# Form factor of Heavy-to-Light Baryonic Transitions in SCET


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work with Wei Wang and Dong Hao Li

# Outline

- Introduction
- Factorization in SCET
- Form factor in SCET
- Conclusion and outlook

PART 01

# Introduction

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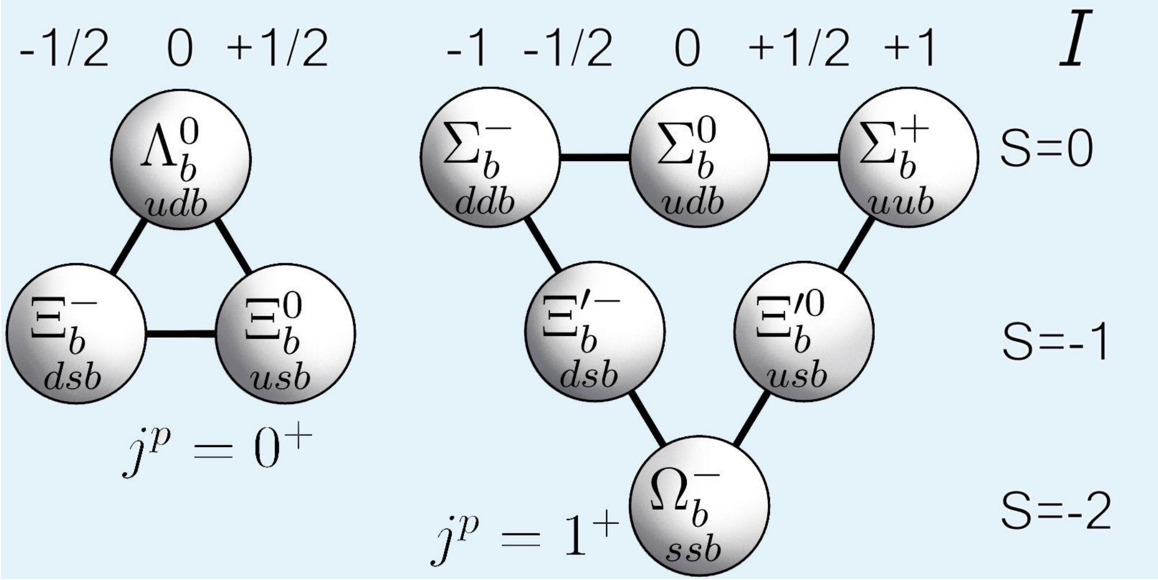
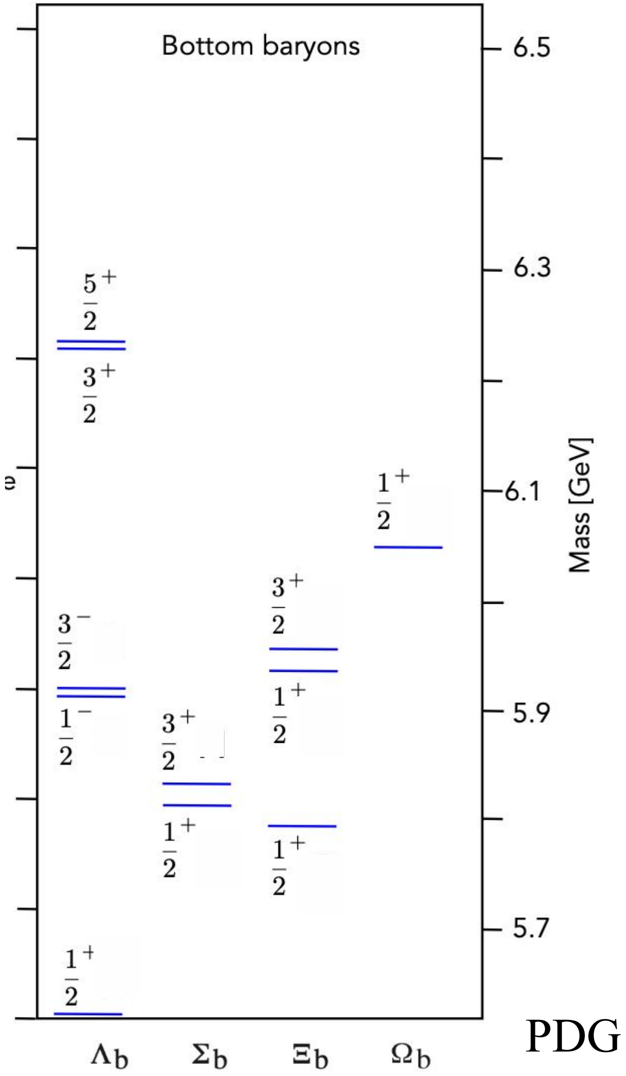
# b-baryons physics




$$\mathbf{3} \otimes \mathbf{3} = \bar{\mathbf{3}}_A \oplus \mathbf{6}_S.$$




PDG

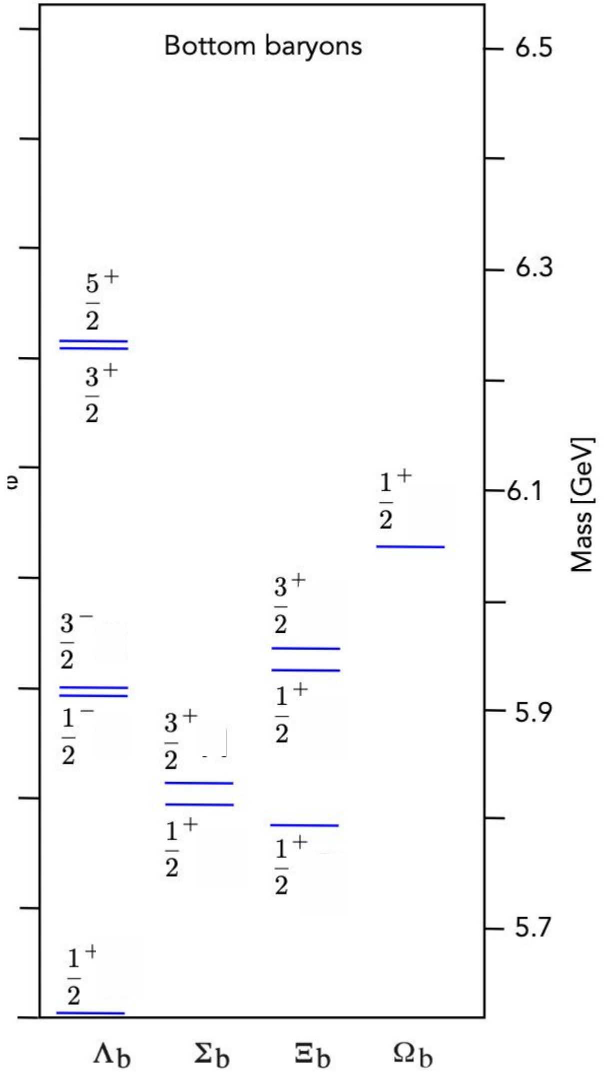
R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

# Introduction

## b-baryons physics

| | | |
|---|---|---|
| Lambda(b)0 | Sigma(b)(6097)- | Omega(b)- |
| Lambda(b)(5912)0 | Xi(b)- | Omega(b)(6316)- |
| Lambda(b)(5920)0 | Xi(b)0 | Omega(b)(6330)- |
| Lambda(b)(6070)0 | Xi(b)'(5935)- | Omega(b)(6340)- |
| Lambda(b)(6146)0 | Xi(b)(5945)0 | Omega(b)(6350)- |
| Lambda(b)(6152)0 | Xi*(b)(5955)- | |
| Sigma(b) | Xi(b)(6100)- | |
| Sigma*(b) | Xi(b)(6227)- | |
| Sigma(b)(6097)+ | Xi(b)(6227)0 | |

R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)



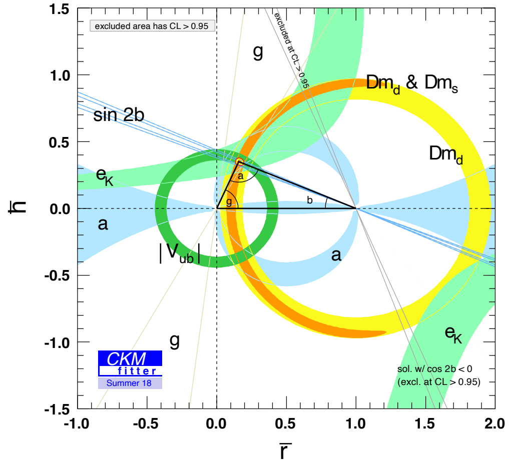
# b-baryons physics in experiment

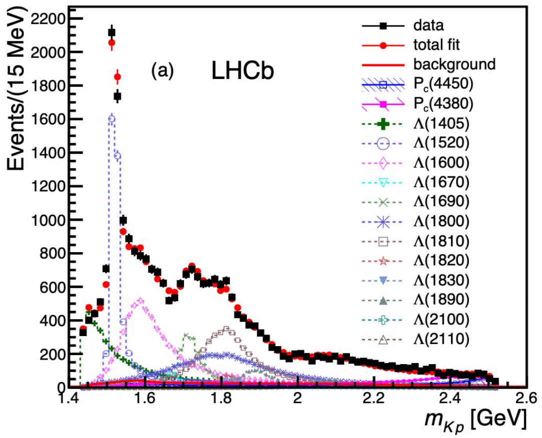
An evidence of CPV has been attained at the confidence level of 3σ in the $\Lambda_b^0 \to p\pi^+\pi^-\pi^-$ decay. (1609.05216)

$$\mathcal{R}_{\Lambda_c} = \frac{\Gamma(\Lambda_b \to \Lambda_c \tau^- \bar{\nu}_\tau)}{\Gamma(\Lambda_b \to \Lambda_c \mu^- \bar{\nu}_\mu)} = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$$

(2201.03497)

Pc(4380) and Pc(4450), firstly observed in the $\Lambda_b^0 \to J/\psi p K^-$ process. (1507.03414 )



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## b-baryons physics in theory

Quark Model: 1207.3477, 1410.6043, 1803.02292, 1803.01297

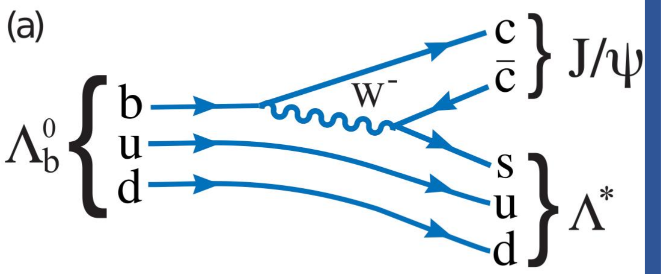
LCSR: 0904.4008, 1001.0227, 1108.2971, 1511.09036, 2205.06095

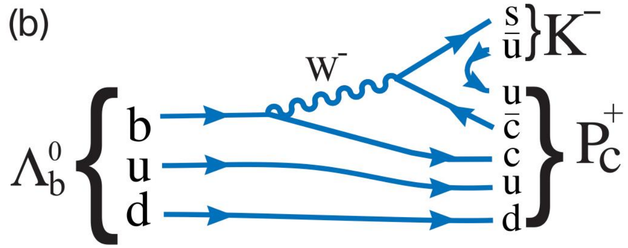
Lattice: hep-lat/9709028, 1503.01421, 1602.01399, 2107.13140

EFT: hep-ph/9810515, 1111.1844, 2003.0836, 2202.04804

Angular distribution: 1410.2115, 2203.13524, 1410.2115

…



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# Form factors in b-baryons physics

$$\langle B(p_2)|\bar{s}\gamma_\mu b|\Lambda_b(p_1)\rangle = \bar{u}_B(p_2)(g_1\gamma_\mu + \frac{g_2}{m_{\Lambda_b}} i\sigma_{\mu\nu}q^\nu + \frac{g_3}{m_{\Lambda_b}} q_\mu)u_{\Lambda_b}(p_1),$$
$$\langle B(p_2)|\bar{s}\gamma_\mu\gamma_5 b|\Lambda_b(p_1)\rangle = \bar{u}_B(p_2)(G_1\gamma_\mu + \frac{G_2}{m_{\Lambda_b}} i\sigma_{\mu\nu}q^\nu + \frac{G_3}{m_{\Lambda_b}} q_\mu)\gamma_5 u_{\Lambda_b}(p_1),$$
$$\langle B(p_2)|\bar{s}i\sigma_{\mu\nu}q^\nu b|\Lambda_b(p_1)\rangle = \bar{u}_B(p_1)(m_{\Lambda_b} f_1\gamma_\mu + f_2 i\sigma_{\mu\nu}q^\nu + f_3 q_\mu)u_{\Lambda_b}(p_1),$$
$$\langle B(p_2)|\bar{s}i\sigma_{\mu\nu}\gamma_5 q^\nu b|\Lambda_b(p_1)\rangle = \bar{u}_B(p_2)(m_{\Lambda_b} F_1\gamma_\mu + F_2 i\sigma_{\mu\nu}q^\nu + F_3 q_\mu)\gamma_5 u_{\Lambda_b}(p_1),$$

**HQET:**

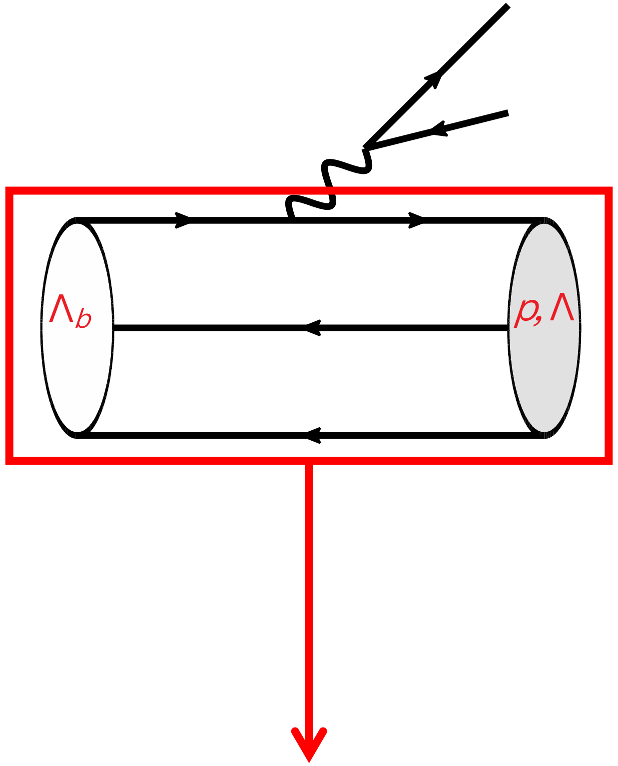
$$\langle B(p_2)|\bar{s}\Gamma b|\Lambda_b(p_1)\rangle = \bar{u}(p_2)[\xi_1(q^2) + \not{v}\xi_2(q^2)]\Gamma u_{\Lambda_b}(p_1),$$

Isgur, Wise, NPB 348, 276(1991); W. Roberts, Ryzak, NPB355, 38-53(1991)

**LE:**

$$\langle B(p_2)|\bar{s}\Gamma b|\Lambda_b(p_1)\rangle = \xi(q^2)\bar{u}(p_2)\frac{\not{n}_+\not{n}_-}{4}\Gamma u_{\Lambda_b}(p_1),$$

Hiller, Kagan, Phys. Rev. D65, 074038 (2002)
Feldmann, Yip,Phys.Rev. D85 01403(2012)
Mannel, Wang, JHEP 1112 (2011) 067




$$\langle B(p_2)|\bar{s}\Gamma b|\Lambda_b(p_1)\rangle$$

## Form factors in SCET

$$
\begin{aligned}
\langle B(p_2)|\bar{s}\gamma_\mu b|\Lambda_b(p_1)\rangle &= \bar{u}_B(p_2)(g_1\gamma_\mu + \frac{g_2}{m_{\Lambda_b}} i\sigma_{\mu\nu}q^\nu + \frac{g_3}{m_{\Lambda_b}} q_\mu)u_{\Lambda_b}(p_1), \\
\langle B(p_2)|\bar{s}\gamma_\mu\gamma_5 b|\Lambda_b(p_1)\rangle &= \bar{u}_B(p_2)(G_1\gamma_\mu + \frac{G_2}{m_{\Lambda_b}} i\sigma_{\mu\nu}q^\nu + \frac{G_3}{m_{\Lambda_b}} q_\mu)\gamma_5 u_{\Lambda_b}(p_1), \\
\langle B(p_2)|\bar{s}i\sigma_{\mu\nu}q^\nu b|\Lambda_b(p_1)\rangle &= \bar{u}_B(p_1)(m_{\Lambda_b}f_1\gamma_\mu + f_2 i\sigma_{\mu\nu}q^\nu + f_3 q_\mu)u_{\Lambda_b}(p_1), \\
\langle B(p_2)|\bar{s}i\sigma_{\mu\nu}\gamma_5 q^\nu b|\Lambda_b(p_1)\rangle &= \bar{u}_B(p_2)(m_{\Lambda_b}F_1\gamma_\mu + F_2 i\sigma_{\mu\nu}q^\nu + F_3 q_\mu)\gamma_5 u_{\Lambda_b}(p_1),
\end{aligned}
$$

$$
\langle \Lambda(p')|\bar{s}\Gamma b|\Lambda_b(p)\rangle = C_i\xi_\Lambda(E)\bar{u}_\Lambda(p')\Gamma u_{\Lambda_b}(p) + \mathcal{O}(\lambda^2\xi_\Lambda),
$$

To leading power, there is only one universal form factor!

**QCD**

↓ **Integrating out hard modes**

**SCET$_{\text{I}}$**

↓ **Integrating out hard-collinear modes**

**SCET$_{\text{II}}$**

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## SCET pow counting

$$\xi_c = \frac{\not{n}_-\not{n}_+}{4}\psi_c \sim \lambda^2, \quad \xi_{hc} = \frac{\not{n}_-\not{n}_+}{4}\psi_{hc} \sim \lambda,$$

$$q_s \sim \lambda^3, \quad h_v = \frac{1+\not{v}}{2}Q_v \sim \lambda^3.$$

$$n_+A_c \sim 1, \quad n_-A_c \sim \lambda^4, \quad A_{\perp c} \sim \lambda^2, \quad A_s \sim \lambda^2,$$

$$n_+A_{hc} \sim 1, \quad n_-A_{hc} \sim \lambda^2, \quad A_{\perp hc} \sim \lambda.$$

$$|\Lambda_b\rangle \sim \lambda^{-3}, \quad |\Lambda\rangle \sim \lambda^{-2},$$

$$\lambda = \sqrt{\Lambda/m_b}$$

$$\psi = \xi_c + \eta_c + \xi_{hc} + \eta_{hc} + q_s$$

$$A = A_c + A_s + A_{hc}$$

$$p_c \sim (1, \lambda^2, \lambda^4)$$

$$q_s \sim (\lambda^2, \lambda^2, \lambda^2)$$

$$p_{hc} \sim (1, \lambda, \lambda^2)$$

# Multipole expension

$$\xi_c(x) = \xi_c(x^-) + \underbrace{x^+\partial^-}_{\lambda^2}\xi_c(x^-) + \underbrace{x_\perp^\mu \partial_\mu^\perp}_{\lambda}\xi_c(x^-),$$

$$\psi_s(x) = \psi_s(x^+) + \underbrace{x^-\partial^+}_{\lambda^2}\psi_s(x^+) + \underbrace{x_\perp^\mu \partial_\mu^\perp}_{\lambda}\psi_s(x^+).$$

PART 02

# Factorization in SCET

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# Factorization in SCET

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## SCET$_\text{I}$ operators

$$O_j^A(s) = (\bar{\xi}_{hc} W_{hc})_s \Gamma_j Y_s^\dagger h_v,$$
$$O_j^B(s_1, s_2) = (\bar{\xi}_{hc} W_{hc})_{s_1} (W_{hc}^\dagger i D_{\perp\mu} W_{hc})_{s_2} \Gamma'_j Y_s^\dagger h_v,$$
$$O_j^C(s_1, s_2, s_3) = (\bar{\xi}_{hc} W_{hc})_{s_1} (W_{hc}^\dagger i D_{\perp\mu_1} W_{hc})_{s_2} (W_{hc}^\dagger i D_{\perp\mu_2} W_{hc})_{s_3} \Gamma'_j Y_s^\dagger h_v,$$
$$O_j^D(s_1, s_2) = (\bar{\xi}_{hc} W_{hc})_{s_1} (W_{hc}^\dagger i n_- D W_{hc} - i n_- D_s)_{s_2} \Gamma'_j Y_s^\dagger h_v,$$
$$O_j^E(s, t) = (\bar{\xi}_{hc} W_{hc})_s (i D_s^\mu)_t \Gamma'_j Y_s^\dagger h_v,$$

**non-zero matrix element** $\langle B | O_j | \Lambda_b \rangle \neq 0$

$$O^A \sim \lambda^4, \quad Q^B \sim \lambda^5, O^{C,D,E} \sim \lambda^6$$

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# QCD current in $\mathrm{SCET_I}$

$$(\bar{\psi}\Gamma_i Q)(x) = e^{-im_b v\cdot x}\left\{\sum_j \int d\hat{s}\, \tilde{C}^0_{ij}\,(\hat{s}, \frac{m_b}{\mu})\, O^0_j(s) + \frac{1}{m_b}\sum_j \int d\hat{s}_1 d\hat{s}_2\, \tilde{C}^{1\mu}_{ij}(\hat{s}_1, \hat{s}_2, \frac{m_b}{\mu})\, O^{1\mu}_j(s_1, s_2)\right\} + \dots,$$

**Integrating out hard modes**

**NEXT:** $\mathrm{SCET_I}$ → (Integrating out hard-collinear modes) → $\mathrm{SCET_{II}}$

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# Matching onto $\mathrm{SCET_{II}}$

$$[\text{objects}] \times (\bar{\xi}_c\{1, \not{n}_+/2\}\Gamma'_k q_s)(\bar{\xi}_c\{1, \not{n}_+/2\}\Gamma'_l q_s)(\bar{\xi}_c\Gamma'_j h_v)$$

$$n_-^\mu,\ n_+^\mu,\ g^{\mu\nu},\ \epsilon^{\mu_\perp\nu_\perp\rho\sigma} n_{-\rho} n_{+\sigma},\ \frac{1}{in_-\partial},\ \frac{1}{in_-\partial},$$

$$\partial_\perp,\ A_{\perp c},\ A_{\perp s},\ n_+\partial,\ n_+A_s,\ n_-\partial,\ n_-A_c,$$

$$\bar{\xi}_c\frac{\not{n}_+}{2}\Gamma'_m\xi_c,\ \bar{q}_s\frac{\not{n}_+}{2}\Gamma'_m q_s,\ \bar{q}_s\frac{\not{n}_-}{2}\Gamma'_m q_s,\ \bar{q}_s\Gamma''_m q_s,$$

# Matching onto SCET$_{\text{II}}$

| | | | | | |
|---|---|---|---|---|---|
| $(in_-\partial)^{-1}$ | $n_-^\mu$ | $\partial_\perp,\ A_{\perp c},\ A_{\perp s}$ | $n_-\partial,\ n_-A_c$ | $\bar{q}_s \frac{\not{n}_+}{2} \Gamma'_m q_s$ | $\bar{q}_s \Gamma''_m q_s$ |
| $n_1$ | $n_3$ | $n_5$ | $n_7$ | $n_{9a}$ | $n_{9c}$ |
| $(in_+\partial)^{-1}$ | $n_+^\mu$ | $n_+\partial,\ n_+A_s$ | $\bar{\xi}_c \frac{\not{n}_+}{2} \Gamma'_m \xi_c$ | $\bar{q}_s \frac{\not{n}_-}{2} \Gamma'_m q_s$ | |
| $n_2$ | $n_4$ | $n_6$ | $n_8$ | $n_{9b}$ | |

$$[\lambda] \qquad [\alpha] \qquad [d]$$

$$[\lambda]_O = n \to O \sim \lambda^n$$

**Boost label:** $n_- \to \alpha n_-$

$n_+ \to \alpha^{-1} n_+$

**Dimension**

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# Matching onto $\mathrm{SCET_{II}}$

$$[\lambda] = 15 - 2n_1 + 2n_5 + 2n_6 + 4n_7 + 4n_8 + 6(n_{9a} + n_{9b} + n_{9c}),$$

$$[\alpha] = 0 = -n_1 + n_2 + n_3 - n_4 - n_6 + n_7 - n_8 - n_{9a} + n_{9b},$$

$$[d] = 9 - n_1 - n_2 + n_5 + n_6 + n_7 + 3(n_8 + n_{9a} + n_{9b} + n_{9c}),$$

$$\Downarrow$$

$$[\lambda] = 6 + [d] - n_3 + n_4 + n_5 + 2n_6 + 2n_7 + 2n_8 + 4n_{9a} + 2n_{9b} + 3n_{9c}.$$

## Matching onto $\text{SCET}_{\text{II}}$

**For $O^A$,**

$$O_j^A(s) = (\bar{\xi}_{hc} W_{hc})_s \Gamma_j Y_s^\dagger h_v,$$

$$[d] = 3, [\lambda] = 9, [\alpha] = 0$$

$$n_1 = n_2 = 3,\ n_3 = n_4 \text{ and } n_i = 0 (i \geq 5)$$

**For $O^B$,**

$$O_j^B(s_1, s_2) = (\bar{\xi}_{hc} W_{hc})_{s_1} (W_{hc}^\dagger i D_{\perp\mu} W_{hc})_{s_2} \Gamma_j' Y_s^\dagger h_v,$$

$$[d] = 4, [\lambda] = 11, [\alpha] = 0$$

$$n_1 = 2,\ n_2 = 3,\ n_4 - n_3 = 1,\ n_i = 0 (i \geq 5)$$

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# Matching onto $\mathrm{SCET_{II}}$

**For $O^A$,** $$O_j^A(s) = (\bar{\xi}_{hc}W_{hc})_s\Gamma_j Y_s^\dagger h_v,$$

$$[d] = 3, [\lambda] = 9, [\alpha] = 0$$

$$n_1 = n_2 = 3,\ n_3 = n_4 \text{ and } n_i = 0 (i \geq 5)$$

$$\langle\Lambda|O^A|\Lambda_b\rangle \sim \lambda^4, \quad \langle\Lambda|O^{B,C,D,E}|\Lambda_b\rangle \sim \lambda^6.$$

$$\frac{1}{in_+\partial + i\epsilon}\phi(x) = -i\int_{-\infty}^{0} ds\,\phi(x+sn_+), \quad \frac{1}{in_-\partial - i\epsilon}\phi(x) = i\int_0^\infty dt\,\phi(x+tn_-).$$

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# Soft from factor

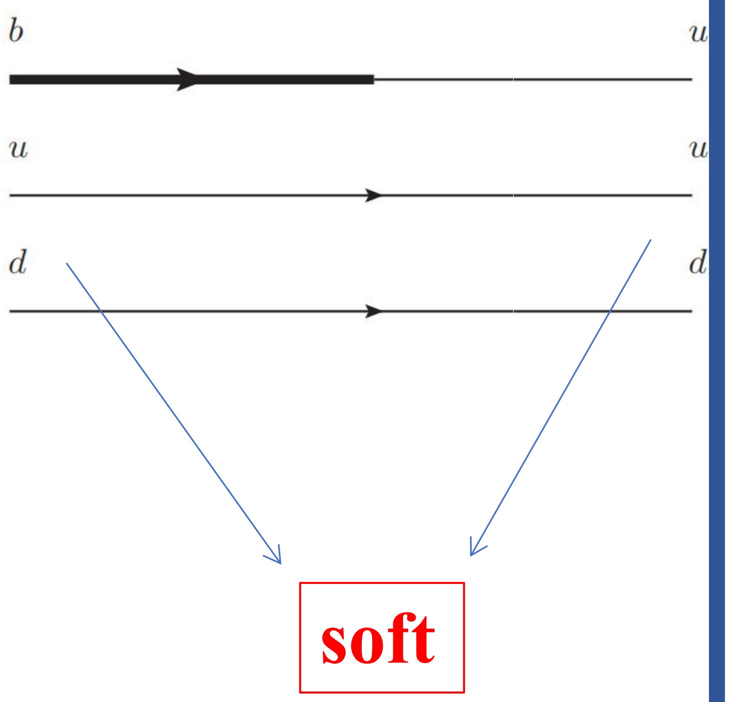
$$\xi_\Lambda(E) = \int \frac{dx_2 d^2\vec{k}_{2\perp} dx_3 d^2\vec{k}_{3\perp}}{(16\pi^3)^2} \psi_{\Lambda_b}(x_2, x_3, \vec{k}_{2\perp}, \vec{k}_{3\perp}) \psi_\Lambda(y_2(x_2), y_3(x_3), \vec{k}_{2\perp}, \vec{k}_{3\perp}),$$

$$\int \frac{dx_2 d^2\vec{k}_{2\perp} dx_3 d^2\vec{k}_{3\perp}}{(16\pi^3)^2} |\psi_{\Lambda_b}(x_2, x_3, \vec{k}_{2\perp}, \vec{k}_{3\perp})|^2 = 1,$$

$$x_{2,3} \sim \lambda^2 \quad k_{2\perp,3\perp} \sim \lambda^2 \qquad \psi_{\Lambda_b}(x_2, x_3, \vec{k}_{2\perp}, \vec{k}_{3\perp}) \sim \lambda^{-6}$$

$$y_{2,3} \sim 1 \longrightarrow \psi_\Lambda(y_2, y_3, \vec{k}_{2\perp}, \vec{k}_{3\perp}) \sim \lambda^{-4}$$

**phase suppression** $\longrightarrow$ $\xi_\Lambda(E) \sim \lambda^6,$



## Factorization in SCET



### Matching onto $\mathrm{SCET_{II}}$

$$\langle\Lambda|O^A|\Lambda_b\rangle\sim\lambda^4,\quad\langle\Lambda|O^{B,C,D,E}|\Lambda_b\rangle\sim\lambda^6.$$

$$\langle\Lambda(p')|\bar{s}\Gamma b|\Lambda_b(p)\rangle=C_i\xi_\Lambda(E)\bar{u}_\Lambda(p')\Gamma u_{\Lambda_b}(p)+\mathcal{O}(\lambda^2\xi_\Lambda),$$

$$F_i^{B\to\pi}(E)=C_i\xi_\pi(E)+\int d\tau C_i'(E,\tau)\Xi_\pi(\tau,E).$$

M.Beneke and T.Feldmann,Nucl. Phys. B 685, 249-296 (2004)

**To leading power, there is only one universal form factor!**

**In B->pi, symmetry breaking effects are at leading power**

PART 03

# Form factor in SCET

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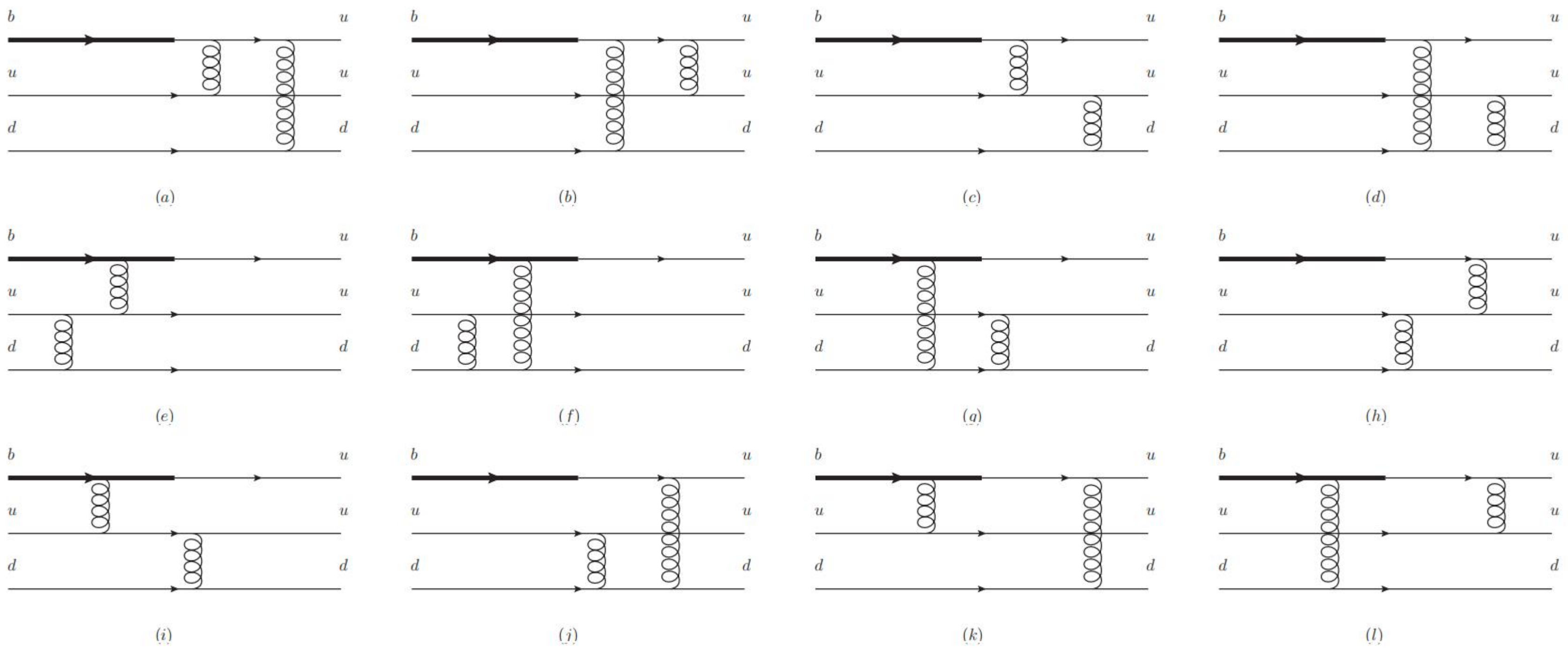
# Form factor in SCET

Form factor in SCET

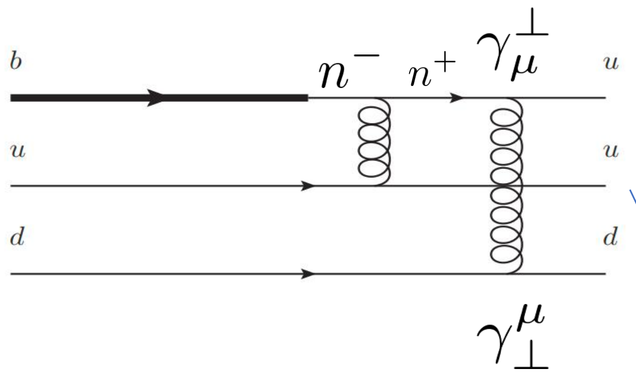
**Leading order in QCD**

$$\left\langle B\left(p,\lambda\right)\left|\bar{\xi}\Gamma h_v^{(b)}\right|H_b(v)\right\rangle = C_i \xi\left(H_b \to B, \bar{n}\cdot p\right)\bar{u}_B\left(p,\lambda\right)\Gamma u_{H_b}(v) + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{\bar{n}\cdot p}\right).$$



$$\langle p|\bar{u}\Gamma b|\Lambda_b\rangle$$

# Form factor in SCET



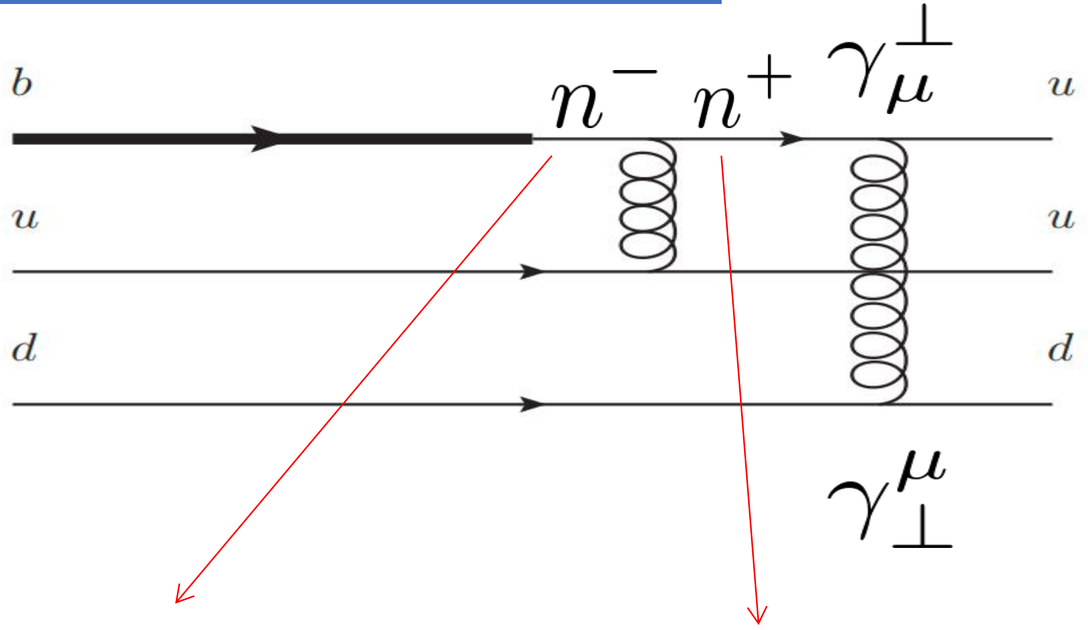

soft field

collinear field

**If both vertices of a hard-collinear gluon are attached to collinear quarks, only the transverse component of this gluon contributes.**

$$[\bar{q}_1\gamma_\mu\ldots] \times [\bar{q}_2\gamma^\mu\ldots] = [\bar{q}_1\gamma_{\perp\mu}\ldots] \times [\bar{q}_2\gamma^{\perp\mu}\ldots],$$

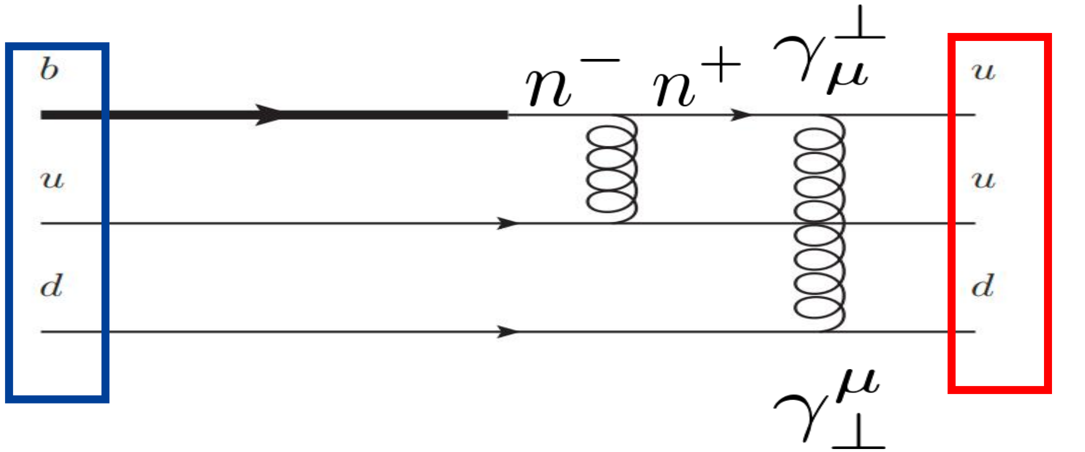
# Form factor in SCET




$$-\frac{i\not{n}_-}{2(x_2+x_3)m_{\Lambda_b}n_-v} \qquad \frac{i\not{n}_+}{2(y_1+y_3)n_+p'}$$

# Form factor in SCET

## Light-Cone Distribution Amplitude




$$\langle p(p,\lambda)|\bar{u}^a_\alpha(a_1 z)\bar{u}^b_\beta(a_2 z)d^c_\gamma(a_3 z)|0\rangle = \frac{\epsilon^{abc}}{6}\frac{n\cdot p}{8}\int [dy] e^{in\cdot p\sum_i a_i y_i}\Big\{(C\bar{\not{n}})_{\beta\alpha}(\bar{u}^p(p,\lambda)\gamma_5)_\gamma V^p(y_1,y_2,y_3) + (C\bar{\not{n}}\gamma^\rho_\perp)_{\beta\alpha}(\bar{u}^p(p,\lambda)\gamma_{\perp\rho}\gamma_5)_\gamma T^p(y_1,y_2,y_3)\Big\},$$

$$\langle 0|u^a_\alpha(t_1)d^b_\beta(t_2)Q^c_\gamma|\Lambda_b\rangle = \frac{\epsilon^{abc}}{6}\frac{v\cdot\bar{n}}{8}f_{\Lambda_b}\psi^n(t_1,t_2)u_\gamma(\not{n}\gamma_5 C^T)_{\beta\alpha},$$

# Form factor in SCET

$$\xi(\Lambda_b \to p) = g^4 C_N \frac{p^+}{64} \int [d\omega] \int [dy] \Psi_{\Lambda_b}(\omega, u) \mathcal{J}(\omega, u, y_i) \Psi_p(y_1, y_2, y_3)$$

$$C_N = \frac{1}{36} \epsilon^{abc} \epsilon^{def} [T^A T^B]_{af} [T^A]_{bd} [T^B]_{ce} = \frac{2}{27}$$

$$\mathcal{J}(\omega, u, y_i) = \sum_{l=V,T} \mathcal{D}_l^a \times \frac{i}{(y_1 + y_3) P^+} \frac{-i}{\omega} \frac{i^2}{y_2 y_3 u(1-u) \omega^2 P^{+2}},$$

$$\mathcal{D}_V^a = \bar{u}^p \gamma_5 \gamma_\perp^\nu \not{n} \gamma_5 C^T \gamma_{\perp\mu}^T C \bar{\not{n}} \gamma_\nu^\perp \frac{\not{n}}{2} \gamma_\perp^\mu \frac{\bar{\not{n}}}{2} \Gamma u_{\Lambda_b} = 0,$$

$$\mathcal{D}_T^a = \bar{u}^p \gamma_\perp^\rho \gamma_5 \gamma_\perp^\nu \not{n} \gamma_5 C^T \gamma_{\perp\mu}^T C \bar{\not{n}} \gamma_\rho^\perp \gamma_\nu^\perp \frac{\not{n}}{2} \gamma_\perp^\mu \frac{\bar{\not{n}}}{2} \Gamma u_{\Lambda_b} = -32 \times \bar{u}^p \Gamma u_{\Lambda_b}$$

# Form factor in SCET

$$\tilde{\psi}_2(\omega,u)=\omega^2 u(1-u)\sum_{n=0}^{2}\frac{a_n}{\epsilon_n^4}\frac{C_n^{3/2}(2u-1)}{\left|C_n^{3/2}\right|^2}\mathrm{e}^{-\omega/\epsilon_n}$$

$$V^{B\neq\Lambda}=A^{B=\Lambda}=120x_1x_2x_3f^B$$

$$T^{B\neq\Lambda}=120x_1x_2x_3f_T^B$$

$$V^{B=\Lambda}=T^{B=\Lambda}=0$$

$$A^{B\neq\Lambda}=0$$

$$\mathcal{J}(\omega,u,y_i)=\sum_{l=V,T}\mathcal{D}_l^a\times\frac{i}{(y_1+y_3)P^+}\frac{-i}{\omega}\frac{i^2}{y_2y_3u(1-u)\omega^2P^{+2}},$$

**no endpoint singularity**

# Form factor in SCET

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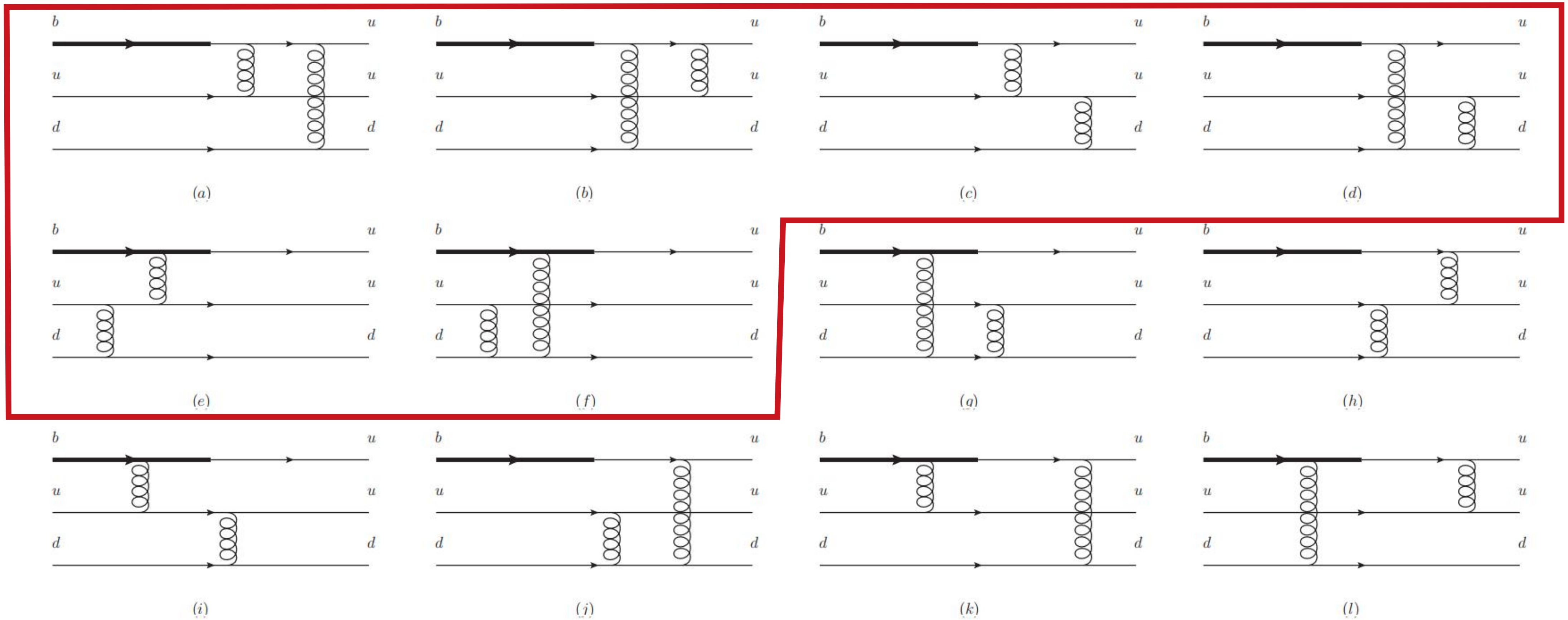
## Form factor in SCET

**Leading power contribution**



PART 04

# Conclusion and outlook

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## Conclusion and outlook

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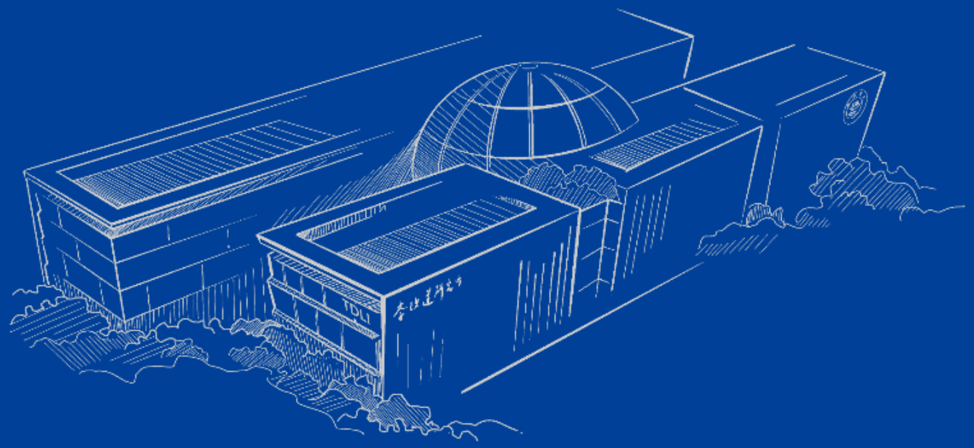
- Leading power arise from 2-gluon exchange and no endpoint singularity.

- The b-baryon triplet to octet baryon form factor are consider.

- We will continue to estimate the b-baryon triplet to decuplet form factor and sixet b-baryon to light baryon form factors.

# Thanks！



# backup

# SCET pow counting

$$\psi = \xi_c + \eta_c + \xi_{hc} + \eta_{hc} + q_s \equiv \psi^{(2)} + \psi^{(3)} + \psi^{(4)} + \psi^{(5)} + \dots$$

$$\psi^{(2)} = \xi_c,$$

$$\psi^{(3)} = \left(1 + \frac{1}{in_-\partial} g\not{A}_{\perp c} \frac{\not{n}_-}{2}\right) q_s,$$

$$\psi^{(4)} = \frac{1}{in_+\partial}(i\not{D}_{\perp c} + g\not{A}_{\perp s} + m)\frac{\not{n}_+}{2}\xi_c$$

$$- \frac{1}{in_-\partial}\left((i\not{D}_{\perp c} + g\not{A}_{\perp s} + m)\frac{1}{in_+\partial} g\not{A}_{\perp s} + g\not{A}_{\perp s}\frac{1}{in_+\partial}(i\not{D}_{\perp c} - m)\right)\xi_c$$

$$- \frac{1}{in_-\partial} g n_- A_{hc}^{(4)} \xi_c + \frac{1}{in_-\partial} g\not{A}_{\perp hc}^{(3)} \frac{\not{n}_-}{2} q_s.$$

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## SCET pow counting

$$A_{\perp hc} = \sum_{n=2}^{\infty} A_{\perp hc}^{(n)} \qquad n_- A_{hc} = \sum_{n=2}^{\infty} n_- A_{hc}^{(n)}$$

$$A_{\perp hc}^{(3)} = g\,T^A \frac{1}{(in_+\partial)(in_-\partial)} \left\{\bar{q}_s \gamma_\perp T^A \xi_c + \text{h.c.}\right\},$$

$$n_- A_{hc}^{(4)} = \frac{2g}{in_+\partial} \left[A_{\mu_\perp c}, A_s^{\mu_\perp}\right],$$

**Leading Term**

## SCET pow counting

$$A_{hc}^{\mu_\perp(4)} = \frac{g}{(in_+\partial)(in_-\partial)}\Big\{ i\mathcal{D}^{\mu_\perp}\big[A_{\nu_\perp c}, A_s^{\nu_\perp}\big] + i\mathcal{D}_{\nu_\perp}\Big(\big[A_s^{\mu_\perp}, A_c^{\nu_\perp}\big] + \big[A_c^{\mu_\perp}, A_s^{\nu_\perp}\big]\Big)$$

$$+ \Big[in_+\partial A_c^{\mu_\perp}, \frac{2g}{in_+\partial}\big[A_c^{\nu_\perp}, A_{\nu_\perp s}\big]\Big] + \frac{in_+\partial}{2}\big[A_s^{\mu_\perp}, n_- A_c\big] + \frac{in_-\partial}{2}\big[A_c^{\mu_\perp}, n_+ A_s\big]$$

$$+ \big[iF_c^{\nu_\perp\mu_\perp}, A_{\nu_\perp s}\big] + \big[iF_s^{\nu_\perp\mu_\perp}, A_{\nu_\perp c}\big]$$

$$+ gT^A\,\bar{\xi}_c\Big(\not{A}_{\perp s}\frac{1}{in_+\partial}\gamma^{\mu_\perp}T^A + \gamma^{\mu_\perp}T^A\frac{1}{in_+\partial}\not{A}_{\perp s}\Big)\frac{\not{n}_+}{2}\,\xi_c$$

$$+ gT^A\,\bar{q}_s\Big(\not{A}_{\perp c}\frac{1}{in_-\partial}\gamma^{\mu_\perp}T^A + \gamma^{\mu_\perp}T^A\frac{1}{in_-\partial}\not{A}_{\perp c}\Big)\frac{\not{n}_-}{2}\,q_s\Big\},$$

$$n_- A_{hc}^{(5)} = -\frac{2}{(in_+\partial)^2}\Big\{ i\mathcal{D}^{\mu_\perp}\big[in_+\partial A^{(3)}_{\mu_\perp hc}\big] - g\,\big[in_+\partial A_c^{\mu_\perp}, A^{(3)}_{\mu_\perp hc}\big]$$

$$+ 2gT^A\Big\{\bar{\xi}_c T^A\Big(\frac{\not{n}_+}{2} - \frac{1}{in_-\partial}\,g\not{A}_{\perp c}\Big)q_s + \text{h.c.}\Big\}\Big\}.$$

## Effective current

QCD → $$J(x) = e^{-im_b v x}\left[\bar{\psi}\Gamma\mathcal{Q}\right](x)$$

$$\psi = \xi_c + \eta_c + \xi_{hc} + \eta_{hc} + q_s \equiv \psi^{(2)} + \psi^{(3)} + \psi^{(4)} + \psi^{(5)} + \ldots$$

$$\mathcal{Q} = \left(1 + \frac{i\not{D}_s}{2m_b}\right) h_v - \frac{1}{n_- v}\frac{\not{n}_-}{2m_b}\left(g\not{A}_{\perp c} + g\not{A}_{\perp hc}\right) h_v + O(\lambda^4 h_v)$$

$$J(x) = e^{-im_b v x}\left[J_{\rm eff}^{(0)}(x) + J_{\rm eff}^{(1)}(x) + J_{\rm eff}^{(2)}(x) + J_{\rm eff}^{(3)}(x) + \ldots\right]$$

**Effective Operator**

# Precision test Standard Model

- **With the operation of more advanced experiments, the heavy quark physics has entered the era of high precision.**

- **More and more new resonants and new decay channel are observed.**

Experiments that start from 2008

LHCb

Experiments that start collecting results recently

Belle II

# Precision QCD Calculations

- **Interesting to understand the strong interaction dynamics of heavy quark decays.**
- **Precision determinations of the CKM matrix elements.**
- **Searching BSM physics.**