Beauty baryon decays: a theoretical overview

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- Semileptonic decay $\Lambda_b \to p \ell \nu_l$ and $|V_{ub}|$ determination.
- FCNC decay $\Lambda_b \to \Lambda \ell \ell$ and non-form-factor corrections.
- Charmless non-leptonic decays $\Lambda_b \to p \pi$ and $\Lambda_b \to p K$.

Why Beauty baryon decays?

- Great efforts on beauty meson decays already, no NP found yet.
- Conceptual aspects of factorization formalism not fully understood.
  Understanding QCD dynamics in beauty baryon decays.
- Beauty baryon decays provide non-trivial tests of CKM mechanism and more opportunities in searching BSM physics.
  - Allow for the study of spin correlations, extract the helicity structure of $\mathscr{H}_{eff}$.
  - 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 [Steven Blusk, Beauty 2014].

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

- Parameterizations of $\Lambda_b \to p$ matrix elements:

$$\langle N(P')|\bar{u}\,\gamma_\mu\, b|\Lambda_b(P)\rangle = \bar{N}(P')\left\{f_1(q^2)\,\gamma_\mu + i\frac{f_2(q^2)}{m_{\Lambda_b}}\,\sigma_{\mu\nu}q^\nu + \frac{f_3(q^2)}{m_{\Lambda_b}}\,q_\mu\right\}\Lambda_b(P),$$

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

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

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

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

  Simper expressions for angular distributions and for unitary bounds.

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

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

  implying the relations

$$f_1 = g_1 = F_1 + \frac{m_N}{m_{\Lambda_b}}\,F_2, \qquad f_2 = f_3 = g_2 = g_3 = F_2.$$

$\Lambda_b \to p$ form factors at large recoil

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

$$\begin{aligned} \langle N(P')|\bar{u}\,\Gamma\, b|\Lambda_b(P)\rangle &= \bar{N}(P')\,(F_1 + F_2 \not{v})\,\frac{\not{n}_+ \not{n}_-}{4}\,\Gamma\,\Lambda_b(P)\,, \\ &= F_1\,\bar{N}(P')\,\Gamma\,\Lambda_b(P)\,. \end{aligned}$$

  implying the relations

$$f_1 = g_1 = F_1\,, \qquad f_2 = f_3 = g_2 = g_3 = 0\,.$$

- Factorization formula of $\Lambda_b \to p$ form factor [Wei Wang, 2011]:

$$F_1 = \Phi_{\Lambda_b}(\omega_i) \otimes H(\omega_i, x_i) \otimes \Phi_N(x_i) + \mathcal{O}(\Lambda_{QCD}/E_N)\,.$$

  - Spectator interaction with two-gluon exchange is of leading power parametrically.
  - Leading power contribution calculable in QCDF and free of end-point divergence.
  - Symmetry relations still hold when including LO spectator interaction.
  - Soft contribution is power suppressed, but numerically dominant.

Calculational tools for beauty baryon form factors

- Lattice QCD [Detmold et al, 2012-2013]:
  - In principle: straight-forward.
  - In practice: difficult/costly to simulate fast light hadrons on a lattice.

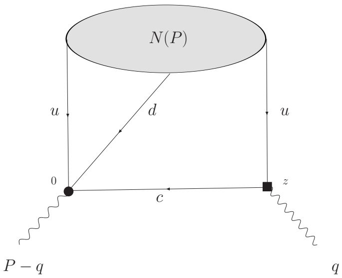
- Light-cone sum rules/SCET sum rules [Khodjamirian et al, 2011; Feldmann and Yip, 2011]:
  - OPE calculation of correlation function at partonic level.
  - Nonperturbative dynamics parameterized by light-cone distribution amplitudes.
  - Matching dispersion relation and OPE calculation with quark-hadron duality.

- QCD/SCET factorization:
  - Systemic analysis of symmetry breaking effect is still absent.
  - Important power corrections.

- TMD factorization [He et al, 2007; Lü et al, 2009]:
  - Importance of the Sudakov mechanism [Botts and Sterman, 1989].
  - Transverse momentum dependence becomes important at the end-points.

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

- Correlation function [Khodjamirian et al, 2011]:

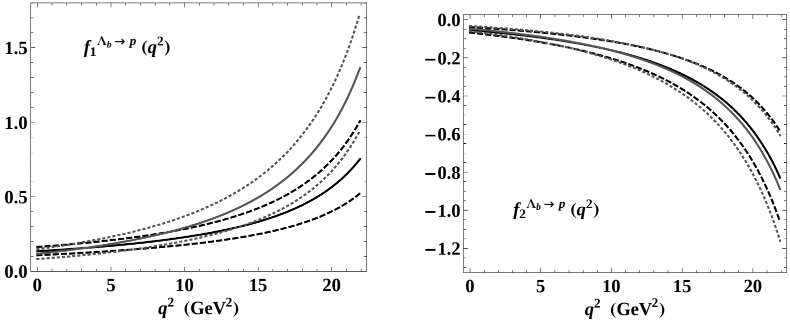


- Interpolating current of Λ_b baryon is not unique.
- Background pollution of negative-parity baryon in the dispersion relation, because fermion is not an eigenstate of parity transformation.
- 27 nucleon LCDAs enter the sum rules of form factors [Braun et al, 2000].

- How to avoid the background pollution?
  - Parity projector matrix $(1 \pm \not{v})/2$ for heavy-baryon sum rule [Bagan et al, 1993].
  - Choose "old-fashioned" correlation function and construct sum rules in the complex q_0-space [Jido et al, 1996].
  - Eliminate the negative-parity baryon contribution by combining sum rules obtained from different kinematical structures [Khodjamirian et al, 2011].

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

- Form factors from LCSR at $q^2 \leq 11\ \mathrm{GeV}^2$ and extrapolated to larger q^2 using the series-parametrization:



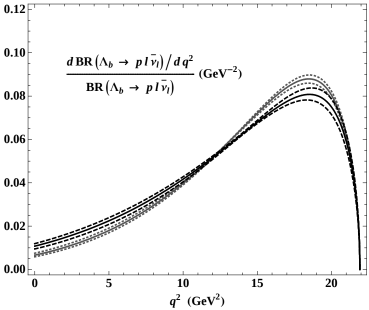
- Form factors calculated from LCSR insensitive to the interpolating current, once the negative baryon effect is included in the hadronic dispersion relation.

- HQET/SCET relations of form factors well reproduced by the LCSR predictions.

- Supersede the calculation from three-point QCD sum rules and earlier LCSR analysis of baryon form factors.

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

- Differential branching ratio [Khodjamirian et al, 2011]:



  - Enhancement in the large q^2 region due to the growth of the form factors and S-wave phase space factor.
  - Integrated BR: $\left(3.3^{+1.5}_{-1.2}\big|_{th.} \pm 0.1\big|_{exp.}\right) \times 10^{-4}$. Twice of BR$(B \to \pi\ell\nu_l)$.

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

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

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

  - Compare with $B \to \pi\ell\nu_l$ (NLO LCSR): $\Delta\zeta(0, 12\text{GeV}^2) = 4.59^{+1.00}_{-0.85}\ \text{ps}^{-1}$.
  - NLO LCSR of beauty baryon form factors can compete with $B \to \pi$ form factors in the determination of $|V_{ub}|$ [for NLO nucleon LCSR, see Anikin, Braun and Offen, 2013].

FCNC decay $\Lambda_b \to \Lambda \ell\ell$

- How to describe $b \to s\ell^+\ell^-$ transition?
  Effective weak Hamiltonian [Buchalla, Buras and Lautenbacher, 96].

- Semileptonic and magnetic operators:

$$O_{7\gamma} = -\frac{e}{16\pi^2}\bar{s}\sigma_{\mu\nu}(m_s L + m_b R)bF^{\mu\nu}, \qquad O_{8g} = -\frac{g_s m_b}{16\pi^2}\bar{s}_i\sigma_{\mu\nu}(1+\gamma_5)T^a_{ij}b_j G^{a\mu\nu},$$
$$O_{9,10} = \frac{\alpha_{em}}{4\pi}\left(\bar{s}_L\gamma_\rho b_L\right)\left(\bar{l}l\right)_{V,A}.$$

- Four-quark operators:

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

- Naive factorization $\Longrightarrow$ heavy-to-light form factors:

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

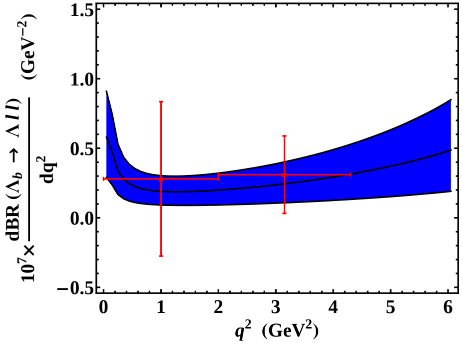
FCNC decay $\Lambda_b \to \Lambda \ell\ell$

- $\Lambda_b \to \Lambda$ form factors [YMW, Li and Lü 2009; Feldmann and Yip 2011; Detmold et al, 2013]:

form factors	QCD LCSR	SCET LCSR	LQCD $\oplus$ dipole model
$f_1(0)$	0.15	0.38	0.31

  - In the SU(3) flavor symmetry limit, $f_1^{\Lambda_b \to \Lambda}(0) = f_1^{\Lambda_b \to p}(0) = 0.14$.
  - LCSR calculation of $\Lambda_b \to p$ form factor in agreement with the data of $\Lambda_b \to p\pi$ decay rate, in the factorization limit.

- Differential branching ratio [YMW, Li and Lü, 2009; LHCb, 2013]:



  - Experimental data from LHCb rather uncertain, CDF 2011 data are more uncertain.
  - Precision measurement will be crucial to understand the QCD dynamics.
  - Theory predictions can be improved due to the recently known subleading corrections to Λ-baryon LCDAs [Liu, Cui and Huang, 2014].

FCNC decay $\Lambda_b \to \Lambda \ell\ell$

- Angular distribution:

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

- Angular functions in the factorization and large energy limit:

$$H_T(q^2) \propto q^2\,|F_1(q^2)|^2 \left\{ \left| C_9^{\rm eff}(q^2) + \frac{2m_b m_{\Lambda_b}}{q^2}\, C_7^{\rm eff} \right|^2 + |C_{10}|^2 \right\},$$

$$H_A(q^2) \propto q^2\,|F_1(q^2)|^2\, {\rm Re}\left[\left(C_9^{\rm eff}(q^2) + \frac{2m_b m_{\Lambda_b}}{q^2}\, C_7^{\rm eff} \right)^* C_{10} \right],$$

$$H_L(q^2) \propto m_{\Lambda_b}^2\,|F_1(q^2)|^2 \left\{ \left| C_9^{\rm eff}(q^2) + \frac{2m_b}{m_{\Lambda_b}}\, C_7^{\rm eff} \right|^2 + |C_{10}|^2 \right\}.$$

  - Ratios of H_i functions independent of form factors in the heavy quark limit.
  - Crossing-point of forward-backward asymmetry determined by [Mannel and YMW, 2011; Feldmann and Yip 2011]:

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

Non-form-factor corrections

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

- Nonlocal hadronic matrix element [See also the Tuesday's talk by Alexander Khodjamirian]:

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

- QED corrections to the hadronic operators $\not\Rightarrow$ the form factors.

  (a) Hard spectator interactions $\not\Rightarrow$ local operators at the m_W scale.

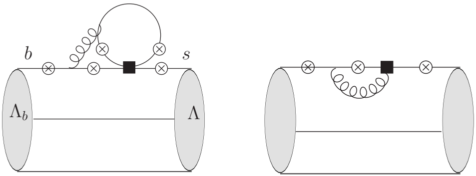
  (b) Soft gluon radiations generate non-local operators.

  (c) Strong phases of the matrix elements.

- Relatively simpler QCD dynamics at larger hadronic recoil.

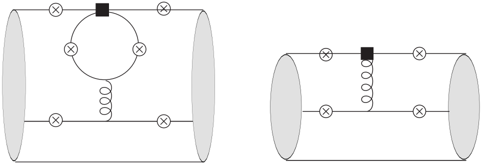
FCNC decay $\Lambda_b \to \Lambda \ell\ell$

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



  - Sizeable two-loop hard vertex corrections due to $\ln(q^2/m_B^2)$ enhancement.

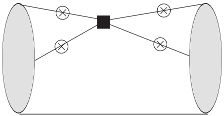
- Hard spectator interactions:

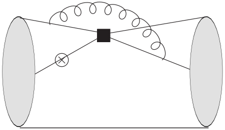


  - Cannot be computed with QCD factorization approach.
  - Can be computed from SCET LCSR with Λ_b LCDAs.
    [Ball, Braun, and Gardi, 2008; Bell et al, 2013]

FCNC decay $\Lambda_b \to \Lambda \ell\ell$

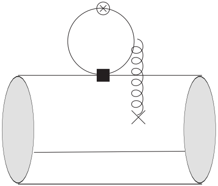
- Weak annihilations:

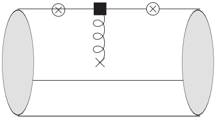




  - Again cannot be computed with QCD factorization approach.
  - Small correction estimated in the soft-overlap approach with diquark model [Mannel and Recksiegel, 1997].

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





  - Soft gluon radiation is power suppressed, but enhanced by the photon pole.

Charmless non-leptonic decays $\Lambda_b \to p\,\pi$ and $\Lambda_b \to p\,K$

- Nontrivial tests of CP violation mechanism and more complicated QCD dynamics.
- Only computed in TMD factorization framework, about 200 Feynman diagrams.
- Sizeable nonfactorizable contribution which cannot be reduced to baryon form factors.
- Decay rates and CP asymmetries [Lü et al, 2008; CDF, 2009, 2014; LHCb, 2012]:

	pQCD	Exp.
$\mathrm{BR}(\Lambda_b \to p\pi)$	$5.21^{+2.42+0.30+0.42}_{-1.89-0.10-0.37} \times 10^{-6}$	$3.5 \pm 0.6 \pm 0.9 \times 10^{-6}$
$\mathrm{BR}(\Lambda_b \to pK)$	$2.02^{+0.78+0.55+0.10}_{-0.86-0.90-0.05} \times 10^{-6}$	$5.6 \pm 0.8 \pm 1.5 \times 10^{-6}$
$\frac{\mathrm{BR}(\Lambda_b \to p\pi)}{\mathrm{BR}(\Lambda_b \to pK)}$	$2.6^{+2.0}_{-0.5}$	$0.66 \pm 0.14 \pm 0.08$ $0.86 \pm 0.08 \pm 0.05$
$A_{\mathrm{CP}}(\Lambda_b \to p\pi)$	$-0.31^{+0.28+0.32+0.01}_{-0.00-0.00-0.01}$	$-0.03 \pm 0.17 \pm 0.05$ $0.06 \pm 0.07 \pm 0.03$
$A_{\mathrm{CP}}(\Lambda_b \to pK)$	$-0.05^{+0.26+0.03+0.01}_{-0.00-0.05-0.00}$	$-0.37 \pm 0.17 \pm 0.03$ $-0.10 \pm 0.08 \pm 0.04$

Conclusions

- Beauty baryon decays can compete with B-meson decays in many aspects and may shed light on BSM physics due to the spin of beauty baryon.

- $|V_{ub}|$ determination from semileptonic decay $\Lambda_b \to p \ell \nu_l$ is promising, due to the novel approach to remove the negative-parity baryon effect.

- FCNC decay $\Lambda_b \to \Lambda \ell\ell$ is of great interest theoretically.
  - Simpler than $B \to K^* \ell\ell$ in the factorization and heavy quark limit.
  - Soft contribution to $\Lambda_b \to \Lambda$ form factor is of subleading power parametrically, but is sizeable/dominant numerically.
  - Non-form-factor corrections to $\Lambda_b \to \Lambda \ell\ell$ are still absent (under study).

- Hadronic decays $\Lambda_b \to p\,\pi$ and $\Lambda_b \to p\,K$ involve complicated QCD dynamics.
  - Some tension concerning the branching ratios, does not appear in B-meson decays.
  - More precision measurements and calculations in demand.