SEARCH FOR THE RARE DECAY $B^+ \to \ell^+\nu_\ell\gamma$ AT BELLE AND BELLE II*

Moritz Gelb

for the Belle II Collaboration

Institute for Experimental Particle Physics (ETP)
Karlsruhe Institute of Technology (KIT)
Karlsruhe, Germany
moritz.gelb@kit.edu

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The Belle Collaboration reported an upper limit on the partial branching fraction on the rare decay $B^+ \to \ell^+\nu_\ell\gamma$ using the full dataset recorded at the $\Upsilon(4S)$ resonance. The decay allows for the extraction of the first inverse momentum of the light-cone distribution amplitude, an important parameter for QCD factorization for non-leptonic B decays. We present a Monte Carlo study applying an improved tagging algorithm developed for the Belle II experiment. We observe an increase in the signal reconstruction efficiency by a factor of three, improving the expected sensitivity to 3.8σ. Furthermore, we give an outlook for the sensitivity of measuring $B^+ \to \ell^+\nu_\ell\gamma$ with the Belle II experiment.

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1. Introduction

The Belle experiment recorded a dataset corresponding to an integrated luminosity of 711 fb^{-1} at the $\Upsilon(4S)$ resonance. Based on this dataset, a search for the rare decay $B^+ \to \ell^+\nu_\ell\gamma$ with $\ell = e, \mu$ using hadronically tagged events was carried out [1]. An upper limit on the partial branching fraction of $\Delta\mathcal{B}(B^+ \to \ell^+\nu_\ell\gamma) < 3.5 \times 10^{-6}$ for high energetic photons above 1.0 GeV was observed.

A new tagging algorithm has been developed for the Belle II experiment with improved efficiency. Using a dedicated conversion tool [2], this new algorithm can be used to re-evaluate the Belle dataset.

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2. The decay

The decay $B^+ \to \ell^+\nu_\ell\gamma$ proceeds via the weak interaction with a coupling strength proportional to the CKM matrix element $V_{\rm ub}$. The helicity suppression of the pure leptonic decay is lifted by the initial state radiation of the photon. The expected branching fraction is of the order of $\mathcal{O}(10^{-6})$ [3].

Following the analysis in reference [3], the differential decay width as a function of the photon energy E_γ can be expressed in terms of two form factors $F_{\rm A}$ and $F_{\rm V}$ as

$$\frac{{\rm d}\Upsilon}{{\rm d}E_\gamma} = \frac{\alpha_{\rm em} G_{\rm F}^2 m_B^4 |V_{ub}|^2}{48\pi^2} x_\gamma^3 (1-x_\gamma) \left[F_{\rm A}^2 + F_{\rm V}^2\right] , \tag{2.1}$$

where m_B is the mass of the B meson, $\alpha_{\rm em}$ is the electromagnetic coupling constant, $G_{\rm F}$ is the Fermi constant and $x_\gamma = 2E_\gamma/m_B$. Under the assumption of high photon energies, the form factors can be written as

$$F_{\rm V}(E_\gamma) = \frac{Q_u m_B f_B}{2E_\gamma \lambda_B(\mu)} R(E_\gamma,\mu) + \left[\xi(E_\gamma) + \frac{Q_b m_B f_B}{2E_\gamma m_b} + \frac{Q_u m_B f_B}{(2E_\gamma)^2}\right] , \tag{2.2}$$

$$F_{\rm A}(E_\gamma) = \frac{Q_u m_B f_B}{2E_\gamma \lambda_B(\mu)} R(E_\gamma,\mu) + \left[\xi(E_\gamma) - \frac{Q_b m_B f_B}{2E_\gamma m_b} - \frac{Q_u m_B f_B}{(2E_\gamma)^2} + \frac{Q_\ell f_B}{E_\gamma}\right] , \tag{2.3}$$

where Q_i denotes the charge of the corresponding particle ($i = u, b, \ell$), f_B is the decay constant of the B meson, λ_B is the first inverse momentum of the light-cone distribution amplitude of the B meson, $R(E_\gamma,\mu)$ is a radiative correction factor and m_b is the mass of the b quark. The expressions in brackets correspond to $1/m_b$ power corrections, where $\xi(E_\gamma)$ is the symmetry-preserving part.

Using the measurement of the partial branching fraction of $B^+ \to \ell^+\nu_\ell\gamma$, the value of λ_B can be extracted. This determination is an important input for QCD factorization calculations of non-leptonic B decays and difficult to predict theoretically. The latest experimental measurement of Belle found an upper limit of $\lambda_B > 238$ MeV at the 90% confidence level [1].

3. The analysis technique

The $\Upsilon(4S)$ resonance decays to exactly two B mesons with no additional particles. By reconstructing both mesons, knowledge of the full event can be used to search for missing energy modes.

We reconstruct the signal-side by combining a lepton and a photon with $E_\gamma > 1.0$ GeV. The accompanying B meson is reconstructed in over 10 000 exclusive hadronic decay channels with relatively large branching fractions.

This allows for a reconstruction of the whole $\Upsilon(4S)$ event. For correctly reconstructed events, no additional particles are expected. Hence, combinatorial background can be efficiently suppressed by requiring that there are no additional charged particles in the event. Further selection cuts are applied to optimize the signal-to-background ratio. Multivariate classifiers are utilized to suppress background from non-resonant (continuum) $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$ and $B^+ \to \pi^0\ell^+\nu_\ell$ decays. The signal yield can be extracted by analyzing the missing mass squared, defined as

$$M^2_{\mathrm{miss}} = (p_{B_{\mathrm{sig}}} - p_\ell - p_\gamma)^2 = \left(\begin{pmatrix} \frac{E_{\mathrm{CMS}}}{2c} \\ -\vec{p}_{B_{\mathrm{tag}}} \end{pmatrix} - p_\ell - p_\gamma \right)^2 , \tag{3.1}$$

where p_X $(\vec{p}_X)$ denotes the four (momentum) vector of the corresponding particle, E_{CMS} is the center-of-mass energy and c is the speed of light. Since the initial state of the $\Upsilon(4S)$ is well-known and both B mesons are produced back-to-back in the center-of-mass frame of the collision, the missing momentum of the neutrino can be calculated. The missing mass squared peaks at zero for correctly reconstructed events.

3.1. The tagging algorithm

The tag-side B meson is reconstructed by an exclusive *B-tagging* algorithm, called the Full Event Interpretation (FEI) [4, 5]. The FEI follows a hierarchical reconstruction starting from the final-state particles into intermediate resonances up to the B meson as illustrated in Fig. 1. The tag-side B meson can either be reconstructed in a hadronic or semileptonic final state. At each reconstruction step, multivariate classifiers are employed to distinguish between correctly reconstructed candidates and background.

The improvement compared to the predecessor algorithm used at the Belle experiment [6] originates from improved classifiers, an internally performed best-candidate selection and the inclusion of additional tag channels. The FEI can be used in two different modes: The *generic* mode is applied on the full event, *i.e.* before the signal-side reconstruction; the *signal-specific* mode is applied on a subset of the event containing all final-state particles not used for the signal-side reconstruction. The latter mode allows for a dedicated training of the involved classifiers on the event topology of a decay.

In this study, we use the signal-specific mode for the hadronic tag-side reconstruction. The tagging algorithm performs differently on data and Monte Carlo (MC) events. These differences are due to, *e.g.* mis-modeled dynamics of hadronic decays, a deficient detector simulation or imprecisely known branching fractions used in the simulation. The selection efficiency

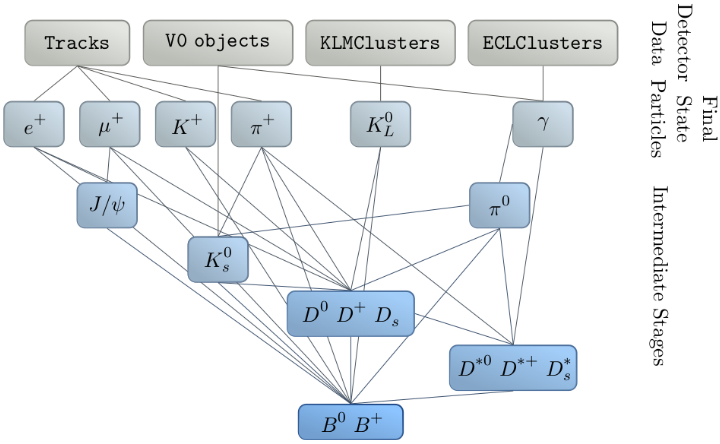


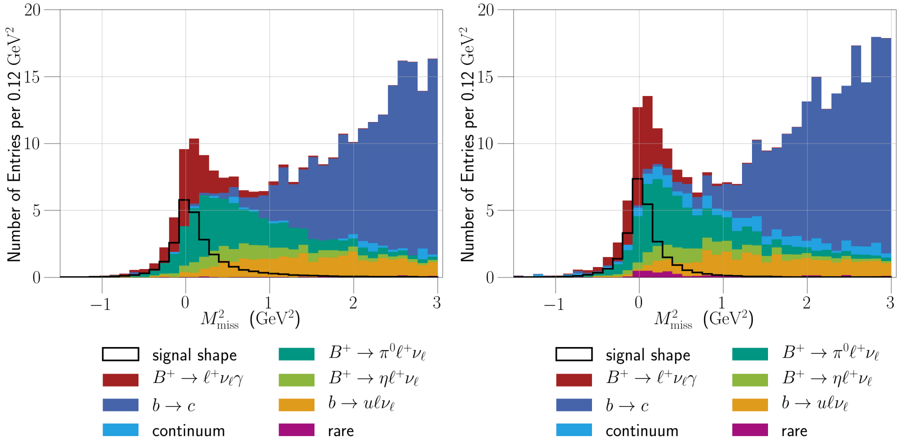
Fig. 1. Illustration of the hierarchical approach of the FEI. The graph depicts possible connections between the individual steps to reconstruct tag-side candidates in the different tag channels. Taken from [4].

of the specific FEI was calibrated using semileptonic calibration channels and a global correction factor in this study was found to be $\epsilon = 0.825 \pm 0.014\,(\mathrm{stat.}) \pm 0.049\,(\mathrm{syst.})$.

4. Conclusion

The missing mass squared distributions after the full signal selection is shown in Fig. 2. We observe an improved signal reconstruction efficiency on MC by a factor of three compared to the previous Belle analysis. The signal yield can be extracted with a binned maximum likelihood fit using template probability density functions. The expected significance is evaluated with a toy MC study for a simultaneous fit in both final states. For a given partial branching fraction of $\Delta\mathcal{B}(B^+ \to \ell^+\nu_\ell\gamma) = 5.0 \times 10^{-6}$, we find a significance of 3.8σ, which corresponds to an increase of 0.9σ compared to the previous analysis. With this improvement, it might be possible to make a first measurement of $B^+ \to \ell^+\nu_\ell\gamma$ on the Belle dataset.

In addition, we estimate the statistical error for the expected Belle II dataset of ~ 50 ab^{-1}. The expected statistical error is evaluated with a toy MC study for a simultaneous fit in both final states. The errors decrease with a larger dataset. The results can be found in Table I.



(a) Electron final state. (b) Muon final state.

Fig. 2. Missing mass squared distributions after the final selection with a simulated partial branching fraction of $\Delta\mathcal{B}(B^+ \to \ell^+ \nu_\ell \gamma) = 5.0 \times 10^{-6}$.

TABLE I

Expected statistical error in 10^{-6} for Belle and Belle II for a simulated partial branching fraction of $\Delta\mathcal{B}(B^+ \to \ell^+ \nu_\ell \gamma) = 5.0 \times 10^{-6}$.

Belle Improved analysis	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$+1.48$ -1.39	$+0.56$ -0.53	$+0.18$ -0.17

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