Exclusive rare decays of Λ_b baryon

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Outline

- Introduction
- Heavy-to-light baryonic form factors
- Phenomenologies of rare Λ_b baryon decays
- Summary

References:

Y. -M. Wang, Y. Li and C. -D. Lü, Eur. Phys. J. C **59** (2009) 861.

A. Khodjamirian, C. .Klein, T. .Mannel and Y. -M. Wang, JHEP **1109** (2011) 106.

T. Mannel and Y. -M. Wang, JHEP **1112** (2011) 067.

T. Feldmann and M. W. Y. Yip, Phys. Rev. D **85** (2012) 014035.

...

I. Motivation and introduction

- Weak decays of heavy-baryons are of high interest:
  determination of CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$,
  allow the study of spin correlations (polarization asymmetries...),
  a multitude of new-physics sensitive observables (A_{FB}, A_{CP}...).

- Theoretical challenges of computing the $\Lambda_b \to \Lambda \ell^+ \ell^-$ amplitudes:

  a) 10 independent $\Lambda_b \to \Lambda$ form factors, nonperturbative dynamacis,

  b) Nonfactorizable contributtions due to e.m. corrections:
  non-local matrix element, light-cone OPE, factorization, ...

  c)More involved hadronic DAs of Λ and Λ_b baryons:
  $24 + 3$ independent Λ DAs, non-asymptotic corrections,
  renormalization of Λ_b DAs, determinations of normalization constants,...

II. Heavy-to-light baryonic form factors

- (Non-lattice) theoretical approaches to compute heavy-to-light form factors:
  a) QCD sum rules on the light-cone [Braun, Khodjamirian, Ball, ...]:
  light-cone expansion for the correlator with “on-shell” light hadron,
  hadronic dispersion relation, parton-hadron duality, Borel transformation.

  b) QCD factorization (BBNS approach)[Beneke et al, ...]:
  soft form factors, spectator interactions, annihilation contribution,
  end-point singularity, power corrections,...

  c) Soft-collinear effective theory (SCET)[Bauer et al, Beneke et al, ...]:
  field decomposition, integrating out the small collinear-field components,
  light-front multipole expansion (ultrasoft fields), gauge invariant Lagrangian, ...

  d) SCET sum rules on the light-cone [De Fazio, Feldmann, Hurth,...]:
  adopting the correlation function with “on-shell” heavy hadron,
  matching QCD current onto SCET current,
  factorization of the hard-collinear and soft scales.

  e) k_T factorization theorem [Keum, Li, Sanda, Lü, Ukai, Yang, ...]:
  hard-scattering picture, transverse momentum in the end-point region,
  soft gluon emission and Sudakov form factor, k_T dependent hadronic WFs, ...

Parameterizations of $\Lambda_b \to \Lambda$ matrix elements

- Definitions of transition form factors in QCD [Isgur, Wise, ...]:

$$
\begin{aligned}
\langle \Lambda(P')|\bar{s}\,\gamma_\mu\, b|\Lambda_b(P)\rangle &= \bar{\Lambda}(P')\{f_1(q^2)\,\gamma_\mu + i\frac{f_2(q^2)}{m_{\Lambda_b}}\,\sigma_{\mu\nu}q^\nu + \frac{f_3(q^2)}{m_{\Lambda_b}}\,q_\mu\}\Lambda_b(P)\,, \\
\langle \Lambda(P')|\bar{s}\,\gamma_\mu\gamma_5\, b|\Lambda_b(P)\rangle &= \bar{\Lambda}(P')\{g_1(q^2)\,\gamma_\mu + i\frac{g_2(q^2)}{m_{\Lambda_b}}\,\sigma_{\mu\nu}q^\nu + \frac{g_3(q^2)}{m_{\Lambda_b}}\,q_\mu\}\gamma_5\Lambda_b(P)\,, \\
\langle \Lambda(P')|\bar{s}\,i\sigma_{\mu\nu}q^\mu\, b|\Lambda_b(P)\rangle &= \bar{\Lambda}(P')\{\frac{q^2}{m_{\Lambda_b}}f_1^T(q^2)\,\gamma_\mu + if_2^T(q^2)\,\sigma_{\mu\nu}q^\nu + f_3^T(q^2)\,q_\mu\}\Lambda_b(P)\,, \\
\langle \Lambda(P')|\bar{s}\,i\sigma_{\mu\nu}\gamma_5 q^\mu\, b|\Lambda_b(P)\rangle &= \bar{\Lambda}(P')\{\frac{q^2}{m_{\Lambda_b}}g_1^T(q^2)\,\gamma_\mu + ig_2^T(q^2)\,\sigma_{\mu\nu}q^\nu + g_3^T(q^2)\,q_\mu\}\gamma_5\Lambda_b(P)\,.
\end{aligned}
$$

- Helicity-based form factor parameterizations [Boyd/Savage 97, ...]:

$$
\begin{aligned}
f_\sigma(q^2) &\equiv \mathcal{N}_{\mathcal{V}}\,\epsilon^*(q,\sigma)\langle \Lambda(P')|\bar{s}\,\gamma_\mu\, b|\Lambda_b(P)\rangle\,, \\
g_\sigma(q^2) &\equiv \ldots\,, f_\sigma^T(q^2) \equiv \ldots\,, g_\sigma^T(q^2) \equiv \ldots\,.
\end{aligned}
$$

- Symmetry-based form factor parametrization [Feldmann/Yip 11]:

$$
\langle \Lambda(P')|\bar{s}\,\Gamma\, b|\Lambda_b(P)\rangle = \xi_{ij}^{(\pm)}\bar{\Lambda}(P')\left(\Gamma_i\frac{\not{n}_\pm\,\not{n}_\mp}{4}\right)\Gamma\left(\tilde{\Gamma}_j\right)\Lambda_b(P)\,.
$$

HQET/SCET limit of $\Lambda_b \to \Lambda$ form factors

- In the heavy quark limit, the spin of Λ_b is equal to the spin of b quark .

$$\langle \Lambda(P')|\bar{s}\,\Gamma\, b|\Lambda_b(P)\rangle = \bar{\Lambda}(P')\,(F_1 + F_2\, \not{v})\,\Gamma \Lambda_b(P)\,.$$

This relation holds in the whole kinematical region! [Mannel, Y.M., 11, Feldmann/Yip 11]

- Collinear equation of motion:

$$0 = \langle \Lambda(P')|\bar{s}\, \not{n}\, b|\Lambda_b(P)\rangle = \bar{\Lambda}(P')\,(F_1 + F_2\, \not{v})\, \not{n}\Lambda_b(P)\,,$$

$$\Rightarrow F_2 = 0\,.$$

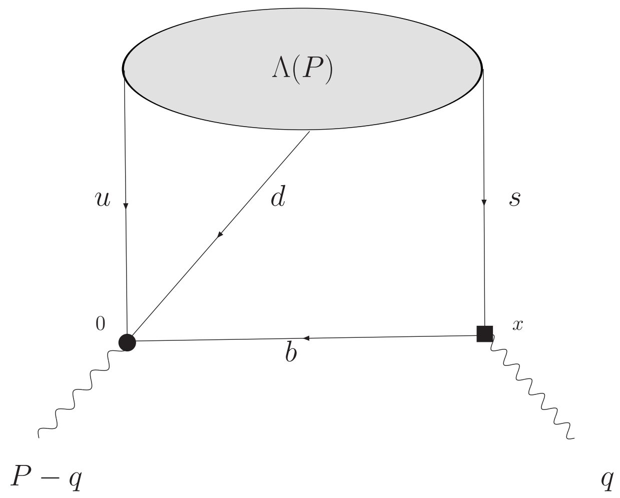
- In the HQET and SCET limit:

$$\langle \Lambda(P')|\bar{s}\,\Gamma\, b|\Lambda_b(P)\rangle = F_1(v \cdot P')\; \bar{\Lambda}(P')\Gamma \Lambda_b(v)\,.$$

Only one universal form factor [$s(\uparrow\downarrow) = \Lambda(\uparrow\downarrow)$]!
Assuming Feynman mechanism dominance!

LCSR for $\Lambda_b \to \Lambda$ form factors

- Correlation function [Y.M./Li/Lü, 09]:



Long story about the baryonic current [Ioffe 1981, Chung et al 1982, ...].

- Hadronic dispersion relation:

$$T_\mu(P,q) = \frac{\langle 0 | j_{\Lambda_b} | \Lambda_b(P-q)\rangle \langle \Lambda_b(P-q) | j_\mu | \Lambda(P)\rangle}{m_{\Lambda_b}^2 - (P-q)^2} + \sum_i \int_{s_0^h}^{\infty} ds \, \frac{\rho_i^{had}(s,q^2)}{s-(P-q)^2} \Gamma_\mu^i \,,$$

Approximation of "structureless" exchanged particles!
One resonance $\oplus$ continuum model!

LCSR for $\Lambda_b \to \Lambda$ form factors

- Light-cone OPE for the correlation function:

$$T_\mu(P,q) = \sum_{ij} T_j(x_k,(P-q)^2,q^2,\mu) \otimes \psi_\Lambda^j(x_k,\mu)\,\Gamma_\mu^i, \equiv \sum_i \Pi_i((P-q)^2,q^2)\,\Gamma_\mu^i,$$

x_k—momentum fractions, T_j—hard kernels, ψ_Λ^j—DAs of Λ baryon.

- Duality approximation:

$$\int_{s_0^h}^{\infty} ds\, \frac{\rho_i^{had}(s,q^2)}{s-(P-q)^2} = \frac{1}{\pi}\int_{s_0}^{\infty} ds\, \frac{\mathrm{Im}_s \Pi_i(s,q^2)}{s-(P-q)^2}.$$

- Borelized sum rules for form factors:

$$\mathcal{F}_i(q^2) = \frac{1}{\lambda_{\Lambda_b}} \int_{m_b^2}^{s_0} ds\, e^{-(s-m_{\Lambda_b}^2)/M^2} \sum_j a_{ij}(m_{\Lambda_b}, m_\Lambda)\, \mathrm{Im}_s \Pi_j(s,q^2).$$

$\mathcal{F}_i(q^2)$ denotes a general $\Lambda_b \to \Lambda$ form factor!

Numerics for $\Lambda_b \to \Lambda$ form factors

- $\Lambda_b \to \Lambda$ Form factors at $q^2 = 0$ [Y.M./Li/Lü 09]:

$$f_1(0) = 0.15^{+0.02}_{-0.02}\,, \qquad f_2(0) = 0.07^{+0.01}_{-0.02}\,.$$

  Tree-level QCD LCSR:

$$f_1(0) = g_1(0) = f_2^T(0) = g_2^T(0)\,,$$
$$f_2(0) = g_2(0) = f_1^T(0) = g_1^T(0)\,.$$

  Consistent with the HQET relations!

- Theoretical uncertainties:
  Normalization constants of Λ_b and Λ baryons,
  Systematic uncertainties from the continuum model,
  Non-asymptotic corrections to Λ DAs.
  Higher-order corrections.

III. Phenomenologies of rare Λ_b baryon decays

- Radiative $\Lambda_b \to \Lambda\gamma$ decay

- Rare semileptonic $\Lambda_b \to \Lambda\ell^+\ell^-$ decay

- Radiative $\Lambda_b \to \Lambda(1520)\gamma$ decay

- Semileptonic $\Lambda_b \to p\ell\nu$ decays

Radiative $\Lambda_b \to \Lambda + \gamma$ decay in LO

- A general dipole transition operator:

$$\tilde{O}_{7\gamma} \;=\; -\frac{e}{32\pi^2} m_b \, \bar{s}\sigma_{\mu\nu}(g_V - g_A\gamma_5) b F^{\mu\nu} \,.$$

- Polarized decay width of $\Lambda_b \to \Lambda + \gamma$:

$$\Gamma(\Lambda_b \to \Lambda\gamma) = \frac{1}{2}\Gamma_0[1 + \alpha \; \hat{\mathbf{n}} \cdot \mathbf{s}] = \frac{1}{2}\Gamma_0[1 + \alpha' \; \hat{\mathbf{n}} \cdot \hat{\xi}] \,.$$

Γ_0 is the total decay with of $\Lambda_b \to \Lambda + \gamma$.

$\hat{\xi}(\mathbf{s})$ is the three-spin vector of Λ baryon in its rest frame (Λ_b rest frame).

$\hat{\mathbf{n}}$ is a unite vector along the direction of Λ-baryon momentum.

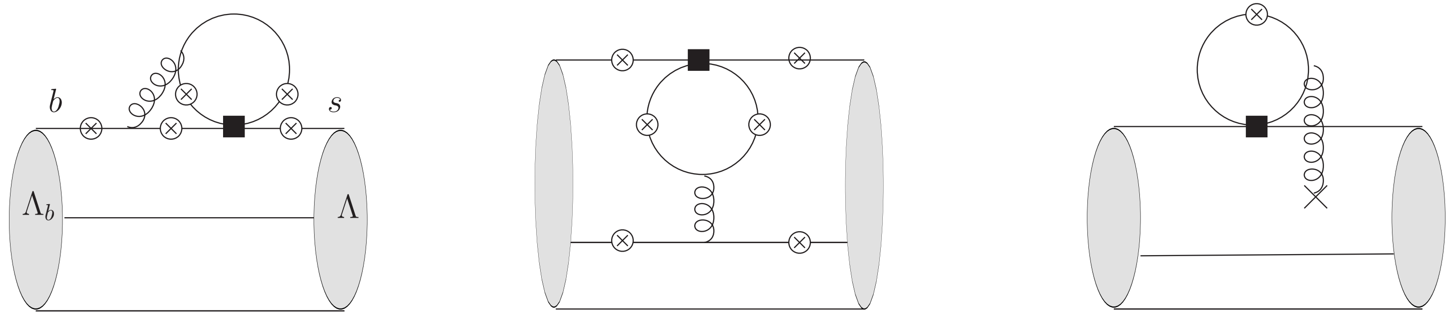
- Polarization asymmetry[Mannel/Y.M. 11, ...]:

$$\alpha = \frac{2x_\Lambda}{1 + x_\Lambda^2}\alpha' = \frac{2x_\Lambda}{1 + x_\Lambda^2}\frac{2g_V g_A}{g_V^2 + g_A^2} + O(\frac{\Lambda_{\rm QCD}}{m_b}) + O(\alpha_s) \,.$$

Only determined by the short-distance coefficients in the LO approximation!

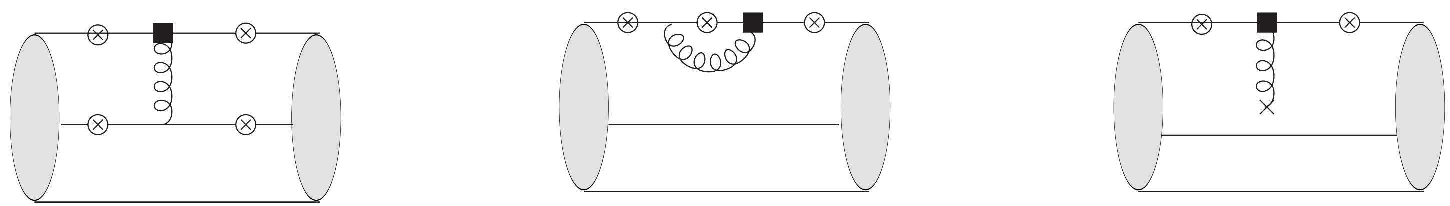
Nonlocal effects in $\Lambda_b \to \Lambda + \gamma$ decay

- Four-quark operator correction [Beneke/Feldmann 01, Khodjamirian et al 10, ...]:



(a) (b) (c)

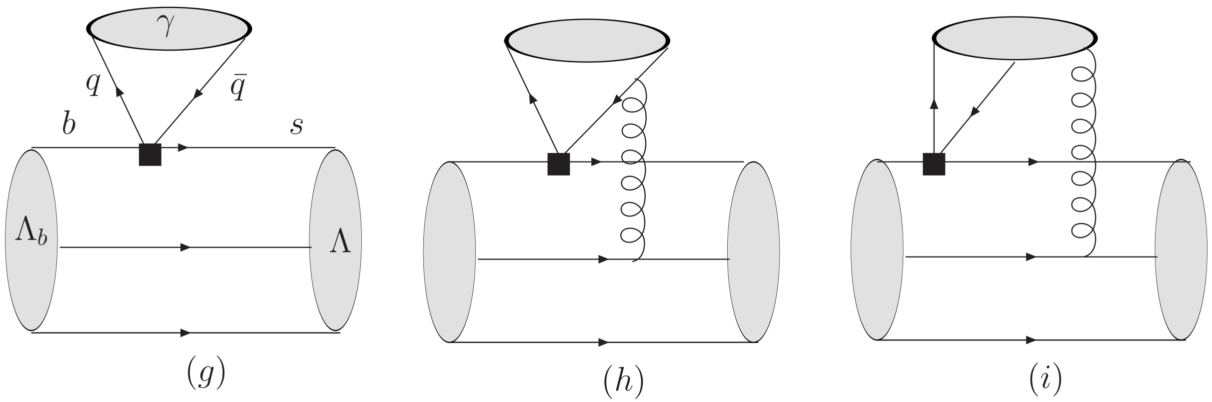
- Glounic penguin correction:



(d) (e) (f)

Nonlocal effects in $\Lambda_b \to \Lambda + \gamma$ decay

- Long-distance photon contribution [Braun, Ball, Khodjamirian, ...]:



- Photon distribution amplitudes [Ball/Braun/Kivel, 2003]:
Defined as the VEV of the non-local quark-gluon operator with light-cone seperation

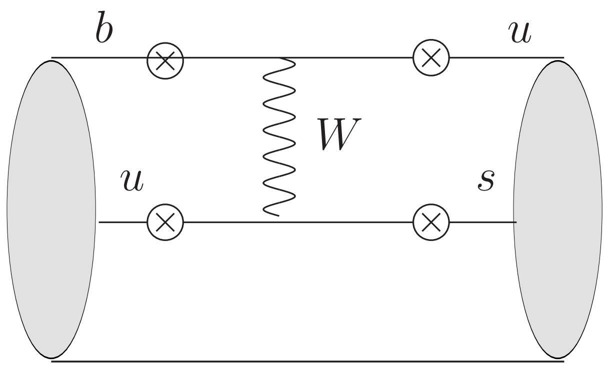
$$\langle 0|\bar{q}(z)\sigma_{\alpha\beta}[z,-z]_F q(-z)|0\rangle_F = e_q \chi \langle \bar{q}q\rangle \int_0^1 du F_{\alpha\beta}((1-2u)z)\phi_\gamma(u)\,,$$

χ—susceptibility of the quark condensate, and

$$\begin{aligned} F_{\mu\nu}(x) &= i\left[\epsilon_\mu(\lambda)q_\nu - \epsilon_\nu(\lambda)q_\mu\right]e^{-iq\cdot x}, \\ \phi_\gamma(u,\mu) &= 6u(1-u)\left[1+\sum_n a_{2n}(\mu)C_{2n}^{3/2}(2u-1)\right]. \end{aligned}$$

Nonlocal effects in $\Lambda_b \to \Lambda + \gamma$ decay

- Internal W-boson exchange diagrams(annihilation topology) [Mannel/Recksiegel, 97]:



(j)

- Collinear factorization breaks down potentially!
- Better understanding of Λ_b DAs in HQET!
- Small correction estimated in the soft-overlap approach with diquark model!

Rare semileptonic $\Lambda_b \to \Lambda + \ell^+\ell^-$ decay in LO

- Double differential decay rate (L, T, A_{FB}):

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

- In the factorization and large-energy limit [Feldmann/Yip 11.]:

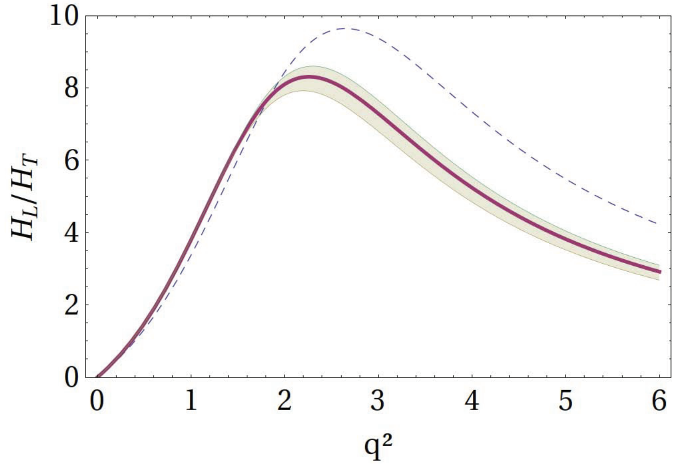
$$\begin{aligned}
H_T(q^2) &\propto q^2\,|F_1(P'\cdot v)|^2\left\{\left|C_9^{\rm eff}(q^2) + \frac{2m_b m_{\Lambda_b} C_7^{\rm eff}}{q^2}\right|^2 + |C_{10}|^2\right\},\\
H_A(q^2) &\propto q^2\,|F_1(P'\cdot v)|^2\,\mathrm{Re}\left[\left(C_9^{\rm eff}(q^2) + \frac{2m_b m_{\Lambda_b} C_7^{\rm eff}}{q^2}\right)^* C_{10}\right],\\
H_L(q^2) &\propto m_{\Lambda_b}^2\,|F_1(P'\cdot v)|^2\left\{\left|C_9^{\rm eff}(q^2) + \frac{2m_b}{m_{\Lambda_b}} C_7^{\rm eff}\right|^2 + |C_{10}|^2\right\}.
\end{aligned}$$

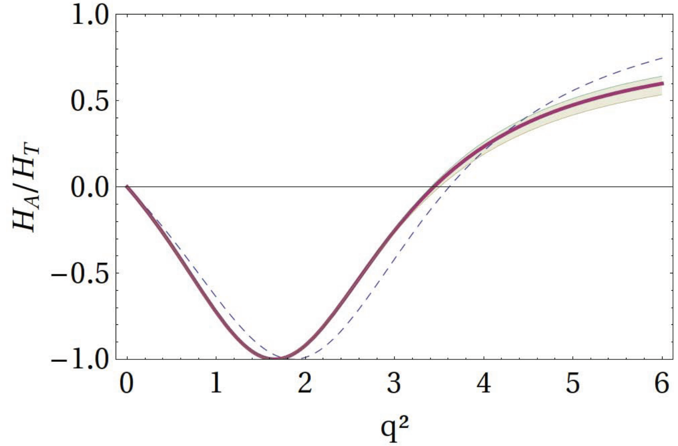
Rations independent on the hadronic dynamics in the first approximation!

Λ_b is the simplest bottom hadron in HQET!

Rare semileptonic $\Lambda_b \to \Lambda + \ell^+\ell^-$ decay in LO

- Ratios of observables H_L/H_T and H_A/H_T [Feldmann/Yip 11.]:





dashed line: symmetry limit,
solid line/grey error band: radiative corrections to FF ratios

- Zero-point of A_{FB} [Mannel, Y.M., 11, Feldmann/Yip 11]:

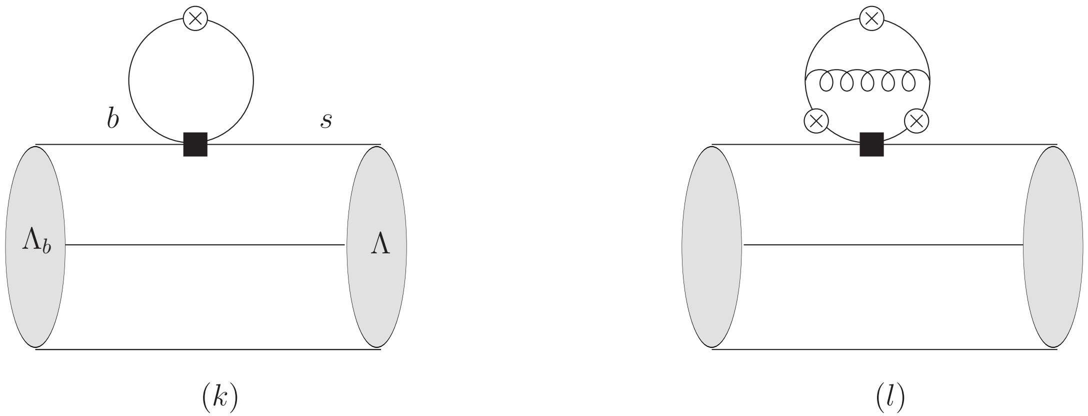
$$[2m_b\, m_{\Lambda_b}\mathrm{Re}(C_{7\gamma}^{eff}) + q^2\mathrm{Re}(C_9^{eff})] + O(\frac{\Lambda_{\mathrm{QCD}}}{m_b}) + O(\alpha_s) = 0.$$

The same as inclusive $b \to s\ell^+\ell^-$ and $B \to K^*\ell^+\ell^-$ decays!

$$q_0^2 \in [3.4, 3.8]\mathrm{GeV}^2.$$

Nonlocal effects in $\Lambda_b \to \Lambda + \ell^+ \ell^-$ decay

- More diagrams compared with $\Lambda_b \to \Lambda + \gamma$ decay :



- Breakdown of (light-cone)-OPE in the time-like region!
  Propagation of quark-loop in the hadronic medium instead of the vacuum!

- Developing models based on the hadronic dispersion relation!

Radiative $\Lambda_b \to \Lambda(1520)\gamma$ decay

- What is a $\Lambda(1520)$ state?

$\Lambda(1520)$ D_{03} $\quad I(J^P) = 0(\frac{3}{2}^-)$

Mass $m = 1519.5 \pm 1.0$ MeV [m]
Full width $\Gamma = 15.6 \pm 1.0$ MeV [m]
$p_{beam} = 0.39$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 82.8$ mb

Λ(1520) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	$45 \pm 1\%$	243
$\Sigma\pi$	$42 \pm 1\%$	268
$\Lambda\pi\pi$	$10 \pm 1\%$	259
$\Sigma\pi\pi$	$0.9 \pm 0.1\%$	169
$\Lambda\gamma$	$0.85 \pm 0.15\%$	350

- Why study $\Lambda_b \to \Lambda(1520)\gamma$ decay?
  Easier from experimental side due to two “tracks” in the final states!
  A serious challenge for theorists to make precise predictions!

Preliminary to Spin-$3/2$ particle:

- Description of a spin-$3/2$ particle (Rarita-Schwinger vector spinor):

$$\Psi_\mu(p,\lambda) = \sum_{\alpha\beta} \langle 1, \frac{1}{2}, \alpha\beta | \frac{3}{2} \lambda \rangle \epsilon_\mu(p,\alpha) u(p,\beta).$$

  8 of 16 components correspond to the physical spin-$3/2$ particle.

- Dirac equation of motion:

$$(\not p - m)\Psi_\mu(p,\lambda) = 0\,,$$

  and two constraints:

$$p^\mu \Psi_\mu(p,\lambda) = 0\,, \qquad \gamma^\mu \Psi_\mu(p,\lambda) = 0\,.$$

  The unwanted spin-$1/2$ components are removed.

- The polarization sum of Rarita-Schwinger spin vectors:

$$\Psi_\mu(p)\bar{\Psi}_\nu(p) = -(\not p + m)\left[g_{\mu\nu} - \frac{1}{3}\gamma_\mu\gamma_\nu - \frac{2}{3m^2}p_\mu p_\nu + \frac{\gamma_\nu p_\mu - \gamma_\mu p_\nu}{3m}\right].$$

Form factors of $\Lambda_b \to \Lambda(1520)$ decay

- In the heavy quark limit [Hiller et al, 07],

$$\langle \Lambda^*(P') | \bar{s}\, \Gamma\, b | \Lambda_b(P) \rangle = \bar{\Psi}_\mu(P') q^\mu \left(G_1 + G_2 \not{v} \right) \Gamma \Lambda_b(P) \,.$$

This relation holds in the whole kinematical region!

- In the HQET and SCET limit:

$$\langle \Lambda^*(P') | \bar{s}\, \Gamma\, b | \Lambda_b(P) \rangle = G_1(P' \cdot v) \bar{\Psi}_\mu(P') q^\mu \Gamma \Lambda_b(P) \,.$$

This relation is the same as $\Lambda_b \to \Lambda$ transitions!

- Physical interpretation [Brodsky/Lepage, 81]:
The total hadron helicity is conserved for a hard QCD process in the leading power approximation!

Radiative $\Lambda_b \to \Lambda(1520) + \gamma$ decay in LO

- Helicity amplitudes in the heavy-quark limit [Hiller et al, 07]:

$$\begin{aligned} \mathcal{A}_{+1/2} &\propto \tilde{C}_{7\gamma}^{eff} \frac{g_V + g_A}{2} G_1(P' \cdot v)\,, \\ \mathcal{A}_{-1/2} &\propto \tilde{C}_{7\gamma}^{eff} \frac{g_V - g_A}{2} G_1(P' \cdot v)\,, \\ \mathcal{A}_{+3/2} &\sim \mathcal{A}_{-3/2} \sim O(\Lambda_{QCD}/m_{\Lambda_b})\,. \end{aligned}$$

The subscript denotes the helicity of $\Lambda(1520)$ baryon.
Consistent with the helicity selection rule!

- Ratios of the helicity amplitudes in the heavy-quark limit:

$$\begin{aligned} R_1 &\equiv \frac{|\mathcal{A}_{+1/2}|^2}{|\mathcal{A}_{-1/2}|^2} = \frac{|\mathcal{A}_{+3/2}|^2}{|\mathcal{A}_{-3/2}|^2} = \frac{|g_V + g_A|^2}{|g_V - g_A|^2}\,, \\ R_2 &\equiv \frac{|\mathcal{A}_{\pm 3/2}|^2}{|\mathcal{A}_{\pm 1/2}|^2} \sim O(\Lambda_{QCD}^2/m_{\Lambda_b}^2)\,. \end{aligned}$$

R_1 sensitive to the helicity structure of the effective Hamiltonian.
R_2 as a benchmark for SCET. Constructing phenomenological observables!

Observables in radiative $\Lambda_b \to \Lambda(1520) + \gamma$ decay

- The proton asymmetry parameter [Legger/Schietinger 06, Hiller et al 07.]:

$$\frac{d\Gamma(\Lambda_b \to (\Lambda^* \to p\,K)\gamma)}{d\cos\theta_p} \propto 1 - \alpha_{p,3/2}\cos^2\theta_p\,, \qquad \alpha_{p,3/2} = \frac{R_2 - 1}{R_2 + \frac{1}{3}}\,.$$

θ_p: $\angle$(the proton momentum in the Λ^* rest frame, the Λ^* momentum in the Λ_b rest frame).

- The photon asymmetry parameter [Legger/Schietinger, 06, Hiller et al 07.]:

$$\frac{d\Gamma(\Lambda_b \to (\Lambda^* \to p\,K)\gamma)}{d\cos\theta_\gamma} \propto 1 - \alpha_{\gamma,3/2} P_{\Lambda_b}\cos\theta_\gamma\,, \qquad \alpha_{\gamma,3/2} = \frac{1 - R_2}{1 + R_2}\cdot\frac{2 g_V g_A}{g_V^2 + g_A^2}\,.$$

P_{Λ_b}—Λ_b polarization(= b-quark polarization in the HQET limit),
θ_γ: $\angle$(the photon momentum in the Λ_b rest frame, the spin of Λ_b baryon)

- Defining a new observable only dependent on the Wilson coefficients

$$\alpha_\gamma \equiv \frac{1}{2}\alpha_{\gamma,3/2}\left(1 - \frac{3}{\alpha_{p,3/2}}\right) = -\frac{2 g_V g_A}{g_V^2 + g_A^2}\,.$$

Actually photon polarization asymmetry [Legger/Schietinger 06.]!

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

- $\Lambda_b \to p$ transition form factors [Khodjamirian/Klein/Mannel/Y.M., 11]:

form factors	$\eta_{\Lambda_b}^{(\mathcal{A})}$	$\eta_{\Lambda_b}^{(\mathcal{P})}$
$f_1(0)$	$0.14^{+0.03}_{-0.03}$	$0.12^{+0.03}_{-0.04}$
$f_2(0)$	$-0.054^{+0.016}_{-0.013}$	$-0.047^{+0.015}_{-0.013}$

- Partially integrated width (FFs from QCD LCSR without extrapolation):

$$\begin{aligned}\Delta\zeta(0, q^2_{max}) &= \frac{1}{|V_{ub}|^2}\int_0^{q^2_{max}} dq^2 \, \frac{d\Gamma}{dq^2}(\Lambda_b \to p l \nu_l)\,, \\ &= 5.5^{+2.5}_{-2.0}\ \mathrm{ps}^{-1} (5.6^{+3.2}_{-2.9}\ \mathrm{ps}^{-1})\,.\end{aligned}$$

from the axial-vector (pseudoscalar) Λ_b-interpolating current.

IV. Summay

- Rare decays of b-baryons are indeed very interesting phenomenologically:

  Polarization asymmetry α of $\Lambda_b \to \Lambda + \gamma$,

  Ratios of helicity amplitudes (H_L/H_T and H_A/H_T) and A_{FB} in $\Lambda_b \to \Lambda + \ell^+\ell^-$,

  The proton and photon asymmetry parameters ($\alpha_{p,3/2}$, $\alpha_{\gamma,3/2}$) in $\Lambda_b \to \Lambda(1520) + \gamma$,

  Differential decay width of $\Lambda_b \to p\ell\nu_\ell$ (determination of $|V_{ub}|$).

- Further improvements:

  Improved estimates of heavy-to-light baryonic form factors,

  Better understanding of baryon distribution amplitudes,

  Higher-order and higher-power corrections,

  Calculations of non-local matrix elements,

  Better understanding of factorization and duality.