Form Factors of $\Lambda_b \to p$ *in PQCD*

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Outline

- Motivation
- Framework
- Form factors at $q^2 = 0$
- Observables
- Summary

Motivation

Predict CPV in b-baryon decay

- Matter-antimatter asymmetry in universe

实验值： $Y_B^{obs} = 8.59 \times 10^{-11}$

理论值： $Y_B^{SM} \simeq 7 \times 10^{-20}$

- *Planck Collaboration (2016)*

- Sakharov three requirements:
  - baryon number violation
  - C and CP violation
  - Out of thermal equilibrium

- *Sakharov (1967)*

- CP violation in K-, B-, D-meson have been confirmed by B-factories and LHCb.

- However, CPV in baryons is not found experimentally by now. Evidence was reported by LHCb

Motivation

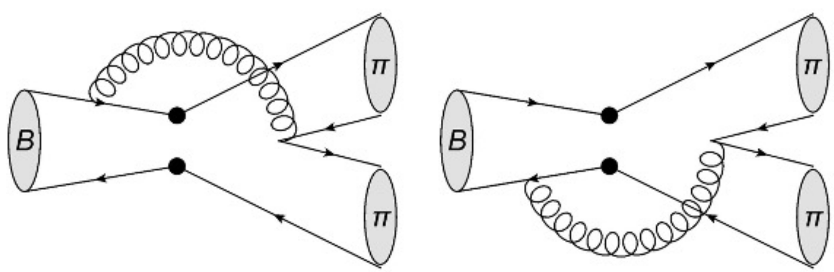
PQCD to predict CPV in B meson

- Direct CPV requires two kinds of decay amplitudes with different weak phases and ***different strong phases***.

$$A_{CP} = \frac{2r\sin\delta\sin\phi}{1+r^2+2r\cos\delta\cos\phi}$$

Direct CPV(%)	FA	BBNS	PQCD	exp.
$B\to\pi^+\pi^-$	-5 ± 3	-6 ± 12	$+30\pm20$	$+32\pm4$
$B\to K^+\pi^-$	$+10\pm3$	$+5\pm9$	-17 ± 5	-8.3 ± 0.4

- Annihilation diagrams can be evaluated well in PQCD.



Motivation

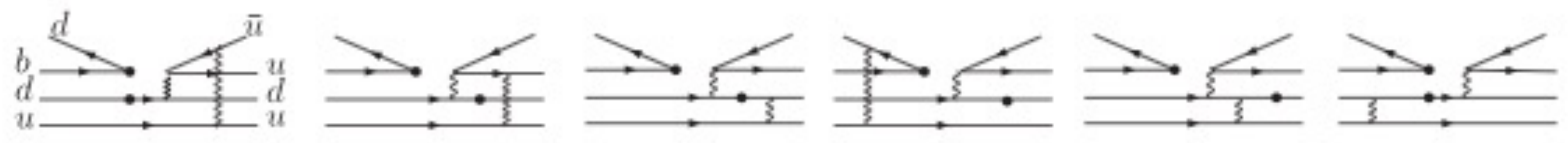
W-exchange/annihilation diagrams in $\Lambda_b \to p\pi$

- W-exchange diagrams (E) *40

- ***Cai-Dian Lu, Yu-Ming Wang, Hao zou (2009)***

- Bow-tie diagrams (B) *40

- Penguin annihilation (P) *40



- There are many W-exchange/annihilation diagrams of Λ_b two-body decay.

Motivation

- Current situation of PQCD calculation for Λ_b decay:
  - ***[1] Nsiang-Nan Li, (1993), Sudakov suppression and the proton form factors***
  - ***[2] B.Kundu, Nsiang-Nan Li, et,al. (1999), The perturbative proton form-factor reexamined***
  - ***[3] H.H.Shih, S.C.Lee, Hsiang-Nan Li, (1998), The $\Lambda_b \to pl\nu$ decay in PQCD***
  - ***[4] Cai-Dian Lv, Yu-Ming Wang, Hao Zou, (2009), $\Lambda_b \to p\pi,\ pK$ decays in PQCD***

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

	LCSR[5]	Lattice[6]	PQCD[3]	PQCD[4]
Form factor $f_1(q^2 = 0)$	0.14 ± 0.03	0.22 ± 0.08	2.3×10^{-3}	$2.2^{+0.8}_{-0.5}\times10^{-3}$

[5] A.Khodjamirian, C.Klein, T.Mannel, Yu-Ming Wang (2011)
[6] W.Detmold, C.Lehner, S.Meinel (2015)

Factorization of Heavy-to-Light Baryonic Transitions in SCET

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Abstract

In the framework of the soft-collinear effective theory, we demonstrate that the leading-power heavy-to-light baryonic form factors at large recoil obey the heavy quark and large energy symmetries. Symmetry breaking effects are suppressed by Λ/m_b or Λ/E, where Λ is the hadronic scale, m_b is the b quark mass and $E \sim m_b$ is the energy of light baryon in the final state. At leading order, the leading power baryonic form factor $\xi_{\Lambda,p}(E)$, in which two hard-collinear gluons are exchanged in the baryon constituents, can factorize into the soft and collinear matrix elements convoluted with a hard-kernel of order α_s^2. Including the energy release dependence, we derive the scaling law $\xi_{\Lambda,p}E) \sim \Lambda^2/E^2$. We also find that this form factor $\xi_\Lambda(E)$ is numerically smaller than the form factor governed by soft processes, although the latter is formally power-suppressed.

- Leading power is smaller than the results from sum rules.

Leading power $\xi_\Lambda(q^2=0)$	$-0.012^{+0.009}_{-0.023}$
Sum rules (Feldman, Yip, 2011)	0.38

- Including high twist light-cone distribution amplitudes.

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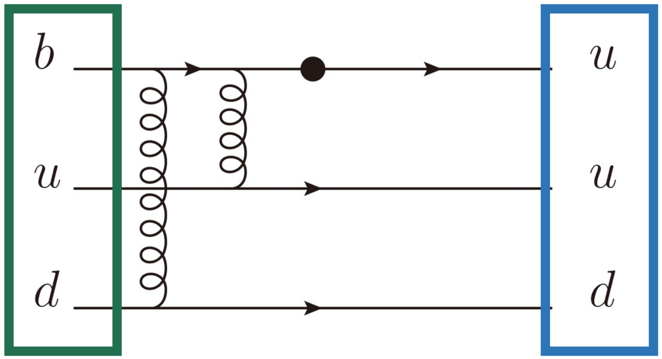
Framework

- Parameterization of this hadronic matrix

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

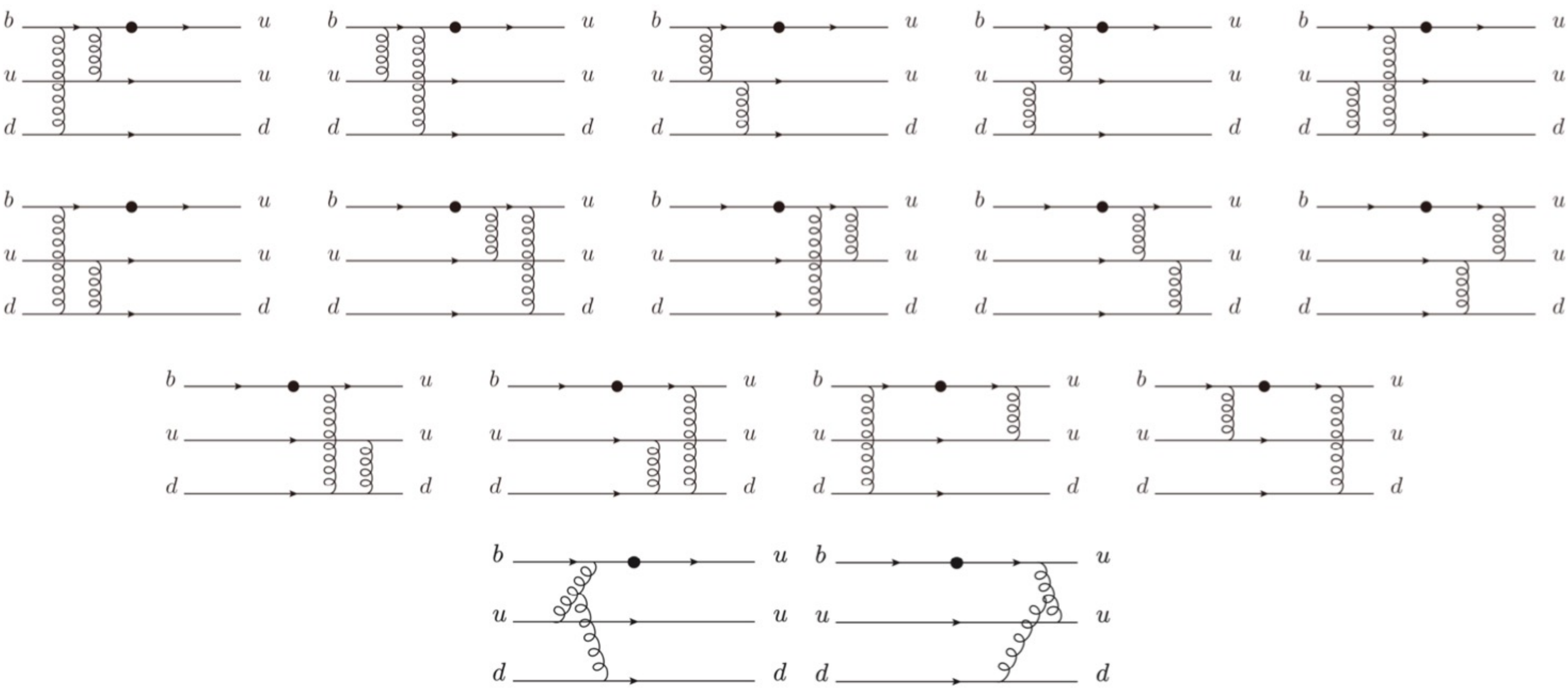
- Transition form factor can be expressed as the convolution of hadronic wave functions ψ_{Λ_b}、 ψ_p and the hard-scattering amplitude T_H

$$F = \int_0^1 [dx][dx'] \int [d^2\mathbf{k}_T] \int [d^2\mathbf{k}'_T] \psi_p(x', \mathbf{k}'_T, p', \mu) \times T_H(x, x', M_{\Lambda_b}, \mathbf{k}_T, \mathbf{k}'_T, \mu) \psi_{\Lambda_b}(x, \mathbf{k}_T, p, \mu),$$



Framework

Diagrams for $\Lambda_b \to p$ under PQCD



Λ_b wave function

$$(Y_{\Lambda_b})_{\alpha\beta\gamma}(k_i,\mu) = \frac{1}{2\sqrt{2}} \int \prod_{l=2}^{3} \frac{dw_l^- d\mathbf{w}_l}{(2\pi)^3} e^{ik_l\cdot w_l} \epsilon^{ijk} \langle 0|T[b^i_\alpha(0) u^j_\beta(w_2) d^k_\gamma(w_3)]|\Lambda_b(p)\rangle$$

- By using Bargmann-Wigner equation in the heavy quark limit

$$\Phi^{\alpha\beta\gamma}_{\Lambda_b} \equiv \langle 0|T[b^i_\alpha(0) u^j_\beta(z_2) d^k_\gamma(z_3)]|\Lambda_b(p)\rangle = \frac{f_{\Lambda_b}}{4}[(\not p + M_{\Lambda_b})\gamma_5 C]_{\beta\gamma}[\Lambda_b(p)]_\alpha \Psi(k_i,\mu)$$

Simplified Λ_b LCDA

$$\Psi(k_i,\mu) = N x_1 x_2 x_3 exp\left(-\frac{M^2_{\Lambda_b}}{2\beta^2 x_1} - \frac{m_l^2}{2\beta^2 x_2} - \frac{m_l^2}{2\beta^2 x_3}\right)$$

- ***F.Hussain, J.G.Korner, M.Kramer, G.Thompson (1991) & F.Schlumpf (1992)***

- General light-cone hadronic matrix element of Λ_b baryon

General Λ_b LCDA

$$\Phi^{\alpha\beta\delta}_{\Lambda_b}(t_1,t_2) \equiv \epsilon_{ijk}\langle 0|[u_i^T(t_1\bar n)]_\alpha[0,t_1\bar n][d_j(t_2\bar n)]_\beta[0,t_2\bar n][b_k(0)]_\delta|\Lambda_b(v)\rangle$$
$$= \frac{1}{4}\left\{ f^{(1)}_{\Lambda_b}(\mu)[\tilde M_1(v,t_1,t_2)\gamma_5 C^T]_{\beta\alpha} + f^{(2)}_{\Lambda_b}(\mu)[\tilde M_2(v,t_1,t_2)\gamma_5 C^T]_{\beta\alpha}\right\}[\Lambda_b(v)]_\delta \quad (23)$$

$$M_1(\omega_1,\omega_2) = \frac{\not{\bar n}\not n}{4}\psi_3^{+-}(\omega_1,\omega_2) + \frac{\not n\not{\bar n}}{4}\psi_3^{-+}(\omega_1,\omega_2) \qquad M_2(\omega_1,\omega_2) = \frac{\not n}{\sqrt{2}}\psi_2(\omega_1,\omega_2) + \frac{\not{\bar n}}{\sqrt{2}}\psi_4(\omega_1,\omega_2)$$

- ***G.Bell, T.Feldmann, Yu-Ming Wang, M.W.Y.Yip (2013)***

(Exponential model)

$$\psi_2(\omega_1,\omega_2) = \frac{\omega_1\omega_2}{\omega_0^4} e^{-(\omega_1+\omega_2)/\omega_0},$$
$$\psi_3^{+-}(\omega_1,\omega_2) = \frac{2\omega_1}{\omega_0^3} e^{-(\omega_1+\omega_2)/\omega_0},$$
$$\psi_3^{-+}(\omega_1,\omega_2) = \frac{2\omega_2}{\omega_0^3} e^{-(\omega_1+\omega_2)/\omega_0},$$
$$\psi_4(\omega_1,\omega_2) = \frac{1}{\omega_0^2} e^{-(\omega_1+\omega_2)/\omega_0}.$$

- ***G.Bell, T.Feldmann, Yu-Ming Wang, M.W.Y.Yip (2013)***

(Free parton model)

$$\psi_2(\omega_1,\omega_2) = \frac{15\omega_1\omega_2(2\bar\Lambda - \omega_1 - \omega_2)}{4\bar\Lambda^5}\Theta(2\bar\Lambda - \omega_1 - \omega_2),$$
$$\psi_3^{+-}(\omega_1,\omega_2) = \frac{15\omega_1(2\bar\Lambda - \omega_1 - \omega_2)^2}{4\bar\Lambda^5}\Theta(2\bar\Lambda - \omega_1 - \omega_2),$$
$$\psi_3^{-+}(\omega_1,\omega_2) = \frac{15\omega_2(2\bar\Lambda - \omega_1 - \omega_2)^2}{4\bar\Lambda^5}\Theta(2\bar\Lambda - \omega_1 - \omega_2),$$
$$\psi_4(\omega_1,\omega_2) = \frac{5(2\bar\Lambda - \omega_1 - \omega_2)^3}{8\bar\Lambda^5}\Theta(2\bar\Lambda - \omega_1 - \omega_2). \quad (4$$

LCDAs of baryons

Proton wave function

➢ ***V.M.Braun, R.J.Fries, N.Mahnke, E.Stein (2001)***

$$(Y_{proton})_{\alpha\beta\gamma}(k_i',\mu) = \frac{1}{2\sqrt{2}N_c}\int\prod_{l=2}^{3}\frac{dz_l^+ d\mathbf{z}_l}{(2\pi)^3}e^{ik_i'\cdot z_i}\epsilon^{ijk}\ \langle 0|T[u_\alpha^i(0)u_\beta^j(z_2)d_\gamma^k(z_3)]|\mathcal{P}(p')\rangle$$

$$\begin{aligned}
\bar{\Phi}^{\alpha\beta\gamma}_{proton} \equiv&\langle\mathcal{P}(p')|\bar{u}^i_\alpha(0)\bar{u}^j_\beta(z_1)\bar{d}^k_\gamma(z_2)|0\rangle\\
=&\frac{1}{4}\{S_1 m_p C_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma + S_2 m_p C_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma + P_1 m_p (C\gamma_5)_{\beta\alpha}\bar{N}^+_\gamma + P_2 m_p (C\gamma_5)_{\beta\alpha}\bar{N}^-_\gamma + V_1(C\not{P})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma\\
&+ V_2(C\not{P})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma + V_3\frac{m_p}{2}(C\gamma_\perp)_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma + V_4\frac{m_p}{2}(C\gamma_\perp)_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma + V_5\frac{m_p^2}{2Pz}(C\not{z})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma\\
&+ V_6\frac{m_p^2}{2Pz}(C\not{z})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma + A_1(C\gamma_5\not{P})_{\beta\alpha}(\bar{N}^+)_\gamma + A_2(C\gamma_5\not{P})_{\beta\alpha}(\bar{N}^-)_\gamma + A_3\frac{m_p}{2}(C\gamma_5\gamma_\perp)_{\beta\alpha}(\bar{N}^+\gamma^\perp)_\gamma\\
&+ A_4\frac{m_p}{2}(C\gamma_5\gamma_\perp)_{\beta\alpha}(\bar{N}^-\gamma^\perp)_\gamma + A_5\frac{m_p^2}{2Pz}(C\gamma_5\not{z})_{\beta\alpha}(\bar{N}^+)_\gamma + A_6\frac{m_p^2}{2Pz}(C\gamma_5\not{z})_{\beta\alpha}(\bar{N}^-)_\gamma - T_1(iC\sigma_{\perp P})_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma\\
&- T_2(iC\sigma_{\perp P})_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma - T_3\frac{m_p}{Pz}(iC\sigma_{Pz})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma - T_4\frac{m_p}{Pz}(iC\sigma_{zP})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma - T_5\frac{m_p^2}{2Pz}(iC\sigma_{\perp z})_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma\\
&- T_6\frac{m_p^2}{2Pz}(iC\sigma_{\perp z})_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma + T_7\frac{m_p}{2}(C\sigma_{\perp\perp'})_{\beta\alpha}(\bar{N}^+\gamma_5\sigma^{\perp\perp'})_\gamma + T_8\frac{m_p}{2}(C\sigma_{\perp\perp'})_{\beta\alpha}(\bar{N}^-\gamma_5\sigma^{\perp\perp'})_\gamma\}
\end{aligned}$$

TABLE I: Twist classification of proton distribution amplitudes.

	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	
Pesudo-Scalar		P_1	P_2	

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Form factors at $q^2 = 0$

Simplified Λ_b wave function + general proton wave function

	$Twist-3$	$Twist-4$	$Twist-5$	$Twist-6$	$Total$
f_1	0.0025	0.021	0.043	0.03×10^{-3}	0.067

General Λ_b + general proton

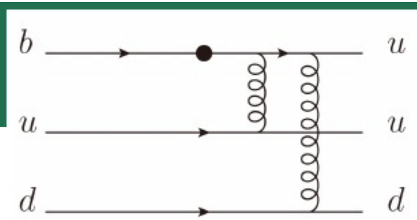
Table 3: Form factor f_1 at $q^2 = 0$.

	$twist-3$	$twist-4$	$twist-5$	$twist-6$	$total$
Exponential model					
$twist-2$	0.00043	0.00005	0.00045	0.00001	0.0009
$twist-3^{+-}$	0.00007	0.0081	0.0012	0.00022	0.0070
$twist-3^{-+}$	0.00012	0.0063	0.00026	0.00071	0.0073
$twist-4$	0.019	0.0011	0.10	0.00005	0.12
$total$	0.019	0.015	0.10	0.00091	$0.13 \pm 0.04 \pm 0.03 \pm 0.03$
Free parton model					
$twist-2$	0.00060	0.00006	0.00073	0.00002	0.0013
$twist-3^{+-}$	0.00008	0.0080	0.0016	0.0012	0.0082
$twist-3^{-+}$	0.00025	0.0123	0.00035	0.0012	0.0139
$twist-4$	0.020	0.007	0.13	0.00009	0.15
$total$	0.020	0.020	0.13	0.0024	$0.17 \pm 0.05 \pm 0.03 \pm 0.03$

Our results agree to PLB 708,119 (Wei Wang, 2012)

	f_1	f_2	g_1	g_2
NRQM [32]	0.043			
heavy-LCSR [50]	$0.023^{+0.006}_{-0.005}$			
light-LCSR-$\mathcal{A}$ [51]	$0.14^{+0.03}_{-0.03}$			
light-LCSR-$\mathcal{P}$ [51]	$0.12^{+0.03}_{-0.04}$			
QCD-light-LCSR [34]	0.018			
HQET-light-LCSR [34]	-0.002			
3-point [33]	0.22			
Lattice [35]	0.22 ± 0.08			
PQCD [67]	$2.2^{+0.8}_{-0.5} \times 10^{-3}$			
This work(exponential)	0.13 ± 0.06			
This work(free parton)	0.17 ± 0.06			

- ***R.Mohanta, A.K.Giri, M.P.Khanna (2001)***
- ***Yu-Ming Wang, Yue-Long Shen, Cai-Dian Lu (2009)***
- ***A.Khodjamirian, C.Klein, T.Mannel, Yu-Ming Wang (2011)***
- ***Ming-Qiu Huang, Dao-Wei Wang (2004)***
- ***Chao-Shang Huang, Cong-Feng Qiao, Hua-Gang Yan (1998)***
- ***W.Detmold, C.Lehner, S.Meinel (2015)***
- ***Cai-Dian Lu, Yu-Ming Wang, Hao zou (2009) & H.H.Shih, S.C.Lee, Hsiang-Nan Li, (1998)***

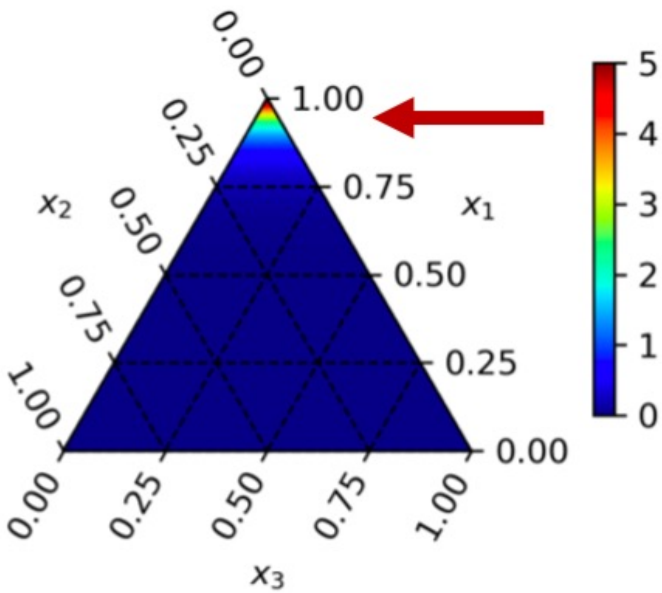


$$= \int [dx][db] \cdot \phi_{\Lambda_b} \cdot T_H \cdot \phi_p$$

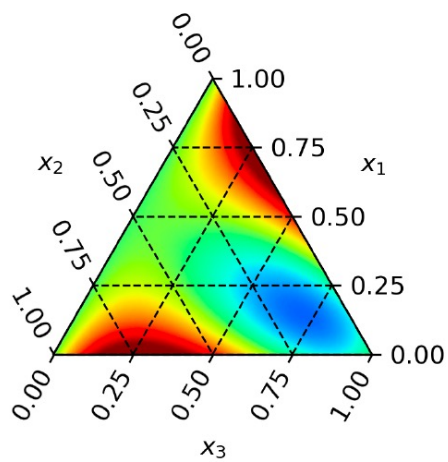
Hard-scattering functions, $r = \frac{m_p}{M_{\Lambda_b}}$, $x_{1,2,3}$: momentum fraction of Λ_b, $x'_{1,2,3}$: momentum fraction of proton

	twist-3	twist-4	twist-5	twist-6
twist-2	$2\sqrt{2}(1-x_2)$	$r \cdot 2\sqrt{2}(1-x_1)x_3$	$r^2 \cdot 2\sqrt{2}x_3$	$r^3 \cdot 4\sqrt{2}(1-x_1)(1-x'_2)$
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

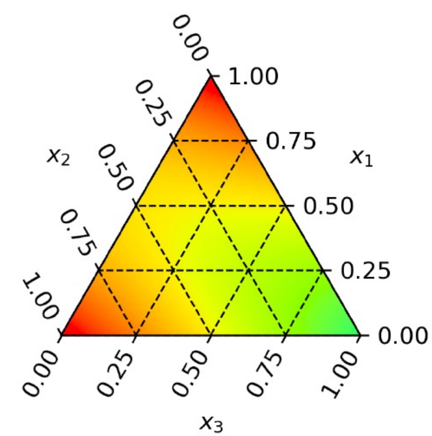
Λ_b twist-4

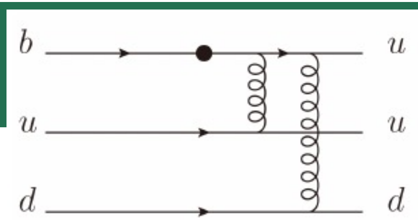


Proton twist-4



Proton twist-5





$$= \int [dx][db] \cdot \phi_{\Lambda_b} \cdot T_H \cdot \phi_p$$

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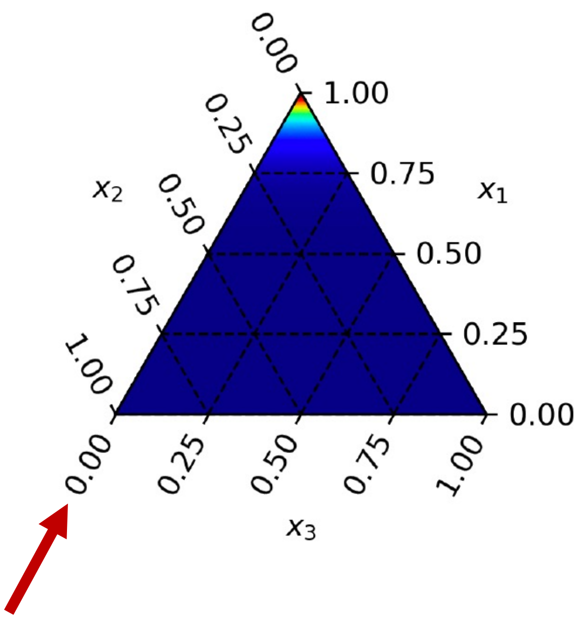
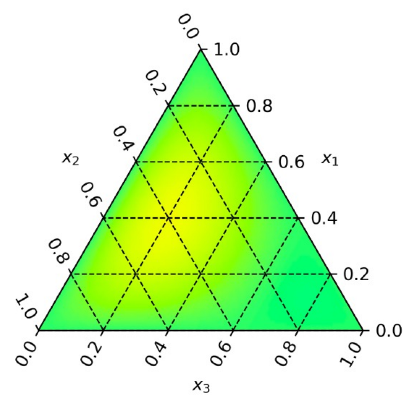
twist-3^{+-}	$x_3(1-x_1)$	$r \cdot x_3$	$r^2 \cdot (1-x_1)(1-x'_2)$	~ 0
twist-3^{-+}	~ 0	$r \cdot x_3$	$r^2 \cdot (1-x_1)(1-x'_2)$	$r^3 \cdot (1-x'_2)$
twist-4	$4\sqrt{2}x_3$	$r \cdot 2\sqrt{2}(1-x_1)(1-x'_2)$	$r^2 \cdot 2\sqrt{2}(1-x'_2)$	~ 0

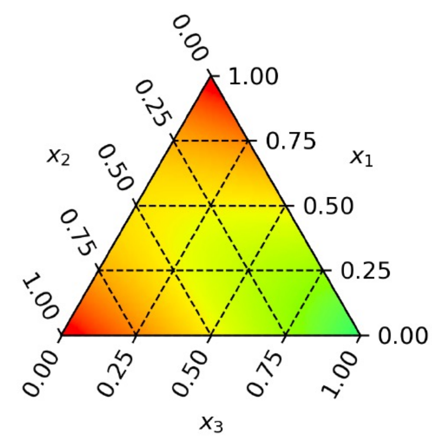
Λ_b twist-4

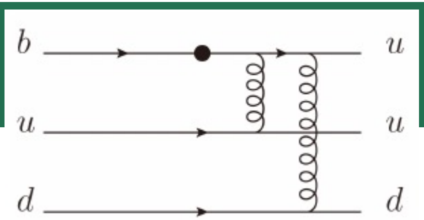


Proton twist-3



Proton twist-5





$$= \int [dx][db] \cdot \phi_{\Lambda_b} \cdot T_H \cdot \phi_p$$

Hard-scattering functions, $r = \frac{m_p}{M_{\Lambda_b}}$, $x_{1,2,3}$: momentum fraction of Λ_b, $x'_{1,2,3}$: momentum fraction of proton

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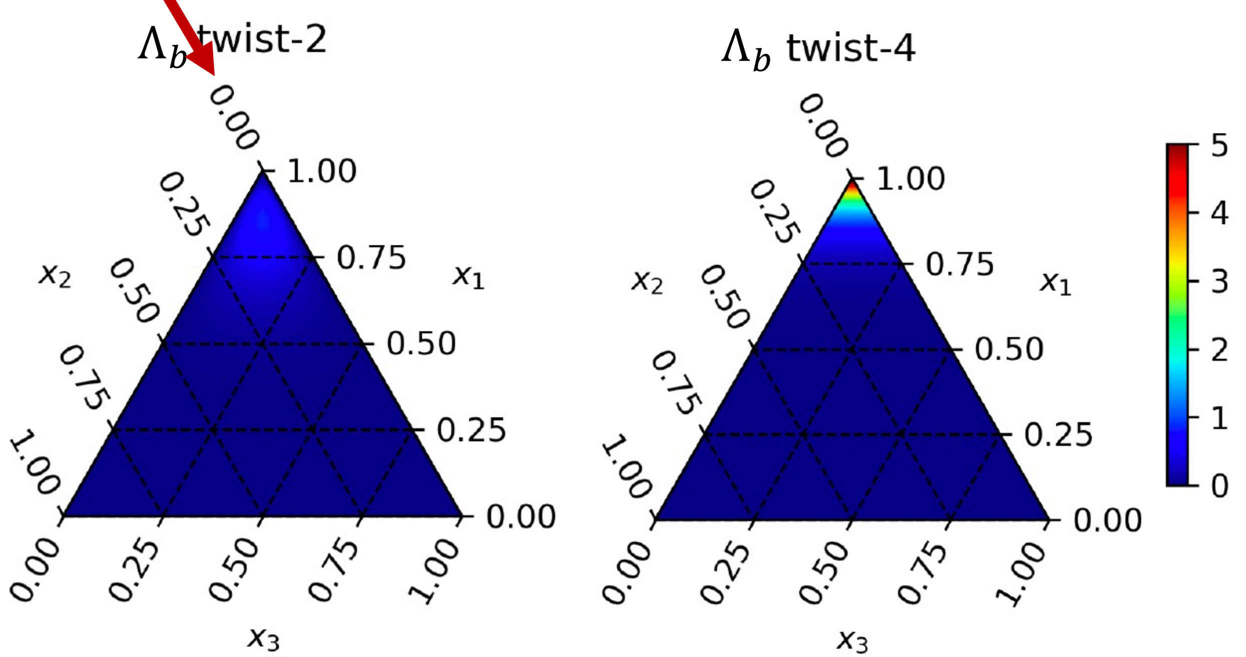
twist-3^{+-}	$x_3(1-x_1)$	$r \cdot x_3$	$r^2 \cdot (1-x_1)(1-x'_2)$	~ 0
twist-3^{-+}	~ 0	$r \cdot x_3$	$r^2 \cdot (1-x_1)(1-x'_2)$	$r^3 \cdot (1-x'_2)$
twist-4	$4\sqrt{2}x_3$	$r \cdot 2\sqrt{2}(1-x_1)(1-x'_2)$	$r^2 \cdot 2\sqrt{2}(1-x'_2)$	~ 0



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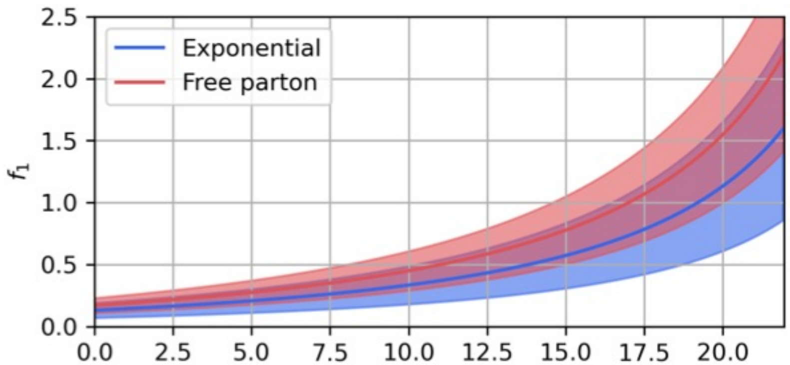
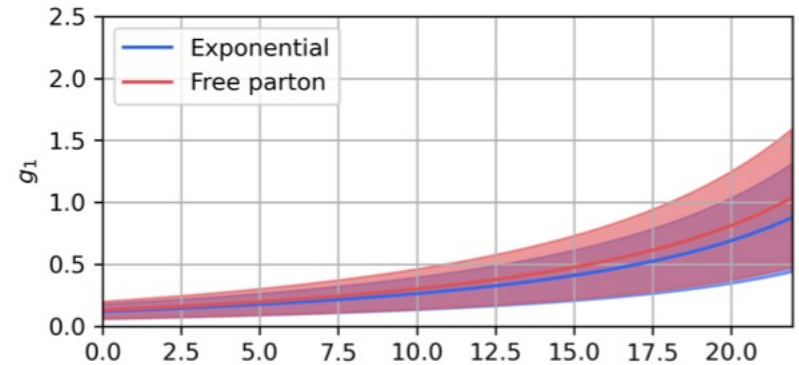
Observables





	$\Lambda_b \to p e \bar{\nu}_e$	$\Lambda_b \to p \mu \bar{\nu}_\mu$	$\Lambda_b \to p \tau \bar{\nu}_\tau$
This work(exponential)	$3.77^{+1.47}_{-1.06} \times 10^{-4}$	$3.77^{+1.47}_{-1.07} \times 10^{-4}$	$2.73^{+1.14}_{-0.85} \times 10^{-4}$
This work(free parton)	$4.89^{+2.07}_{-1.50} \times 10^{-4}$	$4.90^{+2.06}_{-1.52} \times 10^{-4}$	$3.78^{+1.67}_{-1.20} \times 10^{-4}$
LHCb [60]		$4.1 \pm 1.0 \times 10^{-4}$	

$\Lambda_b \to p \pi^-$(exponential)	$2.75^{+3.22}_{-2.0} \times 10^{-6}$
$\Lambda_b \to p \pi^-$(free parton)	$4.26^{+4.07}_{-2.67} \times 10^{-6}$
$\Lambda_b \to p \pi^-$(LHCb) [45]	$4.5 \pm 0.8 \times 10^{-6}$

Outline

- Motivation
- Framework
- Form factors at $q^2 = 0$
- Observables
- Summary

Summary

- **The PQCD approach can be used to calculate baryonic decay.**
- Contributions from high twist LCDAs are dominant in $\Lambda_b \to p$ form factors.
- More researches of high-twist LCDAs of baryons are urgently needed
- Form factors in this work are consistent with that from other approaches.

Outlook:

- CPV in b-baryon two-body decay $\Lambda_b \to p\pi, pK$
- Including TMD LCDAs
- Improve PQCD Framework in baryonic decays