QCD calculations of heavy baryon form factors

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Why beauty baryon decays?

- Systematic studies in QCD not yet available.
  - Novel factorization properties for heavy baryon form factors.
  - Renormalization properties for the LCDAs of heavy baryons beyond the leading twist.
  - Perturbative calculations of short-distance functions more challenging.

- Great efforts on beauty meson decays already, no NP found yet.
  - Topical anomalies and tensions?

- Beauty baryon decays provide non-trivial tests of the SM.
  - Allow for the study of spin correlations, extract the helicity structure of $\mathscr{H}_{eff}$.
  - $\Lambda_b \to \Lambda(\to N\pi)\ell\ell$ offers complementary information on the short-distance physics.
  - Λ_b baryon is simpler than B meson in the heavy quark limit.

- A lot of progresses on the measurements of beauty baryon decays from CDF and LHCb.
  - Semileptonic decays: $\Lambda_b \to p\,\ell\,\nu$, $\Lambda_b \to \Lambda\,\ell\,\ell$, $\Lambda_b \to \Lambda_c\,\ell\,\nu$. ($\to$ this talk!)
  - Hadronic decays: $\Lambda_b \to p\,\pi$, $\Lambda_b \to p\,K$, $\Lambda_b \to \Lambda\,\phi$, $\Lambda_b \to \Lambda_c\,\pi$, etc.

Calculational tools for beauty baryon form factors

- Lattice QCD (→ Next talk by Stefan Meinel).

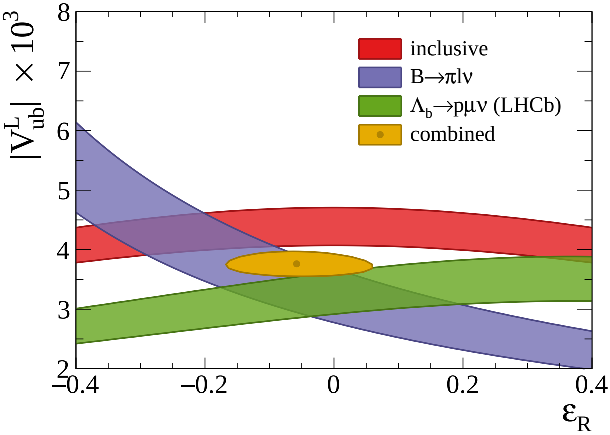
- Light-Cone Sum Rules in QCD/SCET:
  - QCD factorization for the correlation function in the appropriate kinematical region.
  - Hadronic dispersion relation for the the correlation function.
  - Matching with the quark-hadron duality and the Borel transformation.
  - Constructions of the sum rules with different LCDAs possible.

- QCD/SCET Factorization:
  - Less assumptions theoretically, more challenging conceptuallly/technically.
  - Parametrically power suppressed corrections numerically dominant.
    → Rapidity divergences in the subleading-power factorization formulae.

- TMD Factorization:
  - Including the Sudakov mechanism, but no definite power counting scheme.
  - Definitions of TMD parton densities more complicated.

Part I: Semileptonic $\Lambda_b \to p\ell\nu_l$ decays

- An alternative way to determine $|V_{ub}|$ exclusively [arXiv:1504.01568].



  - Strong interaction dynamics described by the transition form factors.
  - Much more complicated when including QED corrections.

General aspects of $\Lambda_b \to p$ form factors

- Traditional parameterizations [Manohar and Wise $\oplus$ many others]:

$$\begin{aligned} \langle N(P^\prime)|\bar{u}\,\gamma_\mu\, b|\Lambda_b(P)\rangle &= \bar{N}(P^\prime)\left\{f_1(q^2)\,\gamma_\mu + i\frac{f_2(q^2)}{m_{\Lambda_b}}\,\sigma_{\mu\nu}q^\nu + \frac{f_3(q^2)}{m_{\Lambda_b}}\,q_\mu\right\}\Lambda_b(P)\,, \\ \langle N(P^\prime)|\bar{u}\,\gamma_\mu\gamma_5\, b|\Lambda_b(P)\rangle &= \bar{N}(P^\prime)\left\{g_1(q^2)\,\gamma_\mu + i\frac{g_2(q^2)}{m_{\Lambda_b}}\,\sigma_{\mu\nu}q^\nu + \frac{g_3(q^2)}{m_{\Lambda_b}}\,q_\mu\right\}\gamma_5\Lambda_b(P)\,. \end{aligned}$$

  Axial-vector matrix element does not vanish, different from $B \to \pi$ transition.

- Helicity-based parameterizations [Feldmann and Yip, 2011]:

$$\begin{aligned} \langle N(P^\prime)|\bar{u}\,\gamma_\mu\, b|\Lambda_b(P)\rangle = \bar{N}(P^\prime)\Big\{ & f_+(q^2)\,\frac{m_{\Lambda_b}+m_N}{s_+}\left(P_\mu + P^\prime_\mu - \frac{q_\mu}{q^2}\,(m_{\Lambda_b}^2 - m_N^2)\right) \\ & + f_\perp(q^2)\left(\gamma_\mu - \frac{2\,m_N}{s_+}\,P_\mu - \frac{2\,m_{\Lambda_b}}{s_+}\,P^\prime_\mu\right) + f_0(q^2)\,(m_{\Lambda_b} - m_N)\,\frac{q_\mu}{q^2}\Big\}\Lambda_b(P)\,. \end{aligned}$$

  Simper expressions for angular distributions and for unitary bounds.

- Symmetry-based parameterizations [Feldmann and Yip, 2011]:

$$\langle N(P^\prime)|\bar{u}\,\Gamma\, b|\Lambda_b(P)\rangle = \xi_{ij}^{(\pm)}(v\cdot P^\prime)\,\bar{N}(P^\prime)\left\{\Gamma_i\,\frac{\not{n}_\pm\,\not{n}_\mp}{4}\,\Gamma\,\Gamma_j\right\}\Lambda_b(P)\,.$$

  $\xi_{ij}^{(-)}(v\cdot P^\prime)$ suppressed in both the HQET and SCET limits.

Symmetry relations of $\Lambda_b \to p$ form factors

- Form factors in the HQET limit [Manohar and Wise 2000]:

$$\langle N(P')|\bar{u}\,\Gamma\, b|\Lambda_b(P)\rangle = \bar{N}(P')\left[F_1(v\cdot P') + F_2(v\cdot P')\,\not{v}\right]\Gamma\Lambda_b(P)\,,$$

implying the relations

$$f_1 = g_1 = F_1 + \frac{m_N}{m_{\Lambda_b}} F_2\,, \qquad f_2 = f_3 = g_2 = g_3 = F_2\,,$$
$$f_0 = g_+ = g_\perp = F_1 + F_2\,, \qquad g_0 = f_+ = f_\perp = F_1 - F_2\,.$$

  - Only two form factors in the HQET limit.

- Form factors in the SCET limit [Mannel and YMW, 2011; Feldmann and Yip, 2011]:

$$\langle N(P')|\bar{u}\,\Gamma\, b|\Lambda_b(P)\rangle = F(n_+\cdot P')\,\bar{N}(P')\,\Gamma\,\Lambda_b(P)\,.$$

  - Only a single (soft) form factor in the large recoil limit.
  - Symmetry relations still hold including the leading-power hard spectator interaction.
  - Symmetry breaking effects induced by the perturbative and power corrections.

SCET factorization for $\Lambda_b \to p$ form factors

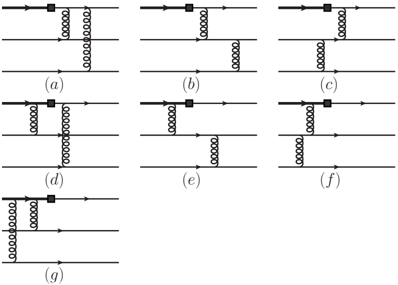
- QCD Factorization at leading power in Λ/m_b [Wei Wang, 2011]:

$$F(n_+ \cdot P') = \Phi_{\Lambda_b}(\omega_i) \otimes H(\omega_i, x_i) \otimes \Phi_N(x_i) + \mathcal{O}(\Lambda_{QCD}/E)\,.$$

  - Leading power contribution due to the exchanges of two hard-collinear gluons.
  - Leading power contribution calculable in QCD factorization.
  - The scaling behaviour (different from the soft contribution):

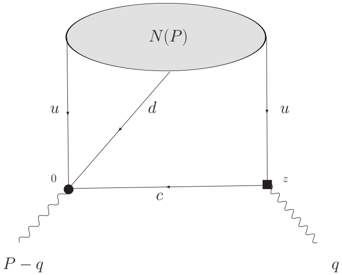
$$F(n_+ \cdot P') \sim \mathcal{O}(\Lambda_{QCD}^2/(n_+ \cdot P')^2)\,.$$

- The LO QCD diagrams:
  - Leading power contributions from the diagrams (a), (b), (f), but (b) + (f) vanishes.
  - For the diagram (a), both two gluons are transverse polarized.
  - Need the light-cone projectors of both the Λ_b-baryon and nucleon for a complete calculation even at tree level [BFWY, 2013; BFMS, 2000].



Light-cone sum rules of $\Lambda_b \to p$ form factors

- Correlation function [Khodjamirian, Klein, Mannel, YMW, 2011]:



  - Interpolating current of Λ_b baryon is not unique.

$$\Pi_a(P,q) = i \int d^4z \, e^{iq\cdot z} \times \langle 0 | \, T\{\eta(0), j_a(z)\} \, | N(P) \rangle \, .$$

    Will consider both the axial-vector and pseudoscalar Λ_b currents.

  - Background pollution from the negative-parity baryons in the dispersion relation.

- How to avoid the background pollution?
  - Parity projector matrix $(1 \pm \not{v})/2$ for heavy-baryon sum rule [Bagan, Chabab, Dosch, Narison, 1993].
  - Choose the “old-fashioned" correlation function and construct sum rules in the complex q_0-space [Jido, Kodama, Oka, 1996].
  - Eliminate the contamination by combining sum rules obtained from different kinematical structures [Khodjamirian, Klein, Mannel, YMW, 2011].

Light-cone sum rules of $\Lambda_b \to p$ form factors

- 27 nucleon LCDAs up to the twist-6 approximation [Braun, Fries, Mahnke, Stein, 2000]:

$$
\begin{aligned}
& 4\,\langle 0|\,\varepsilon^{ijk} u^i_\alpha(a_1 z) u^j_\beta(a_2 z) d^k_\gamma(a_3 z)\,|N(P)\rangle \\
= \quad & \mathscr{S}_1 m_N C_{\alpha\beta}\,(\gamma_5 u_N)_\gamma + \mathscr{S}_2 m_N^2 C_{\alpha\beta}\,(\not{z}\gamma_5 u_N)_\gamma + \mathscr{P}_1 m_N\,(\gamma_5 C)_{\alpha\beta}\,(u_N)_\gamma \\
& + \mathscr{P}_2 m_N^2\,(\gamma_5 C)_{\alpha\beta}\,(\not{z} u_N)_\gamma + \left(\mathscr{V}_1 + \frac{z^2 m_N^2}{4}\mathscr{V}_1^M\right)(\not{P}C)_{\alpha\beta}\,(\gamma_5 u_N)_\gamma \\
& + \mathscr{V}_2 m_N\,(\not{P}C)_{\alpha\beta}\,(\not{z}\gamma_5 u_N)_\gamma + \mathscr{V}_3 m_N\,(\gamma_\mu C)_{\alpha\beta}\,(\gamma^\mu\gamma_5 u_N)_\gamma \\
& + \mathscr{V}_4 m_N^2\,(\not{z}C)_{\alpha\beta}\,(\gamma_5 u_N)_\gamma + \mathscr{V}_5 m_N^2\,(\gamma_\mu C)_{\alpha\beta}\,(i\sigma^{\mu\nu} z_\nu \gamma_5 u_N)_\gamma \\
& + \mathscr{V}_6 m_N^3\,(\not{z}C)_{\alpha\beta}\,(\not{z}\gamma_5 u_N)_\gamma + \left(\mathscr{A}_1 + \frac{z^2 m_N^2}{4}\mathscr{A}_1^M\right)(\not{P}\gamma_5 C)_{\alpha\beta}\,(u_N)_\gamma \\
& + \mathscr{A}_2 m_N\,(\not{P}\gamma_5 C)_{\alpha\beta}\,(\not{z} u_N)_\gamma + \mathscr{A}_3 m_N\,(\gamma_\mu\gamma_5 C)_{\alpha\beta}\,(\gamma^\mu u_N)_\gamma \\
& + \mathscr{A}_4 m_N^2\,(\not{z}\gamma_5 C)_{\alpha\beta}\,(u_N)_\gamma + \mathscr{A}_5 m_N^2\,(\gamma_\mu\gamma_5 C)_{\alpha\beta}\,(i\sigma^{\mu\nu} z_\nu u_N)_\gamma \\
& + \mathscr{A}_6 m_N^3\,(\not{z}\gamma_5 C)_{\alpha\beta}\,(\not{z} u_N)_\gamma + \left(\mathscr{T}_1 + \frac{z^2 m_N^2}{4}\mathscr{T}_1^M\right)(P^\nu i\sigma_{\mu\nu} C)_{\alpha\beta}\,(\gamma^\mu\gamma_5 u_N)_\gamma \\
& + \mathscr{T}_2 m_N\,(z^\mu P^\nu i\sigma_{\mu\nu} C)_{\alpha\beta}\,(\gamma_5 u_N)_\gamma + \mathscr{T}_3 m_N\,(\sigma_{\mu\nu} C)_{\alpha\beta}\,(\sigma^{\mu\nu}\gamma_5 u_N)_\gamma \\
& + \mathscr{T}_4 m_N\,(P^\nu \sigma_{\mu\nu} C)_{\alpha\beta}\,(\sigma^{\mu\rho} z_\rho \gamma_5 u_N)_\gamma + \mathscr{T}_5 m_N^2\,(z^\nu i\sigma_{\mu\nu} C)_{\alpha\beta}\,(\gamma^\mu\gamma_5 u_N)_\gamma \\
& + \mathscr{T}_6 m_N^2\,(z^\mu P^\nu i\sigma_{\mu\nu} C)_{\alpha\beta}\,(\not{z}\gamma_5 u_N)_\gamma + \mathscr{T}_7 m_N^2\,(\sigma_{\mu\nu} C)_{\alpha\beta}\,(\sigma^{\mu\nu}\not{z}\gamma_5 u_N)_\gamma \\
& + \mathscr{T}_8 m_N^3\,(z^\nu \sigma_{\mu\nu} C)_{\alpha\beta}\,(\sigma^{\mu\rho} z_\rho \gamma_5 u_N)_\gamma\,.
\end{aligned}
$$

Light-cone sum rules of $\Lambda_b \to p$ form factors

- Conformal expansion of the LCDAs:

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

  - All DAs expanded up to the NLO conformal spin.
  - For the d-wave contributions to the twist-3 DAs, see [Lenz et al, 2009].
  - For more recent update, see [Anikin, Braun, Offen, 2013].

- Input parameters [Braun, Fries, Mahnke, Stein, 2000]:

$$
f_N = (5.0 \pm 0.5) \times 10^{-3}\,\mathrm{GeV}^2\,, \qquad \lambda_1 = -(27 \pm 9) \times 10^{-3}\,\mathrm{GeV}^2\,, \qquad \lambda_2 = (54 \pm 19) \times 10^{-3}\,\mathrm{GeV}^2\,.
$$

QCDSR estimates already confronted with the lattice calculations [Braun et al, 2014]:

$$
f_N = 2.84(1)(33) \times 10^{-3}\,\mathrm{GeV}^2\,, \qquad \lambda_1 = -4.13(2)(20) \times 10^{-3}\,\mathrm{GeV}^2\,, \qquad \lambda_2 = 8.19(5)(39) \times 10^{-3}\,\mathrm{GeV}^2\,.
$$

5 additional parameters taken from [Braun, Lenz, Wittmann, 2006].

Light-cone sum rules of $\Lambda_b \to p$ form factors

- LCSR predictions $q^2 = 0$ [Khodjamirian, Klein, Mannel, YMW, 2011]:

form factors	$\eta_{\Lambda_b}^{(\mathscr{A})}$	$\eta_{\Lambda_b}^{(\mathscr{P})}$
$f_1(0)$	$0.14^{+0.03}_{-0.03}$	$0.12^{+0.03}_{-0.04}$
$f_2(0)$	$-0.054^{+0.016}_{-0.013}$	$-0.047^{+0.015}_{-0.013}$
$g_1(0)$	$0.14^{+0.03}_{-0.03}$	$0.12^{+0.03}_{-0.03}$
$g_2(0)$	$-0.028^{+0.012}_{-0.009}$	$-0.016^{+0.007}_{-0.005}$

  - The SCET relations $f_1(0) = g_1(0)$ and $f_2(0) = g_2(0) \sim \mathscr{O}(\Lambda/m_b)$ hold numerically.
  - The LCSR predictions insensitive to the choices of the Λ_b current.
  - All twist 3, 4, 5 components of nucleon DAs numerically important.
  - Only Feynman mechanism considered here.

Light-cone sum rules of $\Lambda_b \to p$ form factors

- Extrapolation toward larger q^2 with the z-series parametrization:

$$z(q^2, t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}\,, \qquad t_+ = (m_B + m_\pi)^2\,.$$

  Conformal mapping of the cut q^2-plane onto the disk $|z(q^2, t_0)| \leq 1$.

- The BCL parametrization [Bourrely, Caprini, Lellouch, 2009]:

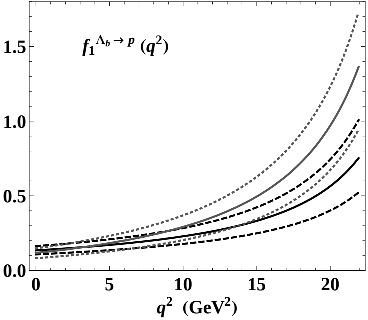
$$f_i(q^2) = \frac{f_i(0)}{1 - q^2/m^2_{B^*(1^-)}} \left\{ 1 + b_i \left(z(q^2, t_0) - z(0, t_0) \right) \right\},$$

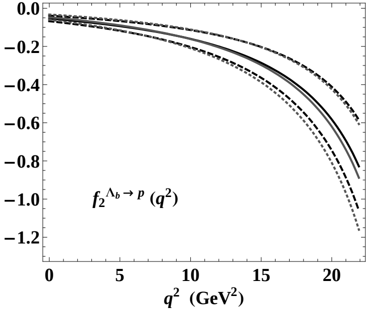
$$g_i(q^2) = \frac{g_i(0)}{1 - q^2/m^2_{B^*(1^+)}} \left\{ 1 + \tilde{b}_i \left(z(q^2, t_0) - z(0, t_0) \right) \right\}.$$

  - Alternative parameterizations possible [Boyd, Grinstein, Lebed, 1995].
  - Unitary bounds improvable [Becher, Hill, 2006].

Light-cone sum rules of $\Lambda_b \to p$ form factors

- Theory predictions of $\Lambda_b \to p$ form factors in the whole q^2 region:

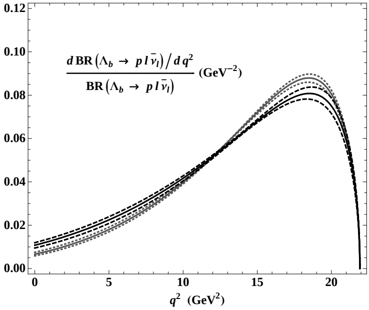




- The q^2-shape of form factors more sensitive to the choice of the Λ_b current at large q^2.
- Confronted with the lattice predictions with extrapolation toward small q^2 [Detmold, Lehner, Meinel, 2015]. $\to$ A combined LCSR $\oplus$ Lattice fit?

Semileptonic $\Lambda_b \to p\ell\nu_l$ decays

- Differential branching ratio [Khodjamirian, Klein, Mannel, YMW, 2011]:



  - Enhancement at large q^2 due to the growing form factors and the S-wave phase space factor.
  - Integrated BR: $\left(3.3^{+1.5}_{-1.2}\big|_{\rm th.} \pm 0.1\big|_{\rm exp.}\right) \times 10^{-4}$. LHCb 2015 data: $(4.1 \pm 1.0) \times 10^{-4}$.
  - About 10% uncertainty of $\mathscr{B}(\Lambda_b \to p\ell\nu)$ at $q^2 > 15\,\mathrm{GeV}^2$ normalized to the Λ_c channel.

- Determination of $|V_{ub}|$:

$$\Delta\zeta(0, q^2_{max}) = \frac{1}{|V_{ub}|^2} \int_0^{q^2_{max}} dq^2 \, \frac{d\Gamma}{dq^2} (\Lambda_b \to pl\nu_l) \,,$$

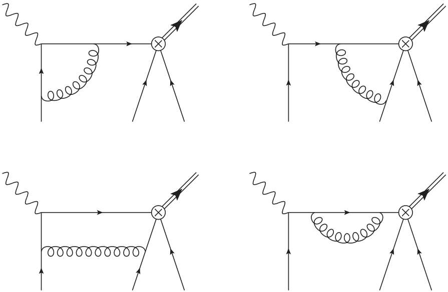
$$\Delta\zeta(0, 11\,\mathrm{GeV}^2) = 5.5^{+2.5}_{-2.0}\,\mathrm{ps}^{-1} \,.$$

  - Compare with $B \to \pi\ell\nu_l$ (NLO LCSR): $\Delta\zeta(0, 12\mathrm{GeV}^2) = 4.59^{+1.00}_{-0.85}\,\mathrm{ps}^{-1}$.
  - Perturbative corrections to $\Lambda_b \to p$ form factors needed to reduce uncertainties.

The nucleon-LCSR at NLO

- Technical aspects of the baryonic correlation functions at NLO:
  - Renormalization (subtraction) scheme in dimensional regularization.
  - Complicated operator mixing beyond the twist four approximation.
  - A large number of the nucleon LCDAs.

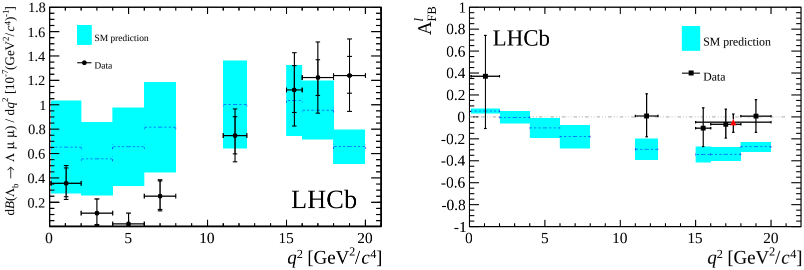
- An example: nucleon form factors[Passek-Kumerički, Peters, 2011; Anikin, Braun, Offen, 2013]
  - The Krankl-Manashov scheme without evanescent operators.
  - Typical NLO diagrams:

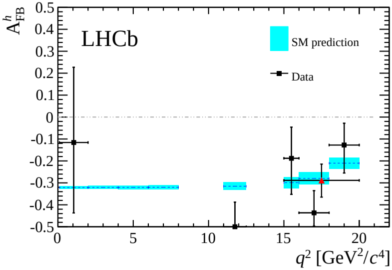


  - More complicated for $\Lambda_b \to p$ form factors due to two hard scales.
    $\to$ Hard-collinear factorization for the QCD matrix elements.

Part II: FCNC $\Lambda_b \to \Lambda \ell \ell$ decays

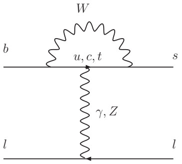
- Experimental status [LHCb, 2015]:

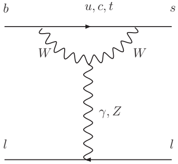


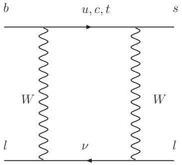


FCNC $\Lambda_b \to \Lambda \ell \ell$ decays

- Partonic $b \to s\ell^+\ell^-$ diagrams in the SM:







  - Effective Hamiltonian [Buchalla, Buras and Lautenbacher, 1996].
  - Semileptonic and magnetic operators:

$$
\begin{aligned}
O_{7\gamma} &\propto \bar{s}\sigma_{\mu\nu}(m_s L + m_b R) b F^{\mu\nu}\,,\\
O_{8g} &\propto \bar{s}_i\sigma_{\mu\nu}(1+\gamma_5) T^a_{ij} b_j G^{a\mu\nu}\,,\\
O_{9,10} &\propto (\bar{s}b)_{V-A}\left(\bar{\ell}\ell\right)_{V,A}\,.
\end{aligned}
$$

  Need C_9 and C_{10} at NNLL, C_7^{eff} and C_8^{eff} at NLL.

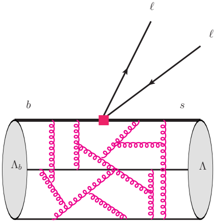
- Four-quark operators [Beneke, Feldmann and Seidel, 2001]:

$$
\begin{aligned}
O_1 &= (\bar{s}p)_{V-A}(\bar{p}b)_{V-A}\,, \qquad O_2 = \left(\bar{s}^j p^i\right)_{V-A}\left(\bar{p}^i b^j\right)_{V-A} \;(p = u, c)\,,\\
O_{3,5} &= (\bar{s}b)_{V-A}\sum_q (\bar{q}q)_{V\mp A}\,, \qquad O_{4,6} = \left(\bar{s}^i b^j\right)_{V-A}\sum_q \left(\bar{q}^j q^i\right)_{V\mp A}\,.
\end{aligned}
$$

In practice the CMM operator basis used [Chetyrkin, Misiak and Münz, 1996].

Naive factorization

- Heavy-to-light form factors:



$$\langle \Lambda(p', s') \ell^+ \ell^- | (\bar{s} b)_{V-A} \left(\bar{\ell}\ell\right)_{V,A} | \Lambda_b(p,s) \rangle$$
$$= \underbrace{\langle \Lambda(p', s') | (\bar{s} b)_{V-A} | \Lambda_b(p,s) \rangle}_{\Lambda_b \to \Lambda \text{ form factors!}} \langle \ell^+ \ell^- | \left(\bar{\ell}\ell\right)_{V,A} | 0 \rangle .$$

Need also tensor form factors!

- Less known Λ-baryon LCDAs [Liu, Cui, Huang, 2014].
  $\to$ (Soft) Helicity form factors of $\Lambda_b \to \Lambda$ computed from the Λ_b-baryon LCSR.

- The Λ_b LCDAs in HQET [Ball, Braun, Gardi, 2008]:

$$\varepsilon^{abc} \langle 0 | \left(u^a(\tau_1 n_-) \, C\gamma_5 \, \not{n}_- \, d^b(\tau_2 n_-) \right) h_v^c(0) | \Lambda_b(v,s) \rangle = f_{\Lambda_b}^{(2)} \, \tilde{\phi}_2(\tau_1, \tau_2) \, u_{\Lambda_b}(v,s) ,$$
$$\varepsilon^{abc} \langle 0 | \left(u^a(\tau_1 n_-) \, C\gamma_5 \, \not{n}_+ \, d^b(\tau_2 n_-) \right) h_v^c(0) | \Lambda_b(v,s) \rangle = f_{\Lambda_b}^{(2)} \, \tilde{\phi}_4(\tau_1, \tau_2) \, u_{\Lambda_b}(v,s) ,$$
$$\varepsilon^{abc} \langle 0 | \left(u^a(\tau_1 n_-) \, C\gamma_5 \, d^b(\tau_2 n_-) \right) h_v^c(0) | \Lambda_b(v,s) \rangle = f_{\Lambda_b}^{(1)} \, \tilde{\phi}_3^s(\tau_1, \tau_2) \, u_{\Lambda_b}(v,s) ,$$
$$\varepsilon^{abc} \langle 0 | \left(u^a(\tau_1 n_-) \, C\gamma_5 \, i\sigma_{\mu\nu} n_+^\mu n_-^\nu \, d^b(\tau_2 n_-) \right) h_v^c(0) | \Lambda_b(v,s) \rangle = 2 f_{\Lambda_b}^{(1)} \, \tilde{\phi}_3^\sigma(\tau_1, \tau_2) \, u_{\Lambda_b}(v,s) .$$

RGE of $\phi_2(\omega_1, \omega_2)$ contains both the Lange-Neubert and Brodsky-Lepage kernels.

Light-cone projectors for the Λ_b-baryon

- General three-quark matrix elements [Bell, Feldmann, YMW, Yip, 2013]:

$$\varepsilon^{abc} \left\langle 0 \right| \left[(u^a_\alpha(z_1)\, d^b_\beta(z_2) \right] h^c_v(0) |\Lambda_b(v,s)\rangle$$

$$\equiv \frac{1}{4} \Big\{ \underbrace{f^{(1)}_{\Lambda_b} \left[\tilde{M}^{(1)}(v,z_1,z_2)\gamma_5 C^T \right]_{\beta\alpha}}_{\text{chiral odd}} + \underbrace{f^{(2)}_{\Lambda_b} \left[\tilde{M}^{(2)}(v,z_1,z_2)\gamma_5 C^T \right]_{\beta\alpha}}_{\text{chiral even}} \Big\} u_{\Lambda_b}(v,s)\,.$$

- Lorentz-covariant parametrization:

$$\begin{aligned} \tilde{M}^{(2)}(v,z_1,z_2) &= \tilde{\Phi}_2(t_1,t_2,z_1^2,z_2^2,z_1\cdot z_2)\, \not{v} + \frac{\tilde{\Phi}_X(t_1,t_2,z_1^2,z_2^2,z_1\cdot z_2)}{4t_1t_2} \left(\not{z}_2 \not{v} \not{z}_1 - \not{z}_1 \not{v} \not{z}_2 \right) \\ &+ \frac{\tilde{\Phi}^{(i)}_{42}(t_1,t_2,z_1^2,z_2^2,z_1\cdot z_2)}{2t_1}\, \not{z}_1 + \frac{\tilde{\Phi}^{(ii)}_{42}(t_1,t_2,z_1^2,z_2^2,z_1\cdot z_2)}{2t_2}\, \not{z}_2\,. \end{aligned}$$

Expanding z_i around the light-cone $(n_- z_i) \ll z_i^\perp \ll (n_+ z_i)$ [$\tau_i = n_+ z_i/2$]:

$$\begin{aligned} \tilde{M}^{(2)}(v,z_1,z_2) \longrightarrow & \frac{\not{n}_+}{2}\, \tilde{\phi}_2(\tau_1,\tau_2) + \frac{\not{n}_-}{2} \left(\tilde{\phi}_2(\tau_1,\tau_2) + \tilde{\phi}^{(i)}_{42}(\tau_1,\tau_2) + \tilde{\phi}^{(ii)}_{42}(\tau_1,\tau_2) \right) \\ & + \frac{\tilde{\phi}^{(i)}_{42}(\tau_1,\tau_2)}{2\tau_1}\, \not{z}_1^\perp + \frac{\tilde{\phi}^{(ii)}_{42}(\tau_1,\tau_2)}{2\tau_2}\, \not{z}_2^\perp \\ & + \tilde{\phi}_X(\tau_1,\tau_2) \left(\frac{\not{z}_1^\perp}{2\tau_1} - \frac{\not{z}_2^\perp}{2\tau_2} \right) \left(\frac{\not{n}_- \not{n}_+}{4} - \frac{\not{n}_+ \not{n}_-}{4} \right) + \mathcal{O}(z^2_{i\perp}, n_- z_i)\,. \end{aligned}$$

Light-cone projectors for the Λ_b-baryon

- Performing the Fourier transformation yields:

$$
\begin{aligned}
M^{(2)}(\omega_1,\omega_2) = & \frac{\not{n}_+}{2}\,\phi_2(\omega_1,\omega_2) + \frac{\not{n}_-}{2}\,\phi_4(\omega_1,\omega_2) \\
& - \frac{1}{2}\,\gamma_\mu^\perp \int_0^{\omega_1} d\eta_1 \left(\phi_{42}^{(i)}(\eta_1,\omega_2) - \phi_X(\eta_1,\omega_2)\right) \frac{\not{n}_+\not{n}_-}{4}\,\frac{\partial}{\partial k_{1\mu}^\perp} \\
& - \frac{1}{2}\,\gamma_\mu^\perp \int_0^{\omega_1} d\eta_1 \left(\phi_{42}^{(i)}(\eta_1,\omega_2) + \phi_X(\eta_1,\omega_2)\right) \frac{\not{n}_-\not{n}_+}{4}\,\frac{\partial}{\partial k_{1\mu}^\perp} \\
& - \frac{1}{2}\,\gamma_\mu^\perp \int_0^{\omega_2} d\eta_2 \left(\phi_{42}^{(ii)}(\omega_1,\eta_2) - \phi_X(\omega_1,\eta_2)\right) \frac{\not{n}_-\not{n}_+}{4}\,\frac{\partial}{\partial k_{2\mu}^\perp} \\
& - \frac{1}{2}\,\gamma_\mu^\perp \int_0^{\omega_2} d\eta_2 \left(\phi_{42}^{(ii)}(\omega_1,\eta_2) + \phi_X(\omega_1,\eta_2)\right) \frac{\not{n}_+\not{n}_-}{4}\,\frac{\partial}{\partial k_{2\mu}^\perp} \,.
\end{aligned}
$$

Four more LCDAs sensitive to the transverse momenta of the light quarks.

- Constraints due to the Wandzura-Wilczek (“on-shell") approximation:

$$
\phi_{42}^{(i)}(\omega_1,\omega_2) - \phi_{42}^{(ii)}(\omega_1,\omega_2) = \frac{\partial}{\partial\omega_1}\left(\omega_1\,\phi_4(\omega_1,\omega_2)\right) - \frac{\partial}{\partial\omega_2}\left(\omega_2\,\phi_4(\omega_1,\omega_2)\right),
$$

$$
2\,\phi_X(\omega_1,\omega_2) + \phi_4(\omega_1,\omega_2) - \phi_2(\omega_1,\omega_2) = \frac{\partial}{\partial\omega_1}\left(\omega_1\,\phi_4(\omega_1,\omega_2)\right) + \frac{\partial}{\partial\omega_2}\left(\omega_2\,\phi_4(\omega_1,\omega_2)\right).
$$

- Can construct the light-cone projectors in the momentum space directly.

$\Lambda_b \to \Lambda$ form factors from the Λ_b-baryon LCSR

- Starting point: correlation function [Feldmann, Yip, 2011; YMW and Shen, 2015]

$$\Pi_{\mu,a}(p,q) = i \int d^4x \, e^{iq\cdot x} \langle 0 | T\{j_\Lambda(x), j_{\mu,a}(0)\} | \Lambda_b(p) \rangle ,$$
$$j_{\mu,a} = \bar{s} \, \Gamma_{\mu,a} \, b , \qquad j_\Lambda = \varepsilon_{ijk} \left(u_i^{\mathrm{T}} C \gamma_5 \not{n} \, d_j \right) s_k .$$

Different choices of the Λ-baryon current possible, but the axial-vector collinear current favored.

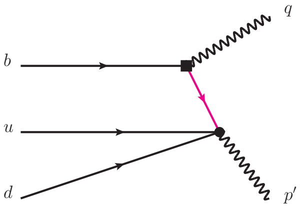
- Hadronic dispersion relations:

$$\Pi_{\mu,V}(p,q) = \frac{f_\Lambda(\mu)\,(n\cdot p')}{m_\Lambda^2/n\cdot p' - \bar{n}\cdot p' - i0} \frac{\not{\bar{n}}}{2} \Bigg[f^T_{\Lambda_b\to\Lambda}(q^2)\,\gamma_{\perp\,\mu} + \frac{f^0_{\Lambda_b\to\Lambda}(q^2) - f^+_{\Lambda_b\to\Lambda}(q^2)}{2\,(1 - n\cdot p'/m_{\Lambda_b})} \, n_\mu$$
$$+ \frac{f^0_{\Lambda_b\to\Lambda}(q^2) + f^+_{\Lambda_b\to\Lambda}(q^2)}{2} \, \bar{n}_\mu \Bigg] \Lambda_b(p)$$
$$+ \int_{\omega_s}^{+\infty} d\omega' \, \frac{1}{\omega' - \bar{n}\cdot p' - i0} \frac{\not{\bar{n}}}{2} \Big[\rho^h_{V,\perp}(\omega', n\cdot p')\,\gamma_{\perp\,\mu} + \rho^h_{V,n}(\omega', n\cdot p')\, n_\mu$$
$$+ \rho^h_{V,\bar{n}}(\omega', n\cdot p')\,\bar{n}_\mu \Big] \Lambda_b(p) .$$

The effects from the negative-parity baryons treated naively.

$\Lambda_b \to \Lambda$ form factors from the Λ_b-baryon LCSR

Factorization at tree level:



$$\Pi^{(0)}_{\mu,V(A)}(p,q) = f^{(2)}_{\Lambda_b}(\mu) \int_0^{+\infty} d\omega_1' \int_0^{+\infty} d\omega_2' \, \frac{\psi_4(\omega_1', \omega_2')}{\omega_1' + \omega_2' - \bar{n}\cdot p' - i0} \times (1, \gamma_5) \, \frac{\not{\bar{n}}}{2} \, (\gamma_{\perp\mu} + \bar{n}_\mu) \, \Lambda_b(v) + O(\alpha_s),$$

Kinematics:

$$n\cdot p' \sim \mathcal{O}(m_b), \qquad |\bar{n}\cdot p'| \sim \mathcal{O}(\Lambda).$$

- The LO LCSR after the continuum subtraction $(\to \omega_s)$ and the Borel transformation $(\to \omega_M)$:

$$F^i_{\Lambda_b\to\Lambda}(q^2) = \frac{f^{(2)}_{\Lambda_b}(\mu)}{f_\Lambda(\mu)\, n\cdot p'} \exp\left[\frac{m_\Lambda^2}{n\cdot p'\, \omega_M}\right] \int_0^{\omega_s} d\omega' \, e^{-\omega'/\omega_M} \, \underbrace{\tilde{\psi}_4(\omega')}_{\equiv \omega' \int_0^1 du \, \phi_4 \left(u\,\omega', (1-u)\,\omega'\right)} + \mathcal{O}(\alpha_s).$$

- Power counting scheme:

$$\omega_s \sim \omega_M \sim \frac{\Lambda^2}{n\cdot p'}, \qquad \Longrightarrow \qquad F^i_{\Lambda_b\to\Lambda}(q^2) \sim 1/(n\cdot p')^3.$$

Suppressed by a factor of $\Lambda/n\cdot p'$ compared to the LP contribution.

Factorization of the correlation functions

- Aim: QCD factorization of the correlation functions [YMW and Shen, 2015]

$$
\begin{aligned}
\Pi_{\mu,V(A)} &= (1,\gamma_5)\,\frac{\not{\bar{n}}}{2}\left[\Pi_{\perp,V(A)}\,\gamma_{\perp\mu} + \Pi_{\bar{n},V(A)}\,\bar{n}_\mu + \Pi_{n,V(A)}\,n_\mu\right]\Lambda_b(v)\,, \\
\Pi_{\perp,V(A)} &= f^{(2)}_{\Lambda_b}(\mu)\,C_{\perp,V(A)}(n\cdot p',\mu)\int_0^\infty d\omega_1\int_0^\infty d\omega_2\,\frac{1}{\omega_1+\omega_2-\bar{n}\cdot p'-i0} \\
&\quad J\left(\frac{\mu^2}{\bar{n}\cdot p'\,\omega_i},\frac{\omega_i}{\bar{n}\cdot p'}\right)\psi_4(\omega_1,\omega_2,\mu)\,.
\end{aligned}
$$

  Similar factorization formulae for the other invariant functions.

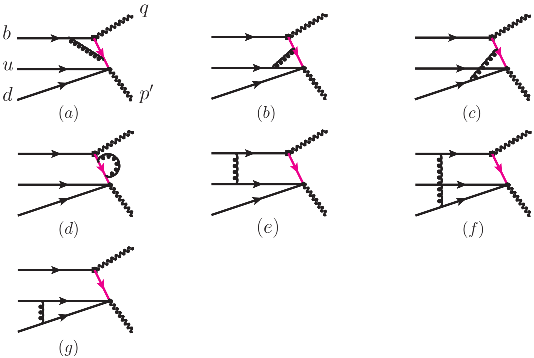
- Hard functions the same as the matching coefficients of weak currents from QCD onto $\mathrm{SCET_I}$.
  - Already known at one loop [Bauer et al, 2000; Beneke et al, 2004] and at two loops [Bonciani et al, 2008; Asatrian et al, 2008; Beneke et al, 2008; Bell, 2008; Bell et al, 2010].

- Two equivalent strategies for computing the jet function:
  - Apply the $\mathrm{SCET_I}$ Feynman rules.
  - Extract the hard-collinear contributions of QCD diagrams with the method of regions. Algebraically simpler [$\rightarrow$ this talk!].

- Factorization-scale independence of the correlation functions:
  - Explicit RGE of $\phi_4(\omega_1,\omega_2,\mu)$ unknown.
  - The Λ-baryon current not renormalization invariant.

Factorization of the correlation functions

- QCD diagrams at one loop:



  - Only hard, hard-collinear and soft regions contribute at LP in Λ/m_b.
  - Soft contributions cancelled by the IR subtraction terms.
    Automatically in SCET, also verified diagrammatically at one loop.
  - Symmetrical diagrams related to each other simply.

Factorization of the correlation functions

- Hard functions:

$$C_{\perp,V(A)}(n\cdot p',\mu) = 1-\frac{\alpha_s(\mu)\,C_F}{4\pi}\left[2\ln^2\frac{\mu}{n\cdot p'}+5\ln\frac{\mu}{m_b}-2\,\mathrm{Li}_2\left(1-\frac{1}{r}\right)\right.$$
$$\left.-\ln^2 r+\frac{3r-2}{1-r}\ln r+\frac{\pi^2}{12}+6\right].$$

  - Similar for the other hard functions, reproduced exactly.
  - All hard functions obey the same RGEs.

- Jet function [YMW and Shen, 2015]:

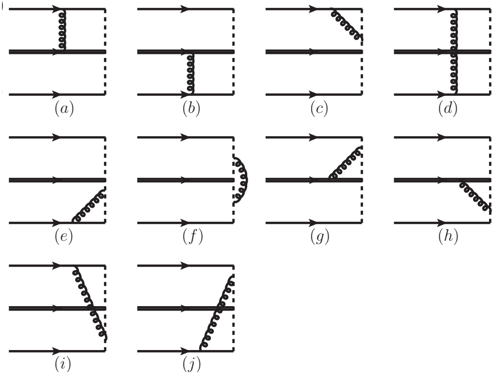
$$J\left(\frac{\mu^2}{\bar n\cdot p'\,\omega_i},\frac{\omega_i}{\bar n\cdot p'}\right)$$
$$=1+\frac{\alpha_s(\mu)}{4\pi}\,\frac{4}{3}\left\{\ln^2\frac{\mu^2}{n\cdot p'\,(\omega-\bar n\cdot p')}-2\ln\frac{\omega-\bar n\cdot p'}{\omega_2-\bar n\cdot p'}\ln\frac{\mu^2}{n\cdot p'\,(\omega-\bar n\cdot p')}\right.$$
$$-\frac{1}{2}\ln\frac{\mu^2}{n\cdot p'\,(\omega-\bar n\cdot p')}-\ln^2\frac{\omega-\bar n\cdot p'}{\omega_2-\bar n\cdot p'}+2\ln\frac{\omega-\bar n\cdot p'}{\omega_2-\bar n\cdot p'}\left[\frac{\omega_2-\bar n\cdot p'}{\omega_1}-\frac{3}{4}\right]$$
$$\left.-\frac{\pi^2}{6}-\frac{1}{2}\right\}.$$

  - Universal jet function for all the form factors.
  - Symmetry property of $\psi_4(\omega_1,\omega_2,\mu)$ used to reduce the expression.

Factorization of the correlation functions

- Factorization-scale dependence:

$$\frac{d}{d\ln\mu}\Pi_{\perp,V(A)} = \frac{\alpha_s(\mu)}{4\pi}\frac{4}{3}\int_0^\infty d\omega_1\int_0^\infty d\omega_2\,\frac{1}{\omega_1+\omega_2-\bar{n}\cdot p'-i0}$$
$$\times\left[4\ln\frac{\mu}{\omega-\bar{n}\cdot p'}-4\ln\frac{\omega-\bar{n}\cdot p'}{\omega_2-\bar{n}\cdot p'}-6\right]\left[f_{\Lambda_b}^{(2)}(\mu)\,\psi_4(\omega_1,\omega_2,\mu)\right]$$
$$+\int_0^\infty d\omega_1\int_0^\infty d\omega_2\,\frac{1}{\omega_1+\omega_2-\bar{n}\cdot p'-i0}\,\frac{d}{d\ln\mu}\left[f_{\Lambda_b}^{(2)}(\mu)\,\psi_4(\omega_1,\omega_2,\mu)\right].$$



Renormalization of $\psi_4(\omega_1,\omega_2,\mu)$ yields

$$-\frac{\alpha_s(\mu)}{4\pi}\frac{4}{3}\int_0^\infty d\omega_1\int_0^\infty d\omega_2\,\frac{1}{\omega-\bar{n}\cdot p'-i0}$$
$$\times\left[4\ln\frac{\mu}{\omega-\bar{n}\cdot p'}-4\ln\frac{\omega-\bar{n}\cdot p'}{\omega_2-\bar{n}\cdot p'}-5\right]$$
$$\times\left[f_{\Lambda_b}^{(2)}(\mu)\,\psi_4(\omega_1,\omega_2,\mu)\right],$$

implying

$$\frac{d}{d\ln\mu}\left[\frac{\Pi_{\perp,V(A)}(n\cdot p',\bar{n}\cdot p',\mu)}{f_\Lambda(\mu)}\right]=0.$$

Resummation of large logarithms

- Distinguish the factorization scale (μ) from the renormalization scales for the Λ-baryon current (ν) and for the weak current in QCD (ν'):

$$J\left(\frac{\mu^2}{\bar{n}\cdot p'\,\omega_i},\frac{\omega_i}{\bar{n}\cdot p'},\nu\right) = J\left(\frac{\mu^2}{\bar{n}\cdot p'\,\omega_i},\frac{\omega_i}{\bar{n}\cdot p'}\right)+\delta J\left(\frac{\mu^2}{\bar{n}\cdot p'\,\omega_i},\frac{\omega_i}{\bar{n}\cdot p'},\nu\right),$$

$$C^A_{T(\tilde{T})}(n\cdot p',\mu,\nu') = C^A_{T(\tilde{T})}(n\cdot p',\mu)+\delta C^A_{T(\tilde{T})}(n\cdot p',\mu,\nu').$$

- Determination of ν and ν' dependence:

$$\frac{d}{d\ln\nu}\ln\delta J\left(\frac{\mu^2}{\bar{n}\cdot p'\,\omega_i},\frac{\omega_i}{\bar{n}\cdot p'},\nu\right) = -\sum_k\left(\frac{\alpha_s(\mu)}{4\pi}\right)^k\gamma_\Lambda^{(k)},$$

$$\frac{d}{d\ln\nu'}\ln\delta C^A_{T(\tilde{T})}(n\cdot p',\mu,\nu') = -\sum_k\left(\frac{\alpha_s(\mu)}{4\pi}\right)^k\gamma_{T(\tilde{T})}^{(k)}.$$

Renormalization conditions:

$$\delta J\left(\frac{\mu^2}{\bar{n}\cdot p'\,\omega_i},\frac{\omega_i}{\bar{n}\cdot p'},\mu\right)=0,\qquad \delta C^A_{T(\tilde{T})}(n\cdot p',\mu,\mu)=0.$$

- NLL resummation for the hard functions by solving the evolution equations in μ and ν'.

NLL resummation of $\Lambda_b \to \Lambda$ form factors

- Resummation improved form factors [YMW and Shen, 2015]:

$$f_\Lambda(\nu)\,(n\cdot p')\,e^{-m_\Lambda^2/(n\cdot p'\,\omega_M)}\left\{f^T_{\Lambda_b\to\Lambda}(q^2), g^T_{\Lambda_b\to\Lambda}(q^2)\right\}$$
$$= f^{(2)}_{\Lambda_b}(\mu)\left[U_1(n\cdot p'/2,\mu_h,\mu)\,C_{\perp,V(A)}(n\cdot p',\mu_h)\right]\int_0^{\omega_s} d\omega'\,e^{-\omega'/\omega_M}\,\psi_{4,\mathrm{eff}}(\omega',\mu,\nu),$$
$$f_\Lambda(\nu)\,(n\cdot p')\,e^{-m_\Lambda^2/(n\cdot p'\,\omega_M)}\left\{f^0_{\Lambda_b\to\Lambda}(q^2), g^0_{\Lambda_b\to\Lambda}(q^2)\right\}$$
$$= f^{(2)}_{\Lambda_b}(\mu)\left[U_1(n\cdot p'/2,\mu_h,\mu)\,C_{\bar n,V(A)}(n\cdot p',\mu_h)\right]\int_0^{\omega_s} d\omega'\,e^{-\omega'/\omega_M}\,\psi_{4,\mathrm{eff}}(\omega',\mu,\nu)$$
$$+ f^{(2)}_{\Lambda_b}(\mu)\left(1-\frac{n\cdot p'}{m_{\Lambda_b}}\right)C_{n,V(A)}(n\cdot p',\mu_h)\int_0^{\omega_s} d\omega'\,e^{-\omega'/\omega_M}\,\tilde\psi_4(\omega',\mu).$$

  - NLL resummation for the twist-4 Λ_b-DA not included (unknown 2-loop RGE).

- Only symmetry-breaking effect from the hard-gluon contribution taken into account.
- Including the hard-collinear symmetry breaking effect [Feldmann and Yip, 2011]

$$f^T_{\Lambda_b\to\Lambda}(q^2) = [...]+\frac{2m_{\Lambda_b}}{n\cdot p'}\,\Delta\xi_\Lambda(n\cdot p'), \qquad g^T_{\Lambda_b\to\Lambda}(q^2) = [...]-\frac{2m_{\Lambda_b}}{n\cdot p'}\,\Delta\xi_\Lambda(n\cdot p'),$$
$$f^0_{\Lambda_b\to\Lambda}(q^2) = [...]-\frac{2m_{\Lambda_b}}{n\cdot p'}\,\Delta\xi_\Lambda(n\cdot p'), \qquad g^0_{\Lambda_b\to\Lambda}(q^2) = [...]+\frac{2m_{\Lambda_b}}{n\cdot p'}\,\Delta\xi_\Lambda(n\cdot p').$$

$\Delta\xi_\Lambda$ defined by the *B*-type SCET current, calculable with the power-suppressed correction function.

The Λ_b-baryon LCDAs

- Light-cone distribution amplitudes of the Λ_b-baryon [Ball, Braun, Gardi, 2008]:

$$\phi_4^{\rm I}(\omega,\mu_0) = \frac{1}{\omega_0^2}\, e^{-\omega/\omega_0}\,,$$

$$\phi_4^{\rm II}(\omega,\mu_0) = \frac{1}{\omega_0^2}\, e^{-(\omega/\omega_1)^2}\,, \qquad \omega_1 = \sqrt{2}\,\omega_0\,,$$

$$\phi_4^{\rm III}(\omega,\mu_0) = \frac{1}{\omega_0^2}\left[1-\sqrt{\left(2-\frac{\omega}{\omega_2}\right)\frac{\omega}{\omega_2}}\right]\theta(\omega_2-\omega)\,, \qquad \omega_2 = \sqrt{\frac{12}{10-3\pi}}\,\omega_0\,.$$

$\phi_4^{\rm (II,III)}(\omega,\mu_0)$ analogy to the mesonic counterparts [De Fazio, Feldmann, Hurth, 2008].

- The shape of $F^i_{\Lambda_b\to\Lambda}(q^2)$ less model dependent.

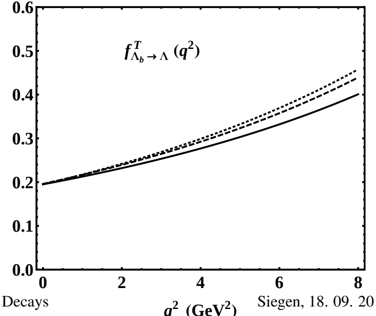
Solid, dotted, and dashed curves from Model-I, II and III.

Fitting $f^+_{\Lambda_b\to\Lambda}(0) = 0.18 \pm 0.04$ $\Rightarrow$

Model-I: $\omega_0 = 280^{+47}_{-38}\,{\rm MeV}$,

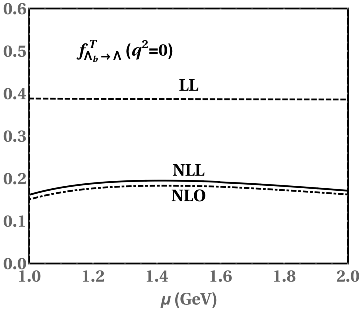
Model-II: $\omega_0 = 386^{+45}_{-37}\,{\rm MeV}$,

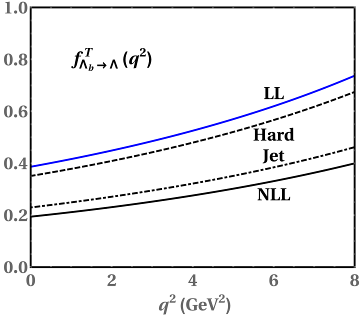
Model-III: $\omega_0 = 273^{+38}_{-29}\,{\rm MeV}$.



$\Lambda_b \to \Lambda$ form factors from the Λ_b-baryon LCSR

- Factorization scale dependence and radiative correction:





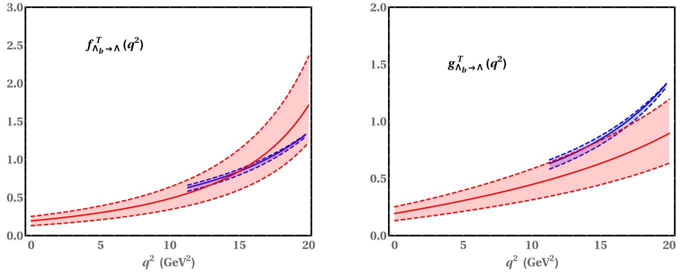
  - Dominant radiative effect from the NLO QCD correction instead of the QCD resummation.
  - NLO correction dominated by the hard-collinear contribution instead of the hard fluctuation. $\Rightarrow$ A complete calculation of the NLO jet function important!
  - Radiative effect can induce 50 % reduction of the form factors.

$\Lambda_b \to \Lambda$ form factors from the Λ_b-baryon LCSR

- Extrapolation toward larger q^2 with the z-series expansion:

$$z(q^2, t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}\,, \qquad t_+ = (m_{B_s} + m_\pi)^2 < (m_{\Lambda_b} + m_\Lambda)^2\,.$$

- The predicted form factors [YMW and Shen, 2015]:



  - Pink and blue bands predicted from LCSR and Lattice QCD [Detmold et al, 2012].
  - Reasonable agreement but different shapes, only HQET form factors from Lattice QCD.
  - Agreement with the lattice results from relativistic b quarks [Detmold and Meinel, 2016].

Non-factorizable corrections

- Hadronic operators enter into the game, when combined with the QED interaction.

- Nonlocal hadronic matrix element:

$$\mathcal{H}_{\mu}^{(\Lambda_b \to \Lambda)}(p,q) = i \int d^4x e^{iq\cdot x} \langle \Lambda(p') | T \left\{ j_{\mu}^{em}(x), H_{eff}(0) \right\} | \Lambda_b(p) \rangle \,.$$

- QED corrections to the hadronic operators $\nRightarrow$ the form factors.

  (a) Hard spectator interactions $\nRightarrow$ local operators at the m_W scale.

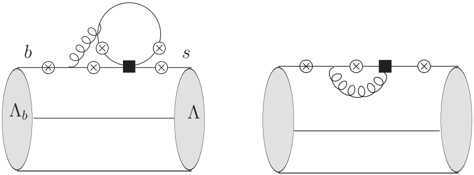
  (b) Soft gluon radiations generate non-local operators.

  (c) Strong phases of the matrix elements.

- Focus on the QCD dynamics at large hadronic recoil.

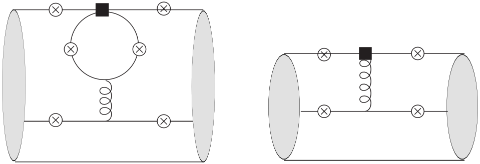
FCNC $\Lambda_b \to \Lambda \ell\ell$ decays

- Hard vertex corrections [Asatyan, Asatrian, Greub and Walker, 2001; Seidel, 2004]:



  - Two-loop matrix elements of penguin operators still missing.
  - Sizeable two-loop hard vertex corrections due to $\ln(q^2/m_b^2)$ enhancement.

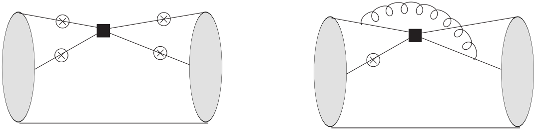
- Hard spectator interactions:



  - Cannot be computed with QCD factorization approach.
  - SCET matrix elements can be computed from the Λ_b-baryon LCSR.

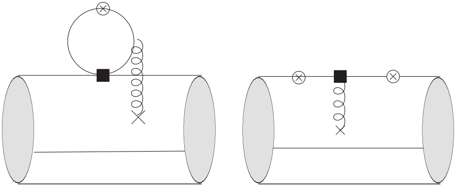
FCNC $\Lambda_b \to \Lambda \ell\ell$ decays

- Weak annihilations:



  - Either CKM or Wilson-coefficient suppressed.
  - Small correction estimated in the soft-overlap approach [Mannel and Recksiegel, 1997].

- Soft gluon radiations [Khodjamirian, Mannel, Pivovarov, YMW, 2010; KMW, 2012]:

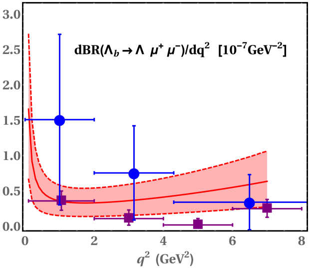


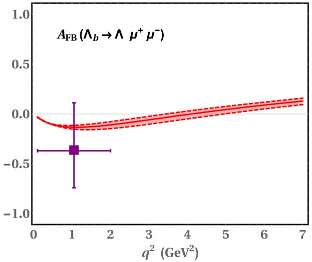
  - Soft gluon radiation power suppressed, but enhanced by the photon pole.
  - Need the still unknown four-particle Λ_b LCDAs in HQET.

Physical observables in $\Lambda_b \to \Lambda \ell\ell$ decays

- Predictions in the factorization limit:

$$\frac{d^2\Gamma(\Lambda_b \to \Lambda \ell^+ \ell^-)}{dq^2 d\cos\theta} = \frac{3}{8}\left[(1+\cos^2\theta) H_T(q^2) + 2\cos\theta H_A(q^2) + 2(1-\cos^2\theta) H_L(q^2)\right].$$

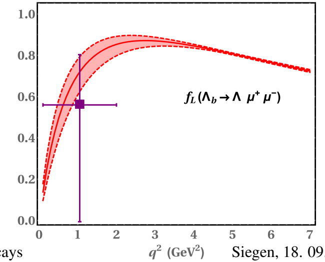




Pink bands predicted by LCSR.

Purple squares from LHCb.

Blue circles from CDF.



Conclusions and Outlook

- Novel factorization properties of beauty baryon decays at large recoil.

- $|V_{ub}|$ determination from the semileptonic $\Lambda_b \to p \ell \nu_l$ decays promising.
  - Subleading power contribution to the form factors dominant numerically.
  - NLO corrections to the nucleon-LCSR necessary to extract $|V_{ub}|$.
  - A direct calculation of the LP contribution at NLO in QCDF possible.
  - Improvement of nonpertubative input parameters from lattice QCD?

- Interesting FCNC $\Lambda_b \to \Lambda \ell \ell$ decays:
  - Sizeable hard-collinear corrections from the Λ_b-baryon LCSR at NLL.
  - Non-form-factor corrections to $\Lambda_b \to \Lambda \ell \ell$ still missing.
    $\to$ SCET factorization $\oplus$ LCSR for the effective matrix elements.
  - Renormalization properties of the higher-twist Λ_b LCDAs.

- Hadronic beauty baryon decays in QCD:
  - Only factorizable contribution at LP in the heavy quark limit?
  - Asymmetries more challenging due to the competing (N)LP contributions.