Probing for new physics in polarized Λ_b decays at the Z pole

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Polarized $\Lambda_b \to \Lambda\gamma$ decays at the Z pole are shown to be well suited for probing a large variety of new physics effects. A new observable is proposed, the angular asymmetry between the Λ_b spin and photon momentum, which is sensitive to the relative strengths of the opposite chirality and standard model chirality $b\to s\gamma$ dipole operators. Comparison with the Λ decay polarization asymmetry and with the Λ_b polarization extracted from semileptonic decays allows important tests of the $V-A$ structure of the standard model. The modifications of the rates and angular asymmetries which arise at next-to-leading order are discussed. The measurements for $\Lambda_b \to \Lambda\gamma$ and the CP conjugate mode, with branching ratios of a few times 10^{-5}, are shown to be sensitive to nonstandard sources of CP violation in the $\Lambda_b \to \Lambda\gamma$ matrix element. Form factor relations for heavy-to-light baryon decays are derived in the large energy limit, which are of general interest.

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I. INTRODUCTION

Flavor-changing neutral current (FCNC) b decays provide important tests of the standard model (SM) at the quantum level and, at the same time, place severe constraints on new physics extensions. In this paper, we investigate the possibility of searching for new physics in radiative FCNC decays induced by $b\to s\gamma$ transitions. The relevant low-energy effective Hamiltonian at leading order (LO) in α_s is given by [1]

$$\mathcal{H}_{\rm eff} = -\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} [C_7 Q_7 + C_7' Q_7'], \tag{1}$$

with the electromagnetic dipole operators Q_7, Q_7' written as

$$Q_7 = \frac{e}{8\pi^2} m_b \bar{s} \sigma_{\mu\nu} R b F^{\mu\nu}, \quad Q_7' = \frac{e}{8\pi^2} m_b \bar{s} \sigma_{\mu\nu} L b F^{\mu\nu}. \tag{2}$$

Here $L\equiv 1-\gamma_5$ and $R\equiv 1+\gamma_5$ are proportional to the left- and right-handed projectors. The renormalization scale dependence of the Wilson coefficients C_i and operator matrix elements is understood. In the SM, the contribution to Q_7' is suppressed with respect to the one to Q_7 by the small mass insertion along the external s-quark line and is usually neglected, i.e., $C'_{7\rm SM} = m_s/m_b C_{7\rm SM}$. However, in many extensions of the SM, new contributions to C_7' are not necessarily suppressed and can be comparable to $C_{7\rm SM}$ since the requisite helicity-flip is along a massive fermion propagator inside the loop. Examples are left-right symmetric models, supersymmetric models with large left-right squark flavor mixing, and models containing new vectorlike quarks.

The branching fraction for inclusive $B\to X_s\gamma$ decays has been measured [2–4] and is consistent with the SM prediction, e.g., [5–8]. The measurement constrains the combination $\mathcal{B}(B\to X_s\gamma) \propto |C_7|^2 + |C_7'|^2 \simeq |C_{7\rm SM}|^2$, which is a circle in the C_7-C_7' plane. Thus, complementary data are needed for a model-independent determination of C_7 and C_7' separately. One suggestion has been to probe the photon helicity via the mixing induced CP asymmetry in neutral $B_{(d,s)} \to M\gamma$ decays, where $M=\omega,\rho,K^*,\phi$ [9]. Other methods have aimed at analyzing the angular distribution of the subsequent decay products. These include correlation studies in the dilepton mode $B\to K^*(\to K\pi)\gamma^*(\to l^+l^-)$ in the low dilepton mass region [10,11], and radiative B decays into excited kaons yielding $K\pi\pi^0\gamma$ final states [12].

We propose here to probe the ratio C_7'/C_7 in polarized $\Lambda_b \to \Lambda\gamma$ decays by measuring the angular asymmetry between the Λ_b spin and the momentum of the photon (or Λ). The longitudinal polarization of Λ_b baryons produced in Z decays has been measured in semileptonic $\Lambda_b \to \Lambda_c l \nu_l X$ decays and is found to retain a sizable fraction of the parent b-quark polarization [13–16]. In addition to the angular asymmetry, which explicitly makes use of the polarization feature of the Λ_b baryons, a second "helicity" observable can be used to probe the quark chiralities: the Λ polarization variable associated with the secondary decays $\Lambda \to p\pi^-$, first proposed in [17] for unpolarized $\Lambda_b \to \Lambda\gamma$ decays. Because these two observables are independent, as we will show, their measurements allow consistency checks and their combined analysis greatly increases the new physics reach. We rederive the Λ decay polarization asymmetry and find an expression which differs from previous ones obtained in the literature [17–19].

From a general Lorenz decomposition it follows that only a single overall hadronic form factor $F(0)$ enters the $\Lambda_b \to \Lambda\gamma$ amplitude, and therefore it cancels in the forward-backward asymmetries. Based on studies of $\Lambda_b \to \Lambda\gamma$ [17] and $B\to K^*\gamma$ decays [20–25], corrections of at most a few percent can be expected from long-distance interactions so there is very little hadronic uncertainty in the SM prediction for the helicity observables.

Heavy quark effective theory (HQET) spin symmetry arguments applied to heavy-to-light baryon form factors [17,26] relate the overall form factor $F(0)$ entering the $\Lambda_b \to \Lambda\gamma$ matrix element to two universal form factors $F_1(0)$ and $F_2(0)$. Consistent estimates for $F_1(0)$ have been obtained from data on semileptonic Λ_c decays [17] and from QCD sum rules [18]. We find that a new application of large energy effective theory (LEET) [27] to heavy-to-light baryon form factors fixes the ratio $F_2(0)/F_1(0)$, which allows us to use the information on $F_1(0)$ to estimate $F(0)$ and therefore the total $\Lambda_b \to \Lambda\gamma$ rate.

At next-to-leading order (NLO) in α_s, direct CP violation can be probed in $b \to s\gamma$ mediated decays. We estimate the dominant NLO effects in the $\Lambda_b \to \Lambda\gamma$ matrix element and allow for nonstandard CP violation in contributions to both the SM and opposite chirality dipole operators. Rates and helicity observables for the untagged (CP-averaged) and flavor tagged cases are worked out. Experimental discrimination between the CP conjugate decays is easy because they are self-tagging.

It should be stressed that while other proposals for probing the ratio C_7'/C_7 [9–12,17] can be carried out at upgraded e^+e^- B factories or at hadron colliders, the angular asymmetry observable using initial-state polarization is unique to a high luminosity e^+e^- machine running at the Z pole. Proposals exist for a so-called GigaZ option with $2\times 10^9 Z$ bosons per year [28,29], corresponding to approximately 3.5×10^7 b-flavored baryon decays. For recent discussions of the b-physics potential at a Z factory, see [30]. With a branching fraction estimate $\mathcal{B}(\Lambda_b \to \Lambda\gamma) \simeq 7.5\times 10^{-5}$, we expect approximately 2600 exclusive $\Lambda_b \to \Lambda\gamma$ decays per year.

This paper is organized as follows. In Sec. II, we discuss form-factor relations for $\Lambda_b \to \Lambda$ transitions following from HQET/LEET. In Sec. III, we define the two angular asymmetry observables for $\Lambda_b \to \Lambda\gamma$ and study their sensitivities, separately and combined, to the ratio C_7'/C_7. Section IV is devoted to a discussion of next-to-leading order effects including CP violation. In Sec. V, we conclude and give a brief outlook on further opportunities in b physics at hadron colliders and at the GigaZ.

II. FORM-FACTOR PRELIMINARIES

The most general decomposition of $\Lambda_b \to \Lambda$ matrix elements for the dipole transition into an on-shell photon is given by

$$\langle \Lambda(p',s')|\bar{s}\sigma_{\mu\nu}(1\pm\gamma_5)q^\nu b|\Lambda_b(p,s)\rangle = F(0)\bar{u}_\Lambda \sigma_{\mu\nu}(1\pm\gamma_5)q^\nu u_{\Lambda_b}, \tag{3}$$

where $p^{(\prime)}$ and $s^{(\prime)}$ denote the baryon momenta and spins, respectively, $q=p-p'$, and u_Λ, u_{Λ_b} are the baryon spinors. We stress that only one overall form factor $F(0)$ enters [this follows from the identity $\sigma^{\mu\nu}\gamma_5 = (i/2)\epsilon^{\mu\nu\rho\sigma}\sigma_{\rho\sigma}$], so that the different helicities do not mix.

In the following, we work out form-factor relations for heavy-to-light baryon decays which follow from certain limits. This provides a realization of the physical picture of helicity conservation, and allows us to estimate $F(0)$ and therefore the total $\Lambda_b \to \Lambda\gamma$ rate in terms of existing form-factor calculations and measurements.

A. The large energy and heavy quark limits

In the decays under consideration a baryon containing a heavy quark decays into a light baryon with small $q^2 \ll m_{\Lambda_b}^2$. In these heavy-to-light decays the energy E of the light baryon $E=(m_{\Lambda_b}^2 + m_\Lambda^2 - q^2)/2m_{\Lambda_b}$ in the parent baryon's rest frame is large compared to the strong interaction scale and the light quark or baryon masses. This is precisely the kinematical situation for which one can consider the large energy effective theory [27], originally introduced in Ref. [31]. It arises from a systematic $1/E$ expansion of the QCD Lagrangian of the final active light quark. Neglecting hard interactions with the spectators and other soft degrees of freedom, the momenta of the final active quark, $p'_{\rm quark}$, and the final hadron, p', are equal modulo a small residual momentum $k \simeq \Lambda_{\rm QCD}$: $p'_{{\rm quark}\,\mu} = E n_\mu + k_\mu$, where $n \equiv p'/E$. At leading order in LEET, n is lightlike $(n^2=0)$, i.e., terms of order m_Λ^2/E^2 are neglected, and the final LEET quark is on-shell with $\not{n} s = 0$. For details, we refer the reader to [27].

The assumption of soft contribution dominance in LEET is consistent with an HQET description of the initial decaying b quark. Symmetries which arise in the combined LEET/HQET limit imply relations among form factors for heavy-to-light decays. They will receive corrections at order $1/m_b$, $1/E$, and α_s. For B-meson decays into a light pseudoscalar or vector meson, the leading-order form-factor relations have been worked out in [27]. Perturbative $O(\alpha_s)$ vertex and hard scattering corrections have been found to typically lie below the 10% level [32]. The soft parts of the form-factor relations, found in [27], have been confirmed in "collinear-soft" effective theory [33].

The $\alpha_s(\sqrt{m_b\Lambda_{\rm QCD}})$ suppression of hard scattering form-factor contributions in heavy-to-light B-meson decays [32] supports the starting assumption of soft dominance and the applicability of HQET in this regime. We will assume that this suppression also holds for heavy-to-light b-baryon decays so that a perturbative expansion in $1/m_b$, $1/E$, and α_s is again sensible. A rigorous treatment of higher-order corrections to heavy-to-light baryon form factors is beyond the scope of this paper and is left for future work. We will, however, briefly comment on $1/m_b$ corrections below.

B. LEET/HQET form-factor relations

Heavy quark spin symmetry implies the following parametrization of hadronic matrix elements [26] in the $m_b \to \infty$ limit:

$$\langle \Lambda(p',s')|\bar{s}\Gamma b|\Lambda_b(p,s)\rangle = \bar{u}_\Lambda [F_1(q^2) + \not{v} F_2(q^2)]\Gamma u_{\Lambda_b}, \tag{4}$$

which involves only two universal form factors for any Dirac structure Γ. This yields, for example, for $\Gamma=\gamma_\mu$,

$$\langle \Lambda(p',s')|\bar{s}\gamma_\mu b|\Lambda_b(p,s)\rangle=\bar{u}_\Lambda\{[F_1(q^2)-F_2(q^2)]\gamma_\mu + 2F_2(q^2)v_\mu\}u_{\Lambda_b}, \qquad (5)$$

where $v=p/m_{\Lambda_b}$ denotes the velocity of the heavy baryon.

Comparing Eq. (3) with Eq. (4) for the dipole transition and using the HQET relation $\not{v}b=b$ yields

$$F(0)=F_1(0)+\frac{m_\Lambda}{m_{\Lambda_b}}F_2(0). \qquad (6)$$

It is apparent from Eq. (4) that the helicity of the Λ_b is determined by the helicity of the heavy b quark, and that the light degrees of freedom in the Λ_b are in a spin-0 state. This is what one would expect in the naive valence quark picture of hadrons, or the diquark picture of baryons. However, in general the correspondence between the helicity of the active light quark and the helicity of the light baryon is broken by the ratio F_2/F_1.

LEET allows us to relate the two form factors F_1 and F_2. Contracting the 4-vector n_μ with the matrix element over the vector current given in Eq. (5) and using $\not{n}s=0, \quad v\cdot n=1$, we derive at lowest order in LEET/HQET

$$F_2(E,m_b)/F_1(E,m_b)=-\frac{m_\Lambda}{2E}, \qquad (7)$$

where the dependence on the expansion parameters has been made explicit. This is in concordance with the physical picture for heavy-to-light B-meson decays recently obtained in Ref. [34]: The helicity of the active light quark is "inherited" by the final hadron. Corrections to this are proportional to light masses and are suppressed by $1/E$. We estimate their size to be less than $m_\Lambda/m_{\Lambda_b}\sim 20\%$. Note that Eq. (7) holds at lowest order in collinear-soft effective theory [33].

Heavy quark relations like Eq. (4) receive $1/m_b$ corrections, which are small near zero recoil $q^2\approx q^2_{\max}$ since there is little energy transfer to the light degrees of freedom. Near maximal recoil, one might think that the light degrees of freedom could receive large excitations so that this is no longer the case. However, in the $E\to\infty$ limit, the LEET/HQET effective theory is independent of the light hadron energy, E, not just the heavy quark mass m_b. The LEET light quark field, in particular, only depends on a "residual" momentum of order $\bar{\Lambda}$. The soft form-factor contribution dominance assumption, which requires that production of the light hadron at low q^2 is governed by the end-point region of its wave function, is used to justify the applicability of LEET/HQET to heavy-to-light decays in this kinematical regime. It implies that $1/m_b$, $1/E$, and perturbative α_s corrections to form-factor relations such as Eq. (4) remain small and well defined.

We briefly comment on the implications of LEET for $1/m_b$ corrections to heavy-to-light baryon form factors at large recoil. To facilitate the discussion, we introduce the general decomposition for the vector current

$$\langle \Lambda(p',s')|\bar{s}\gamma_\mu b|\Lambda_b(p,s)\rangle=\bar{u}_\Lambda[V_1(q^2)\gamma_\mu+V_2(q^2)v_\mu + V_3(q^2)n_\mu]u_{\Lambda_b}, \qquad (8)$$

where at leading order, by comparison with Eq. (5),

$$V_1(q^2)=F_1(q^2)-F_2(q^2),$$
$$V_2(q^2)=2F_2(q^2),$$
$$V_3(q^2)=0. \qquad (9)$$

In HQET, additional nonperturbative form factors are introduced at order $1/m_b$ [35], which lead to shifts in the V_i. The use of LEET leads to relations among the new form factors entering at order $1/m_b$. Remarkably, they imply that neglecting radiative corrections, the leading-order relation

$$V_2(E,m_b)/V_1(E,m_b)=2F_2(E,m_b)/F_1(E,m_b) = -\frac{m_\Lambda}{E}, \qquad (10)$$

remains unchanged. An analogous result holds for the corresponding axial vector current form factors. We also find that the infinite m_b relation $F(0)=F_1(0)+O(m^2_\Lambda/E^2)$, see Eq. (6), is modified so that $F(0)=F_1(0)[1+O(\bar{\Lambda}/m_b)]$.

The form-factor relations apply generally to any $b\to q$ mediated heavy-to-light baryon decay, where $q=u,d,s$. Examples are $\Lambda_b\to p l^- \bar{\nu}_l$, which is sensitive to V_{ub}, rare $\Lambda_b\to\Lambda+X$ decays like the one under consideration, and their Cabibbo-Kobayashi-Maskawa (CKM) suppressed counterparts $\Lambda_b\to n+X$, where $X=\gamma, l^+l^-, \nu\bar{\nu}$, etc. Note that the flavor dependence of the ratio F_2/F_1 in Eq. (7) is small, since the light baryon mass differences are small compared to m_{Λ_b}. However, it indicates that F_2/F_1 decreases for lighter final-state baryons.

It is interesting to compare the LEET prediction in Eq. (7) with other determinations of the form-factor ratio. For the radiative decay $\Lambda_b\to\Lambda\gamma$, with $E=2.9$ GeV, we obtain the LEET ratio

$$F_2(0)/F_1(0)=-0.19. \qquad (11)$$

This agrees well with a QCD sum-rule calculation [18], which gives $F_2(0)/F_1(0)=-0.20\pm0.06$. For $\Lambda_b\to p$, we obtain $F_2(0)/F_1(0)|_p=-0.16$, which is also consistent with the QCD sum-rule result $F_2(0)/F_1(0)|_p=-0.18\pm0.07$ [36].

For charmed baryons, there exists a CLEO measurement of this ratio coming from semileptonic $\Lambda_c^+\to\Lambda e^+\nu_e$ decays, $\langle F_2/F_1\rangle_c^{\text{data}}=-0.25\pm0.14\pm0.08$, where the flavor of the decaying heavy quark and an average over phase space are indicated [37]. Although naively we do not expect LEET to be applicable to charm decays since the maximal hadronic energy is not much larger than m_Λ, it is interesting to note that the LEET/HQET prediction $\langle F_2/F_1\rangle_c^{\text{theory}}=-0.44$ agrees with the CLEO result in sign and size at the 1σ level. Note that we have evaluated Eq. (7) at the average value of q^2, $\langle q^2\rangle=0.7$ GeV^2.

TABLE I. Ranges of the ratio $|r|=|C_7'/C_7|$ that can be probed at 5σ (3σ in parentheses) by measuring the angular asymmetry $\mathcal{A}^\gamma$ in $\Lambda_b\to\Lambda\gamma$ decays (left column) for a given number of Z's. In the right column, we combined measurements from $\mathcal{A}^\gamma$ and $\mathcal{A}_{\theta_p}$ and averaged over CP conjugate decays. For details, see Sec. III A. At NLO, the left column corresponds to ranges of $|r^{\rm eff}|$ obtained from $\mathcal{A}^\gamma$. In the right column are shown the corresponding ranges for the ratio $r_{\rm av}$ of CP even quantities, obtained from combined measurements of $\mathcal{A}^\gamma$ and $\mathcal{A}_{\theta_p}$. See Sec. IV for details.

No. Z's	$\mathcal{A}^\gamma$	$\mathcal{A}^\gamma,\mathcal{A}_{\theta_p},CP$
2×10^9	$0.50\leq\|r\|<2.0$ $(0.34\leq\|r\|<2.9)$	$0.30\leq\|r\|<3.3$ $(0.23\leq\|r\|<4.4)$
4×10^9	$0.38\leq\|r\|<2.6$ $(0.28\leq\|r\|<3.6)$	$0.25\leq\|r\|<4.0$ $(0.19\leq\|r\|<5.3)$
10×10^9	$0.29\leq\|r\|<3.5$ $(0.21\leq\|r\|<4.7)$	$0.19\leq\|r\|<5.2$ $(0.15\leq\|r\|<6.8)$

The authors of Ref. [17] have used the same CLEO data on semileptonic Λ_c decays together with Eq. (4) to obtain $F_1(0)=0.22$ (dipole) and $F_1(0)=0.45$ (monopole) for Λ_b decays. As indicated, this requires an assumption about the q^2 dependence of the form factors in order to extrapolate from charm to bottom decays, which leads to large theoretical uncertainties [34]. However, the latter (monopole) value of $F_1(0)$ is in reasonable agreement with $F_1(0)=0.50\pm0.03$, derived from QCD sum rules [18]. Noting that to leading order in HQET/LEET $F(0)=F_1(0)$, we choose $F(0)=0.50$ to estimate the normalization of the decays under investigation. We recall that the dependence on the form factor drops out in the angular asymmetry observables.

We briefly mention an interesting application of our results for heavy-to-light baryon form factors at large recoil. In Ref. [38], to which we refer the reader for details, it has been empirically observed that the position of the zero of the dilepton forward-backward asymmetry in $\Lambda_b\to\Lambda l^+l^-$ decays parametrically has very little dependence on the form factors. We argue that this is a consequence of LEET: corrections to the universal zero in inclusive $b\to sl^+l^-$ decays are proportional to m_Λ^2/E^2 and $m_\Lambda/EF_2/F_1$, which are of higher order in LEET.

III. ANGULAR ASYMMETRY IN $\Lambda_b\to\Lambda\gamma$ AND NEW PHYSICS

The ratio $r\equiv C_7'/C_7$ can be probed by looking at the angular distributions of the spin degrees of freedom with respect to the photon (or Λ) momentum vector in $\Lambda_b\to\Lambda\gamma$ decays. At the Z, both initial and final baryons will be polarized. We therefore begin by giving the differential decay width with the dependence on both baryon spins included. Using Eq. (3), we obtain the exact LO result, which is in agreement with the corresponding expression for baryon $\to$baryon+vector decays derived in [39] in the limit of a massless transverse vector state

$$d\Gamma(\Lambda_b\to\Lambda\gamma)=\Gamma_0|C_7|^2\frac{d\Omega_S}{4\pi}\frac{d\Omega_s}{4\pi}\{(1+|r|^2)[1-(\vec{S}\cdot\hat{p}_\Lambda)\times(\vec{s}\cdot\hat{p}_\Lambda)]+(1-|r|^2)[\vec{S}\cdot\hat{p}_\Lambda-\vec{s}\cdot\hat{p}_\Lambda]\}. \quad (12)$$

Here, $\vec{S}$ and $\vec{s}$ are unit vectors parallel to the spins of the Λ_b and Λ in their respective rest frames, Ω_S and Ω_s are their solid angle elements, $\hat{p}_\Lambda$ is a unit vector pointing in the direction of the Λ momentum, and

$$\Gamma_0\equiv\frac{\alpha G_F^2|V_{tb}V_{ts}^*|^2}{32\pi^4}m_{\Lambda_b}^3m_b^2\left(1-\frac{m_\Lambda^2}{m_{\Lambda_b}^2}\right)^3|F(0)|^2. \quad (13)$$

The total decay rate is $\Gamma=\Gamma_0|C_7|^2(1+|r|^2)$, and our estimate for the branching fraction is [40]

$$\mathcal{B}(\Lambda_b\to\Lambda\gamma)=\frac{1.23\ \text{ps}}{\tau(\Lambda_b)}\left(\frac{m_b}{4.4\ \text{GeV}}\right)^2\left|\frac{V_{tb}V_{ts}^*}{0.04}\right|^2\left|\frac{F(0)}{0.5}\right|^2\times\left|\frac{C_7}{-0.31}\right|^2(1+|r|^2)\times7.9\times10^{-5}. \quad (14)$$

Taking $F(0)\approx0.5$, as discussed in the previous section and $|C_7|^2+|C_7'|^2\approx|C_{7\rm SM}|^2$, the SM branching fraction can be expected to lie in the range $(3-10)\times10^{-5}$.

Note that there are long-distance effects due to intermediate $c\bar{c}$ states which can lead to small helicity-changing contributions. A model-independent $\Lambda_{\rm QCD}/m_c$ expansion has been performed for both inclusive $b\to s\gamma$ [41] and exclusive $B\to K^*\gamma$ decays [20], yielding contributions which are only a few percent of the short-distance amplitudes. Resonance exchange models making use of photoproduction data to evaluate the charmonium couplings at the right kinematical point [25] are consistent with the $1/m_c$ expansion. A model calculation for $\Lambda_b\to\Lambda\gamma$ decays [17] based on [25] again yields contributions at the few percent level. Cabbibo-suppressed internal W exchange has also been found to contribute at the percent level to both $B\to K^*\gamma$ [21] and $\Lambda_b\to\Lambda\gamma$ decays [17]. As the overall long-distance uncertainties turn out to be well below the experimental sensitivity, see Table I, they will be neglected in this work.

We now introduce our observable, the angular asymmetry for polarized Λ_b baryons. We define θ_S as the angle between $\vec{S}$ and $\hat{p}_\Lambda$. Starting from Eq. (12), it is straightforward to obtain the forward-backward asymmetry $\mathcal{A}_{\theta_S}$,

$$\mathcal{A}_{\theta_S} \equiv \frac{1}{\Gamma}\left(\int_0^1 d\cos\theta_S \frac{d\Gamma}{d\cos\theta_S} - \int_{-1}^0 d\cos\theta_S \frac{d\Gamma}{d\cos\theta_S} \right) = \frac{1}{2}\frac{1-|r|^2}{1+|r|^2}. \quad (15)$$

The polarization P_{Λ_b} of Λ_b baryons produced in Z decays then gives us the angular asymmetry observable, $\mathcal{A}^\gamma$, defined (in the Λ_b rest frame) as the forward-backward asymmetry of the photon momentum with respect to the Λ_b boost axis,

$$\mathcal{A}^\gamma \equiv -P_{\Lambda_b}\mathcal{A}_{\theta_S} = -\frac{P_{\Lambda_b}}{2}\frac{1-|r|^2}{1+|r|^2}. \quad (16)$$

For $r \ll 1$, as in the SM, small angles $\theta_S \simeq 0$ are favored and the photon is emitted back-to-back with respect to the spin of the Λ_b, or preferentially parallel to the boost axis since $P_{\Lambda_b} < 0$.

To make contact with experiment, we relate $\mathcal{A}^\gamma$ to the average longitudinal momentum of the photon with respect to the Λ_b boost axis, $\langle q_\parallel^* \rangle = 2/3 E_\gamma^* \mathcal{A}_\gamma$, where $E_\gamma^* = (m_{\Lambda_b}^2 - m_\Lambda^2)/(2m_{\Lambda_b}) = 2.7$ GeV is the photon energy (starred quantities are in the Λ_b rest frame, unstarred quantities are in the lab frame). Finally, we arrive at an expression for the average longitudinal momentum $\langle q_\parallel \rangle_\beta$ of the photon in the lab frame with respect to the boost axis for a fixed boost $\beta = |\vec{p}_{\Lambda_b}|/E_{\Lambda_b}$,

$$\langle q_\parallel \rangle_\beta = \gamma(\beta E_\gamma^* + \langle q_\parallel^* \rangle) = \gamma E_\gamma^* (\beta + \tfrac{2}{3}\mathcal{A}_\gamma), \quad (17)$$

which allows the extraction of $\mathcal{A}_\gamma$.

The sensitivity of $\mathcal{A}^\gamma$ to new physics effects depends on the magnitude of the Λ_b polarization. In the heavy quark limit, Λ_b's produced in Z decays pick up the (longitudinal) polarization of the b quark, $P_b = -0.94$ for $\sin^2\theta_W = 0.23$. Depolarization effects during the fragmentation process were studied in Ref. [42]. Based on HQET and poorly known nonperturbative parameters extracted from data, the average longitudinal Λ_b polarization was estimated to be $P_{\Lambda_b}^{\rm HQET} = -(0.69 \pm 0.06)$. We will instead use the central value of the OPAL Collaboration's measurement, $P_{\Lambda_b} = -0.56^{+0.20}_{-0.13} \pm 0.09$ [15], as an input in our analysis. The CERN e^+e^- collider LEP measurements of P_{Λ_b} [14–16] are obtained from the lepton spectra in semileptonic $\Lambda_b \to \Lambda_c l \nu_l X$ decays, assuming purely SM $V-A$ currents [13]. With a few times 10^2 more events at a GigaZ machine, the error should decrease substantially. This issue certainly deserves further study.

Next we discuss the second "helicity" observable which follows from a spin analysis of the final baryon. The Λ polarization variable α_Λ is defined in the differential decay width as [40] $d\Gamma/d\Omega_s \propto (1 + \alpha_\Lambda \vec{s}\cdot\hat{p}_\Lambda)$. Comparing with Eq. (12), we find

$$\alpha_\Lambda = 2\mathcal{A}_{\theta_s} = -\frac{1-|r|^2}{1+|r|^2}, \quad (18)$$

where we have noted the relation to the forward-backward asymmetry $\mathcal{A}_{\theta_s}$ (the analog of $\mathcal{A}_{\theta_S}$) for the angle θ_s between the Λ spin vector and $\hat{p}_\Lambda$. Our expression for α_Λ differs from Refs. [17,18] by different functions of baryon masses and from [19] by an overall sign. The variable α_Λ is determined by measuring the angle θ_p in the Λ rest frame between the proton momentum vector from the secondary decay $\Lambda \to p\pi^-$ and the direction parallel to $\hat{p}_\Lambda$ or opposite to the Λ_b momentum. The distribution for this angle is proportional to $(1 + \alpha_\Lambda \alpha \cos\theta_p)$, where α is the weak decay parameter for $\Lambda \to p\pi^-$ which has been measured to high precision, $\alpha = 0.642 \pm 0.013$ [40]. Thus, α_Λ can be related to the observable forward-backward asymmetry in the angle θ_p,

$$\mathcal{A}_{\theta_p} = \frac{1}{2}\alpha_\Lambda \alpha = -\frac{\alpha}{2}\frac{1-|r|^2}{1+|r|^2}. \quad (19)$$

It is apparent from Eqs. (16) and (19) that both observables $\mathcal{A}^\gamma$ and $\mathcal{A}_{\theta_p}$ can only probe $|r|$. In Sec. IV we show, however, that at NLO in α_s we are sensitive to direct CP violation in the decay amplitudes, and measurements of the CP-averaged and flavor-tagged observables contain information beyond the magnitude of the coupling ratio.

Although data indicate that the $b \to c$ vertex is predominantly left-handed [43], the possibility exists that new physics could induce tree-level $V+A$ currents. In a SM-based analysis of $b \to c l \nu_l$ mediated decays, a significant right-handed admixture would yield an effective Λ_b polarization that differs from its true value. We have assumed here so far that this is not the case. This hypothesis can itself be tested at a GigaZ facility by comparing the value of P_{Λ_b} extracted from different measurements. To be specific, *comparison of* $\mathcal{A}^\gamma$ *and the* Λ *polarization observable* $\mathcal{A}_{\theta_p}$ *provides an independent measurement of the* Λ_b *polarization*, $P_{\Lambda_b} = \alpha\mathcal{A}^\gamma/\mathcal{A}_{\theta_p}$. A discrepancy with the value of P_{Λ_b} measured in semileptonic $\Lambda_b \to \Lambda_c l \nu_l X$ decays would indicate the presence of nonstandard right-handed $b \to c$ currents.

Besides providing the above important consistency check, we show in the next section that combining the measurements of $\mathcal{A}^\gamma$ and $\mathcal{A}_{\theta_p}$ has another advantage, namely a significant increase in the statistical sensitivity to $|r|$.

A. Sensitivity of the observables $\mathcal{A}^\gamma$ and $\mathcal{A}_{\theta_p}$ to new physics

To illustrate the sensitivity of the angular asymmetry $\mathcal{A}^\gamma$ to the ratio $|r|$, we take $\mathcal{B}(\Lambda_b \to \Lambda\gamma) = 7.5 \times 10^{-5}$, corresponding to approximately 2600 $\Lambda_b \to \Lambda\gamma$ decays for 2×10^9 Z bosons per year at a Z factory. We recall that the large theoretical uncertainty in the rate drops out in $\mathcal{A}^\gamma$. To estimate the number of fully reconstructed signal events,[1] the

[1]We thank Su Dong for the reconstruction efficiency estimates.

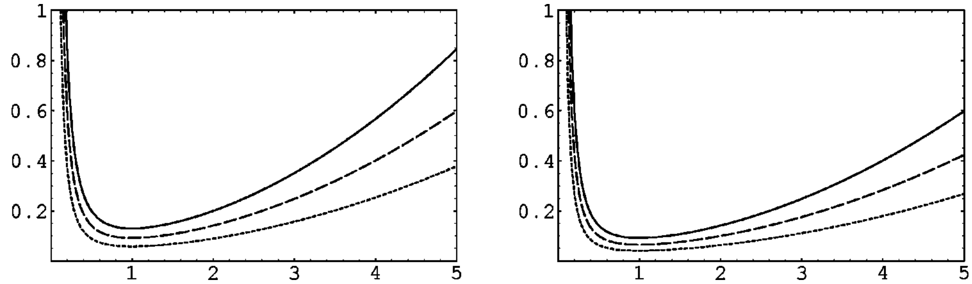

FIG. 1. (a) Relative statistical error in $|r|=|C_7'/C_7|$ as a function of $|r|$ obtained from the angular asymmetry $\mathcal{A}^{\gamma}$ for 2×10^9 (solid), 4×10^9 (long dashed), and 10^{10} (short-dashed) Z bosons, corresponding to 760, 1520, and 3800 fully reconstructed $\Lambda_b\to\Lambda\gamma$ decays, respectively, given the efficiency estimates in the text and $\mathcal{B}(\Lambda_b\to\Lambda\gamma)=7.5\times10^{-5}$. (b) Same as (a) but with twice the statistics, obtained by combining $\mathcal{A}^{\gamma}$ and $\mathcal{A}_{\theta_p}$. At NLO, the figures give relative statistical errors in $|r^{\rm eff}|$ as a function of $|r^{\rm eff}|$. (b) also gives the relative error in the ratio $r_{\rm av}$ of CP-even quantities, obtained from either $\mathcal{A}^{\gamma}$ or $\mathcal{A}_{\theta_p}$.

total efficiency to reconstruct $\Lambda\to p\pi^-$ decays is taken to be around 50%, which includes acceptance losses, tracking efficiency, and the probability that the Λ sometimes travels too far into the central tracking system to leave much of a track when it decays. In addition, the efficiency for photon reconstruction is expected to be around 90%. Including the branching ratio of $\mathcal{B}(\Lambda\to p\pi^-)=0.639\pm0.005$ [40], we obtain approximately $N=760$ fully reconstructed signal events per year, ignoring cuts for background subtraction. We further fix $P_{\Lambda_b}=-0.56$, and do not take into account the experimental uncertainty from the boost. The (absolute) statistical error in $\mathcal{A}^{\gamma}$ is $\delta\mathcal{A}^{\gamma}=\sqrt{1-\mathcal{A}^{\gamma 2}}/\sqrt{N}$. Our findings for the statistical sensitivity are displayed in Fig. 1(a) for one, two, and five years of running at design luminosity of 2×10^9 Z's corresponding to 760, 1520, and 3800 fully reconstructed decays.

Comparing the expressions for $\mathcal{A}^{\gamma}$ and $\mathcal{A}_{\theta_p}$ in Eqs. (16) and (19), it is clear that for comparable magnitudes of α and P_{Λ_b} as indicated by HQET and LEP measurements, the statistical sensitivities of the two observables to $|r|$ are similar. Furthermore, there should not be a significant additional uncertainty in $\mathcal{A}_{\theta_p}$ due to the extra boost from the Λ_b to Λ rest frames, since these decays are fully reconstructed. In Fig. 1(b), we show the sensitivity obtained from combined measurements of $\mathcal{A}^{\gamma}$ and $\mathcal{A}_{\theta_p}$. Finally, by the time that the GigaZ will be in operation, we will already know from the B factories whether or not there is significant direct CP violation in $b\to s\gamma$ mediated decays. In the limit of none or very little CP violation like in the SM, $\mathcal{A}^{\gamma}$ and $\mathcal{A}_{\theta_p}$ are CP-even or close to it. In this case, we can roughly quadruple the statistical power by combining the measurements of $|r|$ extracted from $\mathcal{A}^{\gamma}$ and $\mathcal{A}_{\theta_p}$ and averaging over the CP conjugate decays. This possibility is illustrated in Fig. 2. The ranges for $|r|$ that can be probed would be substantially increased as demonstrated in Table I. Here we show, for comparison, the 5σ ranges (3σ in parentheses) obtained from analyzing $\mathcal{A}^{\gamma}$ alone, and those obtained by combining with $\mathcal{A}_{\theta_p}$ and including both the Λ_b and CP conjugate decays.

We return to the issue of CP violation below, and show that even with sizeable CP violation the CP-averaged observables are useful, yielding information on the CP-even part of an effective coupling ratio rather than on $|r|$.

IV. NLO CONSIDERATIONS AND *CP* VIOLATION

In this section, we estimate next-to-leading order (NLO) effects in $\Lambda_b\to\Lambda\gamma$ decays, where use is made of the corresponding results for inclusive $B\to X_s\gamma$ decays [5,6]. An important addition to the LO analysis is the sensitivity to CP violation at $O(\alpha_s)$. In the following sections, we give the matrix element for $\Lambda_b\to\Lambda\gamma$ decays at NLO, discuss CP-violating effects, and work out the relations between the coefficients appearing in the modified matrix element and the observables defined in Sec. III.

A. The $\Lambda_b\to\Lambda\gamma$ matrix element at $O(\alpha_s)$

As already mentioned in Sec. III, helicity changing long-distance effects are expected to alter the $\Lambda_b\to\Lambda\gamma$ amplitude [17,20,21] and therefore the angular asymmetry observables $\mathcal{A}^{\gamma}$ and $\mathcal{A}_{\theta_p}$ by at most a few percent. In the following, we ignore these effects, but will allow for contributions from

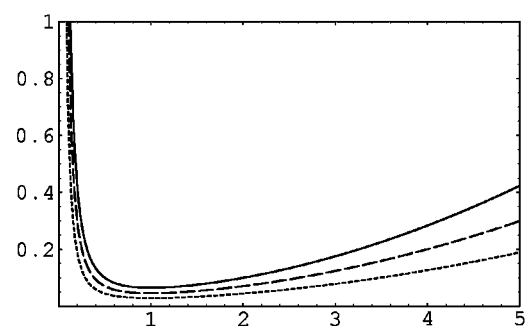

FIG. 2. Relative statistical error in $|r|=|C_7'/C_7|$ as a function of $|r|$ extracted from the angular asymmetry $\mathcal{A}^{\gamma}$ for 2×10^9 (solid), 4×10^9 (long dashed), and 10^{10} (short-dashed) Z bosons, corresponding to 760, 1520, and 3800 fully reconstructed $\Lambda_b\to\Lambda\gamma$ decays, respectively, obtained by combining the values of $|r|$ extracted from $\mathcal{A}^{\gamma}$ and $\mathcal{A}_{\theta_p}$ and averaging over CP conjugate decays, in the limit of no CP violation. At NLO, the figure gives the relative statistical error in the ratio $r_{\rm av}$ of CP-even quantities, obtained by combining $\mathcal{A}^{\gamma}$ and $\mathcal{A}_{\theta_p}$. See Sec. IV for details.

hard gluon exchanges beyond leading order. The $\Lambda_b \to \Lambda \gamma$ amplitude can be parametrized in terms of effective coefficients D, D' as

$$A(\Lambda_b \to \Lambda \gamma) = -\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} (D \langle \Lambda \gamma | Q_7 | \Lambda_b \rangle + D' \langle \Lambda \gamma | Q_7' | \Lambda_b \rangle), \tag{20}$$

where $\langle Q_7 \rangle, \langle Q_7' \rangle$ are the leading-order matrix elements following from Eq. (3). To $O(\alpha_s)$,

$$D = C_7^{(0)} + \frac{\alpha_s}{4\pi} (C_7^{(1)} + C_2^{(0)} k_2 + C_8^{(0)} k_8),$$
$$D' = C'^{(0)}_7 + \frac{\alpha_s}{4\pi} (C'^{(1)}_7 + C'^{(0)}_8 k_8). \tag{21}$$

Here, the coefficients k_i account for the $O(\alpha_s)$ matrix elements of the operators $Q_i^{(\prime)}$ and include CP-conserving strong phases. As usual, $Q_2 = (\bar{c} \gamma_\mu L b)(\bar{s} \gamma^\mu L c)$ is the current-current operator and $Q_8^{(\prime)}$ is the chromomagnetic dipole operator analog of $Q_7^{(\prime)}$, see, e.g., [1]. We have further assumed that the flipped current-current operator $O_2' = (\bar{c} \gamma_\mu R b)(\bar{s} \gamma^\mu R c)$ is of negligible strength and does not contribute to the α_s-corrected matrix element. The superscripts (0) and (1) denote LO and NLO contributions to the Wilson coefficients, respectively.

The coefficients k_i receive contributions from gluonic loops in the $b \to s \gamma$ transition [5,6] as well as from hard interactions with the spectator quarks. Studies for exclusive $B \to K^* \gamma$ decays have shown that α_s corrections from diagrams involving spectator quarks are smaller than those without spectator interactions [44,45]. Thus, while an explicit NLO calculation for $\Lambda_b \to \Lambda \gamma$ decays would be desirable, existing calculations of the k_i for inclusive $b \to s \gamma$ decays should provide an estimate of the dominant NLO effects to the exclusive decay. Note that in Eq. (21) we have absorbed the "factorizable" vertex correction of the operators Q_7, Q_7' into the form factor [44,45,32].

We will allow for weak CP-violating phases in the Wilson coefficients of the operators $Q_7^{(\prime)}$ and $Q_8^{(\prime)}$. The effective coefficients $\bar{D}$ and $\bar{D}'$ for the CP conjugate decay $\bar{\Lambda}_b \to \bar{\Lambda} \gamma$ are then obtained by replacing $C_7^{(0),(1)}$, $C_8^{(0)}$, and their primed counterparts in Eq. (21) with their complex conjugates.

B. Direct CP violation

Direct CP-violating effects can arise at $O(\alpha_s)$ from interference between the weak and strong phases in the decay amplitudes, for example inducing a nonzero asymmetry in the decay rates:

$$a_{CP}^{\Lambda_b} \equiv \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}, \tag{22}$$

where $\Gamma, \bar{\Gamma}$ denote the total decay rates for $\Lambda_b \to \Lambda \gamma$ and the CP conjugate mode, respectively. In general, the CP asymmetry in $b \to s$ transitions is CKM-suppressed in scenarios which only contain the weak CKM phase of the SM: $a_{CP} \sim \alpha_s(m_b) \mathrm{Im}[V_{us}^* V_{ub} / V_{ts}^* V_{tb}] = \alpha_s(m_b) \lambda^2 \eta$, where λ and η are Wolfenstein parameters, and $\lambda^2 \eta \sim 0.02$. We estimate $a_{CP}^{\Lambda_b} \leqslant O(1)\%$ in the SM from calculations of the inclusive $B \to X_s \gamma$ [46] or exclusive $B \to K^* \gamma$ [44,47] rate asymmetries and neglect such small CKM-induced effects below. However, new CP-violating contributions to $Q_7^{(\prime)}$ or $Q_8^{(\prime)}$ can give rise to sizable effects. In particular, it has been shown that CP-violating rate asymmetries of order 10% or larger are possible for inclusive $B \to X_s \gamma$ decays in a variety of new physics models [46], so that similarly large values for exclusive asymmetries can be expected. Experimentally, the current best bound is given as $a_{CP}(B \to K^* \gamma) = -0.035 \pm 0.076 \pm 0.012$ [48], whereas inclusive CP asymmetries are not very constrained yet $-0.27 < a_{CP}(B \to X_s \gamma) < +0.10$ at 90% C.L. [49].

Below, we will discuss the angular asymmetries beyond leading order, allowing in general for CP-violating effects. We will see that by combining measurements of these observables with branching ratio measurements, for the CP conjugate decay modes, it will be possible to determine the CP-odd and CP-even components of both the SM and opposite chirality contributions to the $\Lambda_b \to \Lambda \gamma$ decay rate.

C. The observables at NLO

In the CP-conserving limit, the angular asymmetry observables $\mathcal{A}^\gamma$ and $\mathcal{A}_{\theta_p}$ are CP-even, i.e., $\mathcal{A}^\gamma = \bar{\mathcal{A}}^\gamma$ and $\mathcal{A}_{\theta_p} = \bar{\mathcal{A}}_{\theta_p}$, where $\mathcal{A}$ and $\bar{\mathcal{A}}$ are the observables for the Λ_b and CP conjugate $\bar{\Lambda}_b$ decays, respectively. However, the angular asymmetries of the CP conjugate modes will in general differ at next-to-leading order and higher if there are new CP-violating contributions to $Q_7^{(\prime)}$ or $Q_8^{(\prime)}$. We parametrize the angular asymmetry observables as

$$\mathcal{A}^\gamma = -\frac{P_{\Lambda_b}}{2} \frac{1 - |r^{\mathrm{eff}}|^2}{1 + |r^{\mathrm{eff}}|^2}, \quad \mathcal{A}_{\theta_p} = -\frac{\alpha}{2} \frac{1 - |r^{\mathrm{eff}}|^2}{1 + |r^{\mathrm{eff}}|^2},$$
$$\bar{\mathcal{A}}^\gamma = -\frac{P_{\Lambda_b}}{2} \frac{1 - |\bar{r}^{\mathrm{eff}}|^2}{1 + |\bar{r}^{\mathrm{eff}}|^2}, \quad \bar{\mathcal{A}}_{\theta_p} = -\frac{\alpha}{2} \frac{1 - |\bar{r}^{\mathrm{eff}}|^2}{1 + |\bar{r}^{\mathrm{eff}}|^2}, \tag{23}$$

where the effective ratios are defined as

$$r^{\mathrm{eff}} \equiv D'/D, \quad \bar{r}^{\mathrm{eff}} \equiv \bar{D}'/\bar{D}. \tag{24}$$

Thus the flavor-specific angular asymmetry observables actually probe the effective ratios $|r^{\mathrm{eff}}|$ and $|\bar{r}^{\mathrm{eff}}|$, rather than the ratio of short-distance Wilson coefficients $|C_7'/C_7|$. It is straightforward to carry over the results obtained in Sec. III for the experimental sensitivity to $|r|$: The ranges in $|r^{\mathrm{eff}}|$ ($|\bar{r}^{\mathrm{eff}}|$) that can be probed by measuring $\mathcal{A}^\gamma$ ($\bar{\mathcal{A}}^\gamma$) can be read off from Fig. 1(a). Measurements of $\mathcal{A}_{\theta_p}$ will give a similar reach since we assumed that P_{Λ_b} is of similar magnitude to the Λ decay parameter α. The sensitivity that can be expected by combining measurements of the two observables is given approximately in Fig. 1(b).

In the following, it is convenient to separate $|D^{(\prime)}|^2$ into CP-even and CP-odd components, denoted by $|D^{(\prime)}|^{2+}$ and $|D^{(\prime)}|^{2-}$, respectively, such that

$$|D^{(\prime)}|^2 = |D^{(\prime)}|^{2+} + |D^{(\prime)}|^{2-},$$
$$|\bar{D}^{(\prime)}|^2 = |D^{(\prime)}|^{2+} - |D^{(\prime)}|^{2-}. \tag{25}$$

At next-to-leading order we obtain

$$|D|^{2+} = |C_7^{(0)}|^2 + \frac{\alpha_s}{2\pi}(\mathrm{Re}[C_7^{(0)}C_7^{(1)*}] + \mathrm{Re}[C_7^{(0)}C_2^{(0)*}]\mathrm{Re}\,k_2 + \mathrm{Re}[C_7^{(0)}C_8^{(0)*}]\mathrm{Re}\,k_8),$$

$$|D|^{2-} = \frac{\alpha_s}{2\pi}(\mathrm{Im}[C_7^{(0)}C_2^{(0)*}]\mathrm{Im}\,k_2 + \mathrm{Im}[C_7^{(0)}C_8^{(0)*}]\mathrm{Im}\,k_8), \tag{26}$$

$$|D'|^{2+} = |C'^{(0)}_7|^2 + \frac{\alpha_s}{2\pi}(\mathrm{Re}[C'^{(0)}_7 C'^{(1)*}_7] + \mathrm{Re}[C'^{(0)}_7 C'^{(0)*}_8]\mathrm{Re}\,k_8),$$

$$|D'|^{2-} = \frac{\alpha_s}{2\pi}\mathrm{Im}[C'^{(0)}_7 C'^{(0)*}_8]\mathrm{Im}\,k_8.$$

Note that the CP-odd components $|D|^{2-}$ and $|D'|^{2-}$ arise only at $O(\alpha_s)$. There are three CP-even observables: the averages over the CP conjugate modes of the branching ratio and of the angular asymmetry observables, denoted $\mathcal{B}_{\rm av}$, $\mathcal{A}^{\gamma}_{\rm av}$, and $\mathcal{A}^{\rm av}_{\theta_p}$, respectively. The three corresponding CP-odd observables are the rate asymmetry $a_{CP}^{\Lambda_b}$ and the angular asymmetry differences $\mathcal{A}^{\gamma} - \bar{\mathcal{A}}^{\gamma}$ and $\mathcal{A}_{\theta_p} - \bar{\mathcal{A}}_{\theta_p}$.

All four components $|D^{(\prime)}|^{2+}$ and $|D^{(\prime)}|^{2-}$ can in principle be uniquely determined from experiment via the relations

$$\mathcal{B}_{\rm av} = \tau(\Lambda_b)\Gamma_0(|D|^{2+} + |D'|^{2+}), \tag{27}$$

$$a_{CP}^{\Lambda_b} = \frac{|D|^{2-} + |D'|^{2-}}{|D|^{2+} + |D'|^{2+}}, \tag{28}$$

$$\mathcal{A}^{\gamma}_{\rm av} + a_{CP}^{\Lambda_b}\frac{\mathcal{A}^{\gamma} - \bar{\mathcal{A}}^{\gamma}}{2} = -\frac{P_{\Lambda_b}}{2}\frac{|D|^{2+} - |D'|^{2+}}{|D|^{2+} + |D'|^{2+}}, \tag{29}$$

$$\frac{\mathcal{A}^{\gamma} - \bar{\mathcal{A}}^{\gamma}}{2} + a_{CP}^{\Lambda_b}\mathcal{A}^{\gamma}_{\rm av} = -\frac{P_{\Lambda_b}}{2}\frac{|D|^{2-} - |D'|^{2-}}{|D|^{2+} + |D'|^{2+}}, \tag{30}$$

plus two equations involving the Λ polarization observables $\mathcal{A}_{\theta_p}$ and α, obtained by substituting for $\mathcal{A}^{\gamma}$ and P_{Λ_b}, respectively, in the last two equations above. Note that the second term on the left-hand side of Eq. (29) first enters at order α_s^2 and should be neglected in a NLO analysis.

An important result following immediately from Eq. (29) is that the CP-averaged angular observables $\mathcal{A}^{\gamma}_{\rm av}$ and $\mathcal{A}^{\rm av}_{\theta_p}$ in general determine the ratio of CP-even quantities

$$r_{\rm av} \equiv \sqrt{\frac{|D'|^{2+}}{|D|^{2+}}} \tag{31}$$

at NLO via equations analogous to Eqs. (16) and (19), respectively. Furthermore, the full statistical reach of a GigaZ facility, as discussed in Sec. III A, is available since both the Λ_b and $\bar{\Lambda}_b$ decays are included in CP-averaged quantities: The sensitivity to $r_{\rm av}$ that could be obtained from measurements of either $\mathcal{A}^{\gamma}_{\rm av}$ or $\mathcal{A}^{\rm av}_{\theta_p}$ can be read off from Fig. 1(b), whereas the sensitivity for a combined analysis is given in Fig. 2, also see Table I. A nonzero measurement of $r_{\rm av}$ would be a clean signal for new physics with nonstandard chirality structure, given that in the SM $r_{\rm av} \sim m_s/m_b$.

D. Estimates of NLO effects

Small measured values for the CP-violating rate asymmetry, $a_{CP}^{\Lambda_b}$, would generally imply that $|D|^{2-}$ and $|D'|^{2-}$, and therefore $\mathcal{A}^{\gamma} - \bar{\mathcal{A}}^{\gamma}$ and $\mathcal{A}_{\theta_p} - \bar{\mathcal{A}}_{\theta_p}$ are small. This can be seen explicitly from Eqs. (28) and (30). Furthermore, if $|D'|^{2-} = 0$, i.e., if the new physics contributions to C'_7 and C'_8 have a common weak phase, then

$$\mathcal{A}^{\gamma} - \bar{\mathcal{A}}^{\gamma} = -2a_{CP}^{\Lambda_b}P_{\Lambda_b}\frac{|D'|^{2+}}{|D|^{2+} + |D'|^{2+}},$$
$$\mathcal{A}_{\theta_p} - \bar{\mathcal{A}}_{\theta_p} = -2a_{CP}^{\Lambda_b}\alpha\frac{|D'|^{2+}}{|D|^{2+} + |D'|^{2+}}, \tag{32}$$

where the equalities hold up to and including terms of $O(\alpha_s^2)$. Setting $|D'|^{2-} = 0$ would be a good approximation if there were a single dominant new physics source, such as the virtual exchange of a new heavy particle, contributing to both the magnetic and chromomagnetic dipole operators. In such models, an upper bound is obtained on the angular CP asymmetries, $|\mathcal{A}^{\gamma} - \bar{\mathcal{A}}^{\gamma}| < 2|a_{CP}^{\Lambda_b}P_{\Lambda_b}|$, and $|\mathcal{A}_{\theta_p} - \bar{\mathcal{A}}_{\theta_p}| < 2|a_{CP}^{\Lambda_b}|\alpha$. Barring large accidental cancellations, data on $a_{CP}(B \to X_s\gamma)$ or $a_{CP}(B \to K^*\gamma)$ may serve here as a first estimate, so roughly $|\mathcal{A}^{\gamma} - \bar{\mathcal{A}}^{\gamma}|, |\mathcal{A}_{\theta_p} - \bar{\mathcal{A}}_{\theta_p}| \lesssim O(10\%)$, using the experimental information given in Sec. IV B.

Finally, we ask by how much $r_{\rm av}$ and $|r^{\rm eff}|$ could differ from the leading-order ratio $|C'^{(0)}_7/C_7^{(0)}|$, which was the focus of the previous sections. At NLO order, we have

$$r_{\rm av}=\frac{|C'^{(0)}_7|}{|C^{(0)}_7|}\left\{1+\frac{\alpha_s}{4\pi}\left(\mathrm{Re}\left[\frac{C'^{(1)}_7}{C'^{(0)}_7}-\frac{C^{(1)}_7}{C^{(0)}_7}\right]+\mathrm{Re}\,k_8\,\mathrm{Re}\left[\frac{C'^{(0)}_8}{C'^{(0)}_7}-\frac{C^{(0)}_8}{C^{(0)}_7}\right]-\mathrm{Re}\,k_2\,\mathrm{Re}\left[\frac{C^{(0)}_2}{C^{(0)}_7}\right]\right)\right\}, \quad (33)$$

$$|r^{\rm eff}|=r_{\rm av}+\frac{|C'^{(0)}_7|}{|C^{(0)}_7|}\frac{\alpha_s}{4\pi}\left(\mathrm{Im}\,k_8\,\mathrm{Im}\left[\frac{C^{(0)}_8}{C^{(0)}_7}-\frac{C'^{(0)}_8}{C'^{(0)}_7}\right]+\mathrm{Im}\,k_2\,\mathrm{Im}\left[\frac{C^{(0)}_2}{C^{(0)}_7}\right]\right).$$

As discussed at the beginning of Sec. IV A, an estimate of the $O(\alpha_s)$ matrix element can be obtained from inclusive $b\to s\gamma$ decays keeping only the finite virtual corrections. The exclusive coefficients k_i can be roughly approximated by the corresponding inclusive ones [5–7], yielding

$$\mathrm{Re}\,k_2\approx-4.09+12.78\left(\frac{m_c}{m_b}-0.29\right)+\frac{416}{81}\ln\frac{m_b}{\mu},$$

$$\mathrm{Im}\,k_2\approx-0.45+5.18\left(\frac{m_c}{m_b}-0.29\right),$$

$$\mathrm{Re}\,k_8\approx\frac{44}{9}-\frac{8\pi^2}{27}-\frac{32}{9}\ln\frac{m_b}{\mu},\qquad \mathrm{Im}\,k_8\approx\frac{8\pi}{9},$$

where μ is the renormalization scale. Taking $C^{(0)}_7$ in Eq. (33) to be approximately equal to the SM value, and allowing μ to vary between $m_b/2$ and m_b, we find that the $O(\alpha_s)$ corrections to $r_{\rm av}$ or $|r^{\rm eff}|$ induced by the matrix element of Q_2 are of order 5–20 %. Shifts due to the matrix elements of Q_8, Q'_8 would be of order 1% if $C_8\sim C_7$ and $C'_7\sim C'_8$, as in the SM. However, in models with enhanced chromomagnetic dipole operators the correction could again be of order 10%. Therefore, although measurements of the observables associated with $\Lambda_b\to\Lambda\gamma$ could give unambiguous evidence for new physics with non-SM chirality, it will be difficult to obtain precision constraints on the underlying short-distance contributions to the dipole operators in the absence of a first-principles calculation of the coefficients k_i in exclusive $\Lambda_b\to\Lambda\gamma$ decays.

V. CONCLUSIONS AND OUTLOOK

We have studied the radiative decay $\Lambda_b\to\Lambda\gamma$ as a probe of new physics. A novel observable was proposed which makes use of the polarization of Λ_b baryons produced at the Z: the angular asymmetry of the photon momentum with respect to the Λ_b boost axis. We have also considered the angular asymmetry associated with the secondary decays $\Lambda\to p\pi^-$. The two observables are sensitive to the ratio C'_7/C_7 of opposite chirality to standard model chirality $b\to s\gamma$ Wilson coefficients. In the standard model, this ratio is only a few percent but can be sizeable in many of its extensions, e.g., the minimal supersymmetric standard model (MSSM) beyond minimal flavor violation. Statistical sensitivities to this ratio were worked out, including reconstruction efficiency estimates. Our findings are compiled in Table I and in three figures for the case of a proposed GigaZ facility [28,29] with $\approx 2\times10^9$ Z's per year. Wide ranges of C'_7/C_7 are accessible to experimental study of angular asymmetries in $\Lambda_b\to\Lambda\gamma$ decays, allowing a clear separation from the SM prediction.

In addition to the search for nonstandard chiralities, one can probe for nonstandard CP phases in $\Lambda_b\to\Lambda\gamma$ decays, if a flavor-tagged analysis of angular asymmetries and branching ratios is performed. In general, at NLO and allowing for direct CP violation, four independent contributions enter the $\Lambda_b\to\Lambda\gamma$ and CP conjugate decay widths: CP-even and CP-odd, each with SM and opposite chiralities. All four can, in principle, be determined from such an analysis. An important result is that the CP-averaged angular observables, which have the greatest statistical reach, determine the relative strengths of the CP-even contributions with opposite and standard model chiralities, generalizing the leading-order dependence on C'_7/C_7. A nonzero measurement of this ratio would provide a clean signal for new physics.

Parts of the analysis presented here, namely measurements of rates and the Λ decay polarization observable, including studies of CP violation, do not require polarized Λ_b's and can be carried out at hadron colliders like the Tevatron and the LHC. It might also be worthwhile to explore the possibility of heavy baryon production with sufficient polarization in a hadronic environment, e.g., with polarized beams.

To estimate the total $\Lambda_b\to\Lambda\gamma$ rate, we derived form-factor relations for heavy-to-light baryon decays in the large energy limit. This allows us to relate the form factors to existing estimates derived using nonperturbative methods and data. We emphasize that the relations we have worked out are useful for many other heavy-to-light decays at large recoil. In particular, we have shown that the zero of the dilepton forward-backward asymmetry in $\Lambda_b\to\Lambda l^+l^-$ decays is independent of form factors to lowest order in the large energy expansion. The form-factor relations are also necessary for predicting the proton angular asymmetry in polarized $\Lambda_b\to p l\nu_l$ decays, which provides an important test of the $V-A$ structure of the $b\to u$ charged current at a GigaZ facility.

We stress the importance of a precise measurement of the Λ_b polarization from semileptonic $\Lambda_b\to\Lambda_c l\bar{\nu}_l X$ decays at the GigaZ; a significant improvement on the LEP measurements will be required. Comparison with the polarization extracted from the angular asymmetries in $\Lambda_b\to\Lambda\gamma$ provides a consistency check of the $V-A$ structure of the $b\to c$ charged current. The latter should also be testable via angular asymmetries in exclusive $\Lambda_b\to(\Lambda_c\to\Lambda\pi,\Sigma\pi)l\bar{\nu}_l$ decays.

It is promising to extend the study presented here to the semileptonic decays $\Lambda_b\to\Lambda l^+l^-$ and $\Lambda_b\to\Lambda\nu\bar{\nu}$, with standard model branching ratios in the interesting range of

10^{-5}–10^{-6}. In a companion paper [50], we discuss rare hadronic two-body decays, focusing on the decay $\Lambda_b \to \Lambda\phi$, which is estimated to have a standard model branching ratio of a few times 10^{-5}. This decay offers a unique sensitivity to the chirality structure of four-quark "penguin" (see, e.g., [1]) operators. The decays $\Lambda_b \to \Lambda\pi, \Lambda\rho$ are also interesting since they violate isospin, thus providing a probe of the electroweak penguin operators. Finally, certain hadronic two-body decays can explore the origin and limitations of the factorization hypothesis [51]. All of this should be part of a rich and unique b-physics program at a future high-luminosity Z factory.

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