SEARCH FOR LEPTON FLAVOR VIOLATING $B \to K\tau\ell$ DECAYS AT BELLE*

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Received 4 April 2025, accepted 24 April 2025, published online 26 June 2025

Lepton Flavor Violation (LFV) in the neutral lepton sector (neutrino oscillation mechanism) compels us to check for LFV in other physics processes to hunt for any New Physics (NP) signatures. LFV B-meson decays $B \to K\tau\ell$ ($\ell = e, \mu$) are one such example, which in some NP scenarios are within the reach of current experimental sensitivity. We are searching for them in Belle, which provides a clean environment to study such processes. Using the boosted decision tree approach, we have significantly suppressed the background. Validation of the analysis approach is performed on two different control modes, and we have found reasonable agreement between the Belle data and Monte Carlo (MC).

DOI:10.5506/APhysPolBSupp.18.5-A27

1. Introduction

The Standard Model (SM) of particle physics describes the fundamental particles and their interactions. In the case of massless neutrinos in SM, individual lepton flavor numbers are anticipated to be conserved [1]. However, the well-established mechanism of neutrino oscillations provided evidence of non-zero neutrino masses [2] and hence confirmed the LFV in the neutral lepton sector. After this confirmation, there is also a need to search for processes involving LFV in the non-neutral lepton sector.

We are studying the $B \to K\tau\ell$ ($\ell = e, \mu$) decays, which are the LFV processes in B-physics. Some NP models (*e.g.* lepto-quark [3]) predict their branching fractions of the order of 10^{-7}. The current Upper Limits (UL) on them (with 90% confidence level) are in the range of $(0.59–2.45) \times 10^{-5}$, which are set by the Belle Collaboration [4] by using the hadronic tagging

* Presented at the 31$^{\text{st}}$ Cracow Epiphany Conference on the *Recent LHC Results*, Kraków, Poland, 13–17 January, 2025.

method [5] and considering mainly the leptonic τ-decay modes. In this analysis, we are using the semileptonic tagging method [6] (which is more efficient as compared to the hadronic tagging) to reconstruct the tag side and using the semileptonic τ-decay mode $\tau \to \pi\nu_\tau$ to improve the existing UL.

2. Experimental overview

The Belle experiment [7] was based on the KEKB [8] asymmetric lepton collider that collected around $1\,\mathrm{ab}^{-1}$ of data in 1999–2010. Energies for e^+ and e^- beams were set to be at 3.5 GeV and 8 GeV respectively. Most of the data was collected at the $\Upsilon(4S)$ resonance energy state which further decays into a pair of B-mesons. This feature (two clean back-to-back B-mesons in the centre-of-mass frame) of the Belle experiment makes it an ideal place to study the different B-physics phenomena.

3. Analysis strategy

In this analysis, we are using the basic kinematic constraints of the Belle experiment to reconstruct the complete decay. As already mentioned, every $\Upsilon(4S)$ resonance state produces a pair of B-mesons. We named one produced B-meson as the B_{sig} and the other as B_{tag} which further decays as follows:

$$\begin{array}{ll} B_{\mathrm{sig}}: & B^+ \to K^+\tau^-(\to \pi^-\nu_\tau)\mu^+ \\ B_{\mathrm{tag}}: & B^- \to X\ell^-\nu_\ell\,, \quad X \text{ is any hadron system}^1. \end{array}$$

The details of the reconstruction of a complete decay are illustrated in Fig. 1. For the signal side reconstruction, first, we assume that τ is missing so that the missing momentum can be constrained around the momentum of $K\mu$ ($p_{K\mu}$), and then we consider the $\tau \to \pi\nu_\tau$ decay and constrain the missing momentum around the momentum of $K\mu\pi$ ($p_{K\mu\pi}$). These two cones represent the two kinematic conditions which should be simultaneously true. So they intersect on two lines and provide the B_{sig} momentum ($p_{B_{\mathrm{sig}}}$) with two fold ambiguity (p_{B_1}, p_{B_2}).

On the tag side, we also have a missing neutrino, so the missing momentum can be constrained around the $p_{\mathrm{vis.tag}}$ (which is the sum of p_X and p_ℓ). We can define a variable $\Delta\mathrm{cos}\theta$ as

$$\Delta\mathrm{cos}\theta = \min\left|\cos\theta_{[1,2]} + \cos\theta_{\mathrm{tag}}\right|, \tag{1}$$

[1] Here, we are only considering the $B^+ \to K^+\tau^-\mu^+$ case, while the same method can be used for the other three cases $B^+ \to K^+\tau^+\mu^-$, $B^+ \to K^+\tau^-e^+$, $B^+ \to K^+\tau^+e^-$. Charge conjugate modes are also incorporated for both B_{sig} and B_{tag}.

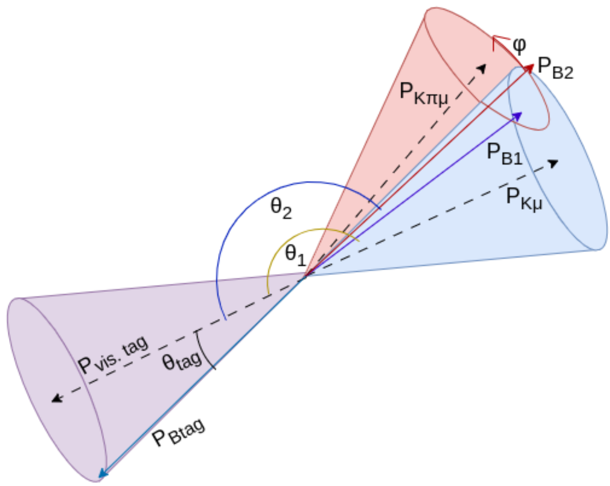

Fig. 1. The illustration of variables used in the event reconstruction.

where $\theta_{[1,2]}$ are the angles between the two $p_{B_{\rm sig}}$ solutions (p_{B_1}, p_{B_2}) and the $p_{\rm vis.tag}$, while $\theta_{\rm tag}$ is the angle between $p_{\rm vis.tag}$ and the $p_{\rm B_{tag}}$ (assuming the beam energy in the centre-of-mass frame and B-meson mass). Variable $\Delta\cos\theta$ contains information from both the signal and tag side, and has a good discriminating power between signal and background. For the true signal events, it should peak at zero as the $B_{\rm sig}$ and $B_{\rm tag}$ should be anti-parallel to each other. More in-depth details about the reconstruction methodology can be found in [9].

4. Boosted Decision Tree approach

Boosted Decision Tree (BDT) is a machine learning technique to effectively distinguish between signal and background. It combines multiple decision trees (using a boosting method such as AdaBoost or Gradient Boosting) based on the different input variables to provide better separation between the signal and background [10]. In this analysis, after making some initial veto selections to reject the obvious background, we use the BDT approach to further improve the signal to background ratio. We are using six input variables ($\Delta\cos\theta$, mass of the hadronic system on tag side, momentum of tag side lepton, total number of photons, difference between the beam energy and the reconstructed $B_{\rm tag}$ energy, total number of leptons) to train the BDT.

For the signal, we are using 1.0 M, $B^+ \to K^+\tau^-(\to \pi^-\nu_\tau)\mu^+$ dedicated signal MC sample (0.7 M is used for training and 0.3 M for testing) and for background we are using Belle generic MC sample ten times Belle data

(70% used for training and 30% for testing). For optimizing the BDT score, we are using the Punzi figure of merit [11], which is defined as

$$\mathrm{FOM}_{\mathrm{Punzi}} = \frac{\epsilon(t)}{\frac{\alpha}{2} + \sqrt{B(t)}}\,, \tag{2}$$

where $\epsilon(t)$ is the signal efficiency, α is the desired significance, and $B(t)$ is the number of background events remaining in the signal region (for the selection t). We have validated the BDT on an independent 4.4 M dedicated $(B^+ \to K^+\tau^-(\to \text{generic})\,\mu^+)$ sample and for background validation, we used the Belle generic MC one times the Belle data set. The BDT score is shown in Fig. 2 for the validated signal and background samples. In the enhanced signal region (BDT > 0.13), we expect $N_{\mathrm{sig}} = 13$ (for the branching fraction of 5×10^{-5}), corresponding to the $N_{\mathrm{bkg}} = 102$. Currently, we are only considering the B^+B^-, $B^0\bar{B}^0$ background as they are the dominant background components.

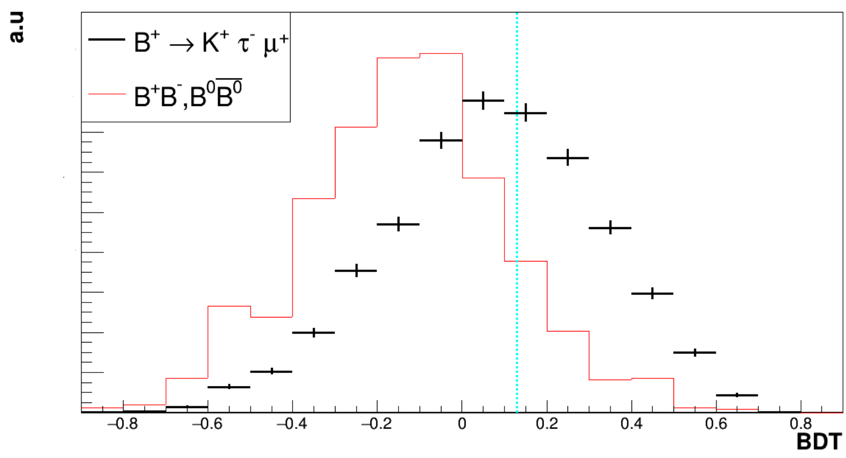

Fig. 2. The BDT score (normalized to one for both signal and background) for dedicated signal and generic (B^+B^-, $B^0\bar{B}^0$) MC. The region to the right of the blue dotted line represents the signal-enhanced region.

5. Control modes validation

As we are doing a blind analysis [12], we have to use some control channel modes to validate the analysis approach (by using the actual Belle data). These are the modes with the similar kinematics as the signal decay and with well-understood properties. We are using the following two modes as control channel modes:

$$
\begin{aligned}
B^+ &\to J/\psi(\to \mu^+\mu^-)K^+ \\
B^+ &\to \bar{D}^0(\to K^+\pi^-)\pi^+ \,.
\end{aligned}
$$

Both these decays are topologically similar to the signal decay and we assume that one particle (μ^-, π^- respectively) is missing so that they can completely replicate the signal reconstruction methodology. We used the full Belle data set and Belle generic MC sample three times the Belle dataset (normalized to the Belle luminosity) to check the data/MC agreement. We have found a reasonable agreement of the shape between data and MC in both control channel modes. The comparison of distributions for the most important variable in the BDT discrimination between signal and background, $\Delta\cos\theta$, is shown in Fig. 3.

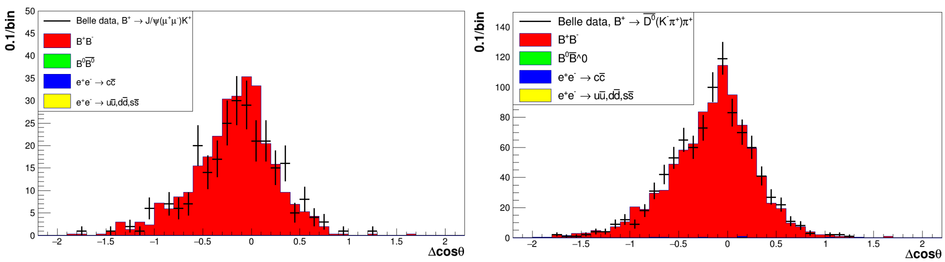

Fig. 3. Distributions of $\Delta\cos\theta$ for $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ (left side) and $B^+ \to \bar{D}^0(\to K^+\pi^-)\pi^+$ (right side).

6. Summary

The analysis strategy for searching for LFV decays, $B \to K\tau\ell$ ($\ell = e, \mu$) decays, using semileptonic tagging at Belle is presented. For suppressing the background, we have used the BDT approach. We have validated the analysis approach on two different control modes and found reasonable agreement between the data and MC.

This work is partially supported by the Polish National Agency for Academic Exchange NAWA under the Programme STER — Internationalisation of doctoral schools, project No. BPI/STE/2023/1/00027/U/00001.

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