Beauty baryon decays: a theoretical overview

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Abstract. I overview the theoretical status and recent progress on the calculations of beauty baryon decays focusing on the QCD aspects of exclusive semi-leptonic $\Lambda_b \to p\,\ell\nu$ decay at large recoil and theoretical challenges of radiative and electro-weak penguin decays $\Lambda_b \to \Lambda\,\gamma, \Lambda\,\ell^+\ell^-$.

1. Introduction

Investigating beauty baryon decays has been initiated in the early days of heavy-quark effective theory (HQET) for the purpose of understanding the general properties of heavy-quark expansion, determining the CKM matrix elements and shedding light on physics beyond the Standard Model (BSM). In contrast to the B-meson decays, the helicity structure of weak effective Hamiltonian can be extracted uniquely in bottom baryon decays with the aid of baryon polarization asymmetry. On the theoretical side, QCD dynamics of a certain beauty baryon (i.e., Λ_b) is even simper than that of B-meson in the heavy quark limit. It is therefore natural to anticipate that beauty baryon decays will be helpful to sharpen our knowledge of the origin of CP violation and of the strong interaction dynamics, in particular taking into account of the fact that no evident BSM signals have been detected yet in the intensive studies of B-meson decays.

The aim of this brief review is to report the current status of theoretical calculations for heavy-to-light form factors of semi-leptonic $\Lambda_b \to p\ell\nu$ decay, and to elaborate the primary challenges of factorizing the QCD dynamics for radiative and electro-weak penguin $\Lambda_b \to \Lambda\,\gamma, \Lambda\,\ell^+\ell^-$ decays.

2. Heavy-to-light $\Lambda_b \to p$ form factors at large recoil

Precision determination of the CKM matrix element $|V_{ub}|$ is among the central topics of heavy quark physics. The longstanding tension (approximately $3\,\sigma$) between exclusive and inclusive extractions has triggered enormous attentions for both new-physics (NP) believers and QCD oriented theorists. Measurement of seme-leptonic $\Lambda_b \to p\ell\nu$ decay spectrum can be used to determine $|V_{ub}|$ complementary to the B-meson decays, provided that $\Lambda_b \to p$ form factors can be computed reliably on the theoretical side.

In general, one can parameterize the (axial)-vector current induced $\Lambda_b \to p$ matrix element in the form

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

$$\langle N(P')|\bar{u}\,\gamma_\mu\gamma_5\,b|\Lambda_b(P)\rangle \;=\; \bar{N}(P')\Big\{g_1(q^2)\,\gamma_\mu + i\frac{g_2(q^2)}{m_{\Lambda_b}}\,\sigma_{\mu\nu}q^\nu + \frac{g_3(q^2)}{m_{\Lambda_b}}\,q_\mu\Big\}\gamma_5\Lambda_b(P)\,. \tag{1}$$

In the HQET limit, two form factors are sufficient to describe the QCD dynamics of hadronic matrix elements [1]

$$\langle N(P')|\bar{u}\,\Gamma\,b|\Lambda_b(P)\rangle = \bar{N}(P')\left[F_1(q^2) + F_2(q^2)\;\not{v}\right]\Gamma\Lambda_b(P)\,, \tag{2}$$

due to the eikonal interaction of soft gluon with heavy quark at leading power. At large hadronic recoil, the fast-moving active u-quark can be well approximated by a collinear filed

$$\xi_c(x) = \frac{\not{n}_+\;\not{n}_-}{4}\,u(x)\,, \tag{3}$$

and then one can easily derive [2, 3]

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

where only the soft gluon interaction with the collinear u-quark is taken into account. A remarkable property of $\Lambda_b \to p$ transition matrix elements is that the QCD dynamics can be parameterized by a universal form factor in the combined heavy-quark and large-recoil limits. It needs to point out that the soft-gluon exchange effect, or the so-called "Feynman mechanism", only contributes to $\Lambda_b \to p$ form factors $f_1(q^2)$ and $g_1(q^2)$ at sub-leading power, and the spectator interaction induced by two-collinear-gluon exchange is of leading power parametrically [4]. Such observations are quite distinct from that of $B \to \pi$ transition form factors at large recoil where both soft-gluon exchange and hard-scattering effect contribute at leading power. The formally leading-power spectator interaction for $\Lambda_b \to p$ form factors is however much suppressed numerically [5, 6, 7], due to the large energy of nucleon (around 2.8 GeV) to be distributed among three valence quarks.

In addition to the fascinating progresses of understanding the factorization of heavy-to-light baryonic form factors, non-perturbative calculations of $\Lambda_b \to p$ form factors are also advanced by a systemic improvement of applying QCD light-cone sum rules (LCSRs) to study the baryon properties [7]. A formidable problem of constructing baryonic sum rule lies in the background pollution of dispersion relation from the unwanted baryons with opposite parity, which cannot be argued to be suppressed after the Borel transformation due to the small mass spitting between a parity doublet. The innovations of [7] consist in the elimination of background contamination by combining the sum rules from different kinematical structures in the Lorenz decomposition of correlation function, and the insensitivity of resulting sum rules to the choices of interpolating currents for a given baryon.

Following the strategy of determining the CKM matrix element $|V_{ub}|$ in semi-leptonic $B \to \pi\ell\nu$ decay [8], one can define a similar quantity

$$\Delta\zeta(0, q^2_{max}) \;=\; \frac{1}{|V_{ub}|^2}\int_0^{q^2_{max}} dq^2\,\frac{d\Gamma}{dq^2}(\Lambda_b \to p l \nu_l) \tag{5}$$

with the upper bound constrained by the applicability of LCSRs for $\Lambda_b \to p$ form factors. The prediction of $\Delta\zeta(0, 11\mathrm{GeV}^2)$ from leading-order sum rule analysis with the axial-vector interpolating current of Λ_b baryon is given by

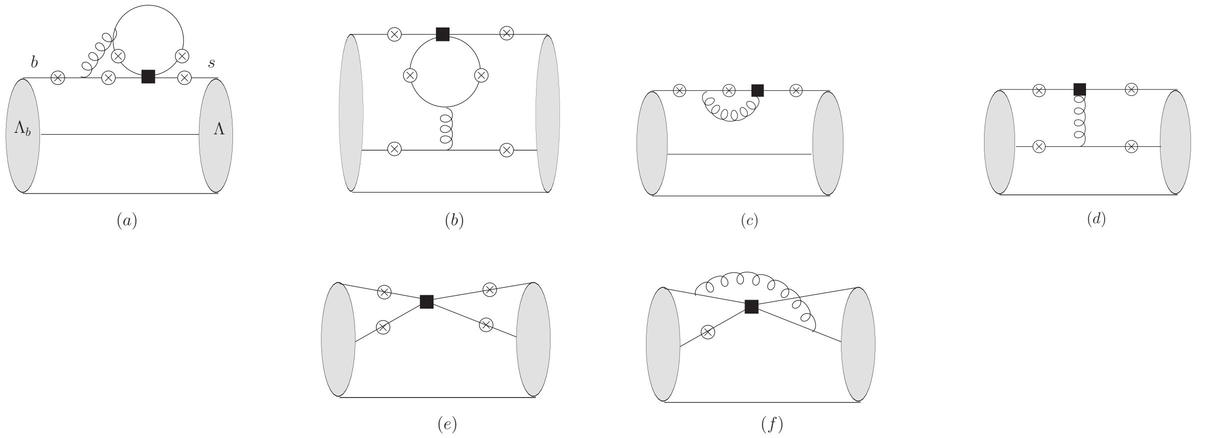
$$\Delta\zeta(0, 11\mathrm{GeV}^2) \;=\; 5.5^{+2.5}_{-2.0}\ \mathrm{ps}^{-1}\,, \tag{6}$$

the accuracy of which is not comparable with that for $B \to \pi\ell\nu$ including NLO QCD correction. Nevertheless, it is expected that much higher accuracy can be achieved for QCD improved LCSRs of $\Lambda_b \to p$ form factors, promoting $\Lambda_b \to p\ell\nu$ as another golden channel to extract the matrix element $|V_{ub}|$ exclusively.

3. FCNC $\Lambda_b \to \Lambda\,\gamma$ and $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decays in QCD

Flavor-changing-neutral-current (FCNC) $b \to s\ell\ell$ induced processes are believed to be among the most sensitive probes of BSM physics. Thanks to a wealth of data accumulated at LHC, measuring the full angular distributions of $B \to K^*\,\ell^+\ell^-$ is already accessible under the push of NP believers. Some deviations from the SM "expectations" revealed by LHCb measurements, in particular the so-called P_5' anomaly, have trigged hot discussions and debates in the community, stimulating various NP-based explanations. It is certainly of great fun to claim more and more puzzles in precision b-quark physics, however, we need to understand in the first place whether we miss some important pieces in the SM calculations for such sophisticated FCNC processes. Apart from many other conceptual issues, the breakdown of operator-product-expansion (OPE) above charm-quark threshold, typically $6 \sim 7\,\mathrm{GeV}^2$, will contaminate the SM calculations within the QCD factorization framework (see [9, 10] for more details).

As discussed in section 2, the QCD dynamics of $\Lambda_b \to \Lambda$ matrix elements can be greatly reduced in the heavy-quark and large-recoil limits. Non-perturbative calculations of $\Lambda_b \to \Lambda$ form factors have been performed extensively at large recoil using LCSRs with Λ-baryon distribution amplitudes (DAs) [11, 12, 13] and Λ_b-baryon DAs [3, 6], and carried out at low recoil with lattice QCD simulation [14]. PQCD calculation of $\Lambda_b \to \Lambda$ form factors [15] based on transverse-momentum-dependent (TMD) factorization theorem implies that the parametrically leading-power hard-scattering contribution is strongly suppressed at finite b-quark mass. In the factorization limit, the calculated di-lepton invariant mass (q^2) spectrum of $\Lambda_b \to \Lambda\,\ell^+\ell^-$ at small q^2 [11] can accommodate the binned data from LHCb [16] within sizable uncertainties.



(a) (b) (c) (d) (e) (f)

Figure 1. NLO QCD corrections to the $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decay matrix elements. Black squares indicate proper insertions of four-quark operators and gluonic penguin operator. Crossed circles denote possible virtual-photon emissions.

Anticipating the higher statistics of LHC RunII data, theoretical calculations of $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decays should be improved with the aid of QCD-based approaches to meet the experimental challenge. Some typical next-to-leading-order (NLO) diagrams contributed to the $\Lambda_b \to \Lambda\,\ell^+\ell^-$ transition matrix elements are displayed in figure 1. While the vertex corrections shown in the diagrams (a) and(c) can still be expressed by $\Lambda_b \to \Lambda$ form factors and perturbatively calculable hard coefficients as that of $B \to K^*\,\ell^+\ell^-$, the factorization properties of spectator-interaction and weak-annihilation induced contributions displayed in the diagrams (b) and(d) are drastically distinct from the mesonic counterpart. This can be understood from the fact that one of the two light valence quarks inside Λ_b-baryon does not participate in the hard scattering process, and the not-light-like separation of this spectator quark and heavy b-quark defines a general Bethe-Salpeter wave functions of Λ_b-baryon. We are therefore not allowed to construct QCD factorization formula to compute one-gluon-exchange spectator interaction and weak annihilation. In this respect, one can resort to LCSRs approach by constructing proper correlation functions encoding the information of non-local $\Lambda_b \to \Lambda\, \ell^+ \ell^-$ matrix elements that we are interested in.

Exploring the physics embedded in $\Lambda_b \to \Lambda\, \ell^+ \ell^-$ decay is also pursued intensively making use of the full angular distributions and baryon polarization information in the SM [17, 18] and beyond [19, 20, 21]. As a by-product, radiative penguin decay $\Lambda_b \to \Lambda\, \gamma$ can be computed straightforwardly by setting the invariant mass of lepton pair to zero, provided that the long-distance photon effect is subdominant numerically. This channel is however of great value on the phenomenological side, since the Λ-baryon polarization asymmetry can be used to determine the chirality structure of electro-magnetic penguin operator O_7 uniquely at leading power [22].

4. Conclusions

To summarize, exclusive Λ_b-baryon decays can provide valuable information on the precision determination of CKM matrix elements, competitive with that from B-meson decays potentially, and serve as powerful probes in pursuit of BSM physics on account of the reduced QCD dynamics in the joint heavy-quark and large-recoil limits. On the experimental side, there has been considerable progresses on the measurements of beauty baryon decays at both LHC and Tevatron. We have good reasonings for a very bright future of beauty-baryon physics which opens a new window to a more fundamental theory attributed to the additional spin information.

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