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

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青島・PQCD组会

In collaboration with Ya Li, Yue-Long Shen, Zhen-Jun Xiao and Fu-Sheng Yu

Outline

- Motivation
- Framework of PQCD
- High twist LCDAs of baryons
- Numerical results
- Discussion and conclusion

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

- *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

$$a_{CP}^{T-odd}(\Lambda_b \to p\pi^+\pi^-\pi^-) = (-0.7 \pm 0.7 \pm 0.2)\% \quad (2.9\sigma)$$

- *LHCb (2020)*

Motivation

PQCD to predict CPV in B meson

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

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

- Naïve factorization approach

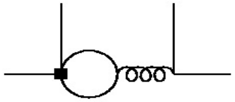
$$\langle \pi^+\pi^- | H_{eff} | B \rangle = a_1 \langle \pi | V-A | 0 \rangle \langle \pi | V-A | B \rangle = \left(C_2 + \frac{C_1}{3} \right) f_\pi F^{B\to\pi}$$

  - The non-factorizable contribution are not predictable.
  - Annihilation diagrams are difficult to calculate.
  - Strong phase can not be evaluated well.

- QCD factorization

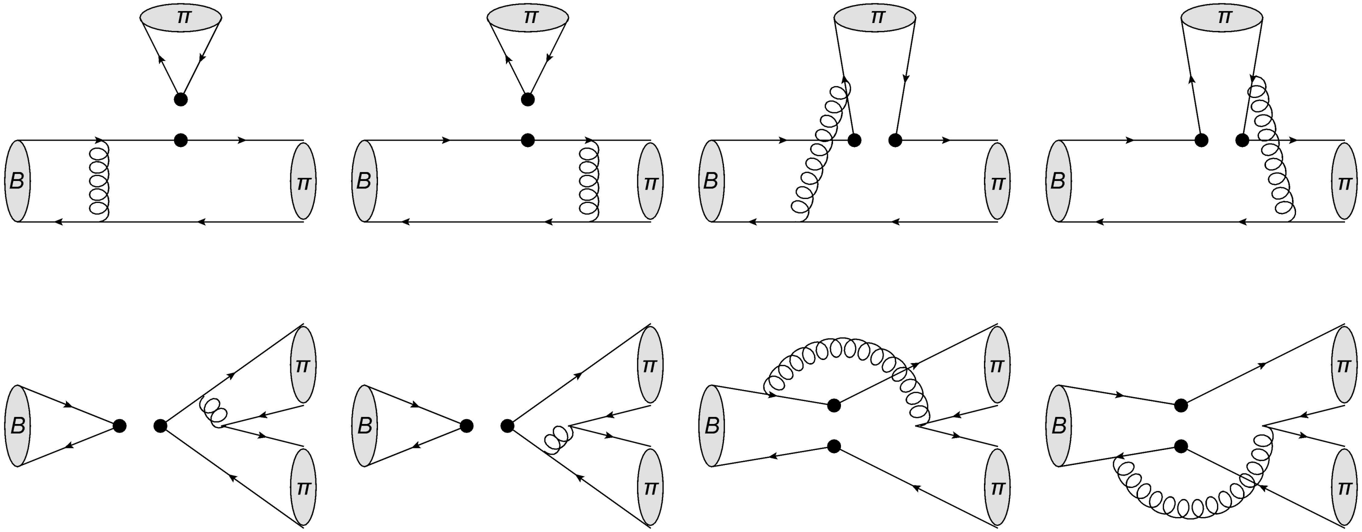
$$\langle \pi^+\pi^- | H_{eff} | B \rangle = \langle \pi | j_1 | 0 \rangle \langle \pi | j_2 | B \rangle [1 + \sum r_n \alpha_s^n + \mathcal{O}(\frac{\Lambda_{QCD}}{m_b})]$$

  - Strong phase of QCDF comes from loop diagram, small due to α_s suppress. Thus CPV is small.
  - Annihilation diagrams are not calculable, being free parameters.



Motivation

PQCD to predict CPV in B meson



- Annihilation diagrams can be evaluated well in PQCD.
- This type of annihilation diagrams are not suppressed, but have large contributions to CP asymmetry (>20%).

Direct CPV(%)	FA	BBNS	PQCD	exp.
$B \to \pi^+\pi^-$	-5 ± 3	-6 ± 12	$+30 \pm 20$	$+32 \pm 4$
$B \to K^+\pi^-$	$+10 \pm 3$	$+5 \pm 9$	-17 ± 5	-8.3 ± 0.4

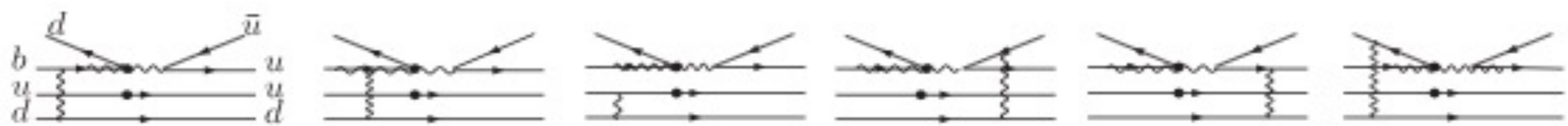
Motivation

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

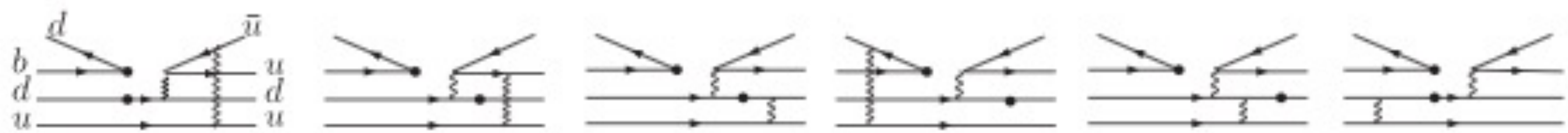
- *Cai-Dian Lu, Yu-Ming Wang, Hao zou (2009)*

- W-exchange diagrams (E) *36

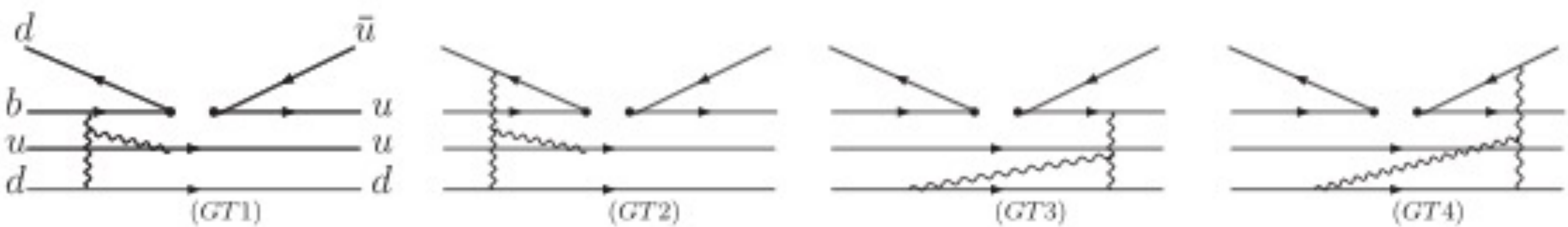
- Bow-tie diagrams (B) *36



- Penguin annihilation (P) *36



- Three-gluon vertex diagrams (G) *20



- Unlike meson decay, annihilation diagrams of Λ_b decay are not color-suppressed.

Motivation

- Advantages of research of Λ_b decay:
  - Large experiment data in LHCb.
  - Easy to construct vast observables.
  - Receive enhancement compared with meson decay.
- Difficulty in research of Λ_b decay:
  - Complex dynamics, large non-perturbative (soft) uncertainty.
  - One more gluon attached to spectator quark in PQCD.
- Current situation of PQCD calculation for Λ_b decay:
  - ***Nsiang-Nan Li, (1993), Sudakov suppression and the proton form factors***
  - ***B.Kundu, Nsiang-Nan Li, et,al. (1999), The perturbative proton form-factor reexamined***
  - ***H.H.Shih, S.C.Lee, Hsiang-Nan Li, (1998), The $\Lambda_b \to pl\nu$ decay in PQCD***
  - ***H.H.Shih, S.C.Lee, Hsiang-Nan Li, (1999), Applicability of PQCD to $\Lambda_b \to \Lambda_c$ decays***
  - ***C.H.Chou, H.H.Shih, S.C.Lee, Nsiang-Nan Li, (2002), $\Lambda_b \to \Lambda J/\psi$ decay in PQCD***
  - ***P.Guo, H.W.K, Yu-Ming Wang, et.al. (2007), Diquarks and semi-leptonic decay of Λ_b in the hybrid scheme***
  - ***Cai-Dian Lv, Yu-Ming Wang, Hao Zou, (2009), $\Lambda_b \to p\pi,\ pK$ decays in PQCD***

Motivation

PQCD calculation for Λ_b decay

- Current situation of form factors of $\Lambda_b \to p$

	f_1	f_2	g_1	g_2
NRQM[16]	0.043			
heavy-LCSR[34]	$0.023^{+0.006}_{-0.005}$			
light-LCSR-$\mathcal{A}$[35]	$0.14^{+0.03}_{-0.03}$			
light-LCSR-$\mathcal{P}$[35]	$0.12^{+0.03}_{-0.04}$			
QCD-light-LCSR[18]	0.018			
HQET-light-LCSR[18]	-0.002			
3-point[17]	0.22			
Lattice[19]	0.22 ± 0.08			
PQCD[20]	$2.2^{+0.8}_{-0.5} \times 10^{-3}$			

- ***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)***

- Factorizable and non-factorizable contributions to coefficients f_1 and f_2 in $\Lambda_b \to p\pi$

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

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

Motivation

Form factors of $\Lambda_b \to p$ in PQCD

$$F = \int_0^1 [dx_i][dx'_i] \int [d\mathbf{b}_i][d\mathbf{b}'_i] \tilde{\mathcal{P}}_p([x'_i], [\mathbf{b}'_i], p', w')$$
$$\times T_H([x_i], [x'_i], [\mathbf{b}_i], [\mathbf{b}'_i], t) \tilde{\mathcal{P}}_{\Lambda_b}([x_i], [\mathbf{b}_i], p, w) S_t(x^{(\prime)})$$
$$\times exp\left[-\sum_{i=2}^{3} s(w, k_i^+) - \frac{8}{3}\int_{\kappa w}^{t} \frac{d\bar{\mu}}{\bar{\mu}} \gamma_q(\alpha_s(\bar{\mu}))\right]$$
$$\times exp\left[-\sum_{i=1}^{3} s(w', k_i'^-) - 3\int_{\kappa w'}^{t} \frac{d\bar{\mu}}{\bar{\mu}} \gamma_q(\alpha_s(\bar{\mu}))\right]$$

- How to improve calculation of $\Lambda_b \to p$ form factors?
  - Hare scattering kernel?
  - Different scale choose?
  - Sudakov factors?
  - High twist light-cone distribution amplitudes?

Motivation

Form factors of $\Lambda_b \to p$ in PQCD

$$F = \int_0^1 [dx_i][dx_i'] \int [d\mathbf{b}_i][d\mathbf{b}_i'] \tilde{\mathcal{P}}_p([x_i'],[\mathbf{b}_i'],p',w')$$
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- How to improve calculation of $\Lambda_b \to p$ form factors?
  - Hare scattering kernel?
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  - Including high twist light-cone distribution amplitudes.

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Framework

Parameterization of form factors

- For the $\Lambda_b \to p$ transition, the hadronic matrix is

$$\mathcal{M}_\mu = \langle P(p')|\bar{u}\gamma_\mu(1-\gamma_5)b|\Lambda_b(p)\rangle.$$

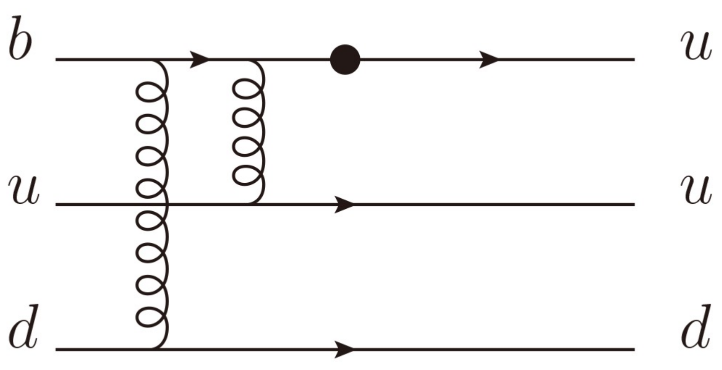
- Parameterization of this hadronic matrix

$$\begin{aligned}\langle P(p',s')|\bar{u}\gamma_\mu(1-\gamma_5)b|\Lambda_b(p)\rangle =& \overline{P}(p')(F_1\gamma_\mu + F_2\frac{p_\mu}{m_{\Lambda_b}} + F_3\frac{p'_\mu}{m_p} \\ & - G_1\gamma_\mu\gamma_5 - G_2\gamma_5\frac{p_\mu}{m_{\Lambda_b}} - G_3\gamma_5\frac{p'_\mu}{m_p})\Lambda_b(p,s).\end{aligned}$$

Framework

A brief review of PQCD approach

- Based on k_T factorization, the PQCD approach provides a framework applied to hard exclusive processes.
  - deal with processes involving different energy scales.
- Hard gluons:
  - is essential to ensure the applicability of the twist expansion.
  - phenomenological, is necessary to construct final state hadrons.
- Soft contributions are expected to be less important owing to the suppression by the Sudakov factor.



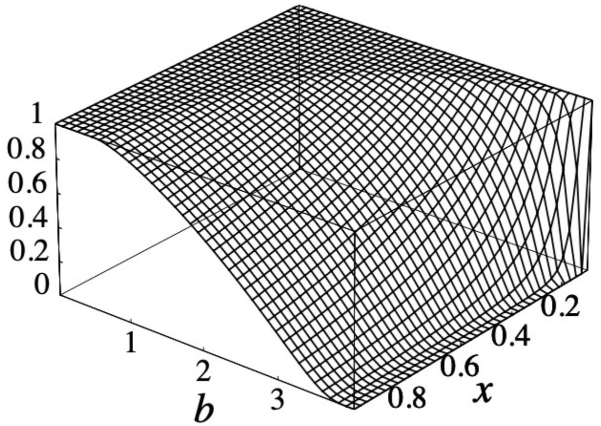
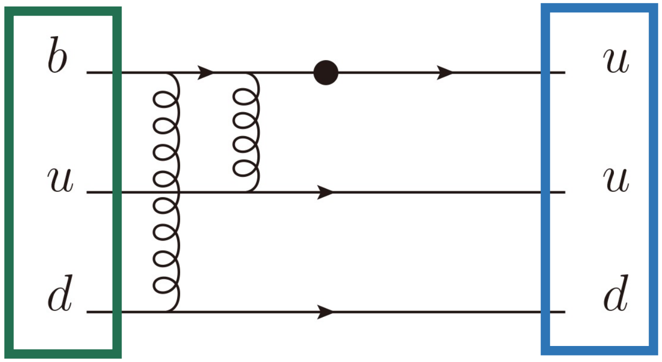


图 7.5 Sudakov 因子效果图

A brief review of PQCD approach

- 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

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



- Transforms to the impact parameter b space, Performing the resummation of double logarithms leads to Sudakov factors

$$F = \int_0^1 [dx][dx'] \int [d^2\mathbf{b}] \int [d^2\mathbf{b}'] \mathcal{P}_p(x', \mathbf{b}', p', \mu) \times T_H(x, x', M_{\Lambda_b}, \mathbf{b}, \mathbf{b}', \mu) \mathcal{P}_{\Lambda_b}(x, \mathbf{b}, p, \mu).$$

Framework

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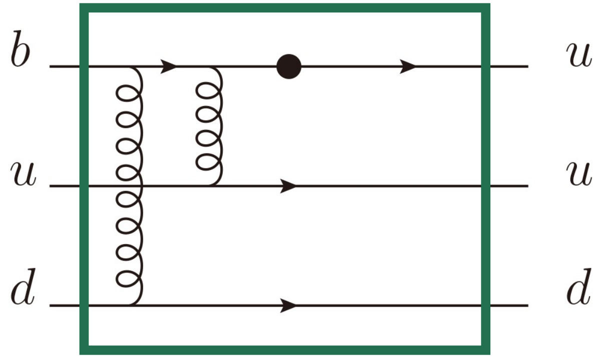

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Framework

A brief review of PQCD approach

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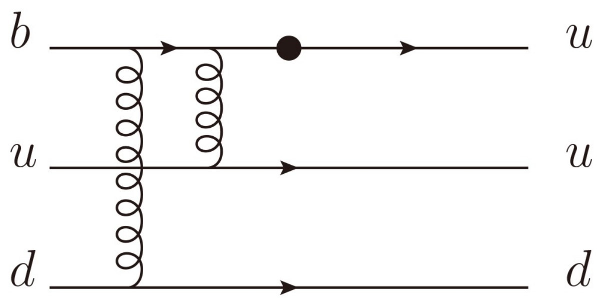


- Transforms to the impact parameter b space, Performing the resummation of double logarithms leads to Sudakov factors

$$F = \int_0^1 [dx][dx'] \int [d^2\mathbf{b}] \int [d^2\mathbf{b}'] \mathcal{P}_p(x', \mathbf{b}', p', \mu) \times T_H(x, x', M_{\Lambda_b}, \mathbf{b}, \mathbf{b}', \mu) \mathcal{P}_{\Lambda_b}(x, \mathbf{b}, p, \mu).$$

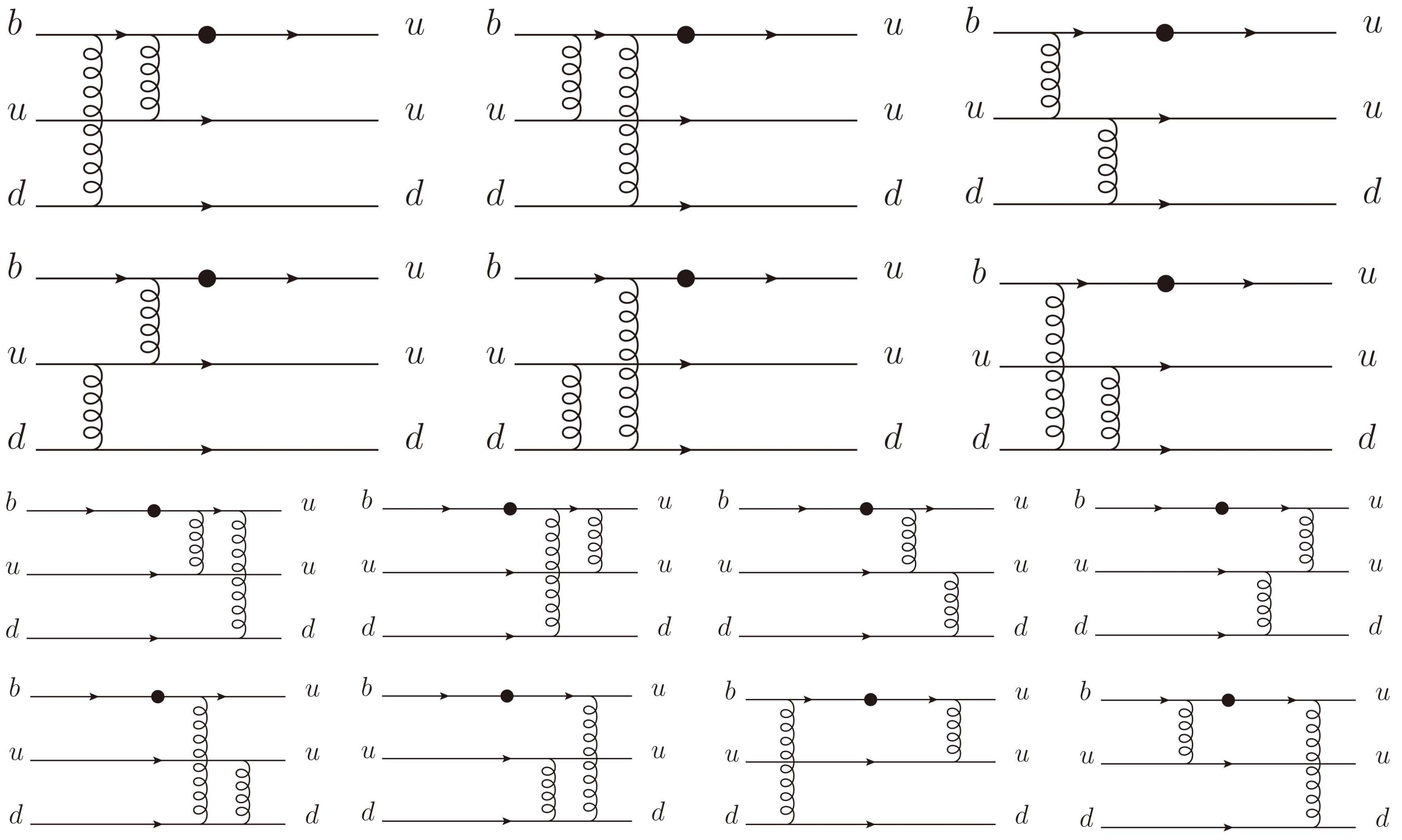
A brief review of PQCD approach

- Collecting everything together, we arrive at the typical expression for the factorization formula of the form factor in the PQCD approach .

$$
\begin{aligned}
F = & \int_0^1 [dx_i][dx'_i] \int [d\mathbf{b}_i][d\mathbf{b}'_i] \tilde{\mathcal{P}}_p([x'_i], [\mathbf{b}'_i], p', w') \\
& \times T_H([x_i], [x'_i], [\mathbf{b}_i], [\mathbf{b}'_i], t) \tilde{\mathcal{P}}_{\Lambda_b}([x_i], [\mathbf{b}_i], p, w) S_t(x^{(\prime)}) \\
& \times exp\left[-\sum_{i=2}^{3} s(w, k_i^+) - \frac{8}{3} \int_{\kappa w}^{t} \frac{d\bar{\mu}}{\bar{\mu}} \gamma_q(\alpha_s(\bar{\mu})) \right] \\
& \times exp\left[-\sum_{i=1}^{3} s(w', k_i'^-) - 3 \int_{\kappa w'}^{t} \frac{d\bar{\mu}}{\bar{\mu}} \gamma_q(\alpha_s(\bar{\mu})) \right]
\end{aligned}
$$

Framework

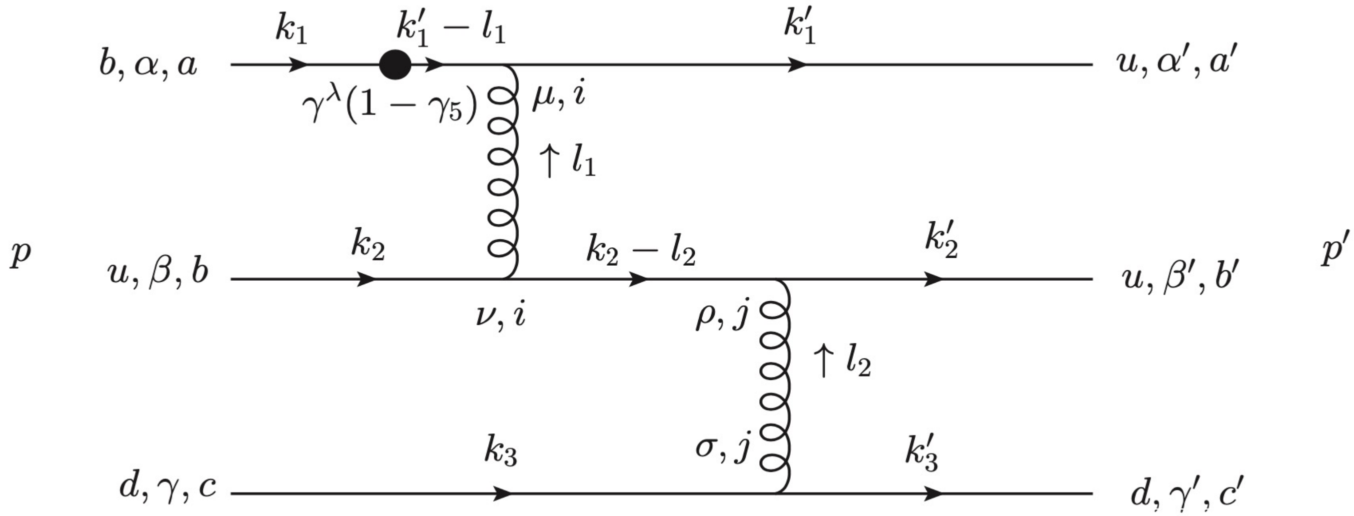
Diagrams for $\Lambda_b \to p$ under PQCD



Framework

kinematics

- In Λ_b rest frame.



- The momentum of the Λ_b is $p = (p^+, p^-, \mathbf{0})$ with $p^+ = p^- = M_{\Lambda_b}/\sqrt{2}$
- The proton recoils in the plus direction and the momentum is defined as $p' = M_{\Lambda_b}/\sqrt{2}(\eta_1, \eta_2, \mathbf{0})$, the momentum tranfer $q = M_{\Lambda_b}/\sqrt{2}(1-\eta_1, 1-\eta_2, \mathbf{0})$

$$
\begin{aligned}
k_1 &= (p^+, x_1 p^-, k_{1T}), & k_1' &= (x_1' p'^+, 0, k_{1T}'), \\
k_2 &= (0, x_2 p^-, k_{2T}), & k_2' &= (x_2' p'^+, 0, k_{2T}'), \\
k_3 &= (0, x_3 p^-, k_{3T}), & k_3' &= (x_3' p'^+, 0, k_{3T}').
\end{aligned}
$$

- For $q^2 = 0$, $\eta_1 = 1$ and $\eta_2 = \frac{m_p^2}{M_{\Lambda_b}^2}$

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LCDAs of baryons

Λ_b wave function

- Λ_b wave function

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

- By using Bargmann-Wigner equation in the heavy quark limit, the light-cone hadronic matrix element can be simplified as
  - ***F.Hussain, J.G.Korner, M.Kramer, G.Thompson (1991)***

$$\Phi_{\Lambda_b}^{\alpha\beta\gamma} \equiv \langle 0|T[b_\alpha^i(0)u_\beta^j(z_2)d_\gamma^k(z_3)]|\Lambda_b(p)\rangle = \frac{f_{\Lambda_b}}{4}[(\not p + M_{\Lambda_b})\gamma_5 C]_{\beta\gamma}[\Lambda_b(p)]_\alpha\Psi(k_i,\mu)$$

- A simple model for Λ_b LCDA $\Psi(k_i,\mu)$
  - ***F.Schlumpf (1992)***

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

- Normalization condition

$$\int dx_1 dx_2 dx_3 \Psi(x_1,x_2,x_3) = 1$$

Simplified Λ_b LCDA

LCDAs of baryons

Λ_b wave function

- ***P.Ball, V.M.Braun, E.Gardi (2008)***
- ***G.Bell, T.Feldmann, Yu-Ming Wang, M.W.Y.Yip (2013)***
- ***Yu-Ming Wang, Yue-Long Shen (2016)***

- introduce the general light-cone hadronic matrix element of Λ_b baryon

$$\Phi_{\Lambda_b}^{\alpha\beta\delta}(t_1,t_2) \equiv \epsilon_{ijk}\langle 0|[u_i^T(t_1\bar{n})]_\alpha[0,t_1\bar{n}][d_j(t_2\bar{n})]_\beta[0,t_2\bar{n}][b_k(0)]_\delta|\Lambda_b(v)\rangle$$
$$= \frac{1}{4}\left\{ f_{\Lambda_b}^{(1)}(\mu)[\tilde{M}_1(v,t_1,t_2)\gamma_5 C^T]_{\beta\alpha} + f_{\Lambda_b}^{(2)}(\mu)[\tilde{M}_2(v,t_1,t_2)\gamma_5 C^T]_{\beta\alpha}\right\}[\Lambda_b(v)]_\delta \quad (23)$$

- performing the Fourier transformation and including the NLO terms off the light-cone leads to the momentum space light-cone projector

$$\begin{aligned} M_2(\omega_1',\omega_2') =& \frac{\not{n}}{2}\psi_2(\omega_1',\omega_2') + \frac{\not{\bar{n}}}{2}\psi_4(\omega_1',\omega_2') \\ &- \frac{1}{D-2}\gamma_\perp^\mu[\psi_{\perp,1}^{+-}(\omega_1',\omega_2')\frac{\not{n}\not{\bar{n}}}{4}\frac{\partial}{\partial k_{1\perp}^\mu} + \psi_{\perp,1}^{-+}(\omega_1',\omega_2')\frac{\not{\bar{n}}\not{n}}{4}\frac{\partial}{\partial k_{1\perp}^\mu}] \\ &- \frac{1}{D-2}\gamma_\perp^\mu[\psi_{\perp,2}^{+-}(\omega_1',\omega_2')\frac{\not{n}\not{\bar{n}}}{4}\frac{\partial}{\partial k_{2\perp}^\mu} + \psi_{\perp,2}^{-+}(\omega_1',\omega_2')\frac{\not{\bar{n}}\not{n}}{4}\frac{\partial}{\partial k_{2\perp}^\mu}] \end{aligned}$$

$$\begin{aligned} M_1(\omega_1',\omega_2') =& \frac{\not{\bar{n}}\not{n}}{8}\psi_3^{+-}(\omega_1',\omega_2') + \frac{\not{n}\not{\bar{n}}}{8}\psi_3^{-+}(\omega_1',\omega_2') \\ &- \frac{1}{D-2}[\Psi_{\perp,3}^{(1)}(\omega_1',\omega_2')\not{v}\gamma_\perp^\mu\frac{\partial}{\partial k_{1\perp}^\mu} + \Psi_{\perp,3}^{(2)}(\omega_1',\omega_2')\gamma_\perp^\mu\not{v}\frac{\partial}{\partial k_{2\perp}^\mu}] \\ &- \frac{1}{D-2}[\Psi_{\perp,Y}^{(1)}(\omega_1',\omega_2')\not{\bar{n}}\gamma_\perp^\mu\frac{\partial}{\partial k_{1\perp}^\mu} + \Psi_{\perp,Y}^{(2)}(\omega_1',\omega_2')\gamma_\perp^\mu\not{\bar{n}}\frac{\partial}{\partial k_{2\perp}^\mu}] \end{aligned}$$

LCDAs of baryons

Λ_b wave function

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$$\Phi^{\alpha\beta\delta}_{\Lambda_b}(t_1,t_2) \equiv \epsilon_{ijk}\langle 0|[u_i^T(t_1\bar{n})]_\alpha[0,t_1\bar{n}][d_j(t_2\bar{n})]_\beta[0,t_2\bar{n}][b_k(0)]_\delta|\Lambda_b(v)\rangle$$
$$= \frac{1}{4}\left\{ f^{(1)}_{\Lambda_b}(\mu)[\tilde{M}_1(v,t_1,t_2)\gamma_5 C^T]_{\beta\alpha} + f^{(2)}_{\Lambda_b}(\mu)[\tilde{M}_2(v,t_1,t_2)\gamma_5 C^T]_{\beta\alpha}\right\}[\Lambda_b(v)]_\delta \quad (23)$$

- performing the Fourier transformation and including the NLO terms off the light-cone leads to the momentum space light-cone projector

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

General Λ_b LCDA

LCDAs of baryons

Λ_b LCDAs

- LCDAs expanded by Gegenbauer polynomial (Gegenbauer-1 model)

  - ***P.Ball, V.M.Braun, E.Gardi (2008)***

$$
\begin{aligned}
\psi_2(\omega,u) =&\omega^2 u(1-u)\left[\frac{1}{\epsilon_0^4}e^{-\omega/\epsilon_0}+a_2 C_2^{3/2}(2u-1)\frac{1}{\epsilon_1^4}e^{-\omega/\epsilon_1}\right]\\
\psi_3^s(\omega,u) =&\frac{\omega}{2\epsilon_3^3}e^{-\omega/\epsilon_3}\\
\psi_3^\sigma(\omega,u) =&\frac{\omega}{2\epsilon_3^3}(2u-1)e^{-\omega/\epsilon_3}\\
\psi_4(\omega,u) =&5\mathcal{N}^{-1}\int_{\omega/2}^{s_0} ds e^{-s/\tau}(s-\omega/2)^3
\end{aligned}
$$

- LCDAs expanded by Gegenbauer polynomial (Gegenbauer-2 model)

  - ***A.Ali, C.Hambrock, A.Y.Parkhomenko (2012)***

$$
\begin{aligned}
\psi_2(\omega,u) =&\omega^2 u(1-u)\left[\frac{a_2^{(2)}}{\epsilon_2^{(2)4}}C_2^{3/2}(2u-1)e^{-\omega/\epsilon_2^{(2)}}\right]\\
\psi_3^s(\omega,u) =&\frac{\omega}{2}\left[\frac{a_2^{(3)}}{\epsilon_2^{(3)3}}C_2^{1/2}(2u-1)e^{-\omega/\epsilon_2^{(3)}}\right]\\
\psi_3^\sigma(\omega,u) =&\frac{\omega}{2}\left[\frac{b_3^{(3)}}{\eta_3^{(3)3}}C_2^{1/2}(2u-1)e^{-\omega/\eta_3^{(3)}}\right]\\
\psi_4(\omega,u) =&\left[\frac{a_2^{(4)}}{\epsilon_2^{(4)2}}C_2^{1/2}(2u-1)e^{-\omega/\epsilon_2^{(4)}}\right]
\end{aligned}
$$

LCDAs of baryons

Λ_b LCDAs

- LCDAs constructed by exponential ansatz (Exponential model)
  - ***G.Bell, T.Feldmann, Yu-Ming Wang, M.W.Y.Yip (2013)***

$$\psi_2(\omega_1,\omega_2) = \frac{\omega_1\omega_2}{\omega_0^4} e^{-(\omega_1+\omega_2)/\omega_0},$$

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

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

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

- LCDAs constructed by exponential ansatz (Free parton model)
  - ***G.Bell, T.Feldmann, Yu-Ming Wang, M.W.Y.Yip (2013)***

$$\psi_2(\omega_1,\omega_2) = \frac{15\omega_1\omega_2(2\bar{\Lambda}-\omega_1-\omega_2)}{4\bar{\Lambda}^5}\Theta(2\bar{\Lambda}-\omega_1-\omega_2),$$

$$\psi_3^{+-}(\omega_1,\omega_2) = \frac{15\omega_1(2\bar{\Lambda}-\omega_1-\omega_2)^2}{4\bar{\Lambda}^5}\Theta(2\bar{\Lambda}-\omega_1-\omega_2),$$

$$\psi_3^{-+}(\omega_1,\omega_2) = \frac{15\omega_2(2\bar{\Lambda}-\omega_1-\omega_2)^2}{4\bar{\Lambda}^5}\Theta(2\bar{\Lambda}-\omega_1-\omega_2),$$

$$\psi_4(\omega_1,\omega_2) = \frac{5(2\bar{\Lambda}-\omega_1-\omega_2)^3}{8\bar{\Lambda}^5}\Theta(2\bar{\Lambda}-\omega_1-\omega_2).$$

LCDAs of baryons

Proton wave function

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

$$(Y_{proton})_{\alpha\beta\gamma}(k'_i,\mu) = \frac{1}{2\sqrt{2}N_c}\int\prod_{l=2}^{3}\frac{dz_l^+ d\mathbf{z}_l}{(2\pi)^3}e^{ik'_i\cdot z_l}\epsilon^{ijk}\ \langle 0|T[u^i_\alpha(0)u^j_\beta(z_2)d^k_\gamma(z_3)]|\mathcal{P}(p')\rangle$$

$$\langle\mathcal{P}(p')|\bar{u}^i_\alpha(0)\bar{u}^j_\beta(z_1)\bar{d}^k_\gamma(z_2)|0\rangle = -\gamma^0_{\beta\rho}\gamma^0_{\lambda\alpha}\gamma^0_{\delta\gamma}\ \langle 0|u^i_\lambda(0)u^j_\rho(z_1)d^k_\delta(z_2)|\mathcal{P}(p')\rangle^\dagger$$

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

LCDAs of baryons

Proton wave function

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

$$\langle\mathcal{P}(p')|\bar{u}_\alpha^i(0)\bar{u}_\beta^j(z_1)\bar{d}_\gamma^k(z_2)|0\rangle = -\gamma^0_{\beta\rho}\gamma^0_{\lambda\alpha}\gamma^0_{\delta\gamma}\ \langle 0|u_\lambda^i(0)u_\rho^j(z_1)d_\delta^k(z_2)|\mathcal{P}(p')\rangle^\dagger$$

$$\begin{aligned}\bar{\Phi}^{\alpha\beta\gamma}_{proton} \equiv&\langle\mathcal{P}(p')|\bar{u}_\alpha^i(0)\bar{u}_\beta^j(z_1)\bar{d}_\gamma^k(z_2)|0\rangle\\ =&\frac{1}{4}\{S_1 m_p C_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma + S_2 m_p C_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma + P_1 m_p (C\gamma_5)_{\beta\alpha}\bar{N}^+_\gamma + P_2 m_p (C\gamma_5)_{\beta\alpha}\bar{N}^-_\gamma + V_1(C\not{P})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma\\ &+ V_2(C\not{P})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma + V_3\frac{m_p}{2}(C\gamma_\perp)_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma + V_4\frac{m_p}{2}(C\gamma_\perp)_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma + V_5\frac{m_p^2}{2Pz}(C\not{z})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma\end{aligned}$$

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	

Outline

- Motivation
- Framework of PQCD
- High twist LCDAs of baryons
- Numerical results
- Discussion and conclusion

Numerical Results

- Simplified Λ_b wave function + general proton wave function are used.

TABLE III: The results of form factors in this work. The form factors in second column labeled by $*$ do not include contributions from terms proportional to proton mass. The total form factors in the last column include contributions from Twist-3,4,5,6.

	Twist-3*	Twist-3	Twist-4	Twist-5	Twist-6	Total
f_1	2.0×10^{-3}	2.8×10^{-3}	0.046	0.042	2.6×10^{-5}	0.093
f_2	3.6×10^{-5}	1.8×10^{-4}	3.2×10^{-3}	1.7×10^{-4}	-6.6×10^{-5}	3.5×10^{-3}
f_3	5.1×10^{-5}	-3.0×10^{-5}	-2.4×10^{-3}	-9.7×10^{-5}	1.4×10^{-4}	-2.3×10^{-3}
g_1	2.0×10^{-3}	3.6×10^{-3}	0.040	0.045	-9.3×10^{-5}	0.090
g_2	-1.8×10^{-5}	8.9×10^{-5}	4.3×10^{-3}	-1.8×10^{-4}	8.3×10^{-5}	4.3×10^{-3}
g_3	-2.2×10^{-5}	-1.4×10^{-4}	-2.2×10^{-3}	-4.3×10^{-4}	1.9×10^{-4}	-2.6×10^{-3}

Numerical Results

General Λ_b + general proton

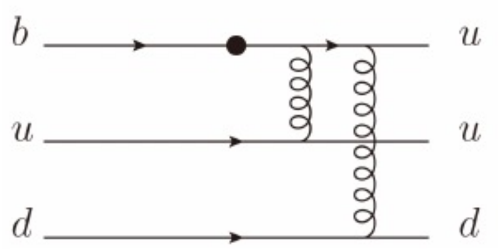
TABLE III: Form factor F_1.

	twist-3	twist-4	twist-5	twist-6	total
twist-2 (gegenbauer1)	0.0011(0)(6)(1)	0.00025(9)(17)(26)	-0.00078(83)(45)(16)	0.000092(16)(41)(8)	0.00071(92)(43)(58)
twist-2 (gegenbauer2)	0.016(0)(0)(2)	-0.000012(5)(17)(20)	0.0000076(88)(99)85)	0.0000034(2)(30)(7)	0.016(0)(0)(2)
twist-2 (exponential)	0.033(0)(5)(4)	0.00000010(99)1)(99)	-0.00018(12)(3)(1)	0.000026(8)(4)(0)	0.033(0)(5)(4)
twist-2 (free parton)	0.034(0)(5)(4)	-0.000042(10)(7)(55)	-0.00026(17)(4)(2)	0.000030(9)(5)(1)	0.033(0)(5)(4)
twist-3^{+-} (gegenbauer1)	-0.00019(7)(3)(4)	0.015(7)(10)(10)	-0.0012(0)(3)(1)	0.00018(59)(41)(44)	0.014(7)(10)(10)
twist-3^{+-} (gegenbauer2)	-0.0000092(97)98)99)	0.0016(13)(34)(31)	-0.000032(3)(43)(44)	-0.00017(20)(2)(20)	0.0014(11)(35)(34)
twist-3^{+-} (exponential)	-0.000044(30)(7)(14)	0.010(0)(1)(4)	-0.00053(12)(8)(5)	0.00011(7)(1)(7)	0.010(0)(1)(4)
twist-3^{+-} (free parton)	-0.0000080(97)13)(99)	0.0032(9)(5)(43)	-0.00051(9)(8)(6)	0.00015(31)(2)(16)	0.0029(4)(4)(46)
twist-3^{-+} (gegenbauer1)	-0.00021(8)(6)(7)	0.0024(9)(26)(51)	-0.00015(17)(10)(8)	-0.000027(97)37)(99)	0.0020(1)(24)(57)
twist-3^{-+} (gegenbauer2)	-0.000024(10)(12)(21)	-0.00096(0)(47)(99)	0.0000060(99)99)99)	-0.00014(7)(0)(22)	-0.0011(1)(4)(21)
twist-3^{-+} (exponential)	-0.000039(1)(6)(26)	0.00077(20)(12)(99)	-0.000043(34)(7)(28)	0.000030(90)(5)(91)	0.00071(8)(11)(99)
twist-3^{-+} (free parton)	-0.00013(1)(2)(3)	0.00091(33)(15)(99)	-0.000096(32)(16)(34)	0.00013(43)(2)(9)	0.00081(13)(13)(99)
twist-4 (gegenbauer1)	0.022(0)(4)(6)	0.0021(13)(35)(6)	0.70(16)(8)(6)	-0.00036(16)(10)(7)	0.72(17)(10)(7)
twist-4 (gegenbauer2)	0.0017(6)(21)(6)	0.00051(40)(37)(43)	0.67(0)(1)(5)	0.000018(4)(4)(2)	0.67(0)(1)(5)
twist-4 (exponential)	0.0082(19)(13)(23)	0.00096(50)(16)(99)	0.23(6)(3)(2)	-0.00012(2)(2)(0)	0.24(6)(4)(2)
twist-4 (free parton)	0.0092(14)(15)(18)	0.0015(4)(2)(14)	0.24(5)(4)(2)	-0.00010(3)(1)(0)	0.26(5)(4)(2)
total (gegenbauer1)	0.023(0)(3)(7)	0.020(4)(13)(17)	0.70(17)(9)(6)	-0.00012(26)(20)(65)	0.74(16)(11)(9)
total (gegenbauer2)	0.017(0)(2)(2)	0.0012(17)(43)(54)	0.67(0)(1)(5)	-0.00029(27)(2)(42)	0.68(0)(1)(6)
total (exponential)	0.042(1)(7)(6)	0.012(0)(2)(7)	0.23(6)(3)(2)	0.000053(5)(8)(99)	0.28(6)(4)(3)
total (free parton)	0.043(1)(7)(6)	0.0056(1)(9)(78)	0.24(5)(4)(2)	0.00020(9)(3)(26)	0.29(5)(4)(3)

Numerical results

	f_1
NRQM[16]	0.043
heavy-LCSR[34]	$0.023^{+0.006}_{-0.005}$
light-LCSR-$\mathcal{A}$[35]	$0.14^{+0.03}_{-0.03}$
light-LCSR-$\mathcal{P}$[35]	$0.12^{+0.03}_{-0.04}$
QCD-light-LCSR[18]	0.018
HQET-light-LCSR[18]	-0.002
3-point[17]	0.22
Lattice[19]	0.22 ± 0.08
PQCD[20]	$2.2^{+0.8}_{-0.5} \times 10^{-3}$
PQCD(exponential)	0.28 ± 0.13
PQCD(free parton)	0.29 ± 0.12

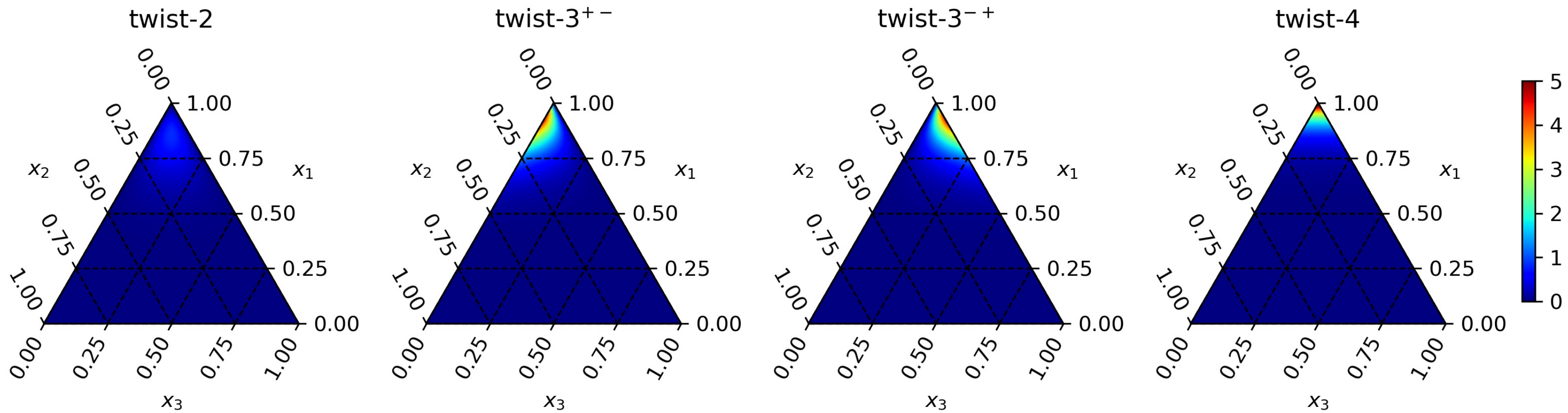
Numerical Results



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

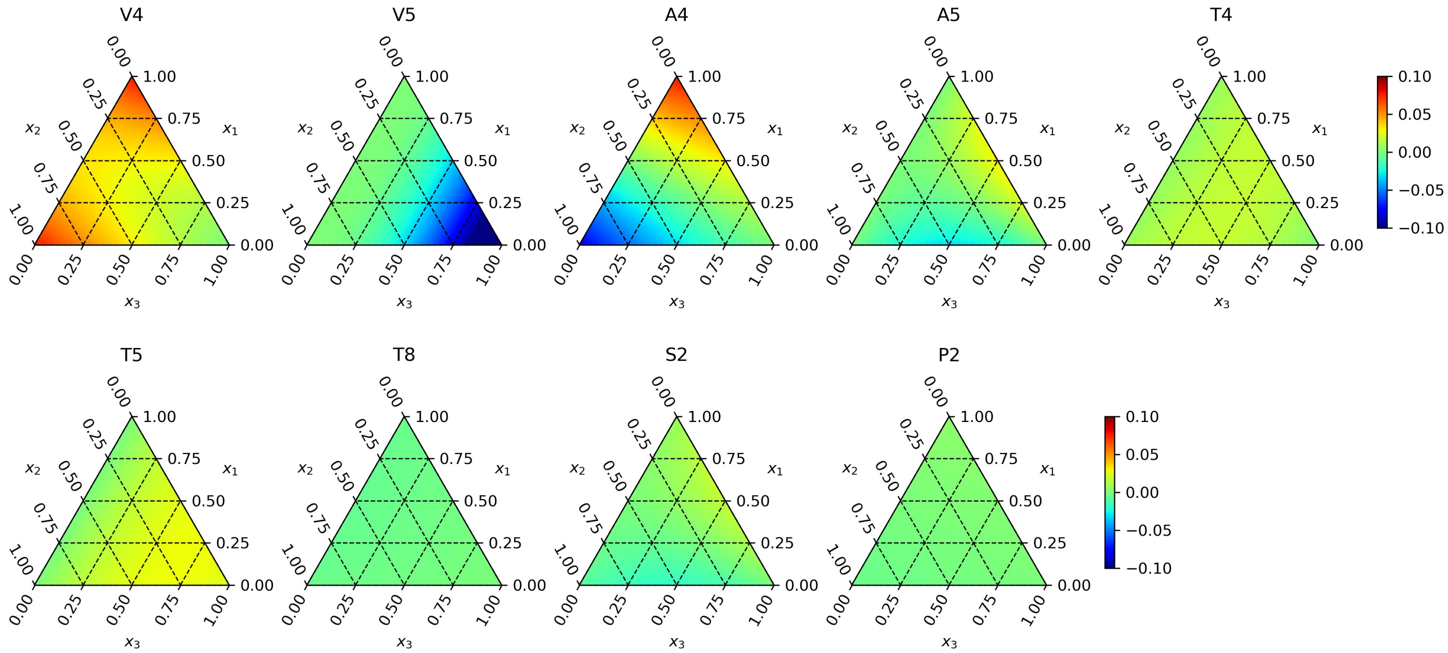
TABLE IX: Hard-scattering functions for form factor $f_1(q^2 = 0)$ of diagramB.

	twist-3	twist-4	twist-5	twist-6
twist-2	0	$2\sqrt{2}(1-x_1)[-M^2_{\Lambda_b}x_3 + 2(1-x'_2)]$	$-2\sqrt{2}(M_{\Lambda_b}+1)x_3$	$4\sqrt{2}(1-x_1)(1-x'_2)$
twist-3^{+-}	$(M^3_{\Lambda_b} + M^2_{\Lambda_b})x_3(1-x_1)$	$-x_3(M^2_{\Lambda_b}+x_1) + (1-x'_2)$	$-(M_{\Lambda_b}+1)(1-x_1)(1-x'_2)$	0
twist-3^{-+}	0	$x_3(M^2_{\Lambda_b}+x_1) - (1-x'_2)$	$(M_{\Lambda_b}+1)(1-x_1)(1-x'_2)$	$-(1-x'_2)$
twist-4	$4\sqrt{2}(M_{\Lambda_b}+1)(-M^2_{\Lambda_b}x_3 + 1 - x'_2)$	$2\sqrt{2}M^2_{\Lambda_b}(1-x_1)(1-x'_2) - 4\sqrt{2}x_3(1-x_1)$	$2\sqrt{2}(M_{\Lambda_b}+1)(1-x'_2)$	0

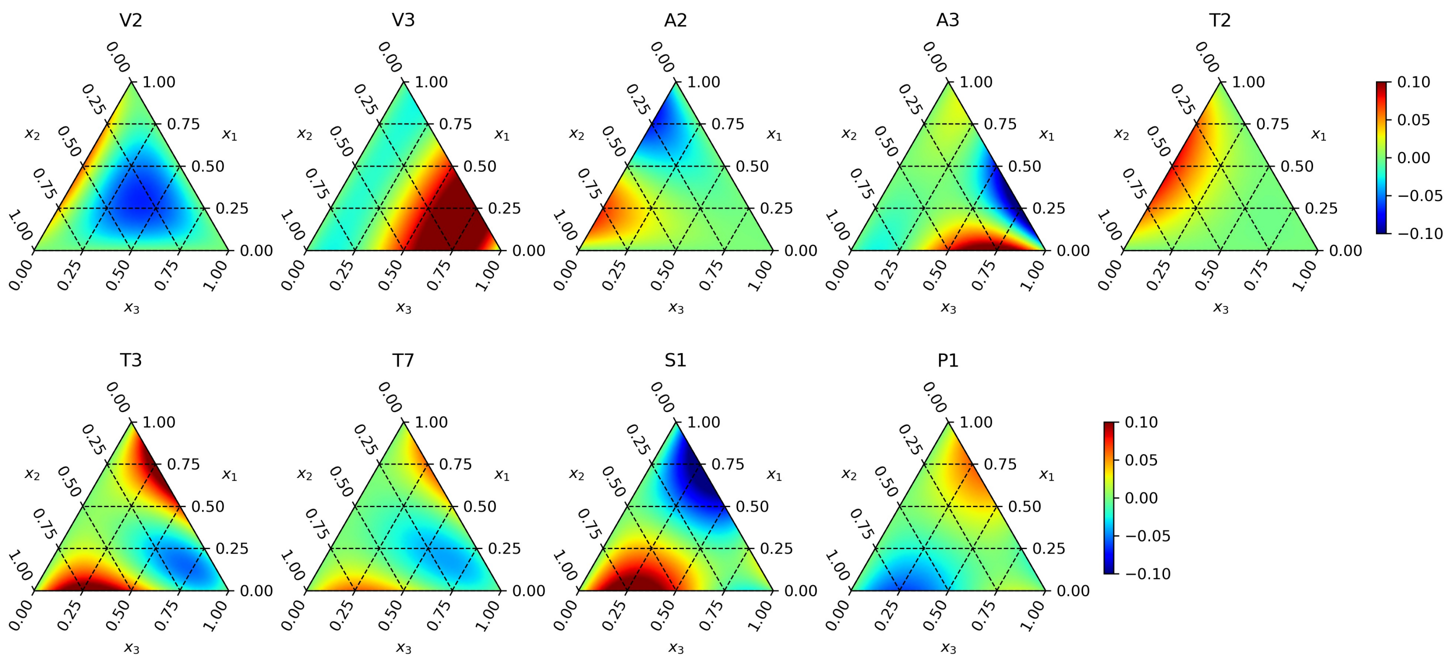


LCDAs of Λ_b in exponential model

Proton twist-4



Proton twist-5



Numerical Results

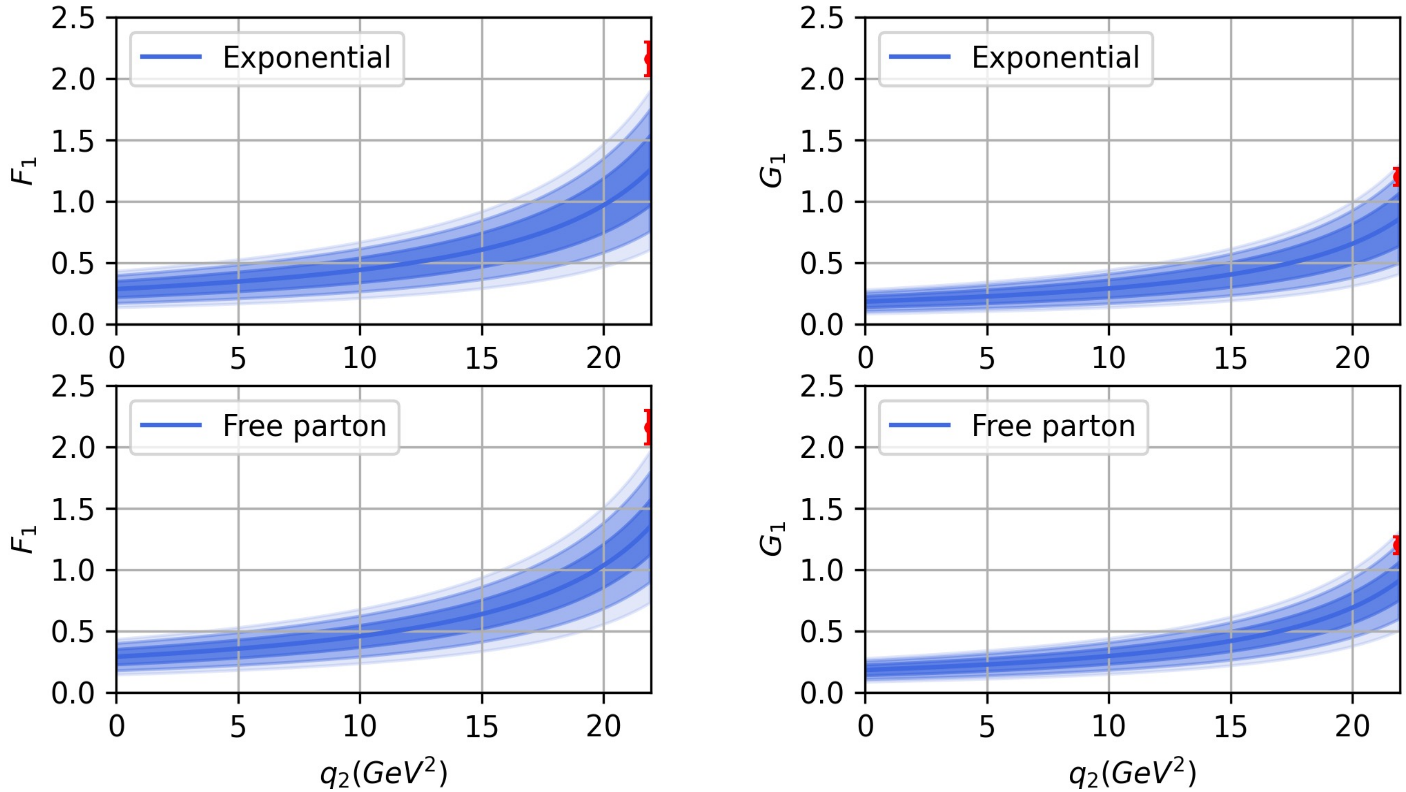
- Fit the form factors by dipole formula

$$F_i(q^2) = \frac{F_i(0)}{1 - a_1 \frac{q^2}{M_{\Lambda_b}^2} + a_2 \frac{q^4}{M_{\Lambda_b}^4}}$$

TABLE X: Values of the dipole fit parameters.

exponential	a_1	a_2	free parton	a_1	a_2
F_1	1.115	0.001	F_1	1.117	−0.016
F_2	1.127	0.086	F_2	1.134	0.113
F_3	1.069	0.004	F_3	1.101	0.048
G_1	1.118	−0.014	G_1	1.121	−0.028
G_2	1.118	0.035	G_2	1.116	−0.008
G_3	1.148	−0.032	G_3	1.119	0.070

Numerical Results



$\Lambda_b \to p\pi^-$(exponential)	$7.70^{+5.90+5.30+4.90}_{-4.24-2.01-0.97} \times 10^{-6}$	$\Lambda_b \to pK^-$(exponential)	$0.63^{+0.48+0.44+0.39}_{-0.35-0.16-0.08} \times 10^{-6}$
$\Lambda_b \to p\pi^-$(free parton)	$8.04^{+6.00+5.50+4.70}_{-4.30-3.36-1.01} \times 10^{-6}$	$\Lambda_b \to pK^-$(free parton)	$0.66^{+0.49+0.44+0.38}_{-0.35-0.18-0.08} \times 10^{-6}$
$\Lambda_b \to p\pi^-$(LHCb)[29]	$4.5 \pm 0.8 \times 10^{-6}$	$\Lambda_b \to pK^-$(LHCb)[29]	$5.4 \pm 1.0 \times 10^{-6}$

Numerical Results

$$H^V_{1/2,0} = \frac{\sqrt{(M_{\Lambda_b} - m_p)^2 - q^2}}{\sqrt{q^2}} \left((M_{\Lambda_b} + m_p)(F_1(q^2) + \frac{M_{\Lambda_b} + m_p}{2}(F_2(q^2) + F_3(q^2))) - \frac{q^2}{2}(F_2(q^2) + F_3(q^2))\right)$$

$$H^A_{1/2,0} = \frac{\sqrt{(M_{\Lambda_b} + m_p)^2 - q^2}}{\sqrt{q^2}} \left((M_{\Lambda_b} - m_p)(G_1(q^2) - \frac{M_{\Lambda_b} - m_p}{2}(G_2(q^2) + G_3(q^2))) + \frac{q^2}{2}(G_2(q^2) + G_3(q^2))\right)$$

$$H^V_{1/2,1} = \sqrt{2((M_{\Lambda_b} - m_p)^2 - q^2)} \left(-(F_1(q^2) + \frac{M_{\Lambda_b} + m_p}{2}(F_2(q^2) + F_3(q^2))) + \frac{M_{\Lambda_b} + m_p}{2}(F_2(q^2) + F_3(q^2))\right)$$

$$H^A_{1/2,1} = \sqrt{2((M_{\Lambda_b} + m_p)^2 - q^2)} \left(-(G_1(q^2) - \frac{M_{\Lambda_b} - m_p}{2}(G_2(q^2) + G_3(q^2))) + \frac{M_{\Lambda_b} - m_p}{2}(G_2(q^2) + G_3(q^2))\right)$$

$$H^V_{1/2,t} = \frac{\sqrt{(M_{\Lambda_b} + m_p)^2 - q^2}}{\sqrt{q^2}} \left((M_{\Lambda_b} - m_p)(F_1(q^2) + \frac{M_{\Lambda_b} + m_p}{2}(F_2(q^2) + F_3(q^2))) + \frac{q^2}{2}(F_2(q^2) - F_3(q^2))\right)$$

$$H^A_{1/2,t} = \frac{\sqrt{(M_{\Lambda_b} - m_p)^2 - q^2}}{\sqrt{q^2}} \left((M_{\Lambda_b} + m_p)(G_1(q^2) - \frac{M_{\Lambda_b} - m_p}{2}(G_2(q^2) + G_3(q^2))) - \frac{q^2}{2}(G_2(q^2) - G_3(q^2))\right)$$

- ***R.Dutta (2016)***

Numerical Results

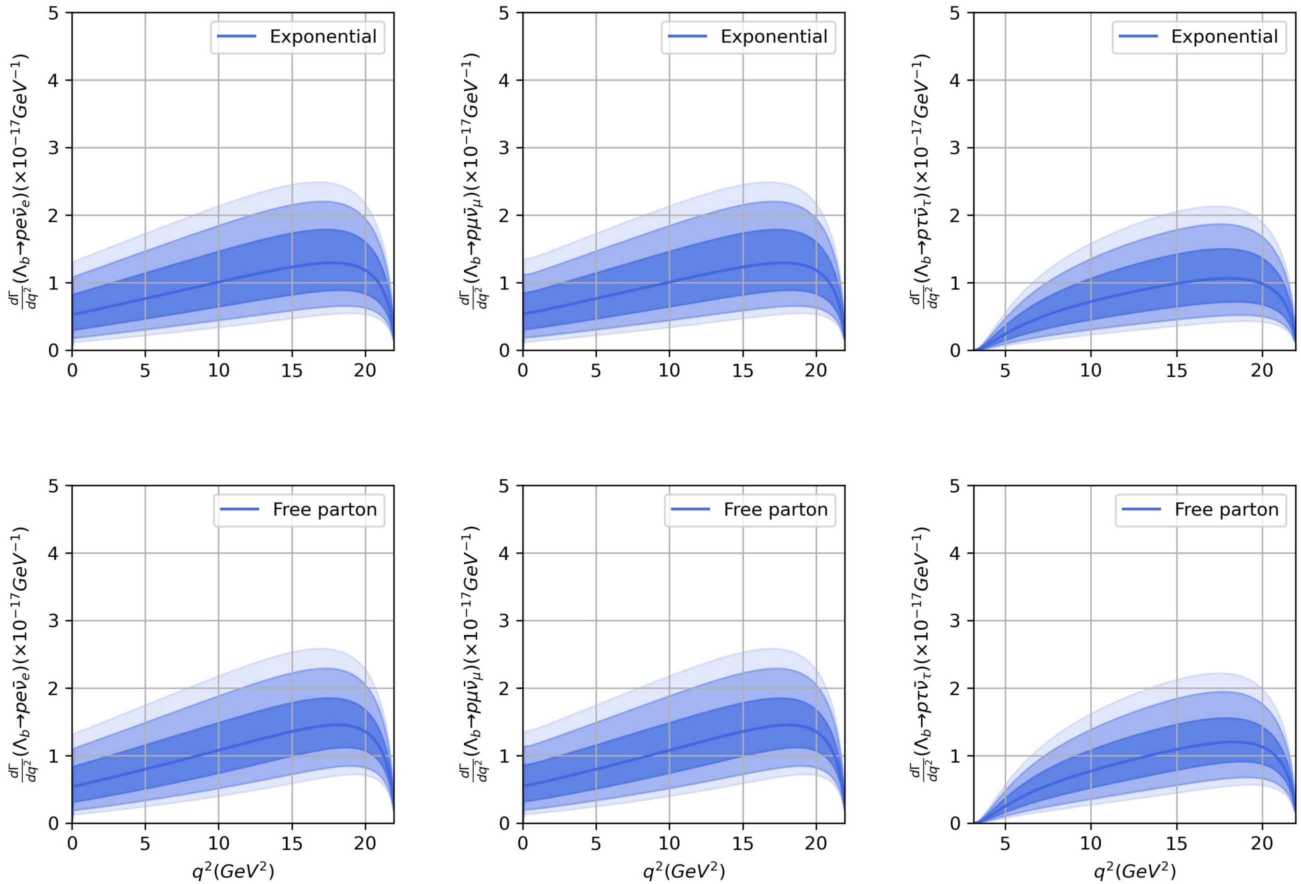
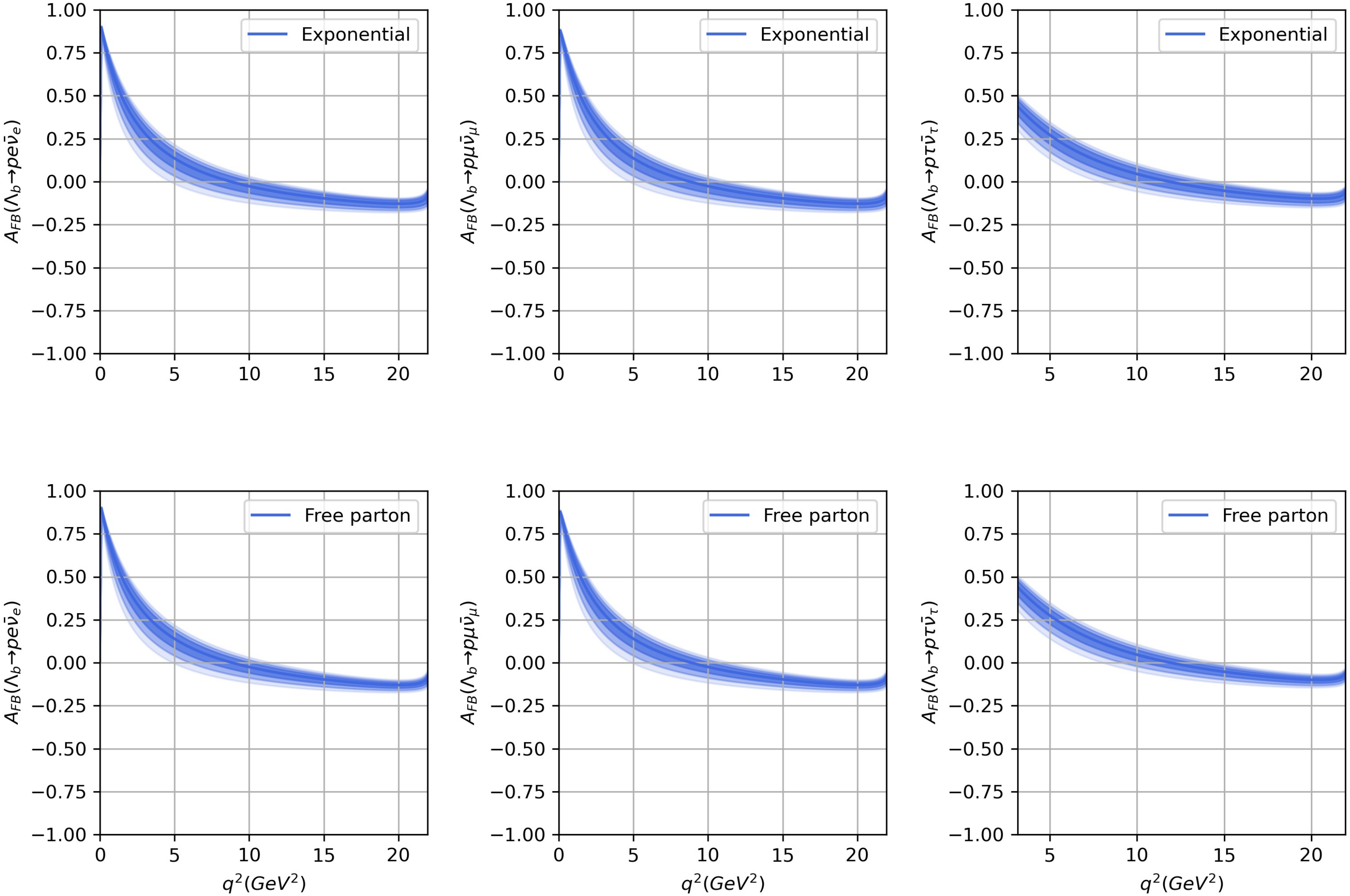


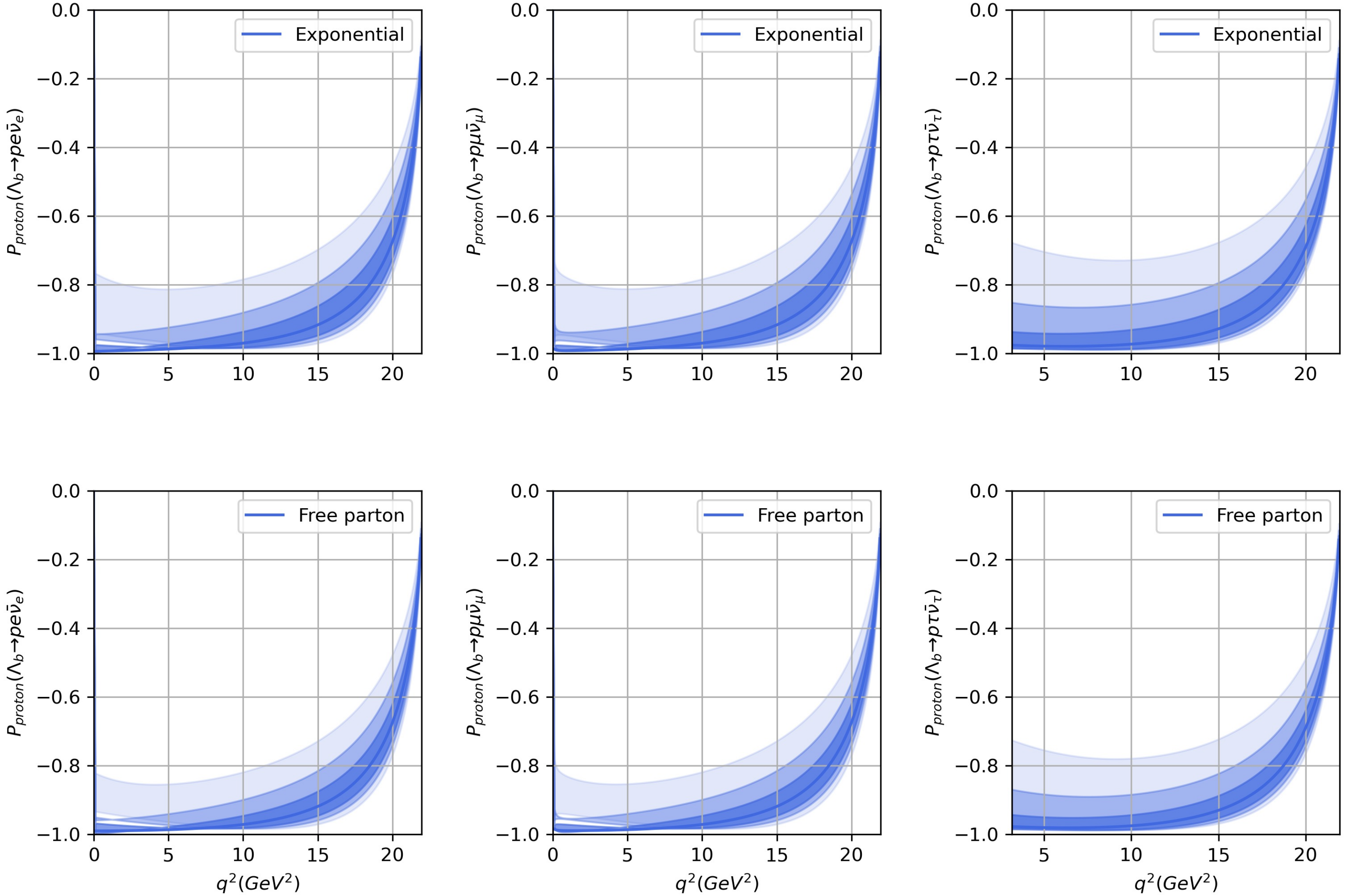
TABLE XIII: Branching fraction of semi-leptonic decay $\Lambda_b \to pl\bar{\nu}_l$.

	$\Lambda_b \to pe\bar{\nu}_e$	$\Lambda_b \to p\mu\bar{\nu}_\mu$	$\Lambda_b \to p\tau\bar{\nu}_\tau$
(exponential)	$4.52^{+1.92+4.64+1.20}_{-1.52-0.88-0.44} \times 10^{-4}$	$4.52^{+1.92+4.64+1.24}_{-1.44-0.88-0.44} \times 10^{-4}$	$3.08^{+1.40+1.12+0.88}_{-1.08-0.60-0.32} \times 10^{-4}$
(free parton)	$4.92^{+1.72+1.68+1.24}_{-1.44-1.00-0.48} \times 10^{-4}$	$4.92^{+1.72+1.68+1.24}_{-1.44-1.00-0.48} \times 10^{-4}$	$3.40^{+1.20+1.20+0.92}_{-0.96-0.72-0.36} \times 10^{-4}$

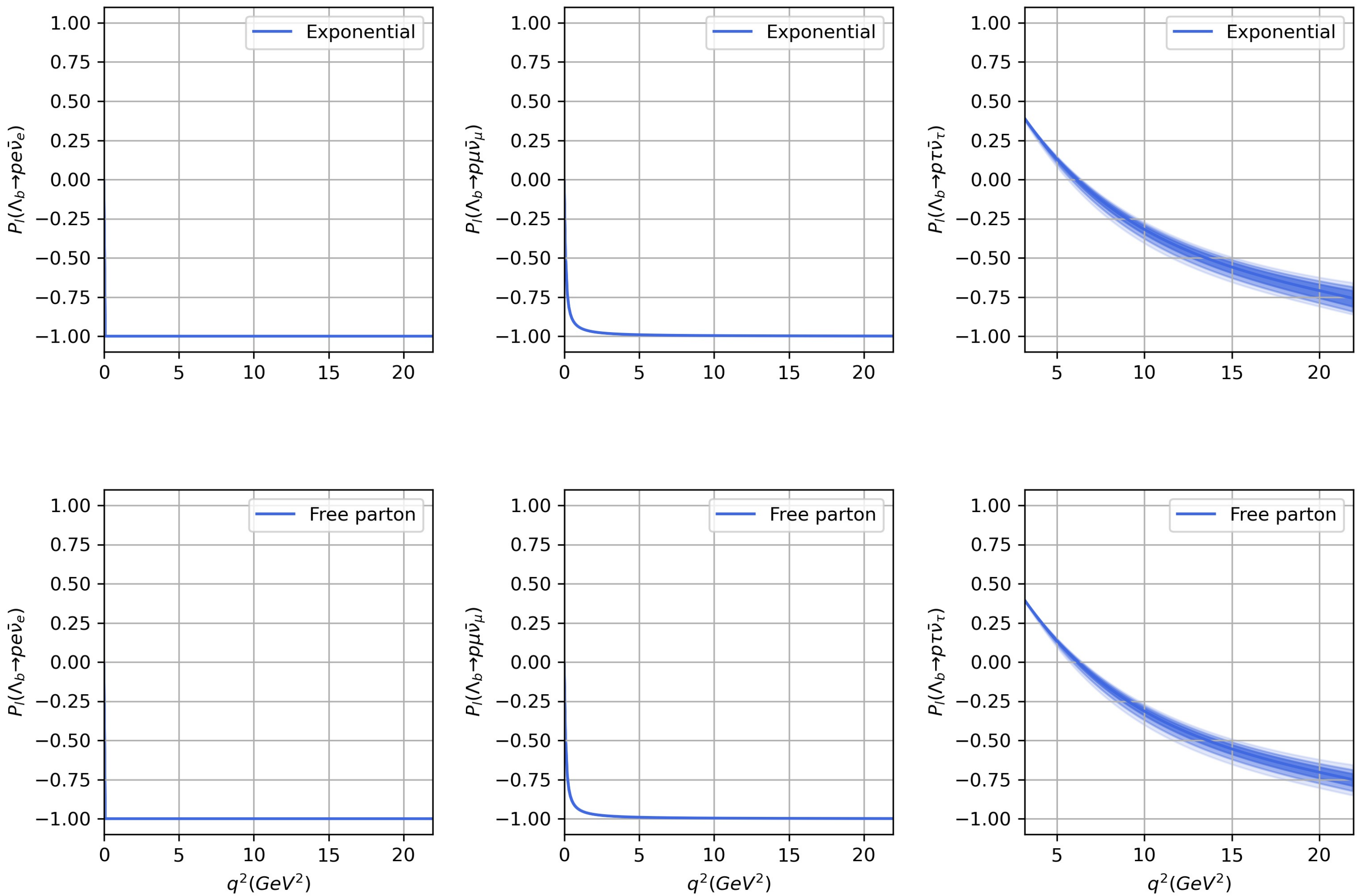
Numerical Results



Numerical Results



Numerical Results



Outline

- Motivation
- Framework of PQCD
- High twist LCDAs of baryons
- Numerical results
- Discussion and conclusion

Conclusion

- Contributions from high twist LCDAs are dominant in $\Lambda_b \to p$ form factors.

- Contributions from different twist depend highly on the form of hard-scattering functions and end-point behavior of LCDAs.

- LCDAs of Λ_b expanded with Gegenbauer polynomial should be taken seriously

- The total form factors in this work are consistent with that from approaches.

- Our results suffer from large uncertainties due to non-perturbative inputs of baryons LCDAs

Outlook:

- CPV in b-baryon two-body decay
- Including TMD LCDAs
- Improve PQCD Framework (Sudakov factors, prove of factorization in baryon decay, …)