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Radiative B decays at Belle and Belle II

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Abstract

Rare decays of B mesons to radiative final states serve as an ideal ground to search for New Physics effects from short range contributions. Being one of the first transitions of the electroweak penguin family to be observed by CLEO in the early 90s, these transitions still serve an important role in testing the predictions of the Standard Model. We present the latest results from Belle and Belle II for the radiative penguin transitions.

1 Introduction

In the Standard Model of particle physics (SM), transitions involving Flavour Changing Neutral Currents (FCNC) are forbidden at the tree level, and occur through electroweak loop diagrams [1, 2]. Physics beyond the SM (BSM) can manifest in the form of contributions within the loop diagrams or by mediating the FCNC process at the tree level, altering the observables of FCNC transitions from their SM predictions.

The radiative decay of B meson to the inclusive final state $X_s\gamma$, where X_s encompasses all final states with net strangeness, is a prototype FCNC transition [3]. This decay offers sensitivity to BSM effects [4]. The photon-energy spectra can provide more insights into parameters such as the b quark mass and its motion within the B meson [5, 6]. BSM searches using radiative decays of B mesons to exclusive final states, like $B \to K^*\gamma$ and $B \to \rho\gamma$, are also promising. In the SM, the dominant contribution to the decay comes from the $b \to s/d\gamma$ operator, facilitating the distinction between SM and BSM physics contributions [7].

The remainder of this document is arranged as follows: Section 2 provides a brief description of Belle and Belle II detector, Section 3 summarizes the measurement of photn energy spectrum obtained for the inclusive $B \to X_s\gamma$ channel using Belle II data, and Section 4 provides a summary of the measurement of observables of exclusive final state $B \to \rho\gamma$ using the combined Belle and Belle II dataset.

2 Belle and Belle II detector

The Belle detector [8, 9] is a large-solid-angle spectrometer that operated at the KEKB asymmetric-energy e^+e^- collider [11, 12]. The energies of electron and positron beams are 8.0 GeV and 3.5 GeV, respectively. The detector consists of a silicon vertex detector, a central drift chamber, an array of aerogel Cherenkov counters and time-of-flight scintillation counters for identification of charged particles, and an electromagnetic CsI(Tl) crystal calorimeter (ECL) surrounded by a superconducting solenoid coil providing a magnetic field of 1.5 T. An iron flux return yoke located outside the coil instrumented with resistive-plate chambers to aided in detecting $K^0_{\rm L}$ mesons and to identify muons.

The Belle II detector [13] is located at the SuperKEKB [14] e^+e^- collider. The energies of electron and positron beams are 7.0 GeV and 4.0 GeV, respectively. Belle II is an upgraded version of the Belle detector. The Belle II detector includes the vertex detector consisting of pixel sensors and double-sided silicon vertex detectors [15] and an upgraded 56-layer central drift chamber. The central drift chamber is surrounded by two types of Cherenkov light detector systems: an azimuthal array of time-of-propagation detectors for the barrel region and an aerogel ring-imaging Cherenkov detector for the forward endcap region. The Belle ECL is reused in Belle II along with the solenoid and the iron flux return yoke. The z axis of the laboratory frame is defined as the solenoid axis, where the positive direction is along the electron beam. This convention applies both to Belle and Belle II.

3 Inclusive measurement of $B \to X_s\gamma$ at Belle II

This section summarizes a measurement of inclusive $B \to X_s\gamma$ decays employing hadronic tagging for the partner B meson (B tag candidate) reconstruction, performed at Belle II [16]. The measurement is based on 189 fb^{-1} of data collected by the Belle II experiment. This approach is complementary to the untagged or lepton-tagged [17] and sum-of-exclusive [18] methods, and gets contribution from different sources of systematic uncertainty. The hadronic tag ensures higher purity, and the kinematic constraints from the tagged B meson enable measurement of observables pertaining to the signal side B meson.

To reconstruct a $B \to X_s\gamma$ candidate, we pair the highest energy photon in the event, satisfying $E^B_\gamma > 1.4$ GeV, with the B tag candidate reconstructed using the full-event-interpretation algorithm (FEI) [19]. Here, the photon energy in the rest frame of signal-B meson is denoted as E^B_γ. The FEI reconstructs hadronic B decays from numerous sub-decay chains. A stochastic gradient-boosted decision tree (BDT) [20] trained on Zernike moments [21] is used to separate high-energy photons from $K^0_{\rm L}$ clusters.

The sources of background include high-energy photons coming from $\pi^0/\eta \to \gamma\gamma$ decays where a photon emitted along the boost direction of π^0/η can be misidentified as signal side high-energy photon. Another contribution comes from $e^+e^- \to q\bar{q}$ decays, where q represents u, d, s, and c quarks. The latter is also referred to as light-quark continuum background. To mitigate the background from π^0 and η photons, the signal-side hard photon is paired with all low-energy photons in the event. Events consistent with $\pi^0/\eta \to \gamma\gamma$ transitions are then vetoed using a dedicated BDT trained on kinematic feature variables such as the diphoton invariant mass, helicity, and properties of the low-energy photon, including energy, polar angle, and the smallest ECL cluster-to-track distance. Another dedicated BDT trained to suppress $e^+e^- \to q\bar{q}$ events is employed. The BDT utilizes input features which are known to have good separation power between B decays and continuum background, these features include the modified Fox-Wolfram moments [22], CLEO cones [23], thrust etc.

A fit to the $M_{\rm bc}$ distribution of the tag-side B candidate in bins of E^B_γ for the region $1.8 < E^B_\gamma$ GeV is performed to extract the signal yield. The selections and fit procedure are validated in a control region $1.4 < E^B_\gamma < 1.8$ GeV. Since the inclusive analysis does not differentiate between $b \to d\gamma$ and $b \to s\gamma$ processes, we subtract the smaller $b \to d\gamma$ contribution based on simulation. The measured $B \to X_s\gamma$ spectrum undergoes correction (unfolding) for smearing effects. The unfolding process utilizes bin-by-bin multiplicative factors, defined as the ratios between the expected number of events of the generated spectrum and the expected number of corresponding events of the reconstructed spectrum within an E^B_γ interval. The integrated branching ratios for various E^B_γ thresholds are shown in Table 1, the results are found to be consistent with the world average values [10].

Table 1: The integrated partial branching fractions for three E^B_γ thresholds.

E^B_γ	$\mathcal{B}(B \to X_s\gamma) \times (10^{-4})$
1.8	3.54 ± 0.78 (stat.) ± 0.83 (syst.)
2.0	3.06 ± 0.56 (stat.) ± 0.47 (syst.)
2.1	2.49 ± 0.46 (stat.) ± 0.35 (syst.)

4 Exclusive measurement of $B \to \rho\gamma$ at Belle and Belle II

This section summarizes the most precise measurement of observables for exclusive $B \to \rho\gamma$ decays, based on the combined data of Belle (711 fb^{-1}) and Belle II (362 fb^{-1}) experiment. The exclusive radiative decay of B meson to $\rho\gamma$ final state allows for an independent search of BSM, complementary to the $b \to s\gamma$ modes. The $B \to \rho\gamma$ being a $b \to d$ transition at the quark level, has a branching fraction one order of magnitude smaller than the radiative B decays involving a $b \to s$ transition. Due to the significant difference in the branching fractions of $b \to d\gamma$ and $b \to s\gamma$ transitions, good particle identification detectors are required in order to reduce the K^+ contamination from $B \to X_s\gamma$ decays. The branching fractions observables give weak constraints on BSM parameters, since the SM predictions suffer from large uncertainties (around 20%) in the form factors [25]. One can instead work with observables such as CP ($\mathcal{A}_{CP}$) and isospin asymmetry (A_I) which are theoretically clean due to the cancellation of such effects. Precision measurement of A_I of $B \to \rho\gamma$ is particularly interesting since the current world average [10] is at a slight tension with the standard model (SM) prediction [24].

The reconstruction of $B \to \rho\gamma$ decay follows a hierarchical approach, starting from the final state particles. High-energy photon candidates exhibiting a shower shape consistent with that of an isolated photon are selected within the energy range 1.8 to 2.8 GeV. Tracks produced near the e^+e^- interaction point are selected based on the requirements $|d_r| < 0.5$ cm and $|d_z| < 2.0$ cm, where d_r (d_z) represents transverse (longitudinal) impact parameters, respectively. A likelihood based particle selector combining information from various detectors of Belle [26] or Belle II is used to select charged tracks.

The π^0 candidates are reconstructed in the diphoton invariant mass range $119 < M_{\gamma\gamma} < 151\,\mathrm{MeV}/c^2$. The photons are further required to satisfy various energy thresholds depending on the detector (Belle or Belle II), and the region of the ECL where the photon is detected. Subsequently, we reconstruct the ρ mesons $\rho^{0(+)} \to \pi^+\pi^{-(0)}$ with the selection $0.64(0.65) < M_{\pi\pi} < 0.89(0.90)\,\mathrm{GeV}/c^2$ for Belle (Belle II). The B meson is reconstructed by combining a high-energy photon with the pion pair. Further selection criteria are applied to the variables $5.20\,\mathrm{GeV}/c^2 < \sqrt{(E^*_{\mathrm{beam}})^2 - (\vec{p}^*_B)^2}(M_{\mathrm{bc}})$ and $-0.3 < E^*_B - E^*_{\mathrm{beam}}(\Delta E) < 0.3\,\mathrm{GeV}$. Here, E^*_{beam} and E^*_B are the beam energy and the energy of the B meson in the center-of-mass frame. For the neutral mode, the momentum of the B meson in the center-of-mass frame is calculated as $\vec{p}^*_{B^0} = \vec{p}^*_{\rho^0} + \frac{\vec{p}^*_\gamma}{|\vec{p}^*_\gamma|} \times (E^*_{\mathrm{beam}} - E^*_{\rho^0})$, to improve the resolution of M_{bc}.

The sources of background, akin to the $B \to X_s\gamma$ channel, are high-energy photons from π^0/η decays, and combinatorial background from $e^+e^- \to q\bar{q}$ events. The background suppression strategy is to use a dedicated BDT classifier to suppress each kind of background, same as the $B \to X_s\gamma$ channel. $B^{+(0)} \to D^{0(-)}\pi^+$ and $B \to K^*\gamma$ control channels are studied to assess the quality of the simulation, and assign systematics for the BDT classifiers. These control channels have similar final state as the $B \to \rho\gamma$ modes, significantly higher statistics, and relatively low background contamination. The invariant mass region for $D^{0(-)}$ and K^* particles are $1.85(1.86) < M_{K^-\pi^+(\pi^+)} < 1.88\,\mathrm{GeV}/c^2$, and $0.817 < M_{K\pi} < 0.967\,\mathrm{GeV}/c^2$, respectively.

The physics observables of $B \to \rho\gamma$ decay are obtained from an extended unbinned maximum likelihood fit to $M_{\rm bc}$, ΔE, and $M_{K\pi}$ distributions, fitted simultaneously for six independent data sets: B^+, B^-, and B^0 in Belle and Belle II. Here, $M_{K\pi}$ is the invariant mass calculated assuming a π^+ to be a K^+. Using $M_{K\pi}$ instead of $M_{\pi\pi}$ aids in better separation of the $B \to K^*\gamma$ background. The measured values of observables for $B \to \rho\gamma$ decay from combined Belle and Belle II dataset are as follows:

$$\mathcal{B}(B^+ \to \rho^+\gamma) = (13.1^{+2.0+1.3}_{-1.9-1.2}) \times 10^{-7}, \tag{4.1}$$

$$\mathcal{B}(B^0 \to \rho^0\gamma) = (7.5 \pm 1.3^{+1.0}_{-0.8}) \times 10^{-7}, \tag{4.2}$$

$$\mathcal{A}_{CP}(B \to \rho\gamma) = -8.2 \pm 15.2^{1.6}_{-1.2}\%, \tag{4.3}$$

$$A_I(B \to \rho\gamma) = 10.9^{+11.2+6.8+3.8}_{-11.7-6.2-3.9}\%. \tag{4.4}$$

These are the most precise measurements of $B \to \rho\gamma$ observables till date, and supersede the previous measurements performed by Belle [27].

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