MONTE CARLO STUDIES OF LEPTON FLAVOR VIOLATING $B \to K\tau\ell$ DECAYS AT BELLE/BELLE II*

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Lepton flavor violating (LFV) B-meson decays are the unique probes to search for new physics and B factories provide an ideal setup to look for them. To study one such type of $B \to K\tau\ell$ ($\ell = e, \mu$) decay, we are using the basic kinematics constraints of the B factories to search for our signal decay. Initial checks for it are performed on the Belle/Belle II signal and generic Monte Carlo (MC). In these preliminary results, we have found that by using this method, we can significantly suppress the background, while retaining a good reconstruction efficiency for the signal decay.

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1. Introduction

Standard Model (SM) of particle physics is a theory that describes elementary particles and their interactions. Despite its enormous success in describing the three fundamental interactions (strong, weak, electromagnetic), it is considered incomplete as it is unable to explain the complete picture of our universe. We still have some open questions (dark matter, dark energy, matter–anti-matter asymmetry, *etc.*) for which we have to go beyond the SM (BSM). One of the ways to study new physics is to search for the decays which are not allowed in the SM and based on it, we will be able to find some new physics or constrain some parameters of the models which are predicting the BSM physics.

In this study, we are looking for one of such $B \to K\tau\ell$ decays which are not allowed in the SM, due to the violation of lepton flavor (LF), which is conserved in the SM interactions. In the neutral lepton sector, its violation is now a well-established concept because of the experimental confirmation of

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the neutrino oscillation mechanism [1]. Confirmation of LFV in the neutral lepton sector and some anomalies in the B physics [2] naturally suggest looking for the processes involving it in the charged lepton sector. $B \to K\tau\ell$ is one of the type of such decays in which LFV occurs and the current upper limit on the branching ratios for them is 2.45×10^{-5} [3], which is measured by considering the leptonic tau decay modes.

2. Experimental overview

Belle II [4] is an upgraded version of the Belle experiment [5]. Belle was located at KEKB [6] and Belle II is located at SuperKEKB [7]. Energies for e^- and e^+ are 8 GeV and 3.5 GeV for Belle and 7 GeV and 4 GeV (respectively) for Belle II. Belle collected overall data of 1 ab^{-1} from 1999–2010 and Belle II started data taking from 2019 and collected 424 fb^{-1} of the overall data in the first run. Belle II has an ambitious goal of collecting multi-ab^{-1} of the data which will enable us to explore the B physics in more detail and further push the precision physics frontiers. Most of the data in both experiments is collected at $\Upsilon(4S)$ resonance which then decays to a pair of B mesons. Because of this, we have a clean environment and well-defined kinematical constraints to study different aspects of the B physics.

3. Analysis strategy

As mentioned earlier, in the B factories, most of the data is collected at $\Upsilon(4S)$ resonance, which further decays to a pair of B mesons *i.e.* $e^+e^- \to \Upsilon(4S) \to B^+B^-$. We termed one B as our signal B (B_{sig}), and the other as tag B (B_{tag}). There are various approaches to studying the produced B mesons depending on the goal of the analysis. In our case, we are reconstructing the B_{sig} first, followed by the reconstruction of the B_{tag}. In the following subsections, we have described our approach to reconstructing the B_{sig} and B_{tag} in detail.

3.1. B_{sig} reconstruction

In this analysis, we are reconstructing the B_{sig} by $B^+ \to K^+\tau^\pm\mu^\mp$ (we are only focusing on μ, while the same method can be used for e and also charge conjugate mode is included throughout the analysis) with $\tau^\pm \to \pi^\pm\nu_\tau$. In our B_{sig} reconstruction, we are using the basic feature of B factories that when we are only able to partially reconstruct the B decays (decays involving neutrinos), *e.g.* $B^+ \to X\ell^+\nu_\ell$, we can calculate neutrino energy by using the basic kinematic condition $E_\nu = E_B - E_{X\ell}$ and can constrain the B momentum on the cone around momentum $\vec{P}_{X\ell}$. By using this concept, first, we consider the missing momentum on the signal side to be constrained around $K\mu$ cone (assuming τ is missing) and then we further consider the $\tau \to \pi\nu_\tau$ decay and constrain the missing momentum around the $K\mu\pi$ cone (missing neutrino). This complete schematic reconstruction is shown in Fig. 1 (left).

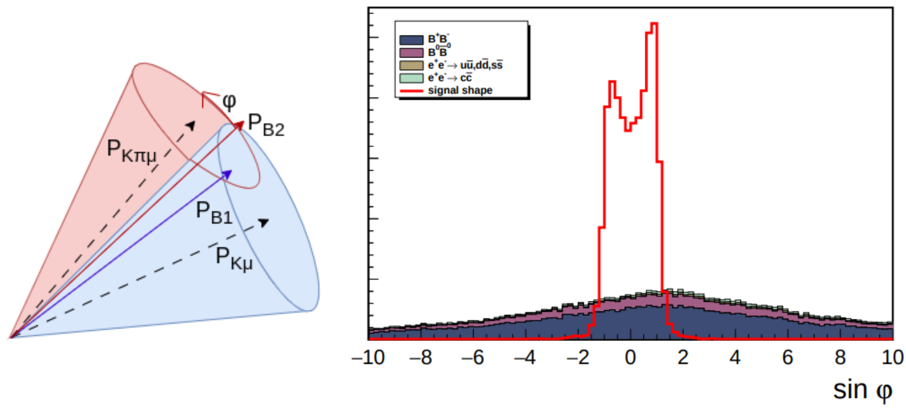

Fig. 1. (Color online) Left: reconstruction of B_{sig}, blue/light gray cone is for the case when τ is missing, while pink/gray cone is for the case when ν is missing. The intersection of these cones provides us with the $\vec{P}_B^{\mathrm{sig}}$ with two-folds ambiguity. Right: distribution of $\sin\varphi$, where red/black line represents the signal and the other colors represent the background components.

These two cones provide us with two kinematics equations that should be simultaneously true and due to this requirement, the two cones intersect with each other at two lines, and we have two possible solutions $(\vec{P}_1^B, \vec{P}_2^B)$ for the B_{sig} momentum. The intersection of these two cones gives us a very powerful discriminator variable $\sin\varphi$ (Eq. (1)), which we use to distinguish between signal and background

$$\sin\varphi = \frac{\cos\theta_{\tau,K\mu}\cos\theta_{\pi,K\mu\pi} - \cos\,\theta_{\tau,K\mu\pi}}{\sin\theta_{\tau,K\mu}\sin\theta_{\pi,K\mu\pi}}\,. \tag{1}$$

One of the best advantages of this approach is that we can recover the B_{sig} momentum independent of the B_{tag} reconstruction.

3.2. B_{tag} reconstruction

To further suppress the background, we will use the information from the B_{tag} side. In our case, we are using the inclusive tag reconstruction technique, in which we collect all the remaining tracks and clusters (after reconstructing the B_{sig}) to form the B_{tag} candidate. Once the B_{tag} candidate is formed, we implement different selection criteria on it to clean the formed

$B_{\rm tag}$ candidate. Once the initial selection is made for $B_{\rm tag}$, we can use further two different methods of reconstructing $B_{\rm tag}$, *i.e.* by using either the hadronic B decays (hadronic tagging [8]) or by using the semileptonic B decays (semileptonic tagging [9]).

3.3. Hadronic tagging

In this tagging approach, we reconstruct the $B_{\rm tag}$ from only hadronic decays of $B_{\rm tag}$. In the case of hadronic B decays, we do not have any missing particles, so we are able to fully reconstruct the $B_{\rm tag}$ and have a complete information about the $B_{\rm tag}$ momentum $\vec{P}_B^{\rm tag}$. As discussed earlier for the signal side reconstruction, we have two possible momentum solutions ($\vec{P}_1^B$, $\vec{P}_2^B$), and in this tagging approach, we have the definite momentum information $\vec{P}_B^{\rm tag}$ of the tag side. Hence, we can calculate the minimum of the cosine angles between the two possible solutions on the signal side and the $\vec{P}_{\rm tag}^B$ (Eq. (3))

$$\cos\theta_1^{\rm had} = \frac{\vec{P}_1^B \cdot \vec{P}_B^{\rm tag}}{\left|\vec{P}_1^B\right| \left|\vec{P}_B^{\rm tag}\right|}\,, \qquad \cos\theta_2^{\rm had} = \frac{\vec{P}_2^B \cdot \vec{P}_B^{\rm tag}}{\left|\vec{P}_2^B\right| \left|\vec{P}_B^{\rm tag}\right|}\,, \tag{2}$$

$$\cos\left(P_B^{\rm sig}, P_B^{\rm tag}\right)^{\rm min} = \min\left(\cos\theta_1^{\rm had}, \cos\theta_2^{\rm had}\right)\,. \tag{3}$$

Based on this distribution, we can suppress the background by using the fact that the signal should peak at -1 (Fig. 2). Using this approach in one of the preliminary studies [10], we were able to suppress the background from (0.5–0.7)%, while retaining the signal side reconstruction efficiency of 77%.

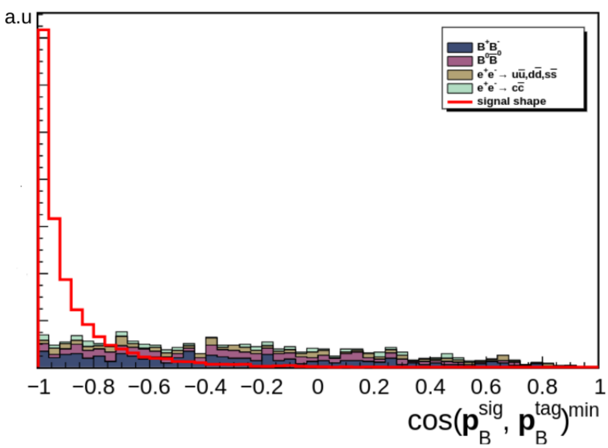

Fig. 2. Distribution of $\cos\left(P_B^{\rm sig}, P_B^{\rm tag}\right)^{\rm min}$. Our signal should peak at -1.

3.4. Semileptonic tagging

In this case, our decay is kinematically constrained as shown in Fig. 3 and we have an additional angle $\theta_{\rm tag}$ (Eq. (4)), which we can use to further tune our analysis

$$\cos\,\theta_{\rm tag} = \frac{2E_B E_{\rm vis} - m_B^2 - m_{\rm vis}^2}{2\left|\vec{P}_B^{\rm tag}\right|\left|\vec{P}_{\rm vis}^{\rm tag}\right|}\,, \tag{4}$$

where E_B is the energy of the B meson in the center-of-mass frame, m_B is the mass of the B meson, $m_{\rm vis}$ is the visible mass of the tag system, and $\vec{P}_{\rm vis}^{\rm tag}$ is the visible momentum on the tag side. We can then calculate the sum of the cosine angles (between the two possible signal side momentum solutions and the visible momentum on the tag side and $\cos\theta_{\rm tag}$), from which we select the best sum of cosine angles (Eq. (6))

$$\cos\,\theta_1 = \frac{\vec{P}_1^B \cdot \vec{P}_{\rm vis}^{\rm tag}}{\left|\vec{P}_1^B\right|\left|\vec{P}_{\rm vis}^{\rm tag}\right|}\,, \qquad \cos\,\theta_2 = \frac{\vec{P}_2^B \cdot \vec{P}_{\rm vis}^{\rm tag}}{\left|\vec{P}_2^B\right|\left|\vec{P}_{\rm vis}^{\rm tag}\right|}\,, \tag{5}$$

$$\Delta\cos\theta = \min\left|\cos\theta_{1,2} + \cos\theta_{\rm tag}\right|\,. \tag{6}$$

Based on the distribution of Eq. (6), we can further suppress background and distinguish between signal and background events by using the fact that $B_{\rm sig}$ and $B_{\rm tag}$ will lie opposite to each other and the signal will peak at zero (Fig. 4).

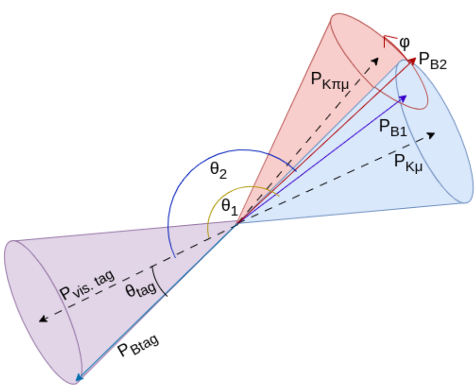

Fig. 3. Kinematic constraints for the semileptonic tag. Due to a missing ν on the tag side, $\vec{P}_B^{\rm tag}$ momentum is constrained on a cone around $\vec{P}_{\rm vis}^{\rm tag}$.

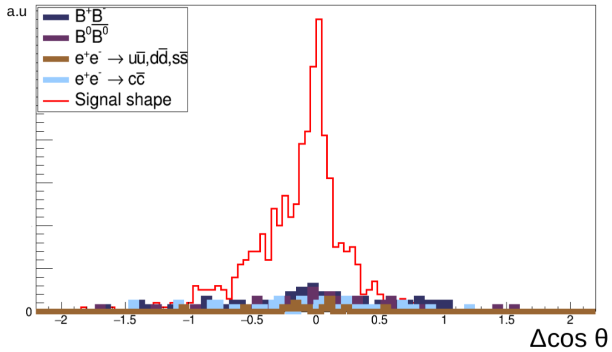

Fig. 4. $\Delta\cos\theta$ distribution for the semileptonic tag, the signal should peak at zero.

4. Summary

By exploiting the basic kinematic constraints provided by the B factories, we are studying the $B \to K\tau\ell$ ($\tau \to \pi\nu_\tau$) decays at Belle/Belle II. In our first set of checks, we have found promising results for the case of $B \to K\tau\mu$.

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