Λ_b decays in the PQCD

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Based on
Eur.Phys.J.C 82(2022)8,686 with *Ya Li, Yue-Long Shen, Hsiang-nan Li, Zhen-Jun Xiao, Fu-Sheng Yu*
&
arXiv:2405.xxxxx with Ji-Xin Yu, Ya Li, Hsiang-nan Li, Zhen-Jun Xiao, Fu-Sheng Yu

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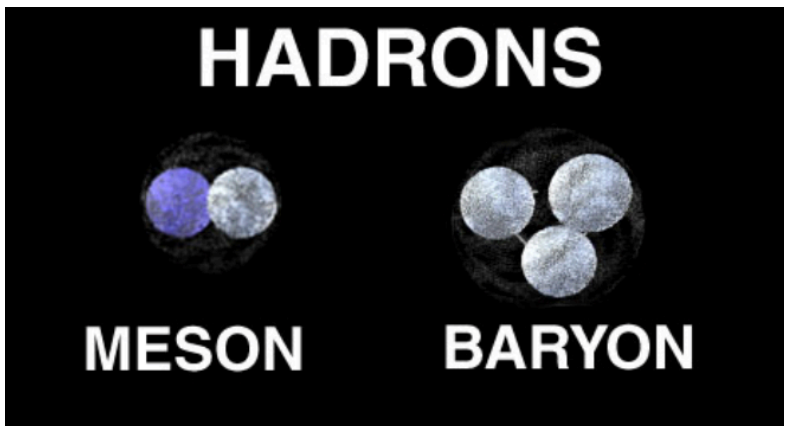
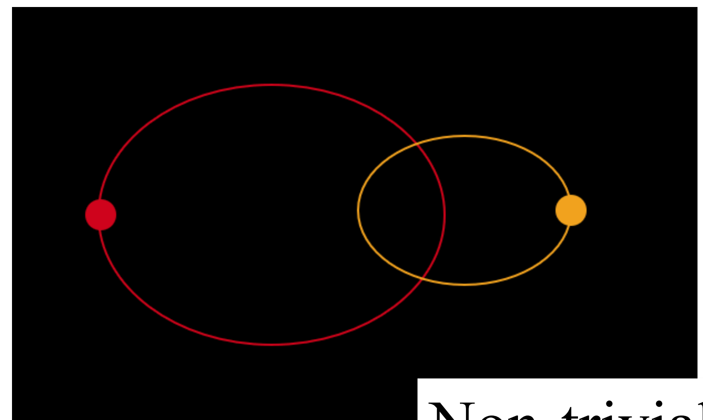
Outline

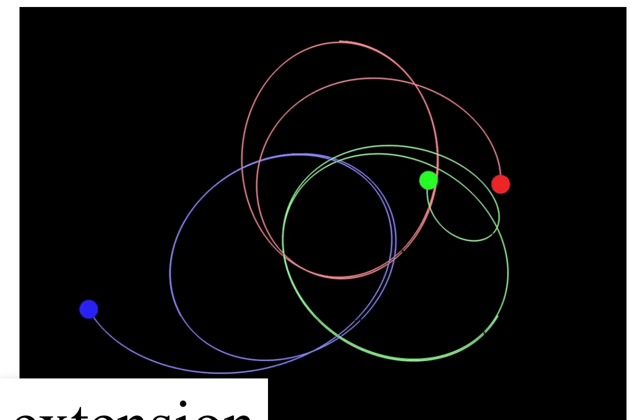
- Why baryon physics?
- Form factors of $\Lambda_b \to p$ in PQCD
- Two-body decay $\Lambda_b \to p\pi^-$ and its CPV in PQCD
- Summary

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.





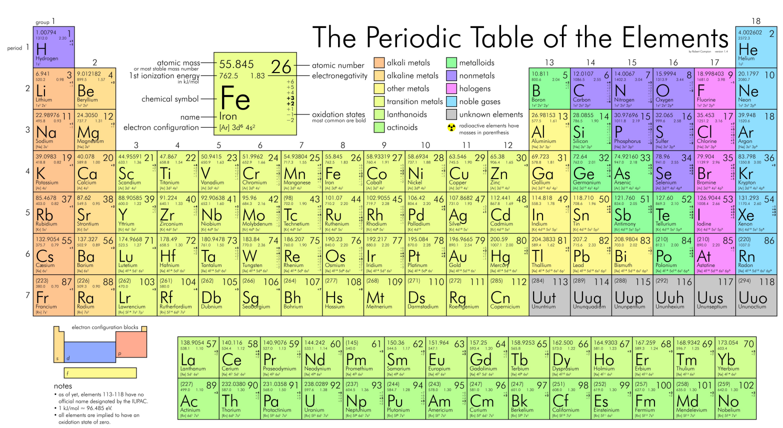


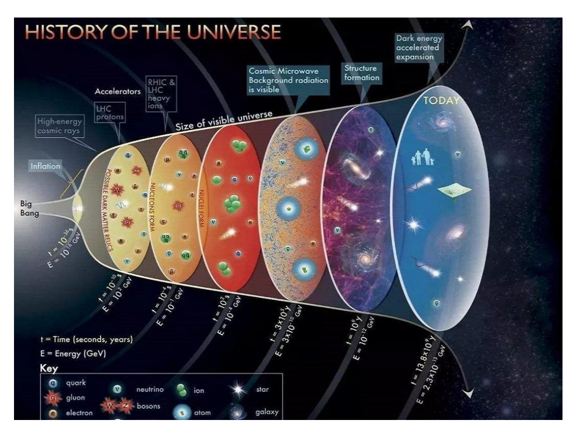
Non-trivial extension
More is different

- 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

- BESIII gives most precise Hyperon CPV:

$$A_{CP}^{\alpha}(\Lambda \to p\pi^-) = -0.002 \pm 0.004$$

BESIII,Nature,2022
BESIII,Nature Phys,2019

- Hyperon CPV in theory: $\mathcal{O}(10^{-5} \sim 10^{-4})$
- LHCb gives most precise charm baryon CPV:

$$A_{CP}(\Lambda_c \to pK^+K^-) - A_{CP}(\Lambda_c \to p\pi^+\pi^-) = 0.003 \pm 0.011$$

LHCb,JHEP,2018

- Charm baryon CPV in theory: $\mathcal{O}(10^{-3})$
- CPV in beauty baryon $\sim 10\,\%$ due to large weak phase difference and $r = \frac{penguin}{tree}$

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

PDG,2022

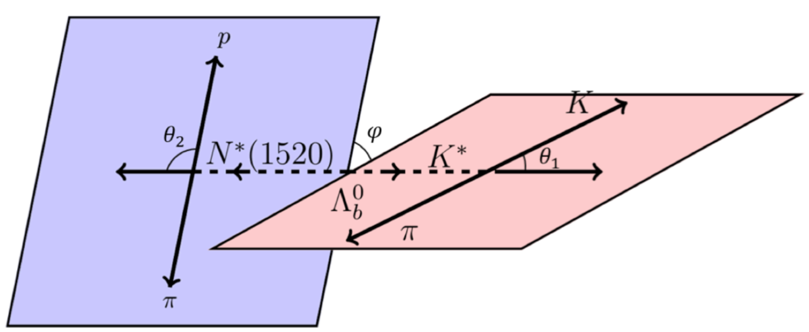
- LHCb is a baryon factory! $\frac{N_{\Lambda_b}}{N_{B^{0,-}}} \sim 0.5 \longrightarrow N_{\Lambda_b} \sim 10^{12}$

LHCb,PRD,2012

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

LHCb,PLB,2018

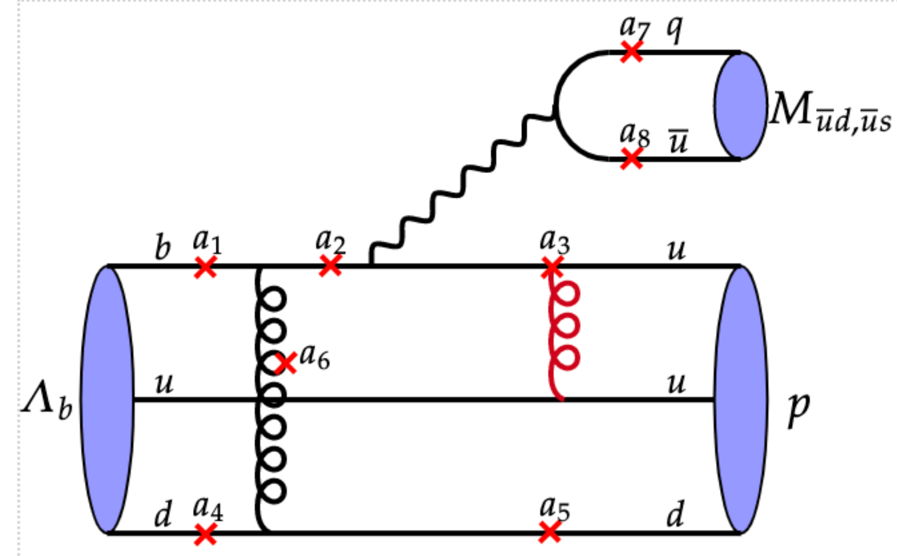
$$A_{CP}(\Lambda_b \to p\pi^-) = (-3.5 \pm 1.7 \pm 2.0)\,\%\,, \quad A_{CP}(\Lambda_b \to pK^-) = (-2.0 \pm 1.3 \pm 1.0)\,\%$$



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

- It can be expected that CPV in beauty baryon be observed soon!

Challenges



- QCD dynamics for baryon are different
  - One more energetic quark, one more hard gluon,
  - Counting rule of power expansion is violated by α_s,
  - Why CPV of $\Lambda_b \to p\pi, pK$ are so small?

- QCD studies on baryon are limited
  - Generalized factorization [Hsiao, Geng, 2015; Liu, Geng, 2021]:
    lost of non-factorizable contributions, such as W-exchange diagrams.
  - QCDF [Zhu, Ke, Wei, 2016, 2018]:
    based on diquark picture, no W-exchange diagrams.
  - PQCD [Lü, Wang, Zou, Ali, Kramer, 2009]:
    only considering leading twist baryon LCDAs.

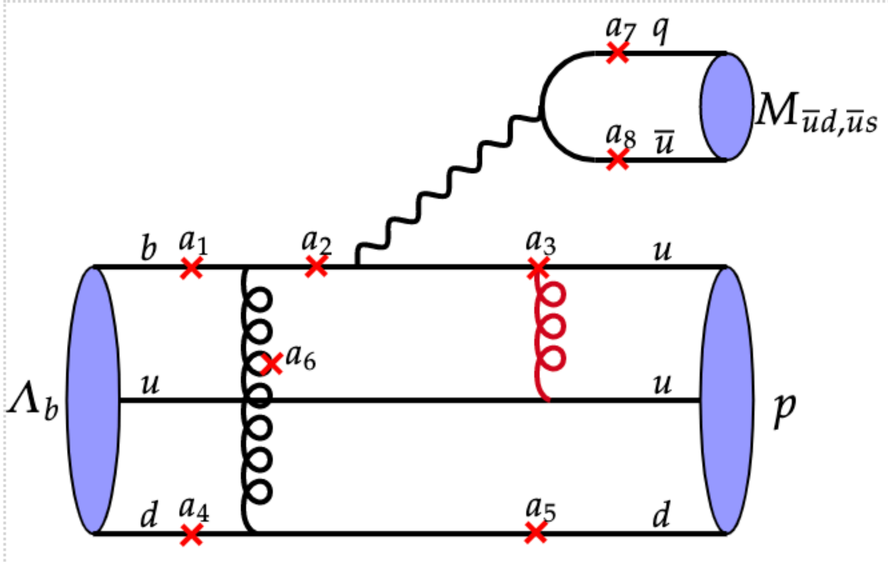
	measurement	Generalized factorization	QCDF	PQCD
$Br(\Lambda_b \to p\pi^-) \times 10^{-6}$	4.5 ± 0.8	4.2 ± 0.7	$4.66^{+2.22}_{-1.81}$	$4.11 \sim 4.57$
$Br(\Lambda_b \to pK^-) \times 10^{-6}$	5.4 ± 1.0	4.8 ± 0.7	$1.82^{+0.97}_{-1.07}$	$1.70 \sim 3.15$
$A_{CP}(\Lambda_b \to p\pi^-)\,\%$	-2.5 ± 2.9	-3.9 ± 0.2	-32^{+49}_{-1}	$-3.74 \sim -3.08$
$A_{CP}(\Lambda_b \to pK^-)\,\%$	-2.5 ± 2.2	5.8 ± 0.2	-3^{+25}_{-4}	$8.1 \sim 11.4$

Theoretical progresses

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

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

- However, the leading-power result is one order smaller than total one
  - Leading-power: $\xi_{\Lambda_b \to \Lambda}(0) = -0.012$ [W.Wang,2011]
  - Total form factor: $\xi_{\Lambda_b \to \Lambda}(0) = 0.18$ [Y.L.Shen,Y.M.Wang,2016]
- Two hard gluons suppressed by α_s^2 at the leading power, compared to the soft contributions in the power corrections.



PQCD approach

- PQCD has successfully predicted CPV in B meson decays

$$A_{CP}(B \to \pi^+\pi^-) = (30 \pm 20)\,\%\,,\quad A_{CP}(B \to K^+\pi^-) = (-17 \pm 5)\,\%$$

[Keum,H-n.Li,Sanda,2000; C.D.Lü,Ukai,M.Z.Yang,2000]

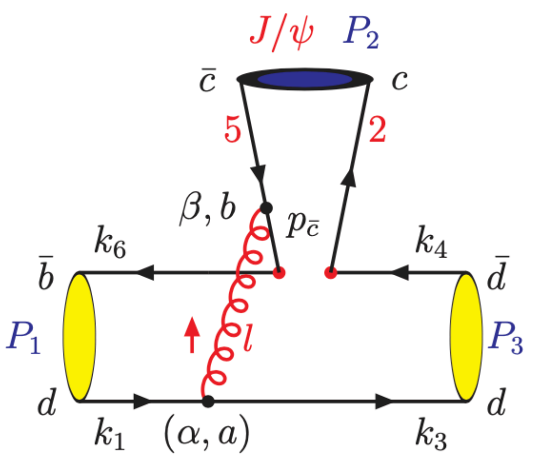
$$A_{CP}(B \to \pi^+\pi^-) = (32 \pm 4)\,\%\,,\quad A_{CP}(B \to K^+\pi^-) = (-8.3 \pm 0.4)\,\%$$

[PDG,2022; first measurements were made in 2001]

Factorization hypothesis:

$$\mathscr{A} = \langle M_2 M_3 | \mathscr{H} | B \rangle$$

$$\sim \int \frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4}\frac{d^4k_3}{(2\pi)^4}\Psi_B(k_1,\mu)\Psi_2(k_2,\mu)\Psi_3(k_3,\mu)\cdot H(k_1,k_2,k_3,\mu)C_i(\mu)$$



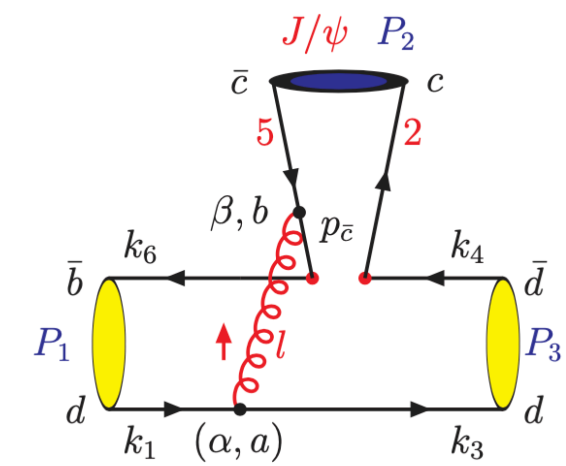
- Under collinear factorization:
  - endpoint singularity: propagator $\sim \dfrac{1}{x_1 x_2 Q^2} \to \infty$ when $x_{1,2} \to 0{,}1$

$$\mathscr{A} \sim \int_0^1 dx_1 dx_2 dx_3 \phi_B(x_1,\mu) * H\left(x_1, x_2, x_3, \mu, \alpha_s(x_i,\mu)\right) * \phi_\eta(x_2,\mu)\phi_{J/\psi}(x_3,\mu)$$

PQCD approach

- PQCD approach (based on k_T factorization): retain transverse momentum of parton k_T

  propagator $\sim \dfrac{1}{x_1x_2Q^2 + |k_{iT}|^2}$



$$\mathscr{A} = \langle M_2M_3 | \mathscr{H} | B \rangle$$

$$\sim \int \frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4}\frac{d^4k_3}{(2\pi)^4}\Psi_B(k_1,\mu)\Psi_2(k_2,\mu)\Psi_3(k_3,\mu)\cdot H(k_1,k_2,k_3,\mu)C_i(\mu)$$

$$\sim \int_0^1 dx_2dx_2dx_3 \int \frac{d^2k_{1T}}{(2\pi)^2}\frac{d^2k_{2T}}{(2\pi)^2}\frac{d^2k_{3T}}{(2\pi)^2}\phi_B(x_1,k_{1T},\mu)\phi_2(x_2,k_{2T},\mu)\phi_3(x_3,k_{3T},\mu)\cdot H(x_1,x_2,x_3,k_{1T},k_{2T},k_{3T},\mu)C_i(\mu)$$

$$H(x_i,k_T,\mu) \sim \frac{N_1(x_1,x_2,x_3)N_2(x_1,x_2,x_3)}{l^2\ p_c^2} = \frac{N_1(x_1,x_2,x_3)}{x_1x_3M_B^2 - |k_{1T}-k_{3T}|^2}\frac{N_2(x_1,x_2,x_3)}{M_B^2(1-x_3) - |k_{3T}|^2}$$

- Resum double-log radiative correction, obtain k_T Sudakov factor $S(x_i, b_i)$ and threshold Sudakov factor $S_t(x_i)$.

[NPB (Collins, 1981)
NPB (Botts, Sterman, 1989)
PRD (Hsiang-nan Li, 1995)
PRL (Hsiang-nan Li, 1995)
PRD (Hsiang-nan Li, 1996)
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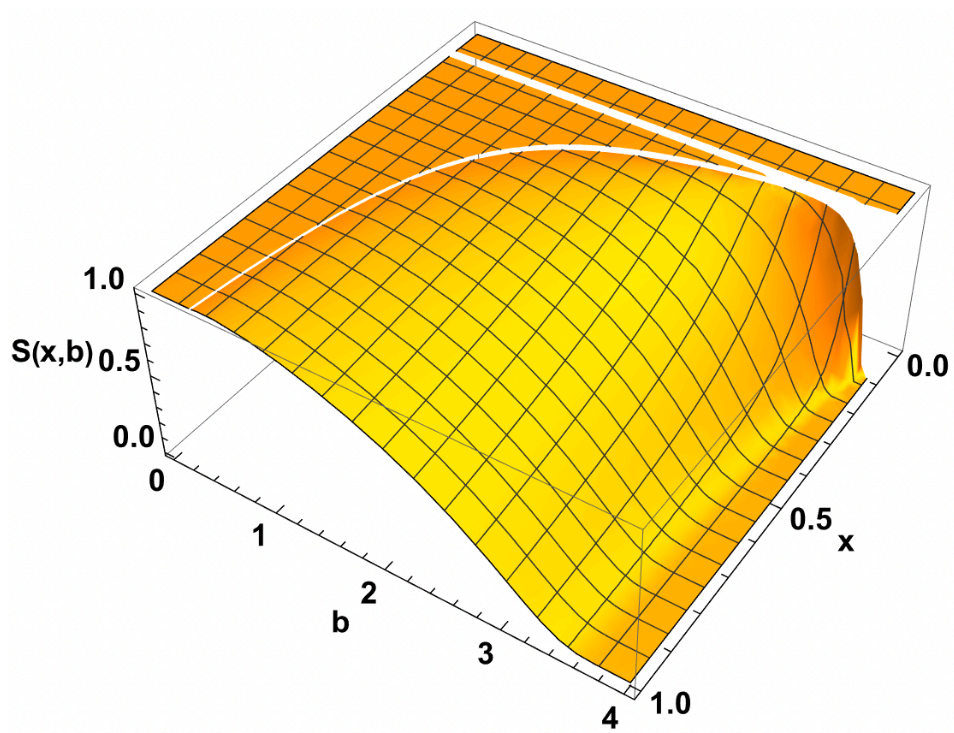
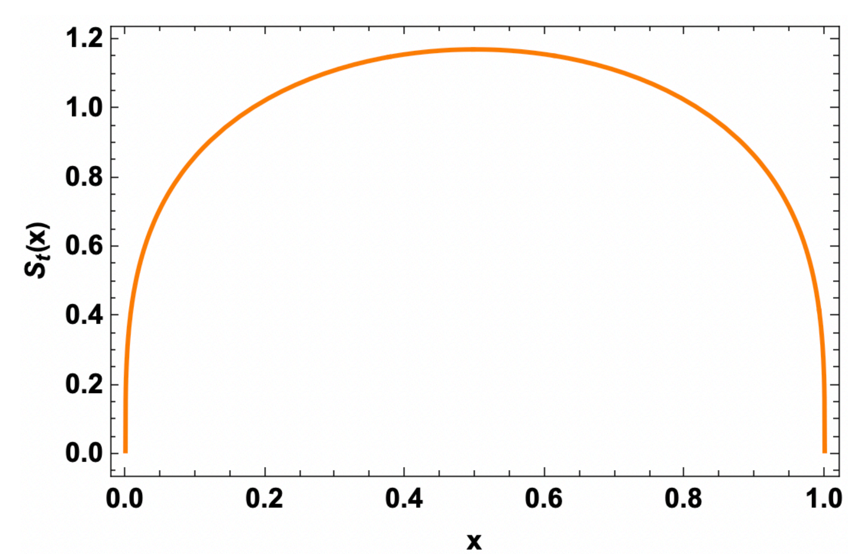
……]





PQCD approach

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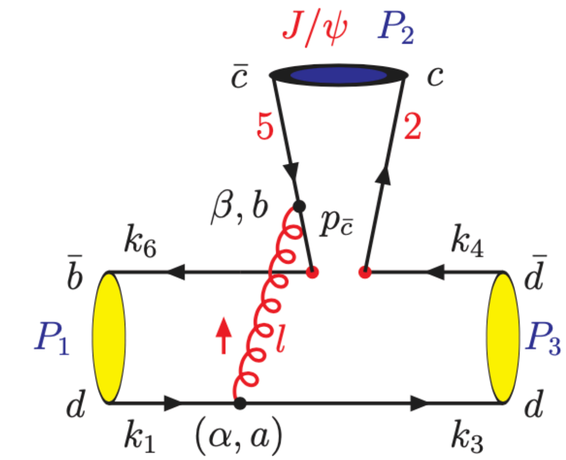
  - propagator $\sim \dfrac{1}{x_1 x_2 Q^2 + |k_{iT}|^2}$



$$\mathscr{A} = \langle M_2 M_3 | \mathscr{H} | B \rangle$$

$$\sim \int \frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4}\frac{d^4k_3}{(2\pi)^4}\Psi_B(k_1,\mu)\Psi_2(k_2,\mu)\Psi_3(k_3,\mu)\cdot H(k_1,k_2,k_3,\mu)C_i(\mu)$$

$$\sim \int_0^1 dx_2 dx_2 dx_3 \int \frac{d^2k_{1T}}{(2\pi)^2}\frac{d^2k_{2T}}{(2\pi)^2}\frac{d^2k_{3T}}{(2\pi)^2}\phi_B(x_1,k_{1T},\mu)\phi_2(x_2,k_{2T},\mu)\phi_3(x_3,k_{3T},\mu)\cdot H(x_1,x_2,x_3,k_{1T},k_{2T},k_{3T},\mu)C_i(\mu)$$

$$H(x_i,b_i) \sim \int \frac{d^2k_{1T}}{(2\pi)^2}\frac{d^2k_{3T}}{(2\pi)^2}e^{ib\cdot k_{1T}}e^{ib\cdot k_{3T}}\frac{N_1(x_1,x_2,x_3)}{x_1x_3M_B^2-|k_{1T}-k_{3T}|^2}\frac{N_2(x_1,x_2,x_3)}{M_B^2(1-x_3)-|k_{3T}|^2}$$

$$\sim N_1(x_1,x_2,x_3)N_2(x_1,x_2,x_3)\cdot\Big[K_0(\sqrt{x_1x_3M_B^2}b_1)I_0(\sqrt{(1-x_3)M_B^2}b_3)K_0(\sqrt{(1-x_3)M_B^2}b_1)\Theta(b_3-b_1)+K_0(\sqrt{x_1x_3M_B^2}b_1)I_0(\sqrt{(1-x_3)M_B^2}b_1)K_0(\sqrt{(1-x_3)M_B^2}b_3)\Theta(b_1-b_3)\Big]$$

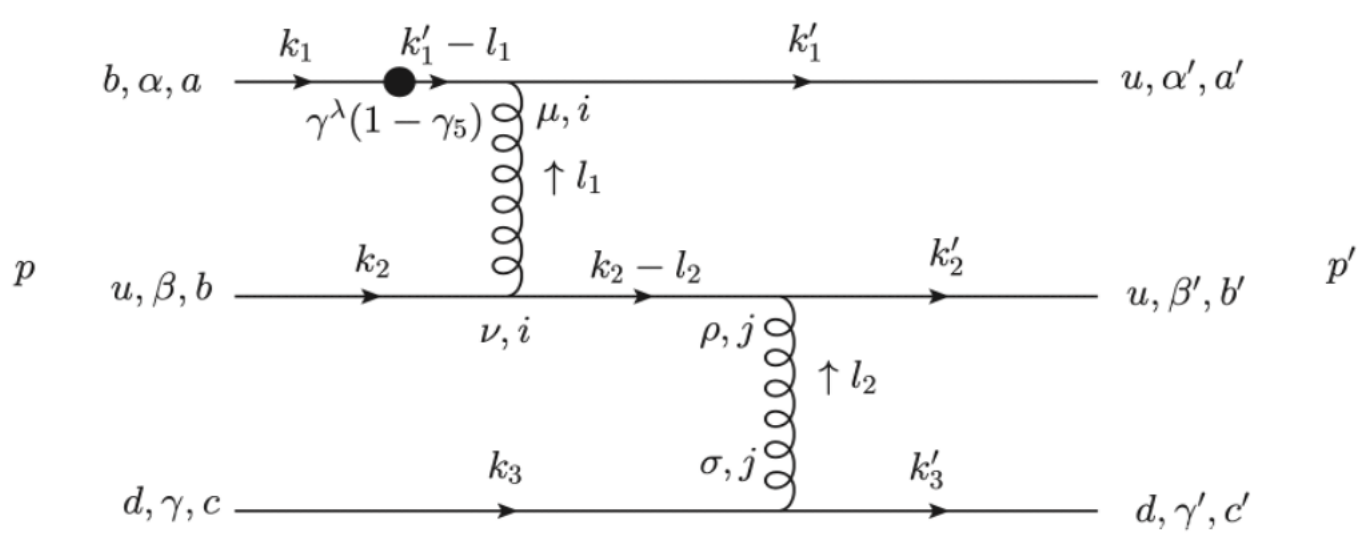
after Fourier tramsform

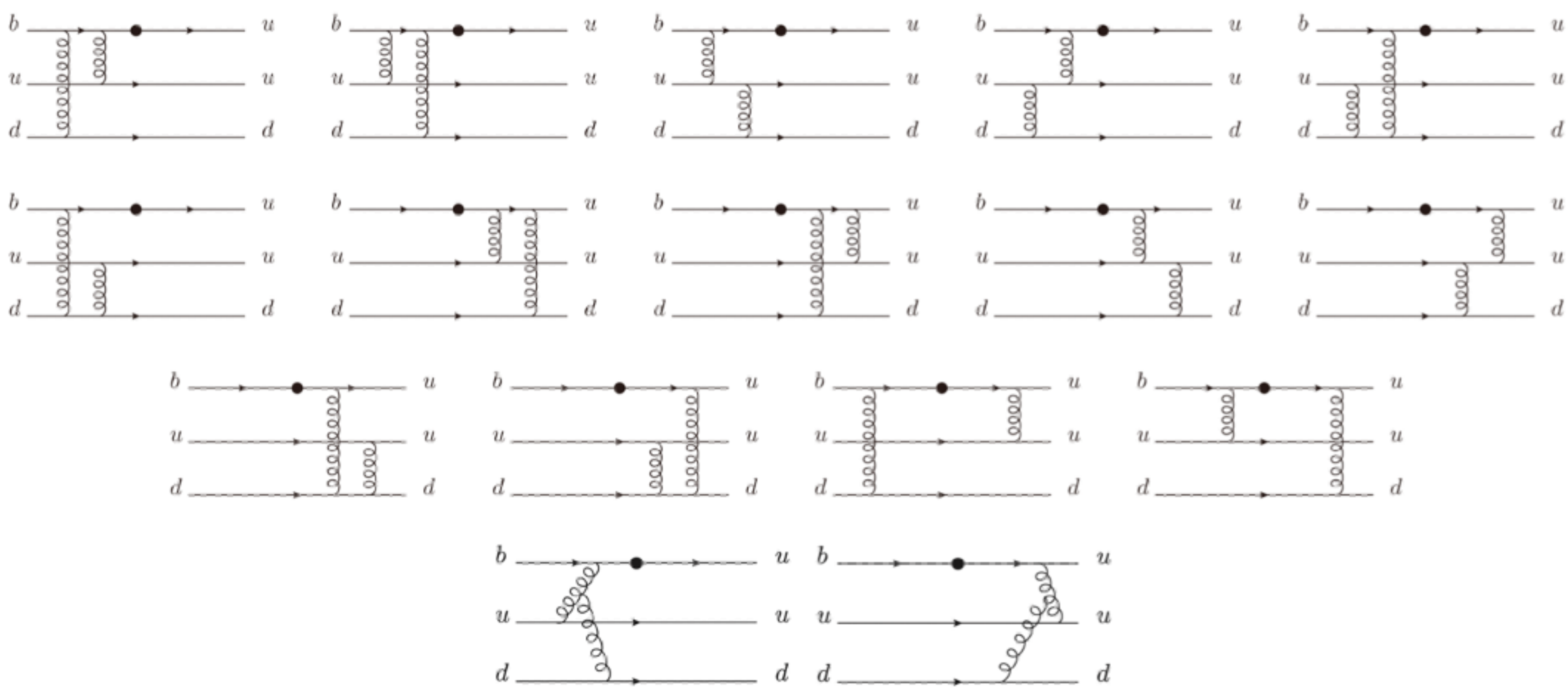
$$\sim \int_0^1 dx_1dx_2dx_3\int d^2b_1d^2b_2d^2b_3\phi_B(x_1,b_1,\mu)\phi_2(x_2,b_2,\mu)\phi_3(x_3,b_3,\mu)\cdot H(x_1,x_2,x_3,b_1,b_2,b_3,\mu)C_i(\mu)\times\Pi_i S(x_i,b_i)\times S_t(x_i)$$

$\Lambda_b \to p$ form factors in PQCD

$$F_i(q^2) \sim \int_0^1 d[x]d[x'] \int d^2[b]d^2[b']\phi_{\Lambda_b}([x],[b],\mu) \cdot H([x],[x'],[b],[b'],\mu)C_i(\mu) \cdot \phi_p([x'],[b'],\mu) \cdot \Pi_i S(x_i,b_i)S_t(x_i)$$

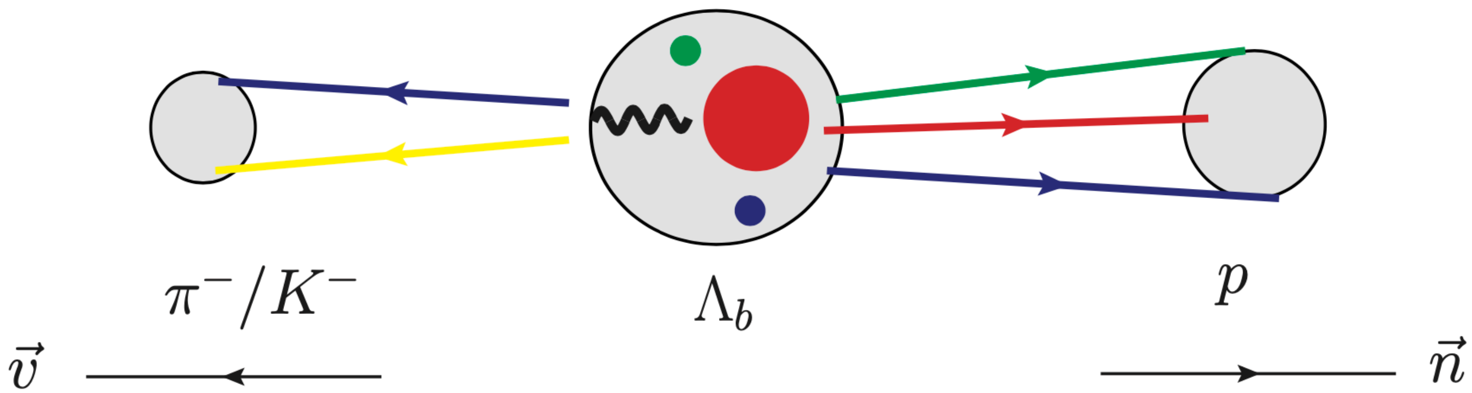
$$\langle p \,|\, \bar{u}\gamma_\mu(1-\gamma_5)b \,|\, \Lambda_b \rangle = \bar{p}(f_1\gamma_\mu - if_2\sigma_{\mu\nu}q^\nu + f_3 q_\mu)\Lambda_b - \bar{p}(g_1\gamma_\mu - ig_2\sigma_{\mu\nu}q^\nu + g_3 q_\mu)\gamma_5\Lambda_b$$





Kinematics

- The momentum of proton is in the plus direction, the momentum of meson is in the minus



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

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

$$\eta^\pm = \left[m_i^2 - m_M^2 + m_f^2 \pm \sqrt{(-m_i^2 + m_M^2 - m_f^2)^2 - 4m_i^2 m_f^2}\right]/(2m_i^2).$$

LCDA for Λ_b

$$(Y_{\Lambda_b})_{\alpha\beta\gamma}(x_i,\mu) = \frac{1}{8N_c}\left\{f^{(1)}_{\Lambda_b}(\mu)[M_1(x_2,x_3)\gamma_5 C^T]_{\gamma\beta} + f^{(2)}_{\Lambda_b}(\mu)[M_2(x_2,x_3)\gamma_5 C^T]_{\gamma\beta}\right\}[\Lambda_b(p)]_\alpha, \tag{29}$$

where N_c is the number of colors, the normalization constants $f^{(1)}_{\Lambda_b} \approx f^{(2)}_{\Lambda_b} \equiv f_{\Lambda_b} = 0.021 \pm 0.004$ GeV^3, which are consistent with $f_{\Lambda_b} = 0.022 \pm 0.001$ GeV^3 quoted from

The remaining parts of the projector in Eq. (29) are expressed as

G.Bell, T.Feldmann, Y.M.Wang, Y.Yip(2013)

$$M_1(x_2,x_3) = \frac{\not{\bar{n}}\not{n}}{4}\psi_3^{+-}(x_2,x_3) + \frac{\not{n}\not{\bar{n}}}{4}\psi_3^{-+}(x_2,x_3), \tag{30}$$

$$M_2(x_2,x_3) = \frac{\not{n}}{\sqrt{2}}\psi_2(x_2,x_3) + \frac{\not{\bar{n}}}{\sqrt{2}}\psi_4(x_2,x_3), \tag{31}$$

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

Exponential model

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

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

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

LCDA for proton

$$
\begin{aligned}
(\overline{Y}_P)_{\alpha\beta\gamma}(x_i',\mu) = \frac{1}{8\sqrt{2}N_c}\Big\{ & S_1 m_p C_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma + S_2 m_p C_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma + P_1 m_p (C\gamma_5)_{\beta\alpha}\bar{N}^+_\gamma \\
& + P_2 m_p (C\gamma_5)_{\beta\alpha}\bar{N}^-_\gamma + V_1(C\not{P})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma + V_2(C\not{P})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma \\
& + V_3\frac{m_p}{2}(C\gamma_\perp)_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma + V_4\frac{m_p}{2}(C\gamma_\perp)_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma + V_5\frac{m_p^2}{2Pz}(C\not{z})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma \\
& + V_6\frac{m_p^2}{2Pz}(C\not{z})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma + A_1(C\gamma_5\not{P})_{\beta\alpha}(\bar{N}^+)_\gamma + A_2(C\gamma_5\not{P})_{\beta\alpha}(\bar{N}^-)_\gamma \\
& + A_3\frac{m_p}{2}(C\gamma_5\gamma_\perp)_{\beta\alpha}(\bar{N}^+\gamma^\perp)_\gamma + A_4\frac{m_p}{2}(C\gamma_5\gamma_\perp)_{\beta\alpha}(\bar{N}^-\gamma^\perp)_\gamma + A_5\frac{m_p^2}{2Pz}(C\gamma_5\not{z})_{\beta\alpha}(\bar{N}^+)_\gamma \\
& + A_6\frac{m_p^2}{2Pz}(C\gamma_5\not{z})_{\beta\alpha}(\bar{N}^-)_\gamma - T_1(iC\sigma_{\perp P})_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma - T_2(iC\sigma_{\perp P})_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma \\
& - T_3\frac{m_p}{Pz}(iC\sigma_{Pz})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma - T_4\frac{m_p}{Pz}(iC\sigma_{zP})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma - T_5\frac{m_p^2}{2Pz}(iC\sigma_{\perp z})_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma \\
& - T_6\frac{m_p^2}{2Pz}(iC\sigma_{\perp z})_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma + T_7\frac{m_p}{2}(C\sigma_{\perp\perp'})_{\beta\alpha}(\bar{N}^+\gamma_5\sigma^{\perp\perp'})_\gamma \\
& + T_8\frac{m_p}{2}(C\sigma_{\perp\perp'})_{\beta\alpha}(\bar{N}^-\gamma_5\sigma^{\perp\perp'})_\gamma\Big\}, \qquad (33)
\end{aligned}
$$

Braun, 2001

	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	
Pesudoscalar		P_1	P_2	

- LCDAs V_i, A_i, T_i, S_i, P_i are functions of parameters $\phi_i^{\pm,0}, \psi_i^{\pm,0}, \xi_i^{\pm,0}$

$$V_1(x_i) = 120x_1x_2x_3[\phi_3^0 + \phi_3^+(1-3x_3)],$$
$$A_1(x_i) = 120x_1x_2x_3(x_2-x_1)\phi_3^-,$$
$$T_1(x_i) = 120x_1x_2x_3[\phi_3^0 + \frac{1}{2}(\phi_3^- - \phi_3^+)(1-3x_3)].$$

Braun, 2001

- The parameters $\phi_i^{\pm,0}, \psi_i^{\pm,0}, \xi_i^{\pm,0}$ depend on 8 parameters

$$\phi_3^0 = \phi_6^0 = f_N, \qquad \phi_4^0 = \phi_5^0 = \frac{1}{2}(\lambda_1 + f_N),$$
$$\xi_4^0 = \xi_5^0 = \frac{1}{6}\lambda_2, \qquad \psi_4^0 = \psi_5^0 = \frac{1}{2}(f_N - \lambda_1).$$

$$\phi_4^- = \frac{5}{4}\Big(\lambda_1(1-2f_1^d-4f_1^u) + f_N(2A_1^u-1)\Big),$$
$$\phi_4^+ = \frac{1}{4}\Big(\lambda_1(3-10f_1^d) - f_N(10V_1^d-3)\Big),$$
$$\psi_4^- = -\frac{5}{4}\Big(\lambda_1(2-7f_1^d+f_1^u) + f_N(A_1^u+3V_1^d-2)\Big),$$

$$\psi_4^+ = -\frac{1}{4}\Big(\lambda_1(-2+5f_1^d+5f_1^u) + f_N(2+5A_1^u-5V_1^d)\Big),$$
$$\xi_4^- = \frac{5}{16}\lambda_2(4-15f_2^d),$$
$$\xi_4^+ = \frac{1}{16}\lambda_2(4-15f_2^d),$$

$$\phi_5^- = \frac{5}{3}\Big(\lambda_1(f_1^d-f_1^u) + f_N(2A_1^u-1)\Big),$$
$$\phi_5^+ = -\frac{5}{6}\Big(\lambda_1(4f_1^d-1) + f_N(3+4V_1^d)\Big),$$
$$\psi_5^- = \frac{5}{3}\Big(\lambda_1(f_1^d-f_1^u) + f_N(2-A_1^u-3V_1^d)\Big),$$
$$\psi_5^+ = \frac{5}{3}\Big(\lambda_1(-1+f_1^u) + f_N(1+A_1^u+V_1^d)\Big),$$
$$\xi_5^- = -\frac{5}{4}\lambda_2 f_2^d,$$
$$\xi_5^+ = \frac{5}{12}\lambda_2(2-3f_2^d),$$

$$\phi_6^- = \frac{1}{2}\Big(\lambda_1(1-4f_1^d-2f_1^u) + f_N(1+4A_1^u)\Big),$$
$$\phi_6^+ = \Big(\lambda_1(1-2f_1^d) + f_N(4V_1^d-1)\Big).$$

	$f_N(GeV^2)$	$\lambda_1(GeV^2)$	$\lambda_2(GeV^2)$	V_1^d
QCDSR(2001) [22]	$(5.3 \pm 0.5) \times 10^{-3}$	$-(2.7 \pm 0.9) \times 10^{-2}$	$(5.1 \pm 1.9) \times 10^{-2}$	0.23 ± 0.03
QCDSR(2006) [23]	$(5.0 \pm 0.5) \times 10^{-3}$	$-(2.7 \pm 0.9) \times 10^{-2}$	$(5.4 \pm 1.9) \times 10^{-2}$	0.23 ± 0.03
LQCD(2019) [23]	$(3.54 \pm 0.06) \times 10^{-3}$	$-(4.49 \pm 0.42) \times 10^{-2}$	$(9.34 \pm 0.48) \times 10^{-2}$	0.19 ± 0.22
	A_1^u	f_1^d	f_2^d	f_1^u
QCDSR(2001) [22]	0.38 ± 0.15	0.6 ± 0.2	0.15 ± 0.06	0.22 ± 0.15
QCDSR(2006) [23]	0.38 ± 0.15	0.4 ± 0.05	0.22 ± 0.05	0.07 ± 0.05
LQCD(2019) [23]	0.30 ± 0.32	...	...	...

$\Lambda_b \to p$ form factors in PQCD

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

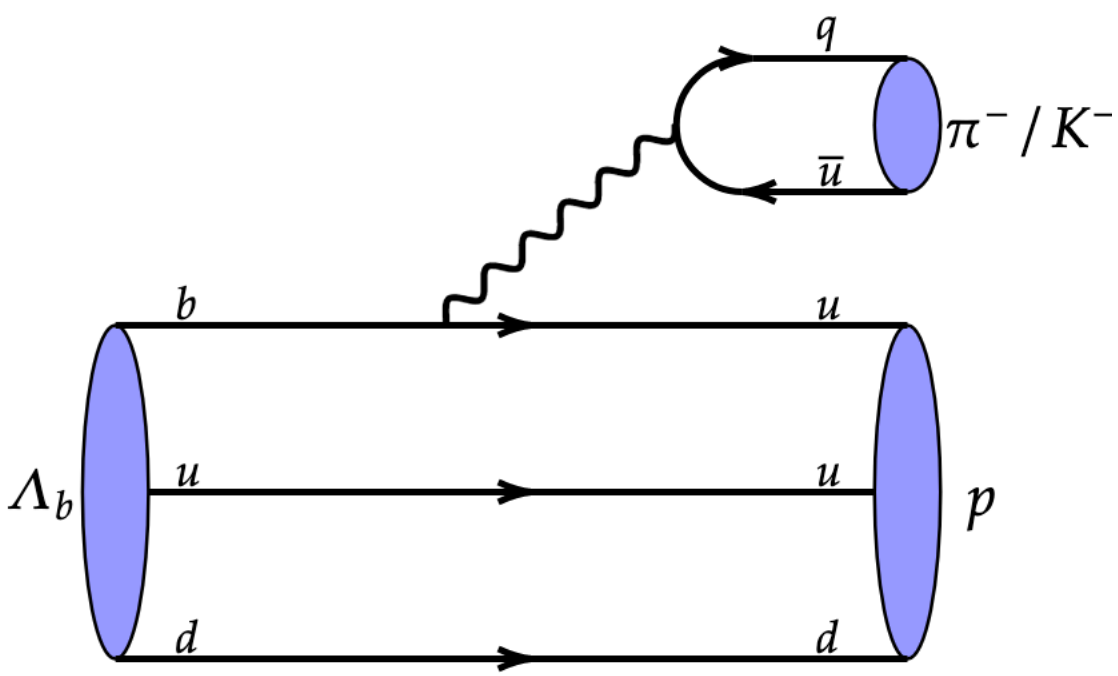
proton

Λ_b

	twist-3	twist-4	twist-5	twist-6	total
exponential					
twist-2	0.0007	-0.00007	-0.0005	-0.000003	0.0001
twist-3^{+-}	-0.0001	0.002	0.0004	-0.000004	0.002
twist-3^{-+}	-0.0002	0.0060	0.000004	0.00007	0.006
twist-4	0.01	0.00009	0.25	0.0000007	0.26
total	0.01	0.008	0.25	0.00007	$0.27 \pm 0.09 \pm 0.07$

	$f_1(0)$	$f_2(0)$	$g_1(0)$	$g_2(0)$
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

Topological Diagrams



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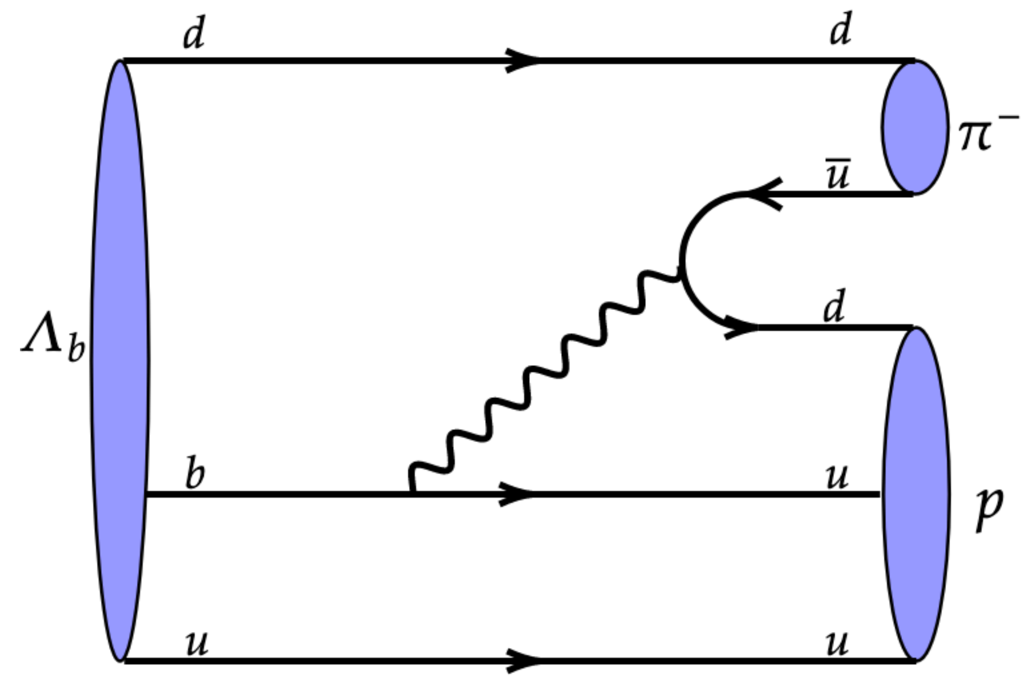
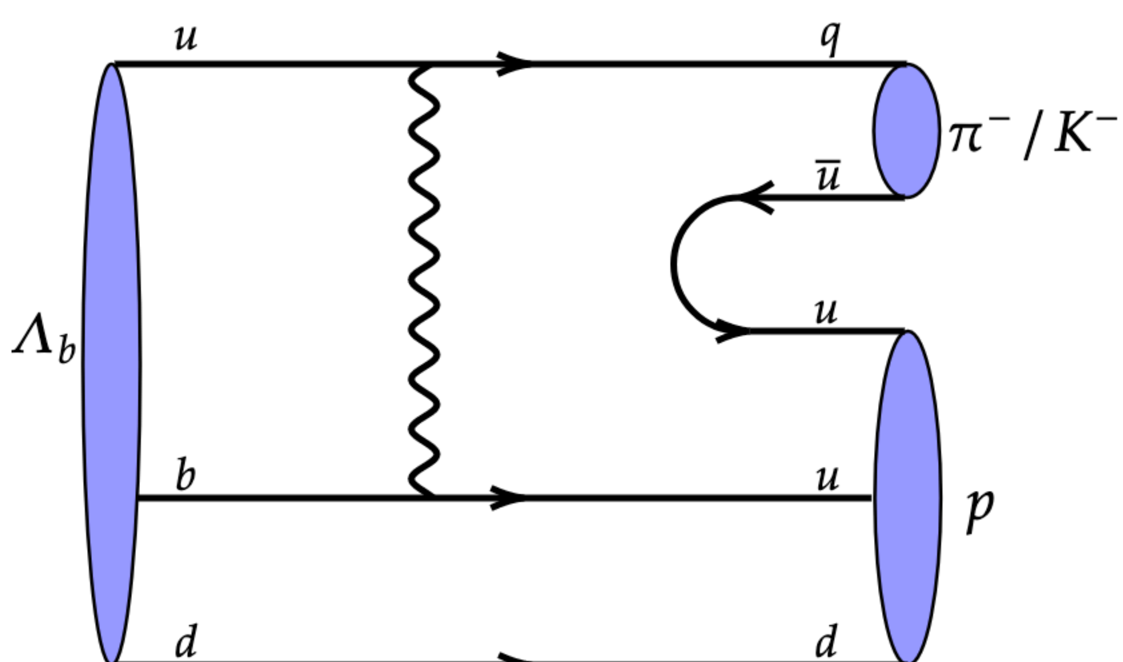
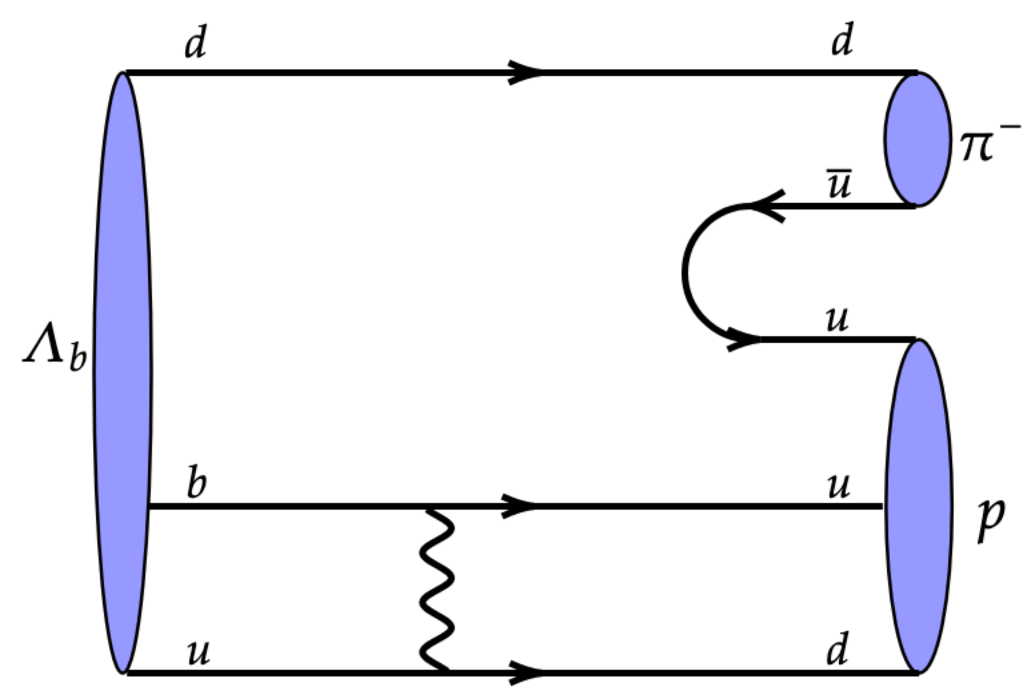


C_2

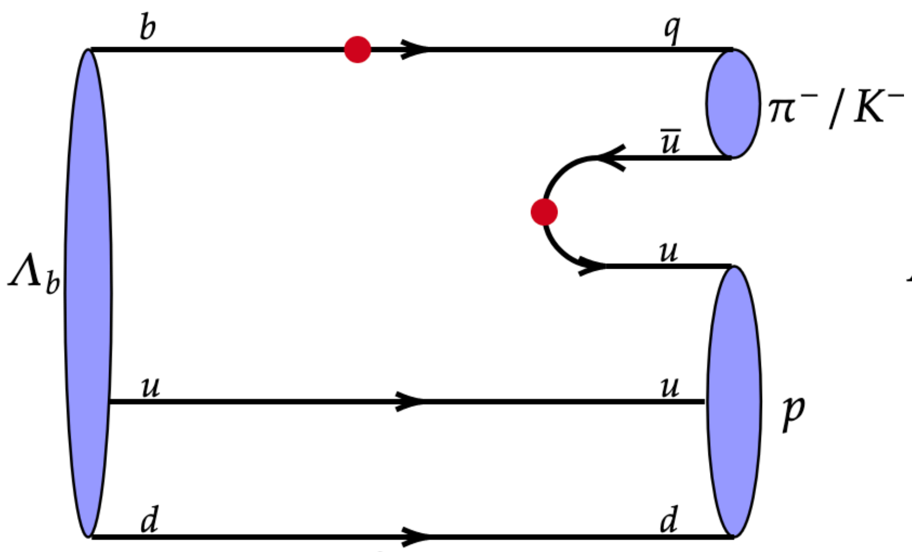


E_2

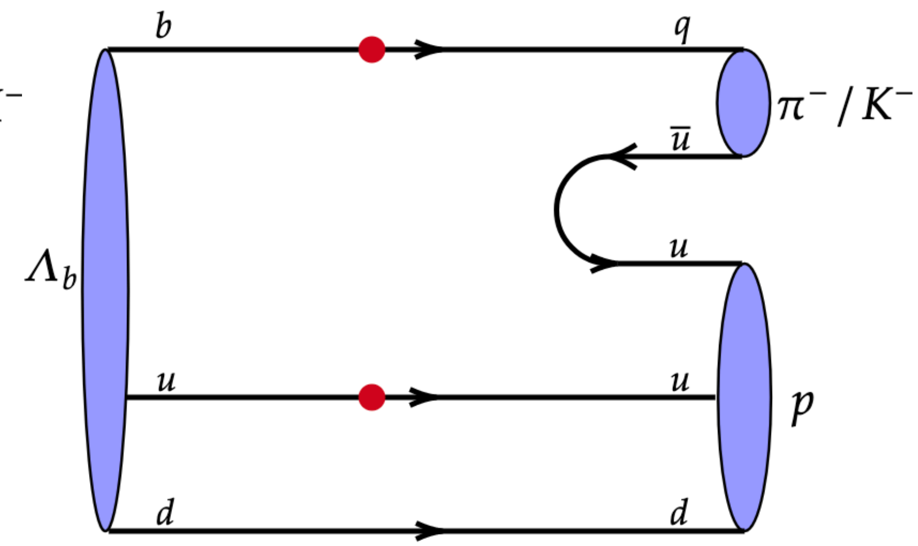


B

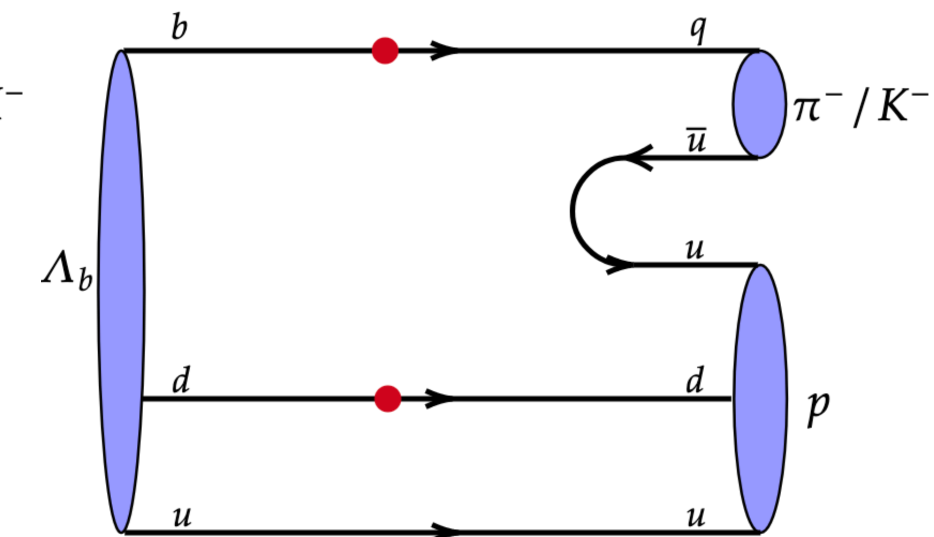
Topological Diagrams



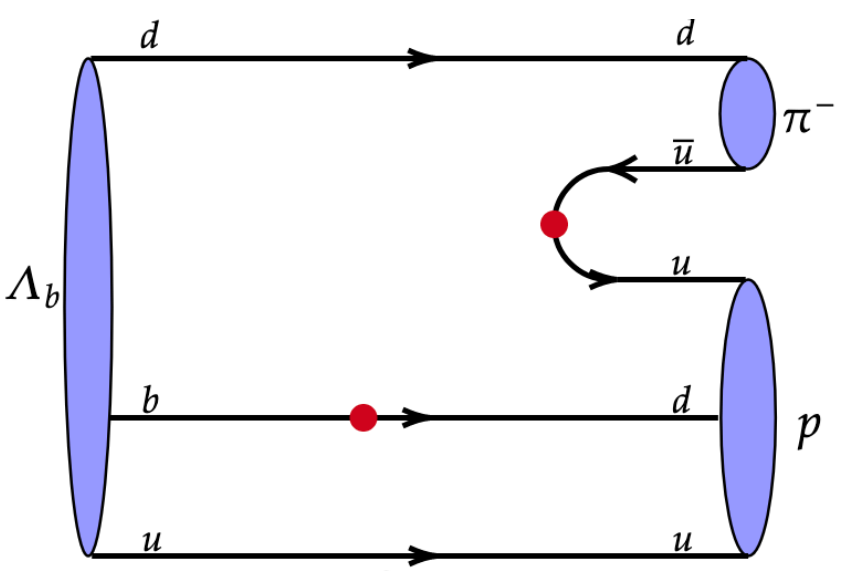
$P^{C_1}_{QCD,EW}$



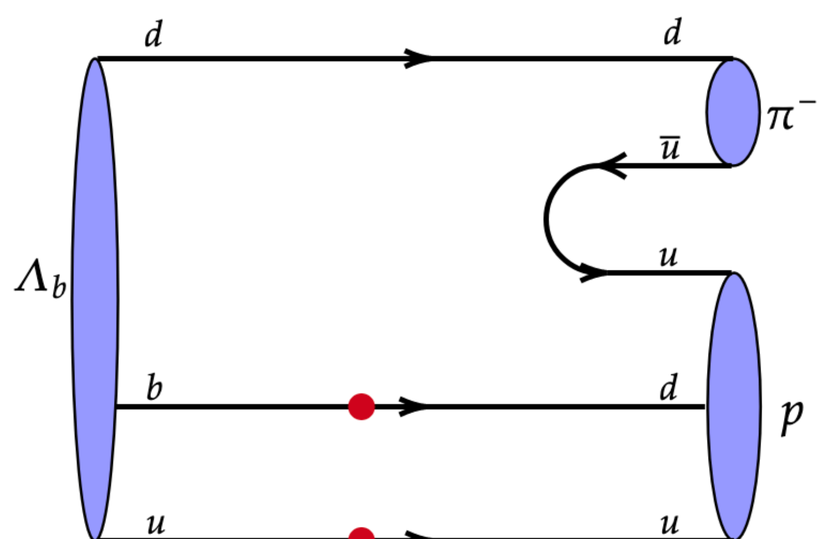
$P^{E_1^u}_{QCD,EW}$



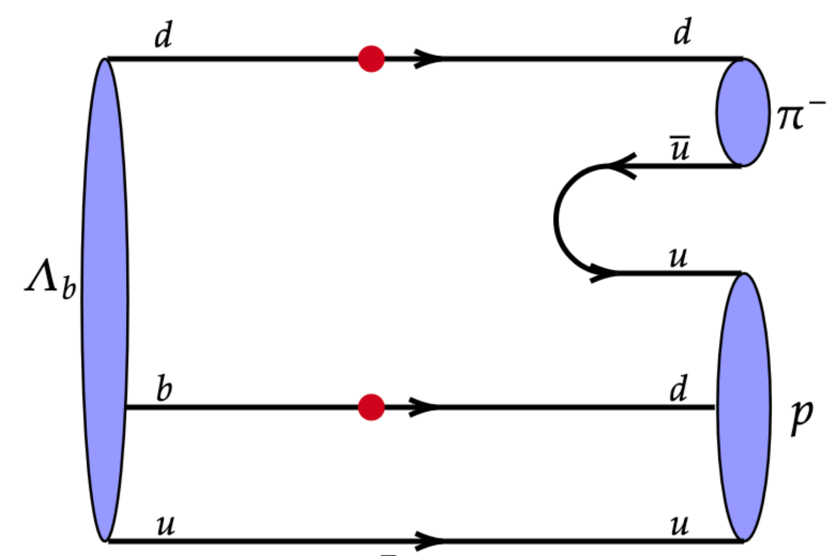
$P^{E_1^d}_{QCD,EW}$



$P^{C_2}_{QCD,EW}$

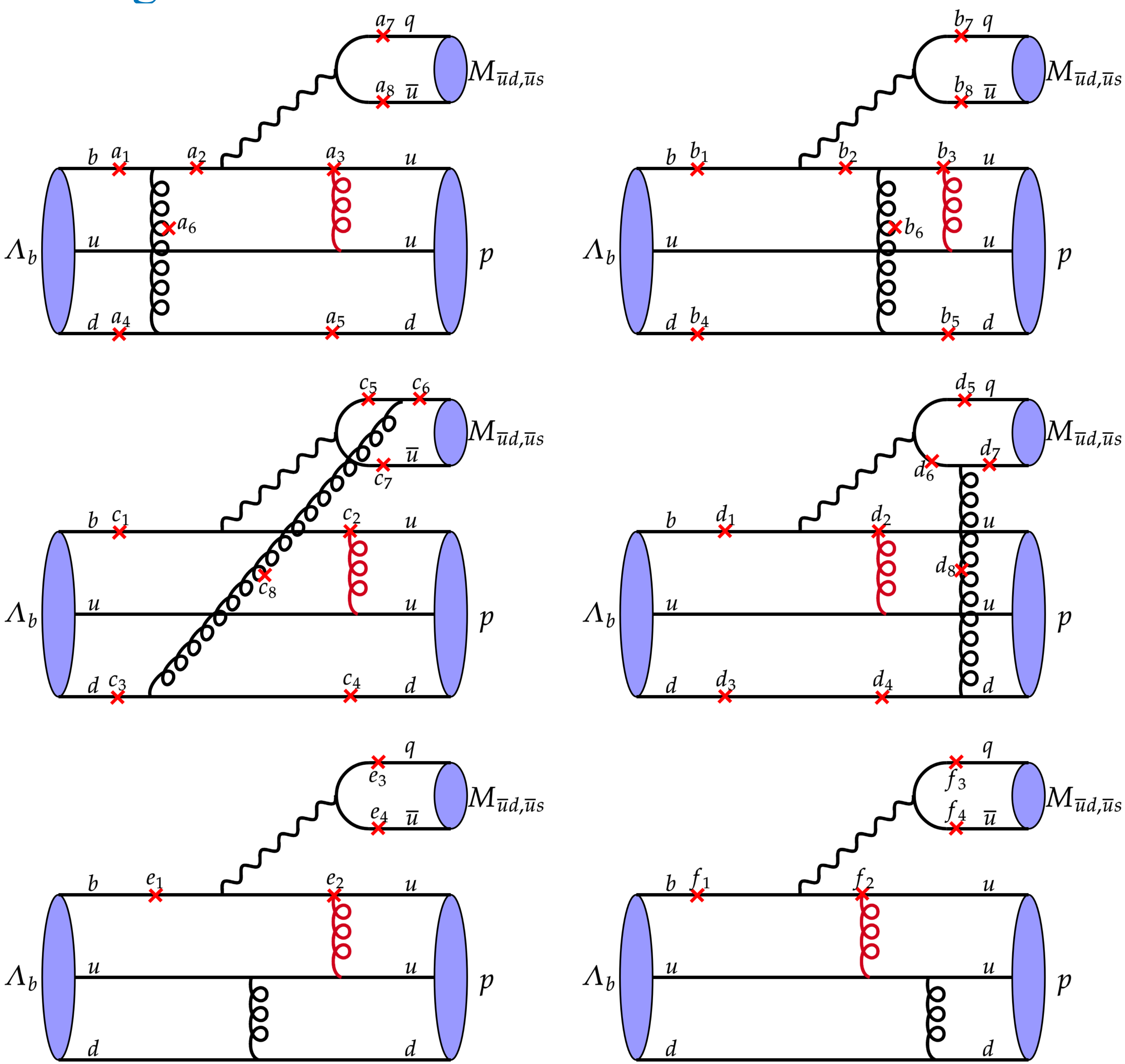


$P^{B}_{QCD,EW}$

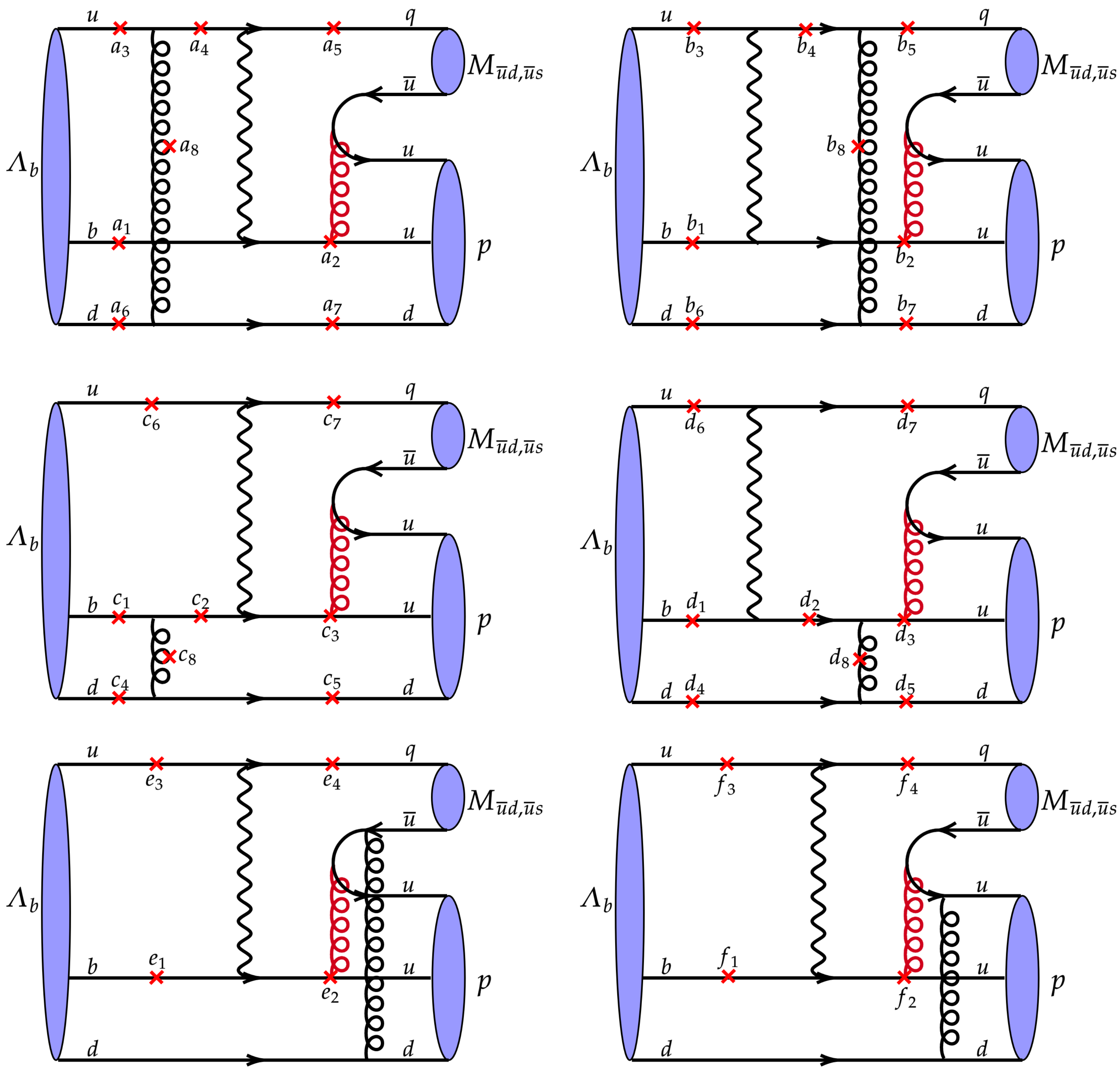


$P^{E_2}_{QCD,EW}$

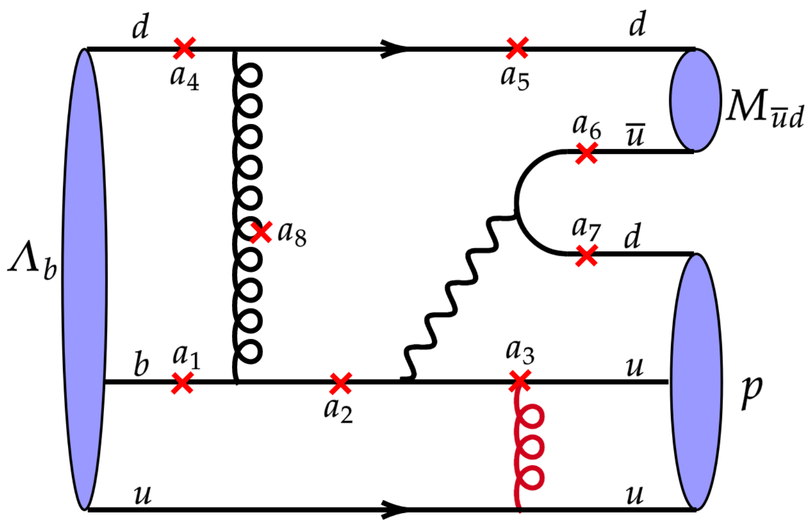
Feynman diagrams — T

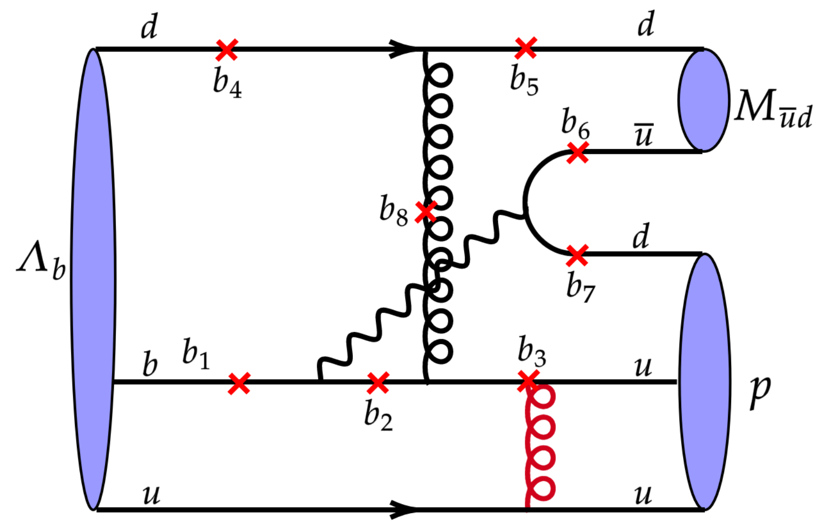


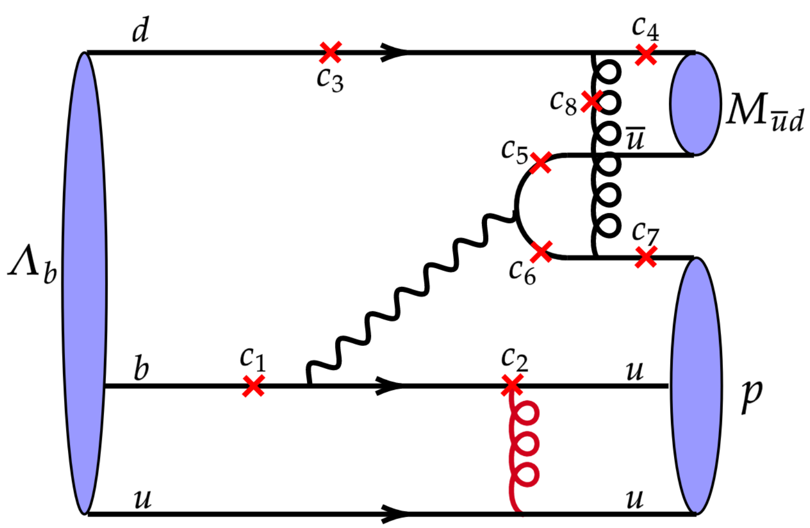
Feynman diagrams — E_2

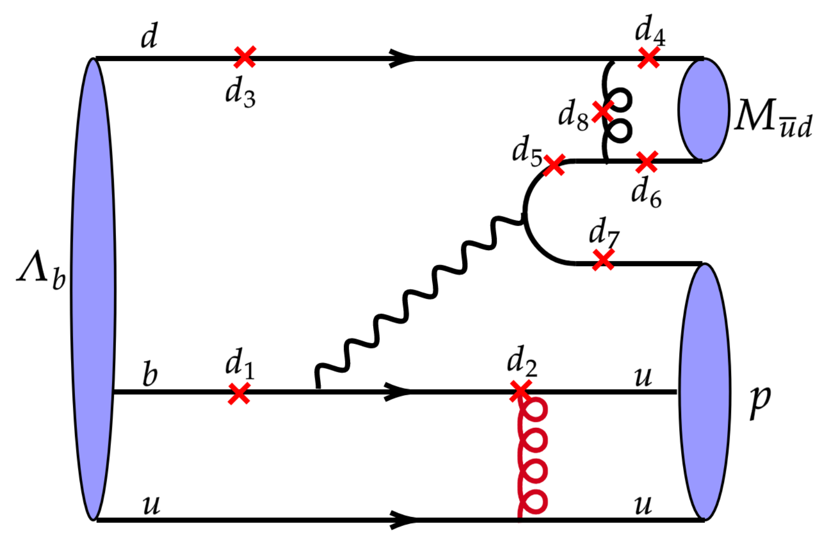


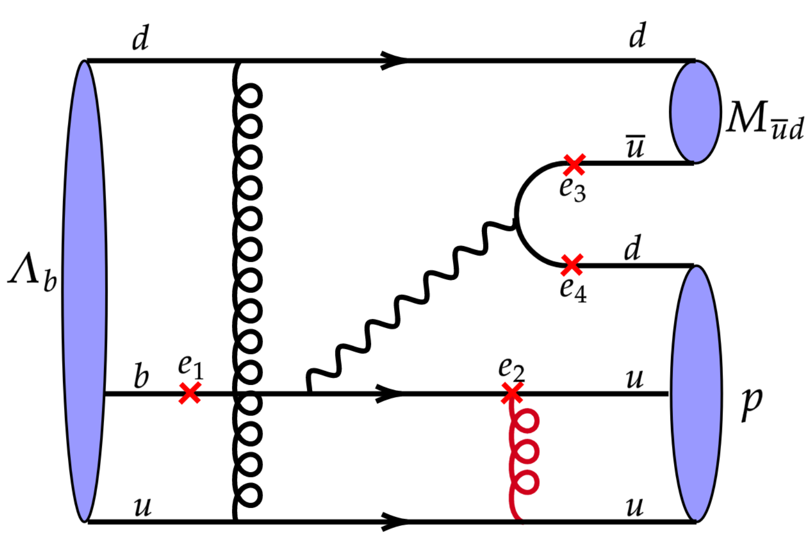
Feynman diagrams — C'

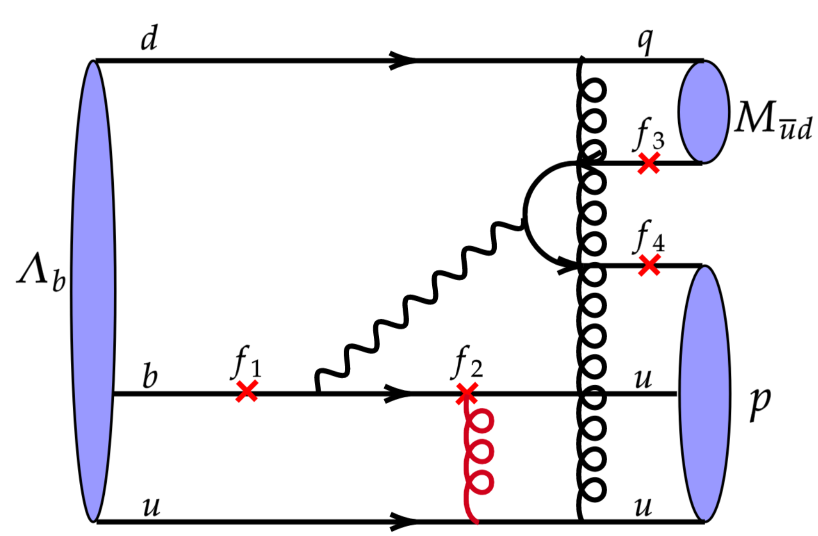




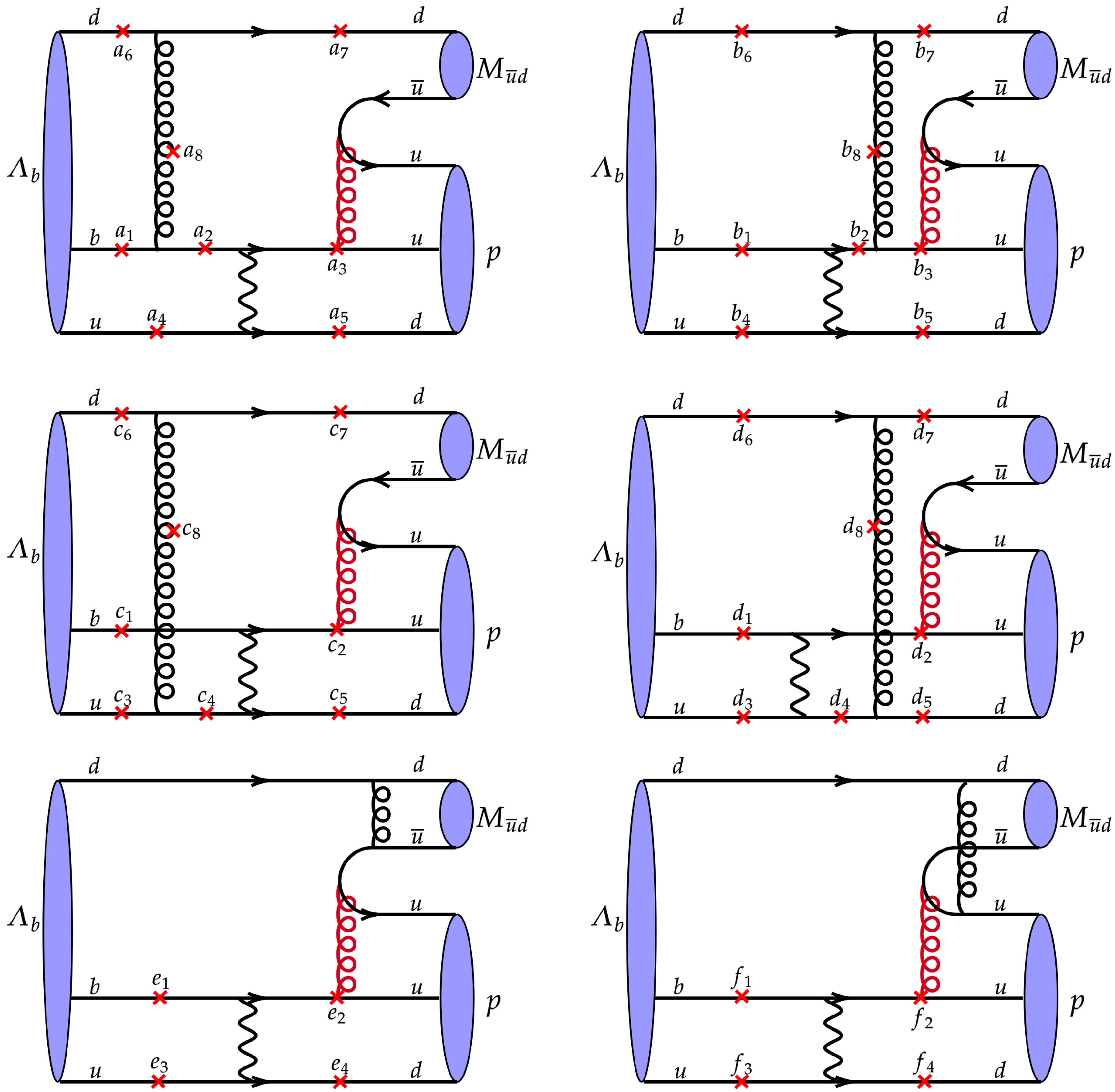




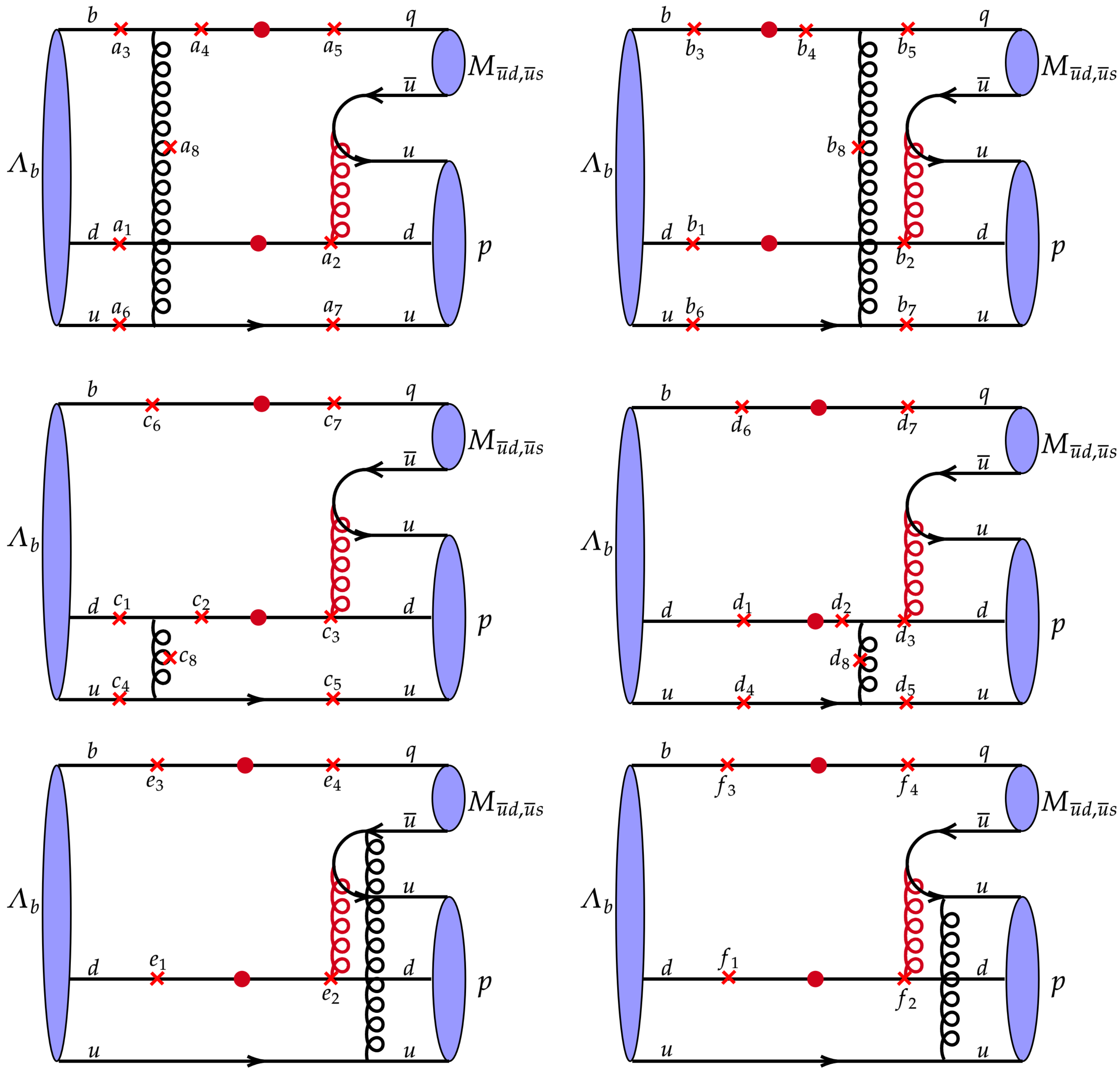




Feynman diagram — B



Feynman diagrams — $P^{E_1^d}$



H_{eff}

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

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

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

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

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

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

LCDA for π^-/K^-

$$\Phi_\pi(p,x,\zeta) \equiv \frac{i}{\sqrt{2N_C}}\gamma_5\left[\not{p}\phi_\pi^A(x) + m_0^\pi \phi_\pi^P(x) + \zeta m_0^\pi(\not{v}\not{n}-1)\phi_\pi^T(x)\right].$$

$$\begin{aligned}
\phi_{\pi(K)}^A(x) &= \frac{f_{\pi(K)}}{2\sqrt{2N_c}}6x(1-x)\left[1 + a_1^{\pi(K)}C_1^{3/2}(2x-1) + a_2^{\pi(K)}C_2^{3/2}(2x-1)\right.\\
&\left. + a_4^{\pi(K)}C_4^{3/2}(2x-1)\right],\\
\phi_{\pi(K)}^P(x) &= \frac{f_{\pi(K)}}{2\sqrt{2N_c}}\left[1 + \left(30\eta_3 - \frac{5}{2}\rho_{\pi(K)}^2\right)C_2^{1/2}(2x-1)\right.\\
&\left. -3\left\{\eta_3\omega_3 + \frac{9}{20}\rho_{\pi(K)}^2(1+6a_2^{\pi(K)})\right\}C_4^{1/2}(2x-1)\right],\\
\phi_{\pi(K)}^T(x) &= \frac{f_{\pi(K)}}{2\sqrt{2N_c}}(1-2x)\left[1\right.\\
&\left. +6\left(5\eta_3 - \frac{1}{2}\eta_3\omega_3 - \frac{7}{20}\rho_{\pi(K)}^2 - \frac{3}{5}\rho_{\pi(K)}^2 a_2^{\pi(K)}\right)(1-10x+10x^2)\right]
\end{aligned}$$

$$\begin{aligned}
C_1^{3/2}(t) &= 3\,t\,,\\
C_2^{1/2}(t) &= \frac{1}{2}\left(3\,t^2-1\right), \quad C_2^{3/2}(t) = \frac{3}{2}\left(5\,t^2-1\right),\\
C_4^{1/2}(t) &= \frac{1}{8}\left(3-30\,t^2+35\,t^4\right), \quad C_4^{3/2}(t) = \frac{15}{8}\left(1-14\,t^2+21\,t^4\right).
\end{aligned}$$

P.Ball, 2005,2006

$$\begin{aligned}
a_1^\pi &= 0, \quad a_2^{\pi,K} = 0.25\pm0.15, \quad a_4^\pi = -0.015, \quad a_1^K = 0.06,\\
\rho_\pi &= m_\pi/m_0^\pi, \quad \rho_K = m_K/m_0^K, \quad \eta_3^{\pi,K,\eta} = 0.015, \quad \omega_3^{\pi,K,\eta} = -3,
\end{aligned}$$

$$m_0^\pi = 1.4\pm0.1\text{ GeV}\,, \quad m_0^K = 1.6\pm0.1\text{ GeV} \qquad \rho_{\pi(K)} = m_{\pi(K)}/m_0^{\pi(K)}$$

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

$$\mathscr{M} = i\bar{u}_p(f_1 + f_2\gamma_5)u_{\Lambda_b}$$

$$f_1 = |f_1^T| e^{i\phi_1^T} e^{i\delta_1^T} + |f_1^P| e^{i\phi_1^P} e^{i\delta_1^P} \qquad f_2 = |f_2^T| e^{i\phi_2^T} e^{i\delta_2^T} + |f_2^P| e^{i\phi_2^P} e^{i\delta_2^P}$$

$$A_{CP}^{dir}(\Lambda_b \to pM) \equiv \frac{\mathcal{B}r(\Lambda_b \to pM) - \mathcal{B}r(\bar{\Lambda}_b \to \bar{p}\bar{M})}{\mathcal{B}r(\Lambda_b \to pM) + \mathcal{B}r(\bar{\Lambda}_b \to \bar{p}\bar{M})}$$

$$A_{CP}^{dir} = \frac{-2A|f_1^T|^2 r_1 sin\Delta\phi_1 sin\Delta\delta_1 - 2B|f_2^T|^2 r_2 sin\Delta\phi_2 sin\Delta\delta_2}{A|f_1^T|^2(1 + r_1^2 + 2r_1 cos\Delta\phi_1 cos\Delta\delta_1) + B|f_2^T|^2(1 + r_2^2 + 2r_2 cos\Delta\phi_2 cos\Delta\delta_2)}$$

$$A = \frac{(M_{\Lambda_b} + M_p)^2 - M_M^2}{M_{\Lambda_b}^2} \qquad B = \frac{(M_{\Lambda_b} - M_p)^2 - M_M^2}{M_{\Lambda_b}^2}$$

$$A_{CP}^{dir}(f_1) = \frac{-2r_1 sin\Delta\phi_1 sin\Delta\delta_1}{(1 + r_1^2 + 2r_1 cos\Delta\phi_1 cos\Delta\delta_1)} \qquad A_{CP}^{dir}(f_2) = \frac{-2r_2 sin\Delta\phi_2 sin\Delta\delta_2}{(1 + r_2^2 + 2r_2 cos\Delta\phi_2 cos\Delta\delta_2)}$$

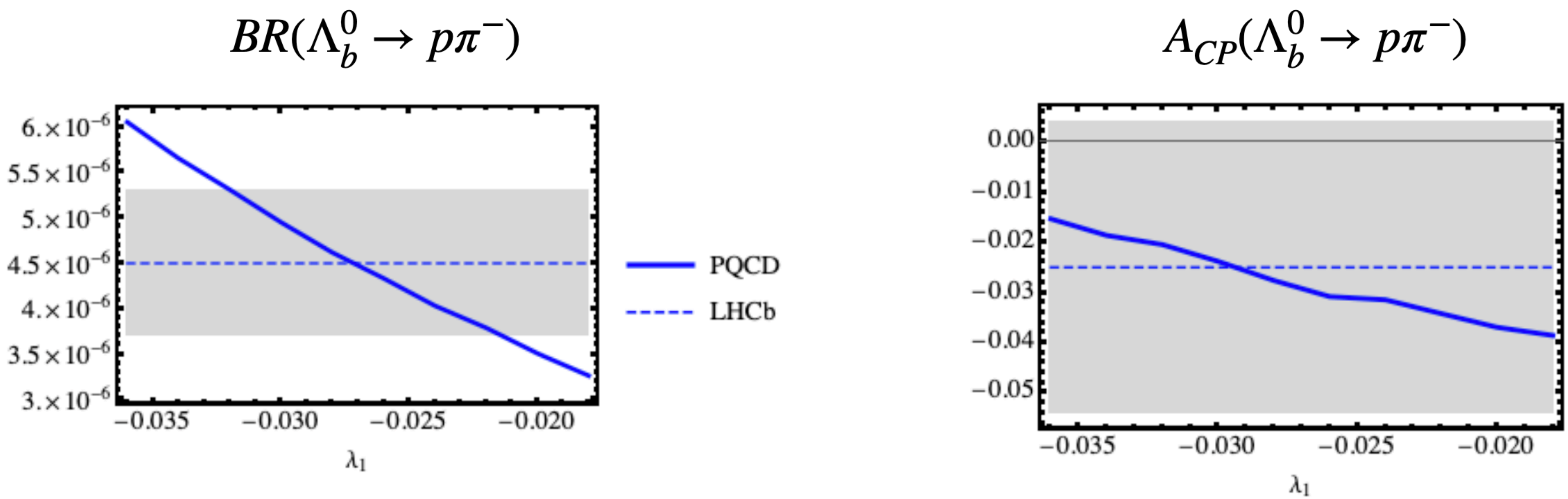
$$\Delta A_{CP}(pK/p\pi) = A_{CP}(\Lambda_b \to pK) - A_{CP}(\Lambda_b \to p\pi)$$

$$\alpha = -\frac{2\kappa Re(f_1^* f_2)}{|f_1|^2 + \kappa^2|f_2|^2} \qquad \beta = -\frac{2\kappa Im(f_1^* f_2)}{|f_1|^2 + \kappa^2|f_2|^2} \qquad \gamma = \frac{|f_1|^2 - \kappa^2|f_2|^2}{|f_1|^2 + \kappa^2|f_2|^2}$$

$$\kappa = \sqrt{(E_p + M_p)/(E_p - M_p)}$$

$$a_{CP}^{\alpha} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} \qquad a_{CP}^{\beta} = \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}} \qquad a_{CP}^{\gamma} = \frac{\gamma - \bar{\gamma}}{\gamma + \bar{\gamma}}$$

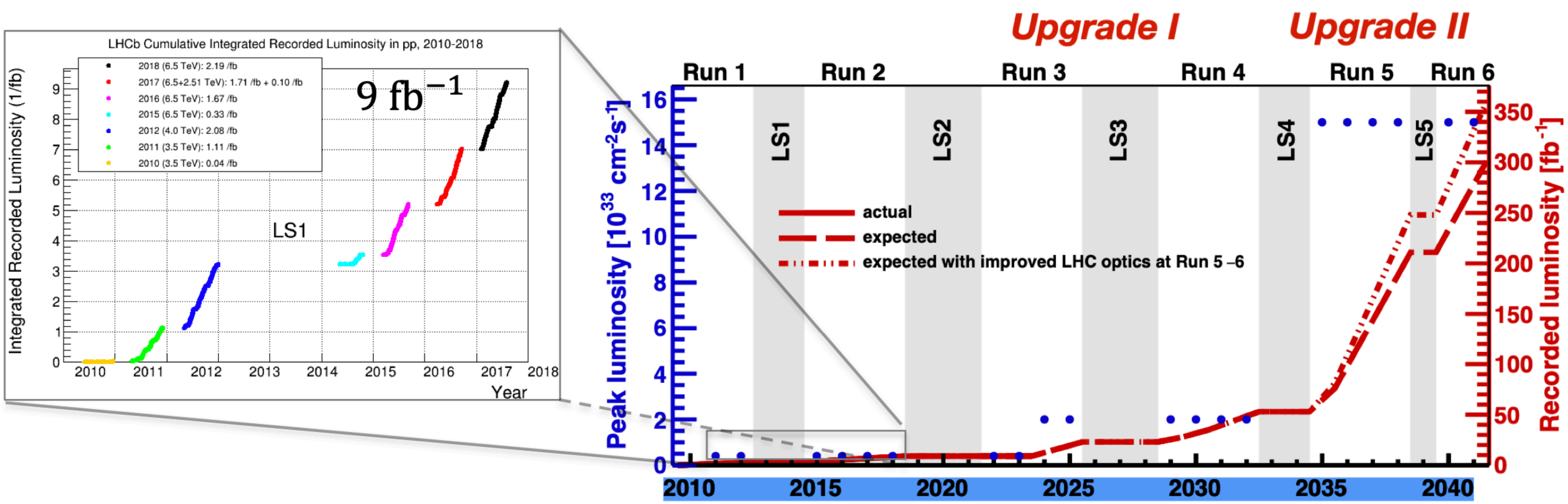
Results of $\Lambda_b \to p\pi^-, pK^-$



- λ_1 is one parameter in the proton LCDAs. Within the allowed region of λ_1, both branching ratio and CPV of $\Lambda_b \to p\pi^-$ can be understood.

- Why CPV of $\Lambda_b \to p\pi^-$ so small, compared to B meson decays?

- # Summary
  - Baryon physics is an opportunity of heavy flavor physics at current stage,
  - LHCb run-3 collecting more data,
  - We are ready to predict CPV of heavy baryon decays.



- # Outlook
  - $\Lambda_b \to pM$ with $M = \pi^-,\ K^-,\ \rho^-,\ K^{*-},\ a_1(1260),\ K_1(1270),\ K_1(1400)$
  - multi-body decays of Λ_b
  - Observables

back up

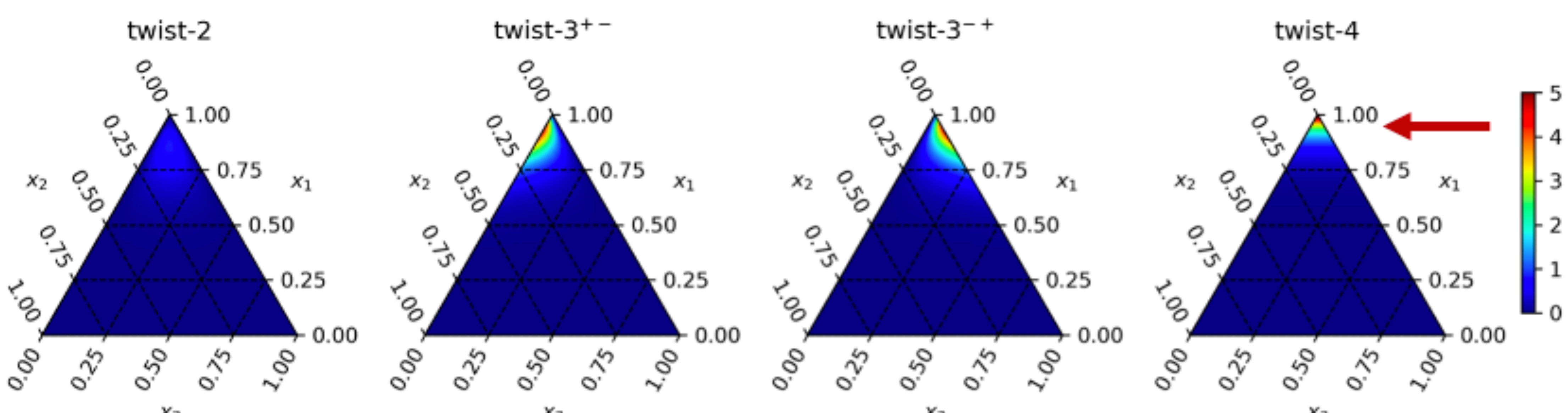
$\Lambda_b \to p$ form factors in PQCD

- Result of form factor f_1

Λ_b	proton contribution				
exponential	twist-3	twist-4	twist-5	twist-6	total
twist-2	0.0007	-0.00007	-0.0005	-0.000003	0.0001
twist-3^{+-}	-0.0001	0.002	0.0004	-0.000004	0.002
twist-3^{-+}	-0.0002	0.0060	0.000004	0.00007	0.006
twist-4	0.01	0.00009	0.25	0.0000007	0.26
total	0.01	0.008	0.25	0.00007	$0.27 \pm 0.09 \pm 0.07$

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

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



Amplitudes

$$M_{T_f}^{V-A\times V-A} \equiv \langle p\mathcal{M}|(\bar{u}b)_{V-A}(\bar{q}u)_{V-A}|\Lambda_b\rangle_T,$$
$$M_{T_f}^{S-P\times S+P} \equiv \langle p\mathcal{M}|(\bar{u}b)_{S-P}(\bar{q}u)_{S+P}|\Lambda_b\rangle_T,$$
$$M_{T_{nf}}^{V-A\times V-A} \equiv \langle p\mathcal{M}|(\bar{q}b)_{V-A}(\bar{u}u)_{V-A}|\Lambda_b\rangle_{P^{C_1}},$$
$$M_{T_{nf}}^{V-A\times V+A} \equiv \langle p\mathcal{M}|(\bar{q}b)_{V-A}(\bar{u}u)_{V+A}|\Lambda_b\rangle_{P^{C_1}},$$

$$M_{T_f} = \frac{G_F}{\sqrt{2}}\left\{V_{ub}V_{uq}^*\left[\frac{1}{3}C_1 + C_2\right]\right\} M_{T_f}^{V-A\times V-A},$$

$$M_{T_{nf}} = \frac{G_F}{\sqrt{2}}\left\{V_{ub}V_{uq}^*\left[C_1 + \mathcal{C}C_2\right]\right\} M_{T_{nf}}^{V-A\times V-A},$$

$$\begin{aligned} M_{P^{C_1}} = &-\frac{G_F}{\sqrt{2}}\left\{V_{tb}V_{tq}^*\left[\frac{1}{3}C_3 + C_4 + \frac{1}{3}C_9 + C_{10}\right]\right\} M_{T_f}^{V-A\times V-A} \\ &-\frac{G_F}{\sqrt{2}}\left\{V_{tb}V_{tq}^*\left[-\frac{2}{3}C_5 - 2C_6 - \frac{2}{3}C_7 - C_8\right]\right\} M_{T_f}^{S-P\times S+P} \\ &-\frac{G_F}{\sqrt{2}}\left\{V_{tb}V_{tq}^*\left[C_3 + \mathcal{C}C_4 + C_9 + \mathcal{C}C_{10}\right]\right\} M_{T_{nf}}^{V-A\times V-A} \\ &-\frac{G_F}{\sqrt{2}}\left\{V_{tb}V_{tq}^*\left[C_5 + \mathcal{C}C_6 + C_7 + \mathcal{C}C_8\right]\right\} M_{T_{nf}}^{V-A\times V+A}. \end{aligned}$$

$$
\begin{aligned}
M_{E_2}^{V-A\times V-A} &\equiv \langle p\mathcal{M}|(\bar{u}b)_{V-A}(\bar{q}u)_{V-A}|\Lambda_b\rangle_{E_2},\\
M_{E_2}^{S-P\times S+P} &\equiv \langle p\mathcal{M}|(\bar{u}b)_{S-P}(\bar{q}u)_{S+P}|\Lambda_b\rangle_{E_2},\\
M_{E_2} =& \frac{G_F}{\sqrt{2}}\left\{V_{ub}V_{uq}^{*}\left[\mathcal{C}C_1+C_2\right]\right\} M_{E_2}^{V-A\times V-A},\\
M_{P^{E_1^u}} =& -\frac{G_F}{\sqrt{2}}\left\{V_{tb}V_{tq}^{*}\left[\mathcal{C}C_3+C_4+\mathcal{C}C_9+C_{10}\right]\right\} M_{E_2}^{V-A\times V-A}\\
&-\frac{G_F}{\sqrt{2}}\left\{V_{tb}V_{tq}^{*}\left[-2\mathcal{C}C_5-2C_6-2\mathcal{C}C_7-2C_8\right]\right\} M_{E_2}^{S-P\times S+P}.
\end{aligned}
$$

$$
\begin{aligned}
M_{C_2}^{V-A\times V-A} &\equiv \langle p\mathcal{M}|(\bar{u}b)_{V-A}(\bar{d}u)_{V-A}|\Lambda_b\rangle_{C_2},\\
M_{C_2}^{S-P\times S+P} &\equiv \langle p\mathcal{M}|(\bar{u}b)_{S-P}(\bar{d}u)_{S+P}|\Lambda_b\rangle_{C_2},\\
M_{C_2} =& \frac{G_F}{\sqrt{2}}\left\{V_{ub}V_{ud}^{*}\left[\mathcal{C}C_1+C_2\right]\right\} M_{C_2}^{V-A\times V-A},\\
M_{P^{C_2}} =& -\frac{G_F}{\sqrt{2}}\left\{V_{tb}V_{td}^{*}\left[\mathcal{C}C_3+C_4+\mathcal{C}C_9+C_{10}\right]\right\} M_{C_2}^{V-A\times V-A}\\
&-\frac{G_F}{\sqrt{2}}\left\{V_{tb}V_{td}^{*}\left[-2\mathcal{C}C_5-2C_6-2\mathcal{C}C_7-2C_8\right]\right\} M_{C_2}^{S-P\times S+P}.
\end{aligned}
$$

$$
\begin{aligned}
M_{B}^{V-A\times V-A} &\equiv \langle p\mathcal{M}|(\bar{u}b)_{V-A}(\bar{d}u)_{V-A}|\Lambda_b\rangle_{B},\\
M_{B}^{S-P\times S+P} &\equiv \langle p\mathcal{M}|(\bar{u}b)_{S-P}(\bar{d}u)_{S+P}|\Lambda_b\rangle_{B},\\
M_{B} =& \frac{G_F}{\sqrt{2}}\left\{V_{ub}V_{ud}^{*}\left[\mathcal{C}C_1+C_2\right]\right\} M_{B}^{V-A\times V-A},\\
M_{P^{B}} =& -\frac{G_F}{\sqrt{2}}\left\{V_{tb}V_{td}^{*}\left[\mathcal{C}C_3+C_4+\mathcal{C}C_9+C_{10}\right]\right\} M_{B}^{V-A\times V-A}\\
&-\frac{G_F}{\sqrt{2}}\left\{V_{tb}V_{td}^{*}\left[-2\mathcal{C}C_5-2C_6-2\mathcal{C}C_7-2C_8\right]\right\} M_{B}^{S-P\times S+P}.
\end{aligned}
$$

$$M_{E_1^d}^{V-A\times V-A} \equiv \langle p\mathcal{M}|(\bar{d}b)_{V-A}(\bar{d}d)_{V-A}|\Lambda_b\rangle_{E_1^d},$$
$$M_{E_1^d}^{V-A\times V+A} \equiv \langle p\mathcal{M}|(\bar{d}b)_{V-A}(\bar{d}d)_{V-A}|\Lambda_b\rangle_{E_1^d},$$
$$M_{E_1^d}^{S-P\times S+P} \equiv \langle p\mathcal{M}|(\bar{d}b)_{S-P}(\bar{d}d)_{S+P}|\Lambda_b\rangle_{E_1^d},$$
$$\begin{aligned} M^{p\pi}_{P^{E_1^d}} = &- \frac{G_F}{\sqrt{2}}\left\{V_{tb}V_{td}^*\left[(1+\mathcal{C})(C_3+C_4+\frac{1}{2}C_9+\frac{1}{2}C_{10})\right]\right\} M_{E_1^d}^{V-A\times V-A} \\ &- \frac{G_F}{\sqrt{2}}\left\{V_{tb}V_{td}^*\left[C_5+\mathcal{C}C_6+\frac{1}{2}C_7+\frac{1}{2}\mathcal{C}C_8\right]\right\} M_{E_1^d}^{V-A\times V+A} \\ &- \frac{G_F}{\sqrt{2}}\left\{V_{tb}V_{td}^*\left[-2\mathcal{C}C_5-2C_6-\mathcal{C}C_7-C_8\right]\right\} M_{E_1^d}^{S-P\times S+P}. \end{aligned}$$

$$M_{E_1^d}^{V-A\times V-A} \equiv \langle p\mathcal{M}|(\bar{s}b)_{V-A}(\bar{d}d)_{V-A}|\Lambda_b\rangle_{E_1^d},$$
$$M_{E_1^d}^{V-A\times V+A} \equiv \langle p\mathcal{M}|(\bar{s}b)_{V-A}(\bar{d}d)_{V-A}|\Lambda_b\rangle_{E_1^d},$$
$$\begin{aligned} M^{pK}_{P^{E_1^d}} = &- \frac{G_F}{\sqrt{2}}\left\{V_{tb}V_{ts}^*\left[(C_3+\mathcal{C}C_4+\frac{1}{2}C_9+\frac{1}{2}\mathcal{C}C_{10})\right]\right\} M_{E_1^d}^{V-A\times V-A} \\ &- \frac{G_F}{\sqrt{2}}\left\{V_{tb}V_{ts}^*\left[C_5+\mathcal{C}C_6+\frac{1}{2}C_7+\frac{1}{2}\mathcal{C}C_8\right]\right\} M_{E_1^d}^{V-A\times V+A}. \end{aligned}$$

determine the parameter ω_0

- The decay mode $\Lambda_b \to pD_s^-$ has only W-external emission diagram, which can be used to determine the parameter ω_0 under naive factorization method.

- (LHCb,2212.12574) recently measured to branching fraction of this mode:

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