66	0.00	2.61	0.00	2.61	0.00
$P_{nf}^{C_1}$	1.83	-109.17	-0.60	-1.73	9.87	-92.94	-0.51	-9.86
P^{C_2}	17.24	-116.06	-7.57	-15.49	13.63	67.60	5.19	12.60
$P^{E_1^u}$	11.22	-90.55	-0.11	-11.22	7.06	112.49	-2.70	6.52
P^B	1.30	-42.87	0.96	-0.89	1.40	-170.77	-1.38	-0.22
$P^{E_1^d} + P^{E_2}$	4.68	-101.65	-0.95	-4.59	1.62	-12.75	1.58	-0.36
Penguin	68.39	-29.72	59.39	-33.91	9.92	61.02	4.81	8.68

TABLE VI: Results of the $\Lambda_b \to p\pi^-$ decay.

Hard kernel only contain leading power of M_{Λ_b}

	$Br(\times 10^{-6})$	A_{CP}^{dir}	A_{CP}^{S}	A_{CP}^{P}	$A_{CP}^{H_{1/2,0}}$	$A_{CP}^{H_{-1/2,0}}$
$\Lambda_b \to p\pi^-$	3.34	0.0514	0.1655	−0.0586	0.6567	0.03922
$\Lambda_b \to p\pi^-(LP)$	3.65	0.0897	0.1733	−0.0619	0.8074	0.0597
	α	β	γ			
$\Lambda_b \to p\pi^-$	−0.9378	0.3351	0.0905			
$\Lambda_b \to p\pi^-(LP)$	−0.8662	0.3121	0.3902			
	a_{CP}^{α}	a_{CP}^{β}	a_{CP}^{γ}	$\langle\alpha\rangle$	$\langle\beta\rangle$	$\langle\gamma\rangle$
$\Lambda_b \to p\pi^-$	0.0241	0.2166	0.1123	−0.9620	0.1185	−0.0219
$\Lambda_b \to p\pi^-(LP)$	0.0582	0.1895	0.1085	−0.9244	0.1226	0.2816

C14 S-P*S+P



$l_1 = q_1 - k_3$

$l_2 = k_2 - k_2'$

$P_1 = k_3' - k_2 + k_2'$

$P_2 = q_1 - k_3 + k_3' - k_2 + k_2'$

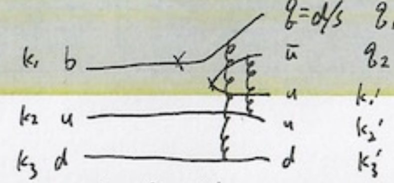
Ⅱ 因子 Λ_b twist4 + proton twist 4 + meson twist2

$(\bar{N}^- \gamma_5)_{proton} \gamma_\rho (\not k_3' - \not k_2 + \not k_2') \gamma_\alpha (\not q_1 - \not k_3 + \not k_3' - \not k_2 + \not k_2')(S+P)(\gamma_5 \not q_1 \not p_\pi^{(A)})_{meson} \gamma^\alpha$

$\cdot (\not p \gamma_5)_{\Lambda_b} \gamma^\rho (\not p')_{proton} (S-P) u_{\Lambda_b}$

π twist-2($*\phi_\pi^A M_{\Lambda_b}^4$)				
S-wave	proton twist-3($*r^0$)	proton twist-4($*r^1$)	proton twist-5($*r^2$)	proton twist-6($*r^3$)
Λ_b ($*\psi_2$)	0	$-8(A_2+A_3+V_2-V_3)$ $x_2(x_2'-x_3+x_3')$	$-8(A_4+A_5-V_4+V_5)$ $x_2(x_2'-x_3+x_3')$	0
Λ_b ($*\psi_3^{+-}$)	0	0	$-4(P_2-S_2-T_4-T_8)$ $(x_2'+x_3')(x_2'-x_3+x_3')$	$8T_6(x_2'+x_3')$ $(x_2'-x_3+x_3')$
Λ_b ($*\psi_3^{-+}$)	$-8T_1x_2$ $(x_2'-x_3+x_3')$	$4(P_1-S_p-T_3-T_7)$ $x_2(x_2'-x_3+x_3')$	0	0
Λ_b ($*\psi_4$)	0	-1.59/-12.67 $8(A_2+A_3+V_2-V_3)$ $(x_2'+x_3')(x_2'-x_3+x_3')$	-0.488/-1.878 $8(A_4+A_5-V_4+V_5)$ $(x_2'+x_3')(x_2'-x_3+x_3')$	0
P-wave	proton twist-3($*r^0$)	proton twist-4($*r^1$)	proton twist-5($*r^2$)	proton twist-6($*r^3$)
Λ_b ($*\psi_2$)	0	$8(A_2+A_3+V_2-V_3)$ $x_2(x_2'-x_3+x_3')$	$-8(A_4+A_5-V_4+V_5)$ $x_2(x_2'-x_3+x_3')$	0
Λ_b ($*\psi_3^{+-}$)	0	0	$4(P_2-S_2-T_4-T_8)$ $(x_2'+x_3')(x_2'-x_3+x_3')$	$8T_6(x_2'+x_3')$ $(x_2'-x_3+x_3')$
Λ_b ($*\psi_3^{-+}$)	$8T_1x_2$ $(x_2'-x_3+x_3')$	$4(P_1-S_p-T_3-T_7)$ $x_2(x_2'-x_3+x_3')$	0	0
Λ_b ($*\psi_4$)	0	4.5d0/17.30 $-8(A_2+A_3+V_2-V_3)$ $(x_2'+x_3')(x_2'-x_3+x_3')$	-0.58/-2.61 $8(A_4+A_5-V_4+V_5)$ $(x_2'+x_3')(x_2'-x_3+x_3')$	0

TN 7 V-A ⊗ V-A O_3 and O_4



Λ_b twist 3^{-+} proton twist3 meson twist2

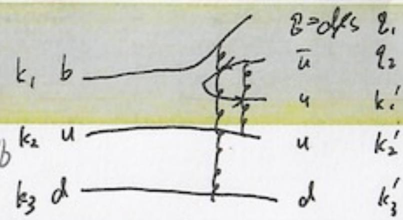
$(\bar{N}^{+}\gamma_5)_{proton}\,\gamma_\rho\,(\ldots)_{\Lambda_b}\,\gamma_\sigma\,(\ldots)_{proton}\,(V-A)(q_2+k_2'-k_2)\,\gamma^\sigma\,(\gamma_5 \ldots)_{meson}$

$\cdot\,\gamma^\rho(q_1+k_3'-k_3)\cdot(V-A)\cdot u_{\Lambda_b}$

$p_1 = q_1 + k_3' - k_3$
$p_2 = q_2 + k_2' - k_2$
$l_1 = k_3' - k_3$
$l_2 = k_2' - k_2$

π twist-2				
S-wave	Proton t-3	Proton t-4	Proton t-5	Proton t-6
Lb t-2	-0.069/-4.32 $-16(A_1-2T_1-V_1)(x_3-y)(x_2+y-1)$	-0.037/-0.243	0.001/0.024	0/-0.014
Lb t-3+-	0/0	0.150/0.726	0.048/0.219	0/0
Lb t-3-+	0.103/5.79 $8(A_1+V_1)x_2'(x_3-y)$	0/0.001	0.040/0.232	0/0
Lb t-4	-0.001/-0.007	-0.129/-1.919	0/0	0/0
P-wave				
Lb t-2	0.458/-6.09 $-16(A_1-2T_1-V_1)(x_3-y)(x_2+y-1)$	0.038/0.479	0.001/0.016	0.003/0.09
Lb t-3+-	0/0	0.065/0.910	-0.037/-0.398	0/0
Lb t-3-+	0.062/-7.44 $-8(A_1+V_1)x_2'(x_3-y)$	0/0.002	-0.007/-0.327	0/0
Lb t-4	0/-0.009	-0.076/2.622	0/0	0/0

TW 7 V-A⊗V+A O_5 and O_6



正…子 Λ_b twist 4 proton twist 3 meson twist 3

$(\bar{N}^{T}\gamma_5)_{proton}\,\gamma_\rho(\not{P}\gamma_5)_{\Lambda b}\,\gamma_\sigma(\not{P}')_{proton}(V+A)(\not{q}_2+\not{k}_2'-\not{k}_2)\gamma^\sigma$

$\cdot(m_0\phi_m^P\gamma_5+m_0\phi_m^T\gamma_5(\not{n}\not{v}-1))_{meson}\cdot\gamma^\rho(\not{q}_1+\not{k}_3'-\not{k}_3)(V-A)\,u_{\Lambda b}$

$p_1 = q_1 + k_3' - k_3$

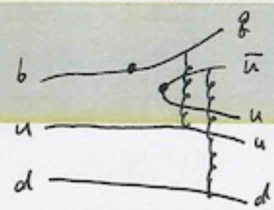
$p_2 = q_2 + k_2' - k_2$

$l_1 = k_3' - k_3$

$l_2 = k_2' - k_2$

π twist-3				
S-wave	Proton t-3	Proton t-4	Proton t-5	Proton t-6
Lb t-2	0/0	0/0	0.006/0.067	0.001/0.008
Lb t-3+-	0/0	-0.073/-1.549	-0.021/-0.143	0/0
Lb t-3-+	0/0	-0.089/-1.333	-0.148/-0.232	0/0
Lb t-4	0.260/2.222 $16\cdot\{2T_1 x_3'(-1+x_2+y)(\phi_m^P-\phi_m^T)$ $-A_1 x_2'(x_3-y)(\phi_m^P+\phi_m^T)+V_1 x_2'(x_3-y)(\phi_m^P+\phi_m^T)\}$	0.048/0.350	0/0	0/0
P-wave				
Lb t-2	0/0	0/0	-0.011/-0.103	0.001/0.011
Lb t-3+-	0/0	0.522/2.318	-0.049/-0.184	0/0
Lb t-3-+	0/0	0.118/1.755	-0.041/-0.427	0/0
Lb t-4	-0.389/-3.056 $-16\{\ \cdots\cdots\ \}$	0.014/0.474	0/0	0/0

$TNll$ $V-A \otimes V-A$ O_3 and O_4



$P_1 = q_1 + k_2' - k_2$ $l_1 = k_2' - k_2$

$P_2 = q_2 + k_3' - k_3$ $l_2 = k_3' - k_3$

正向 Λ_b twist 2 proton twist 3 meson twist 2

$$(\bar{V}^+ \gamma_5)_{proton} \gamma_\rho (\not{p} \gamma_5)_{\Lambda b} \gamma_\rho (\not{p}')_{proton} (V-A)(\not{q}_2 + \not{k}_3' - \not{k}_3)\gamma^\sigma (\gamma_5 \not{q} \phi_m^A)_{meson}$$

$$\cdot \gamma^\rho (\not{q}_1 + \not{k}_2' - \not{k}_2)(V-A)\, u_{\Lambda b}$$

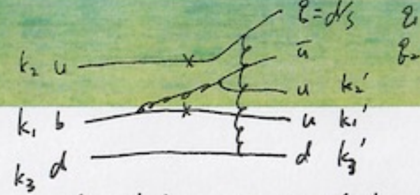
π twist-2				
S-wave	Proton t-3	Proton t-4	Proton t-5	Proton t-6
Lb t-2	-0.336/-4.076 $-16(A_1-2T_1-V_1)(x_2-y)(x_3+y-1)$	0.061/0.883	0/0.081	0/-0.005
Lb t-3+-	0.025/-1.14	0/0.001	0.012/0.180	0/0
Lb t-3-+	0/0	-0.008/-1.385	0.002/0.130	0/0
Lb t-4	0/-0.005	0.001/-0.647	0/0	0/0
P-wave				
Lb t-2	0.194/-3.886 $-16(A_1-2T_1-V_1)(x_2-y)(x_3+y-1)$	-0.019/-1.147	0.004/0.137	0.001/0.007
Lb t-3+-	-0.18/1.17	0/0.001	-0.021/-0.245	0/0
Lb t-3-+	0/0	-0.109/-1.842	-0.016/-0.201	0/0
Lb t-4	0/-0.007	0.106/0.979	0/0	0/0

Λ_b twist4 proton twist4 meson twist2

$(\bar{N}\gamma_5)_{proton}\gamma_\sigma(\not{h}\gamma_5)_{\Lambda_b}\gamma^\sigma(\not{k}_2-\not{k}_3'+\not{k}_3)\gamma_\rho(\not{k}_2-\not{k}_3'+\not{k}_3-\not{l}_2-\not{k}_2')(S+P)$

$(\bar{\chi}\gamma_5\phi_m^A)_{meson}\gamma^\rho(\not{P}')_{proton}(S-P)u_{\Lambda_b}$

E b   S-P ⊗ S+P O_5 and O_6



$l_1=k_3'-k_3$ $p_1=k_2-k_3'+k_3$

$l_2=l_2+k_2'$ $p_2=k_2-k_3'+k_3-l_2-k_2'$

π twist-2				
S-wave	Proton t-3	Proton t-4	Proton t-5	Proton t-6
Lb t-2	0/0	0.004/0.269	-0.003/0.098	0/0
Lb t-3+-	-0.171/-1.498 $4(A_1-V_1)(x_2+x_3)(x_2'+x_3')$	-0.071/-0.387	0.014/0.139	0.001/0.008
Lb t-3-+	-0.037/-0.786	0.001/-0.161	0.018/0.068	0/0.003
Lb t-4	0/0	-0.21/-2.02 $8(A_3-V_3)x_3'(x_2'+x_3')$	-0.016/-0.203	0/0
P-wave				
Lb t-2	0/0	-0.034/-0.378	-0.013/0.137	0/0
Lb t-3+-	0.331/2.112	0.071/-0.568	-0.024/-0.201	0.002/0.011
Lb t-3-+	0.267/1.133	0.001/-0.223	-0.011/-0.096	0.001/0.005
Lb t-4	0/0	-0.657/2.89	-0.037/-0.281	0/0