PROCEEDINGS OF SCIENCE

Measurements of electroweak penguin and lepton-flavour violating B decays to final states with missing energy at Belle and Belle II

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Electroweak penguin and lepton-flavor violating B decays are key focuses of the Belle II physics program. These processes are particularly challenging due to the presence of neutrinos in the final states, resulting in 'missing energy' in the rare $b \to s$ transitions. Using electron-positron collision data collected at the $\Upsilon(4S)$ resonance, we present the first evidence for $B^+ \to K^+ \nu\bar{\nu}$ decay and the most stringent upper limit on $B^0 \to K^{*0}\tau^+\tau^-$ decay. Additionally, combining Belle and Belle II data, we report the first search on lepton-flavor violating $B^0 \to K_S^0 \tau^\pm \ell^\mp$ ($\ell = e, \mu$) decays.

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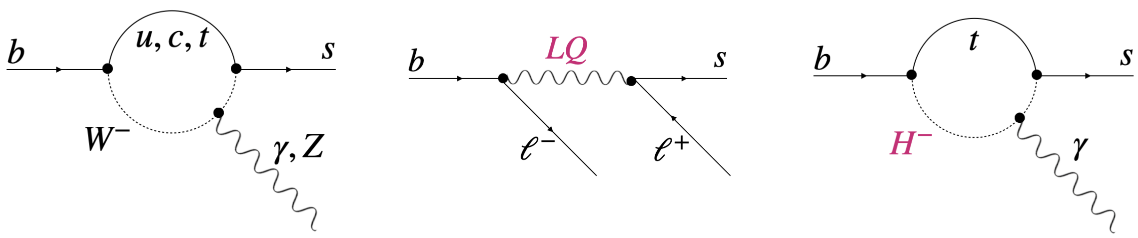
1. Introduction

The transition of a b quark to a s quark, involving a flavor-changing neutral current (FCNC), serves as an excellent probe for physics beyond the Standard Model (SM). In the SM, FCNC processes are forbidden at the tree level and only occur through loop diagrams, such as the 'electroweak penguin' transitions shown in Fig. 1a. Due to the suppression of these loop diagrams and the rarity of $b \to s$ transitions, branching fractions typically range from $O(10^{-7})$ to $O(10^{-5})$. Studies of these decays at Belle (II) aim to detect alterations in decay rates due to New Physics (NP) contributions, which could manifest as new interactions at the tree level (Fig. 1b) or as reduced GIM cancellations in loop corrections (Fig. 1c). Additionally, NP mediators might cause the decay rates of lepton-flavor violating (LFV) decays, which are strictly forbidden in the SM, to become non-zero.



(a) SM contributions **(b)** Leptoquark scenario **(c)** Charged Higgs scenario

Figure 1: Diagrams representing $b \to s$ transitions: SM contributions (a) and possible NP scenarios (b,c).

Belle [1] operated at the KEKB asymmetric e^+e^- collider [2] in Tsukuba, Japan. Its successor, Belle II [3], operates at SuperKEKB, which is designed to achieve forty times higher instantaneous luminosity than KEKB [4]. (Super)KEKB collides e^+e^- at the energy threshold of the $\Upsilon(4S)$, producing almost exclusively $B\bar{B}$ pairs, resulting in a relatively low-background environment compared to $p\bar{p}$ colliders. The $B\bar{B}$ (on-resonance) data samples used in this work correspond to integrated luminosities of 711 fb^{-1} from Belle and 362 fb^{-1} from Belle II. The production of a $B\bar{B}$ pair with no additional particles is a key element in the study of final states involving neutrinos, where the decays cannot be fully reconstructed as neutrinos are invisible to the detector. The missing energy from the neutrinos coming from the signal B meson (B_{sig}) can be deduced from the other accompanying B meson, known as the tag B meson (B_{tag}). The Belle (II) detector, with its large solid-angle coverage and well-known initial kinematics, is perfectly suited for studying channels with missing energy using the two tagging methods listed below.

Inclusive tagging: employed first by Belle, this method exploits the inclusive properties of accompanying B meson decays, which offer high efficiency but large background and strong dependence on simulations.

Hadronic tagging: fully reconstruct a list of specific hadronic B decays using a machine-learning-based algorithm called Full Event Interpretation (FEI) algorithm [5]. This approach minimizes the B_{tag} background and provides the strictest constraint on B_{sig} by enforcing $\mathbf{p}(B_{\text{sig}}) = -\mathbf{p}(B_{\text{tag}})$ at the center mass of $\Upsilon(4S)$. However, this method has a very low efficiency, typically less than 1%.

This report is organized as follows: Sections 2 and 3 cover the searches for FCNC decays $B^+ \to K^+\nu\nu$ (described in Ref. [6]) and $B^0 \to K^{*0}\tau^+\tau^-$ at Belle II. Section 4 presents the search for LFV decay $B^0 \to K_S^0 \tau^\pm \ell^\mp$ ($\ell = e, \mu$) at Belle and Belle II. The latter two results are new for ICHEP 2024.

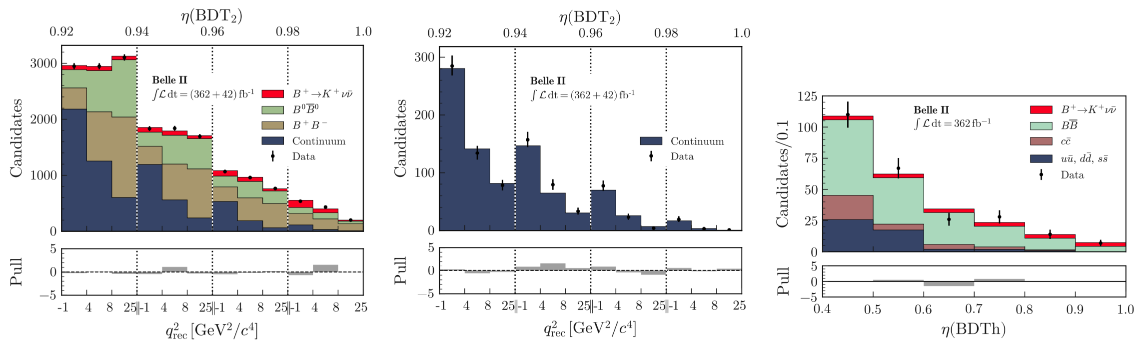
2. Evidence of $B^+ \to K^+ \nu\bar{\nu}$ at Belle II

The $b \to s\nu\bar{\nu}$ transitions involve a large amount of missing energy, a challenge for the reconstruction of potential signals. Belle II's features—such as its hermeticity and knowledge of initial-state kinematics—enable effective searches for these events using a tagging method. For $B^+ \to K^+\nu\bar{\nu}$ searches at Belle II, both inclusive and hadronic tagging approaches have been employed.

In the inclusive approach, the kaon with the highest transverse momentum (p_T) is selected. Backgrounds are suppressed using two consecutive Boosted Decision Trees (BDT_1 and BDT_2). BDT_2 is trained on simulated samples restricted to high BDT_1 output (η). The signal yield is extracted through a binned maximum likelihood fit in bins of $\eta(\text{BDT}_2) \times q^2$, using data from the $\Upsilon(4S)$ resonance and 60 MeV below (off-resonance data), as shown in Fig. 2a and 2b. The $B^+ \to K^+\nu\bar{\nu}$ branching fraction is measured to be $(2.7 \pm 0.5(\text{stat.}) \pm 0.5(\text{syst.})) \times 10^{-5}$, with a 3.5σ significance and a 2.9σ deviation from the SM.

The hadronic tagging method selects events with only 2% overlap in the signal region with the inclusive tagging analysis, making it essentially an independent sample. As shown in Fig. 2c, a single BDT is used to suppress the backgrounds and the output $\eta(\text{BDTh})$ is considered as the final observable to extract the signal yield. The $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$ is measured to be $(1.1\ ^{+0.9}_{-0.8}(\text{stat.})^{+0.8}_{-0.5}(\text{syst.})) \times 10^{-5}$, with a significance of 1.1σ and a 0.6σ deviation from the SM. The two $\mathcal{B}$ results are consistent with each other in 1.2σ.

The combined $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$ is $(2.3 \pm 0.7) \times 10^{-5}$ with 3.5σ signal significance and 2.7σ deviation above the SM expectation. This is the first evidence of the $B^+ \to K^+\nu\bar{\nu}$ decay.



(a) (b) (c)

Figure 2: Observed yields and fit results in bins of (a,b) the $\eta(\text{BDT}_2) \times q^2_{\text{rec}}$ space obtained by simultaneous fit to the on and off-resonance data using the inclusive tagging method and in bins of (c) the $\eta(\text{BDTh})$ space using the hadronic tagging method [6].

3. Search for $B^0 \to K^{*0}\tau^+\tau^-$ using hadronic tagging at Belle II

Searches of the $b \to s\tau^+\tau^-$ transitions have been performed at LHCb and BaBar [7, 8] but with no observation, due to the challenging experimental reconstruction of τ decays and the very low SM branching fractions of $\mathcal{O}\left(10^{-7}\right)$ [9, 10]. However, significant enhancements to the rates are predicted for the same scenarios leading to an excess in $R(D^{(*)})$ [11]. For the $\mathcal{B}\left(B^0 \to K^{*0}\tau^+\tau^-\right)$ measurement, Belle has set an upper limit (UL) at 90% confidence level (CL) of 3.1×10^{-3} [12].

Belle II searches for the $B^0 \to K^{*0}\tau^+\tau^-$ decay using the FEI algorithm for hadronic B-tagging and extended to additional τ decay modes to increase the efficiency. Based on the τ decay products (t_τ), the signal channels are divided into $\ell\ell$, $\ell\pi$, $\pi\pi$, and ρX (where X can be ℓ, π, or ρ) categories, with the $\ell\ell$ category having the highest sensitivity. A BDT classifier is trained to suppress the background using variables such as the missing energy, the unreconstructed energy in the electromagnetic calorimeter, the invariant mass of the $K^* t_\tau$ pair, and q^2. Figure 3(left) shows the q^2 distribution as an example. The BDT output η(BDT) is used to extract the signal yield through a simultaneous fit to the four categories as shown in Fig. 3(right).

No significant signal is observed, and the UL is determined to be $\mathcal{B}^{\rm UL} = 1.8 \times 10^{-3}$ at 90% CL, representing an improvement of about a factor of 2 compared to the Belle result, despite using a sample corresponding to only half of the Belle data sample. This improvement is primarily attributed to the increased efficiency due to the hadronic tagging. This result represents the best UL on the $B^0 \to K^{*0}\tau^+\tau^-$ decay and on $b \to s\tau^+\tau^-$ transitions in general.

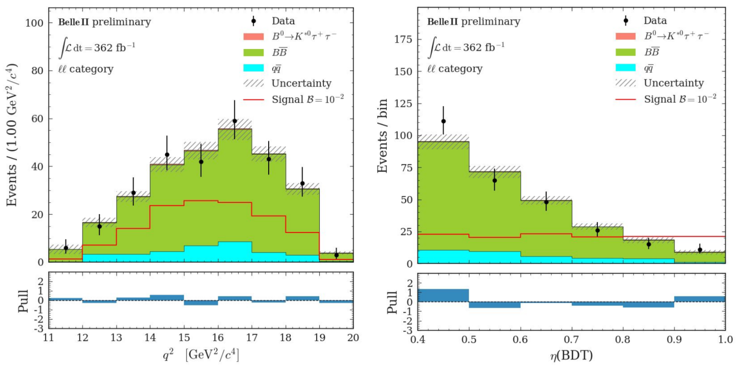


Figure 3: Distributions of q^2 (left) and η (BDT) (right) in the signal region for the $\ell\ell$ signal category.

4. Search for $B^0 \to K^0_S\tau^\pm\ell^\mp, (\ell = e, \mu)$ using hadronic tagging at Belle and Belle II

The Belle $\Upsilon(4S)$ dataset, the largest ever collected at B-factory experiments, remains an invaluable sample for searching very rare or forbidden B decays. By converting the Belle detector data into a basf2[1]-compatible format, these searches can benefit from the enhanced analysis tools available in Belle II [14]. The $b \to s\ell\ell'$ searches have been stimulated by the persistent anomalies in B decays. Extensions of the SM [15–17] that aim to explain the discrepancies observed in $B^+ \to K^+\nu\bar{\nu}$ and $R(D^{(*)})$ would predict enhancements in the rates of LFV $b \to s\tau\mu$ decays, which are strictly forbidden in the SM, up to $\mathcal{O}(10^{-6})$.

[1]Belle II analysis software framework [13]

We search for $B^0 \to K_S^0 \tau^\pm \ell^\mp (\ell = e, \mu)$ decays using the Belle and Belle II data samples. This analysis includes four distinct modes, each representing a specific set of couplings for theoretical interpretation and different background characteristics. The $B_{\rm tag}$ reconstructed via FEI with precise e^+e^- collision kinematics, allowing to infer the 4-momentum of the $B_{\rm sig}$ meson. As a consequence of this approach all the missing energy derives from a single τ lepton. We compute and fit the recoil mass M_τ using the $B_{\rm tag}$ and the $K_S^0 \ell$ system to derive the signal yield, as shown in Fig. 4.

The dominant $B \to D(\to K_S^0 X)\ell\nu$ background, where ℓ is the primary signal lepton and X represents any other particles, is suppressed by requiring $M(K_S^0 t_\tau)$ to exceed the D mass threshold. A BDT classifier is trained to suppress the remaining continuum (<15%) and $B\bar{B}$ background leading by $B \to D(\to K_S^0 \ell\nu)X$ decays using the variables such as $M_{K_S^0 \ell}$, the unreconstructed energy in the calorimeter, event shape variables, etc. As no evidence of signal is found, the ULs on the branching fractions are set at 90% CL:

$$\mathcal{B}(B^0 \to K_S^0 \tau^+ \mu^-) < 1.1 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^- \mu^+) < 3.6 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^+ e^-) < 1.5 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^- e^+) < 0.8 \times 10^{-5}$$

This is the first search on $B^0 \to K_S^0 \tau^\pm \ell^\mp$ channels. The results on the $B^0 \to K_S^0 \tau^\pm e^\mp (\mu^\mp)$ decays are (among) the best UL on $b \to s\tau\ell$ transition to date.

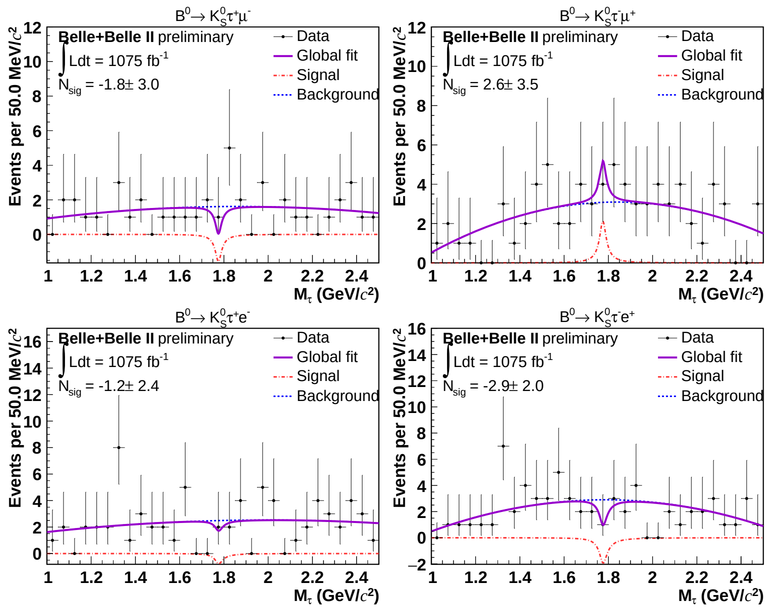


Figure 4: Observed M_τ fits. The black dots with error bars show the data, the red curve shows the signal component, the blue curve shows the background component, and the purple curve shows the global fit.

5. Conclusion

The Belle (II) detector, with its solid-angle coverage and well-known initial kinematics, offers an ideal place for studying B meson decays involving missing energy through various tagging methods.

Current results show that Belle II can achieve competitive, or even world-leading, precision already with a relatively limited amount of data.

Using 362 fb^{-1} data from Belle II, the FCNC process $B^+ \to K^+\nu\bar{\nu}$ has been analyzed with both inclusive and hadronic tagging methods. The combined branching fraction $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (2.3 \pm 0.7) \times 10^{-5}$ exhibits a 3.5σ signal significance and a 2.7σ deviation from the SM expectation, providing the first evidence for this decay.

Additionally, the FCNC process $B^0 \to K^{*0}\tau^+\tau^-$ has been investigated using hadronic tagging with the same Belle II data sample. The most stringent UL for this process is set at 1.8×10^{-3} at 90% CL, representing the tightest constraint on $b \to s\tau^+\tau^-$ to date.

A search for the LFV decay $B^0 \to K_S^0\tau^\pm\ell^\mp$ ($\ell = e, \mu$) has been conducted for the first time using hadronic tagging with combined Belle and Belle II data samples. The ULs measured are $[0.8 - 3.6] \times 10^{-5}$ at 90% CL, with the results for the $B^0 \to K_S^0\tau^\pm e^\mp$ and $B^0 \to K_S^0\tau^\pm\mu^\mp$ channels being the best and among the best ULs on $b \to s\tau\ell$ transitions achieved to date.

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