

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

Gaetano de Marino*, on behalf of the Belle II collaboration

Presented at the 32nd International Symposium on Lepton Photon Interactions at High Energies, Madison, Wisconsin, USA, August 25-29, 2025

Abstract

The Belle and Belle II experiments have collected a 1.2 ab^{-1} sample of collisions at a center-of-mass energy corresponding to the $Y(4S)$ resonance. These data, with low particle multiplicity and constrained initial state kinematics, are an ideal environment to search for rare electroweak penguin B decays and lepton-flavor-violating B decays to final states with missing energy from neutrinos. Results from $b \rightarrow s\nu\bar{\nu}$ processes and their interpretation are presented. In addition, we provide an overview of the search for the $B \rightarrow K^{*0}\tau^+\tau^-$ decays and the lepton-flavor violating decays $B \rightarrow K^{(*)}\tau^\pm\ell^\mp$, where ℓ is an electron or a muon.

1 Introduction

B meson decays are exhibiting, at different levels of significance, discrepancies – or *anomalies* – with respect to the Standard Model (SM) predictions, which might hint at common New Physics (NP) effects [1, 2, 3]. In flavor-changing neutral current processes, beyond-SM particles can contribute through additional diagrams where they appear as mediators, either at tree or loop level, or in the final state. Given the current experimental status, final states involving third-generation leptons (τ, ν_τ) are expected to couple more strongly to NP particles potentially related to these anomalies. However, the presence of undetectable particles (missing energy) makes the corresponding searches and measurements particularly challenging.

These proceedings summarize recent published and preliminary results obtained using the data collected by the Belle and Belle II experiments. The transitions $b \rightarrow s\nu\bar{\nu}$, $b \rightarrow s\tau\bar{\tau}$, and $b \rightarrow s\tau\bar{\ell}$ are discussed in dedicated sections below.

*Jožef Stefan Institute, Jamova cesta 39, 1000 Ljubljana. Email: gaetano.demarino@ijs.si

2 B-factories and missing energy

The B -factories KEKB and its upgrade SuperKEKB have collected e^+e^- collision data at the $Y(4S)$ resonance corresponding to 711 fb^{-1} (Belle) and 365 fb^{-1} (Run 1) + 125 fb^{-1} (Run 2) for Belle II. The results presented here use either Belle II-only or combined Belle and Belle II samples, excluding Run 2 data.

The $Y(4S)$ decays almost exclusively into $B^0\bar{B}^0$ or B^+B^- pairs. For analyses involving missing energy, a reconstruction of the companion B meson (B -tagging) is performed to interpret the event and infer the otherwise inaccessible signal- B properties. In the inclusive tagging approach, all reconstructed particles other than the signal are used to define the tag- B , a method well suited for low-multiplicity decays such as $B \rightarrow K\nu\bar{\nu}$. Other analyses employ hadronic tagging, in which the tag- B candidates are fully reconstructed in known hadronic modes. This method provides precise event kinematics knowledge but suffers from low efficiency, which is mitigated using multivariate algorithms [4].

3 $b \rightarrow s\nu\bar{\nu}$ searches

The first evidence of the $B^+ \rightarrow K^+\nu\bar{\nu}$ decays reported by Belle II [1] assumes the Standard Model (SM) signal expectation [5]. To further investigate the observed 2.7σ excess, a reinterpretation using a histogram reweighting method [6] is performed for the first time. With the null hypothesis being built from the SM cross section, alternative models can be probed by applying the appropriate weights. For $B^+ \rightarrow K^+\nu\bar{\nu}$ decays, these weights depend on $q^2 = (p_\nu + p_{\bar{\nu}})^2$, mapped to the reconstructed variable $q_{\text{rec}}^2 = s/4 + M_K^2 - \sqrt{s}E_K^{*1}$, together with the signal classifier output. This approach enables quantitative inference on alternative scenarios, including those with additional dimension-six operators in the weak effective theory (WET) framework. The data favor enhanced vector and nonzero tensor contributions compared to the SM prediction (Fig. 1a). The paper [7] shows the feasibility of the method and provides the likelihood inputs for ready-to-use reinterpretations.

We have recently performed a search for $B \rightarrow X_s\nu\bar{\nu}$ decays using a sum-of-exclusive approach and Belle II data. This technique, applied for the first time to decays with missing energy, improves upon the only previous measurement [8], whose upper limit remains well above the precise SM prediction [9]. The analysis employs hadronic B -tagging, followed by reconstruction of the X_s system in 30 modes with strangeness $S = \pm 1$. Background suppression relies on a multivariate algorithm (boosted decision trees, BDT's), where strong discrimination is provided by the residual energy in the electromagnetic calorimeter originating from unreconstructed particles or background. The fit to the data (Fig. 1b) is performed in three different X_s reconstructed invariant mass ranges, which are enhanced in the K , $K^*(892)$ and higher-mass X_s modes. For signal extraction, the reconstructed mass is converted back to the true one $M(X_s)$. The branching fractions measured in the three X_s mass regions are not statistically significant, and upper limits are set. The result in the K mass region agrees with that of Ref. [1] (hadronic tag). The combined 90% confidence level limit on $\mathcal{B}(B \rightarrow X_s\nu\bar{\nu})$ is the most stringent obtained so far.

¹ s is the squared center-of-mass (c.m.) energy, M_K the known K^+ mass, and E_K^* the reconstructed kaon energy in the c.m. frame.

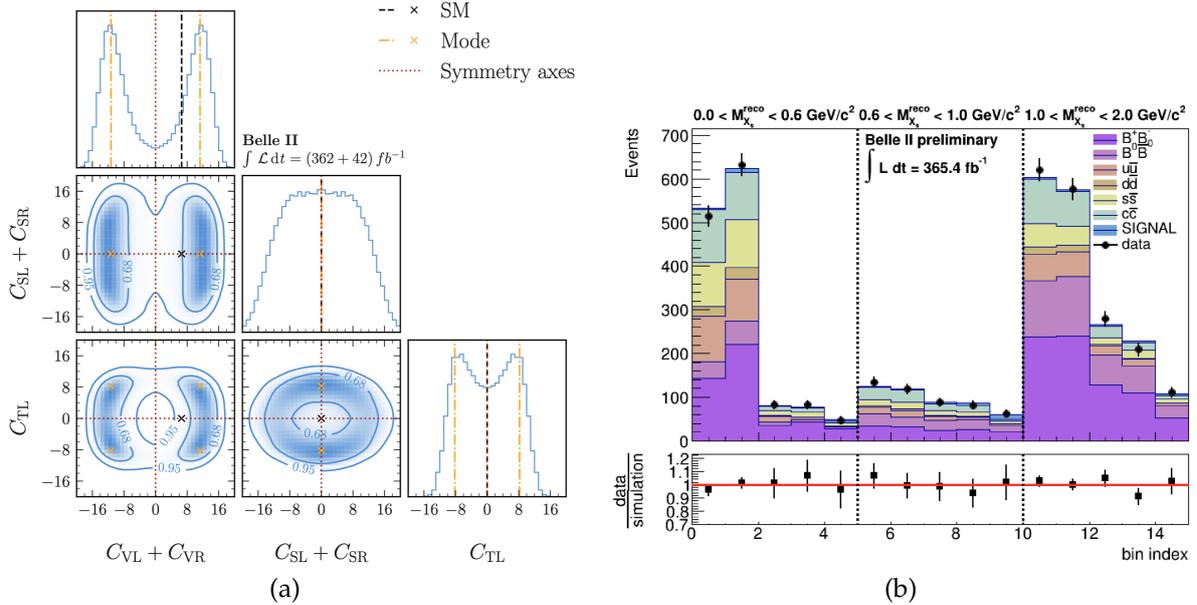


Figure 1: ($b \rightarrow s\nu\bar{\nu}$) recent Belle II results. (a): Reinterpretation [7] of the $B^+ \rightarrow K^+\nu\bar{\nu}$ evidence with marginalized posterior for WET Wilson coefficients (real C_{V_R, S_R, T_R} sums). Contours: 68/95% credible intervals; dashed: SM; dash-dotted: mode; dotted: symmetry axes for sample symmetrization. (b): $B \rightarrow X_s\nu\bar{\nu}$ data and post-fit histogram templates in three X_s mass regions, with bins representing optimized BDT output ranges. Backgrounds are separated into charged and neutral B decays, and four $e^+e^- \rightarrow q\bar{q}$ components ($q = u, d, s, c$).

4 $b \rightarrow s\tau\bar{\tau}$ searches

The $b \rightarrow s\tau^+\tau^-$ decays have SM branching fractions of $\mathcal{O}(10^{-7})$, far below current experimental sensitivity. However, they can be significantly enhanced — by up to three orders of magnitude in new physics scenarios addressing the anomalies in $R(D^{(*)})$ and $\mathcal{B}(B^+ \rightarrow K^+\nu\bar{\nu})$. At Belle II, we search for $B^0 \rightarrow K^{*0}\tau^+\tau^-$ decays [10] using the hadronic B -tagging approach, reconstructing both τ leptons in their dominant one-prong decay modes. A BDT is employed to suppress backgrounds, exploiting missing-energy information, reconstructed q^2 , kinematic variables, and K^{*0} properties. Calibration and validation are performed using off-resonance data², same-flavor events, and clean $B^0 \rightarrow K^{*0}J/\psi$ decays. The signal yield is extracted from a fit to the BDT output in a signal-enhanced region, performed simultaneously across four di- τ final-state categories with different purities and background compositions. No significant signal is observed, and an upper limit on the branching fraction is set, improving substantially over the previous Belle result [11].

5 $b \rightarrow s\tau\{e\mu\}$ searches

Charged lepton flavor violation (cLFV) is allowed in the SM via neutrino mixing, but at rates far below experimental sensitivity. Several NP models addressing tensions in B decays, while respecting other flavor constraints, can produce measurable cLFV

²Collected about 60 MeV below the $Y(4S)$ resonance, providing a $B\bar{B}$ -free sample.

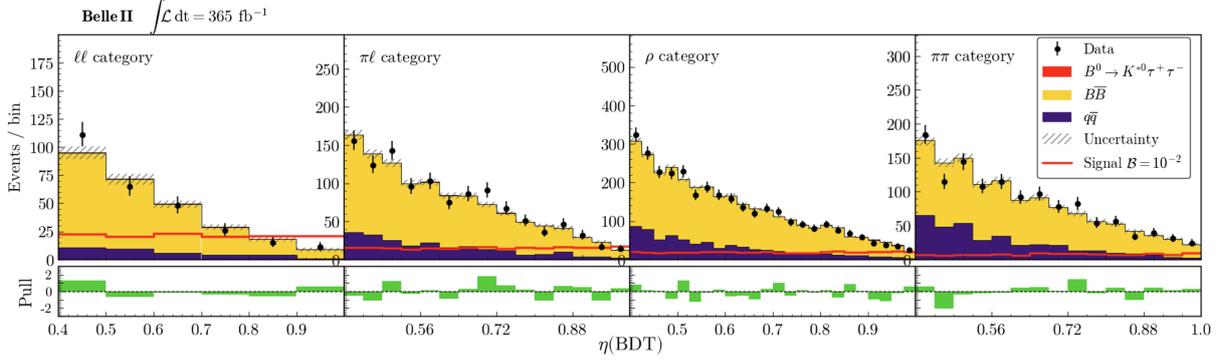


Figure 2: Transformed BDT distributions for four signal categories, showing $B\bar{B}$ and $q\bar{q}$ ($q = u, d, s, c$) backgrounds, the $B^0 \rightarrow K^0 \tau^+ \tau^-$ signal, and a reference signal at $\mathcal{B} = 10^{-2}$. From [10].

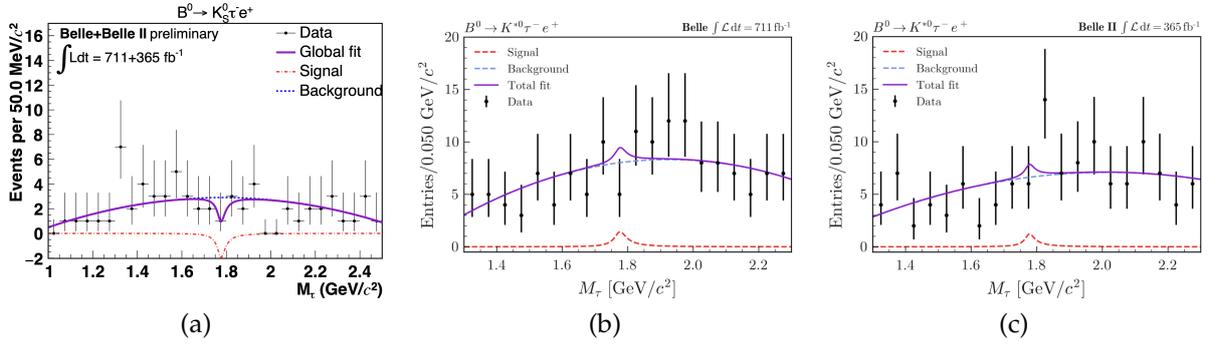


Figure 3: Fits to the recoil mass in the $\bar{b} \rightarrow \bar{s} \tau^- e^+$ data for the (a): K_S^0 mode, where Belle and Belle II data are combined (from [15]); (b),(c): K^{*0} mode, with a simultaneous fit to the two datasets (from [16]).

rates [12]. The experimental sensitivity for $b \rightarrow s \tau \ell$ decays has now reached the sub- 10^{-5} level with Belle [13] and LHCb [14].

These proceedings focus on recent searches for $B^0 \rightarrow K_S^0 \tau \ell$ [15] and $B^0 \rightarrow K^0 \tau \ell$ [16] using combined Belle and Belle II datasets with hadronic B -tagging. The signal appears as a peak at the τ mass in the recoil mass, which offers excellent resolution and smooth backgrounds without peaking components. Sidebands of the recoil mass allow to validate the simulation used to train background-suppressing classifiers. We exploit event-shape variables for $q\bar{q}$ ($q = u, d, s, c$) background suppression, and kinematic variables to reduce the $B\bar{B}$ component; for example, the invariant mass of the kaon and ℓ (or the τ daughter, depending on the considered $b \rightarrow s \tau^\pm \ell^\mp$ charge configuration), effective against D -meson background. $B^0 \rightarrow D^- D_s^+$ decays with similar topology compared to $B^0 \rightarrow K^{(*)} \tau \ell$ are used to calibrate the signal shape and the BDT cut efficiency. Fits to data for the K_S^0 and K^0 channels in a representative $\tau \ell$ configuration are shown in Fig. 3. Selection efficiency maps as functions of the relevant degrees of freedom are provided in Refs. [15, 16] to enable reinterpretation, with the two modes being sensitive to different NP mediators.

6 Conclusion

Electroweak penguin and lepton-flavor-violating B decays provide sensitive probes of the Standard Model and beyond. Recent results from Belle and Belle II demonstrate the competitiveness, and in some cases the uniqueness, of B -factories compared to other flavor experiments [17]. While analyzing and accumulating more Run 2 data, Belle II is refining its methodologies and exploring new approaches to enhance sensitivity in B decays with missing energy, while establishing frameworks for the quantitative reinterpretation of its results.

Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation program under the ERC grant agreement No. 884719.

References

- [1] BELLE II collaboration. *Phys. Rev. D* **109** (2024) 112006 [2311.14647].
- [2] LHCb collaboration. *JHEP* **09** (2024) 026 [2405.17347].
- [3] HFLAV Collaboration. <https://hflav-eos.web.cern.ch/hflav-eos/semi/spring25/html/RDsDsstar/RDRDs.html>.
- [4] T. Keck et al.. *Computing and Software for Big Science* **3** (2019) 6.
- [5] HPQCD collaboration. *Phys. Rev. D* **107** (2023) 014511. Erratum: *Phys. Rev. D* **107**, 119903(E) (2023).
- [6] L. Gärtner et al.. *Eur. Phys. J. C* **84** (2024) 693 [2402.08417].
- [7] BELLE II collaboration. *Phys. Rev. D* (2025) .
- [8] ALEPH collaboration. *Eur. Phys. J. C* **19** (2001) 213 [hep-ex/0010022].
- [9] A.J. Buras, J. Girrbach-Noe, C. Niehoff and D.M. Straub. *JHEP* **02** (2015) 184 [1409.4557].
- [10] BELLE II collaboration. *Phys. Rev. Lett.* **135** (2025) 151801 [2504.10042].
- [11] BELLE collaboration. *Phys. Rev. D* **108** (2023) L011102.
- [12] L. Allwicher, D. Becirevic, G. Piazza, S. Rosauero-Alcaraz and O. Sumensari. *Phys. Lett. B* **848** (2024) 138411 [2309.02246].
- [13] BELLE collaboration. *Phys. Rev. Lett.* **130** (2023) 261802.
- [14] LHCb collaboration. [2506.15347].
- [15] BELLE, BELLE II collaboration. *Phys. Rev. Lett.* **135** (2025) 041801 [2412.16470].
- [16] BELLE, BELLE II collaboration. *JHEP* **08** (2025) 184 [2505.08418].
- [17] ATLAS, BELLE II, CMS, LHCb collaboration 2503.24346.