

# Latest results and BSM searches from Belle II

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**Abstract.** Belle II is a flavor physics experiment at the asymmetric electron-positron collider SuperKEKB at KEK in Japan. Belle II aims to record an order of magnitude more data than the previous Belle experiment. Belle II started operation in 2019 and has accumulated  $530 \text{ fb}^{-1}$  of data to date. Recent results from Belle II with a focus on BSM searches, including the first evidence for the  $B^+ \rightarrow K^+ \nu \bar{\nu}$  decay, search for a lepton-flavor violating  $\tau$  and  $B$  decays and tests of lepton flavor universality, are presented.

**Keywords:** flavor physics, BSM, lepton flavor violation,  $B$  mesons

## 1 Introduction

Belle II [1] is a flavor physics experiment at KEK with the SuperKEKB asymmetric  $e^+e^-$  collider (4 GeV on 7 GeV) [2], a successor of the Belle experiment operated from 1999 to 2010. Belle II aims to collect an integrated luminosity of  $50 \text{ ab}^{-1}$ . In the Run 1 operation from 2019 to 2022, SuperKEKB achieved the world's highest luminosity of  $4.7 \times 10^{34} \text{ cm}^2\text{s}^{-1}$ . After a 1.5 year long shutdown (LS1), SuperKEKB resumed its operation in January 2024. As of October 2024, Belle II accumulated  $530 \text{ fb}^{-1}$  of data.

A large number of  $B$  mesons, charm hadrons and  $\tau$  leptons are produced at SuperKEKB. Precise measurements of their decays provide information about the beyond-the-standard-model (BSM) physics. Recent results from Belle II, with a focus on BSM searches are reported below<sup>1</sup>.

## 2 $B^+ \rightarrow K^+ \nu \bar{\nu}$

The  $b \rightarrow s$  transition is a flavor changing neutral current process going through a loop diagram, and is sensitive to BSM physics.  $B^+ \rightarrow K^+ \nu \bar{\nu}$  is a good probe, because its branching fraction is precisely predicted in the Standard Model (SM). The prediction including long-distance effect  $B^+ \rightarrow \tau^+ (\rightarrow K^+ \bar{\nu}) \nu$  is  $\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu}) = (0.56 \pm 0.05) \times 10^{-5}$ , where the uncertainty is dominated

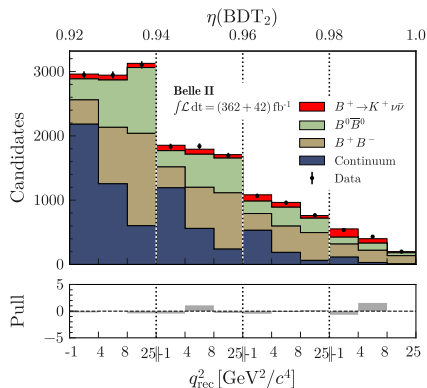
<sup>1</sup> Charge conjugate modes are implied unless explicitly stated. First and second uncertainties are statistical and systematic.

by the hadronic form factors [3]. Measurement of this decay is experimentally challenging due to two neutrinos in the final states, and such a measurement is unique to an  $e^+e^-$  collider.

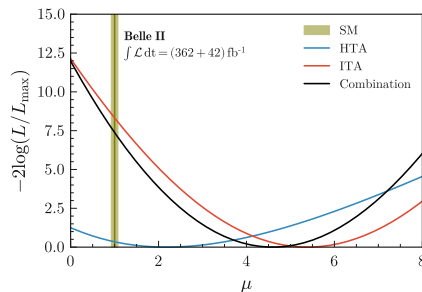
Belle II searched for the  $B^+ \rightarrow K^+\nu\bar{\nu}$  decay using  $365 \text{ fb}^{-1}$  of data collected at the center-of-mass (c.m.) energy of the  $\Upsilon(4S)$  mass [4]. The analysis combines two methods: Hadronic Tag Analysis (HTA) and Inclusive Tag Analysis (ITA). HTA is a conventional method where the tag side  $B$  meson is reconstructed with hadronic decay modes. This method has relatively low background, while the efficiency of the tag side reconstruction is as low as around 1%. ITA is a method newly developed at Belle II. We first pick up only one  $K^+$  from the signal  $B$  and exploit the rest of event to suppress backgrounds. This method is more sensitive than HTA, though it suffers larger background. In this measurement, HTA is used as validation of ITA.

The analysis uses boosted decision trees (BDTs) trained using simulated data to combine various quantities for background suppression. Various control samples, including  $B^+ \rightarrow J/\psi K^+$  where  $J/\psi$  is removed from the reconstruction to imitate the signal topology, are used for validation. The contribution from other  $B$  decays, especially decays with  $K_L^0$  in the final states, are studied in detailed. Figure 1 shows the distribution in bins of a BDT and  $q_{\text{rec}}^2$  (mass squared of the neutrino pair) in ITA analysis, where a small excess of the signal components is seen.

Finally, the result from ITA and HTA are combined after removing common events to both analysis from ITA. The likelihood distribution of ITA, HTA and combined results are shown in Fig. 2. The obtained branching fraction is  $\mathcal{B}(B^+ \rightarrow K^+\nu\bar{\nu}) = (2.4 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}$  with the significance of  $3.5\sigma$ . The result shows the first evidence of  $B^+ \rightarrow K^+\nu\bar{\nu}$  and is  $2.7\sigma$  away from the SM prediction.



**Fig. 1.** Distribution in bins of a BDT variable ( $\eta(\text{BDT}_2)$ ) and  $q_{\text{rec}}^2$  in ITA analysis [4]



**Fig. 2.** Likelihood distribution of ITA, HTA and combined results. The signal strength  $\mu$  is the signal branching fraction relative to the SM expectation.

### 3 $B^0 \rightarrow K^{*0}\tau^+\tau^-$

If  $b \rightarrow s\nu\bar{\nu}$  is enhanced by the BSM,  $b \rightarrow s\tau^+\tau^-$  may also be enhanced by a few orders of magnitude. Measurement of  $b \rightarrow s\tau^+\tau^-$  is experimentally challenging due to two taus that decay to one or more neutrinos. The SM prediction of  $B^0 \rightarrow K^{*0}\tau^+\tau^-$  is  $(0.9 \pm 0.10)^{-7}$  [5], while the previous result by Belle using a data of  $711 \text{ fb}^{-1}$  is  $\mathcal{B}(B^0 \rightarrow K^{*0}\tau^+\tau^-) < 3.1 \times 10^{-3}$  [6].

A new Belle II analysis with a data of  $365 \text{ fb}^{-1}$  uses the hadronic tag method. The analysis is divided into 4 categories based on the charged particles from  $\tau$ :  $\ell\ell$ ,  $\ell\pi$ ,  $\pi\pi$  and  $\rho X$  ( $\ell = e, \mu$  and  $X = \ell, \pi$ ). The signal is extracted using background suppression variable  $\eta(\text{BDT})$  copomposed from the extra energy,  $q^2$ , the invariant mass of a system of  $K^*$  and a track from  $\tau$  and other kinematic and topological quantities. No signal is seen and the upper limit of  $\mathcal{B}(B^0 \rightarrow K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3}$  is set. This result is the most stringent limit and is twice more sensitive than Belle, even though the data set is only half.

### 4 $B^0 \rightarrow K_S^0\tau\ell$

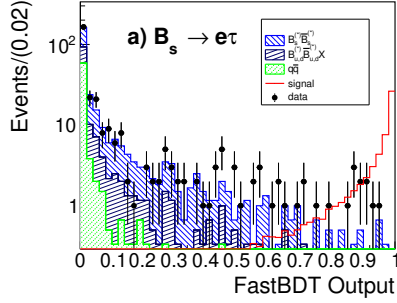
Lepton Flavor Violation (LFV) in charged leptons is inhibited in the SM, and is a clear signature of BSM. The excess in  $B^+ \rightarrow K^+\nu\bar{\nu}$  seen by Belle II motivates the search for LFV in the  $b \rightarrow s$  process. Past searches done for  $b \rightarrow s\tau\ell$  were for  $B^+ \rightarrow K^+\tau\ell$  and  $B^0 \rightarrow K^{*0}\tau\ell$ . Belle II searches for  $B^0 \rightarrow K_S^0\tau\ell$  for the first time using combined Belle and Belle II data of  $711 + 365 \text{ fb}^{-1}$ .

The hadronic tag method is used in this analysis. The signal is extracted from the  $\tau$  recoil mass distribution calculated from  $K_S^0$ ,  $\ell^+$  and a track from  $\tau$ . The result is  $\mathcal{B}(B^0 \rightarrow K_S^0\tau^+\mu^-) < 1.1 \times 10^{-5}$ ,  $\mathcal{B}(B^0 \rightarrow K_S^0\tau^-\mu^+) < 3.6 \times 10^{-5}$ ,  $\mathcal{B}(B^0 \rightarrow K_S^0\tau^+e^-) < 1.5 \times 10^{-5}$ ,  $\mathcal{B}(B^0 \rightarrow K_S^0\tau^-e^+) < 0.8 \times 10^{-5}$ . These results are the most stringent limit among the search for the  $b \rightarrow s\tau\ell$  process.

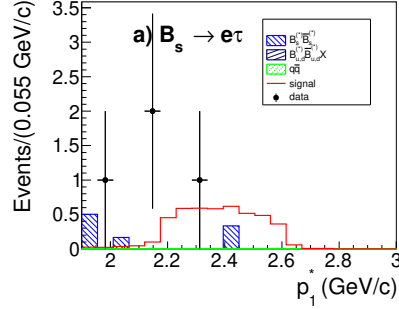
### 5 $B_s \rightarrow \ell^-\tau^+$ and $\Upsilon(2S) \rightarrow \ell^-\tau^+$

LFV decays can be searched for by the decays of other mesons. Belle searched for  $B_s \rightarrow \ell\tau$  using a data of  $121 \text{ fb}^{-1}$  collected at the energy of the  $\Upsilon(5S)$  mass, including around 16 million  $B_s$  pairs [7]. In this analysis, we tag a  $B_s$  using a semileptonic  $B_s$  decay, i.e., we search for  $B_s \rightarrow \ell_1^-\tau^+$  ( $\rightarrow \ell_2^+\bar{\nu}_\tau\nu_{\ell_2}$ ) with  $\bar{B}_s^0$  tagged by the decay  $\bar{B}_s^0 \rightarrow D_s^+\ell_3^-(X')\bar{\nu}_{\ell_3}$ , where  $X'$  stands for any particles or their combinations. Here, the charge of  $\ell_1$  is required to be the same as that of  $\ell_3$  to reduce combinatorial background, though the opposite charge combination can also occur due to  $B_s$  mixing.

Large background is suppressed using a BDT. The distribution of the BDT output is shown in Fig. 3. The signal is characterized by a primary lepton  $\ell_1$  that has the c.m. momentum  $p_1^*$  of around 2.4 GeV. Figure 4 shows the  $p_1^*$  distribution for  $B_s \rightarrow e\tau$ . By counting the number of signal candidates, we obtain  $\mathcal{B}(B_s \rightarrow e^-\tau^+) < 14 \times 10^{-4}$  and  $\mathcal{B}(B_s \rightarrow \mu^-\tau^+) < 7.3 \times 10^{-4}$ . This is the



**Fig. 3.** Distribution of the BDT output for  $B_s \rightarrow e^- \tau^+$  [7]



**Fig. 4.**  $p_1^*$  distribution for  $B_s \rightarrow e^- \tau^+$  [7]

first measurement of  $B_s \rightarrow e\tau$ . The limit for the muon mode is not competitive with LHCb.

Belle also took data of  $25 \text{ fb}^{-1}$  at the energy of  $\Upsilon(2S)$ , corresponding to 158 million  $\Upsilon(2S)$  mesons. Belle searched  $\Upsilon(2S) \rightarrow \ell^- \tau^+$  with  $\tau^+ \rightarrow \ell^+ \nu \bar{\nu}$  or  $\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}$  [8]. Here, the primary lepton and the lepton from  $\tau$  are required to be of a different species to avoid overwhelming Bhabha or  $e^+e^- \rightarrow \mu^+\mu^-$  processes. Other background are suppressed using a BDT. The trigger efficiency ( $\sim 98\%$  for  $\Upsilon(2S) \rightarrow \mu\tau$ ,  $\sim 88\%$  for  $\Upsilon(2S) \rightarrow e\tau$ ) causes largest systematic uncertainty.

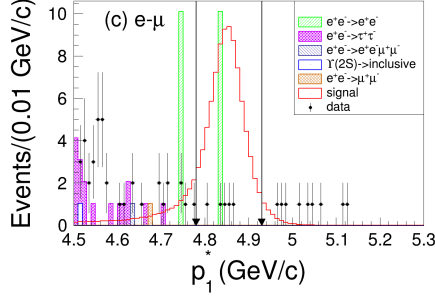
Figures 5 and 6 shows the c.m. momentum of the primary lepton ( $p_1^*$ ) for  $\Upsilon(2S) \rightarrow e^- \tau^+$  with  $\tau^+ \rightarrow \mu^+ \nu \bar{\nu}$  and  $\Upsilon(2S) \rightarrow \mu^- \tau^+$  with  $\tau^+ \rightarrow e^+ \nu \bar{\nu}$ . Combining with the  $\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}$  modes, we find 3 and 12 events in the signal region set around 4.85 GeV, and set the upperlimit of  $0.23 \times 10^{-6}$  and  $1.12 \times 10^{-6}$ , respectively for  $\Upsilon(2S) \rightarrow e^- \tau^+$  and  $\mu^- \tau^+$ . The result gives the most stringent limits on these decays.

In future, Belle II can also take data at non- $\Upsilon(4S)$ , which can enlarge its physical potential.

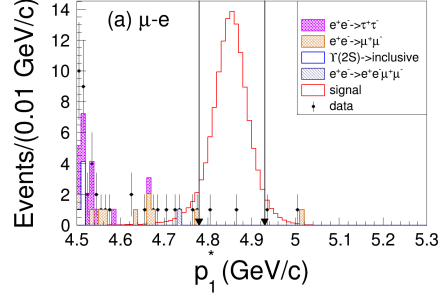
## 6 $\tau^- \rightarrow \mu^- \mu^+ \mu^-$

Search for  $\tau$  LFV is an important topic at Belle II. The cross section of  $e^+e^- \rightarrow \tau^+\tau^-$  is around 0.9 nb; therefore, Run1 data ( $424 \text{ fb}^{-1}$  taken at or near  $\Upsilon(4S)$ ) of Belle II contains 389 million  $\tau$ -pairs, and one or two order larger  $\tau$  sample is expected in future. There are many possible LFV  $\tau$  decays, and current upper limits of the branching fractions are mostly set by the Belle experiment to the order of  $10^{-7}$ . Belle II aims to explore the search to the region of  $10^{-8}$  to  $10^{-9}$ .

Recently, Belle II reported the result on a search for  $\tau^- \rightarrow \mu^- \mu^+ \mu^-$  [9]. In this analysis, an inclusive approach to allow at most 3 tracks in the tag side is adopted. Thanks to this method, the efficiency is around 20%, which is 3



**Fig. 5.** The  $p_1^*$  distribution for  $\Upsilon(2S) \rightarrow e^- \tau^+$  with  $\tau^+ \rightarrow \mu^+ \nu \bar{\nu}$  [8]



**Fig. 6.** The  $p_1^*$  distribution for  $\Upsilon(2S) \rightarrow \mu^- \tau^+$  with  $\tau^+ \rightarrow e^+ \nu \bar{\nu}$  [8]

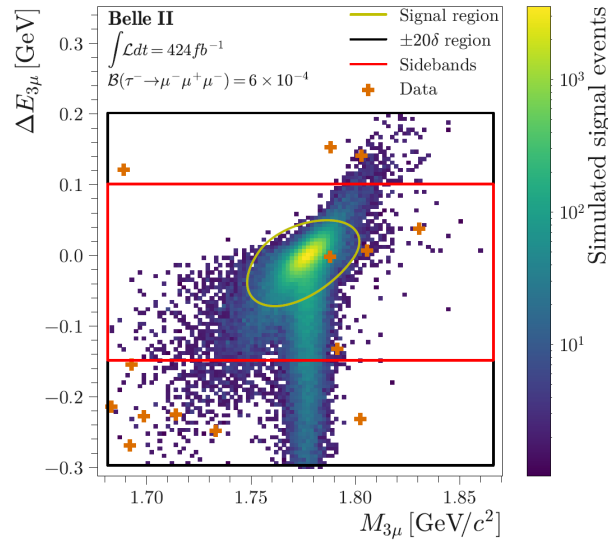
times higher than the previous Belle analysis using the conventional method to allow only 1 track in the tag side. This causes the increase of the combinatorial background, which is suppressed using BDT. Figure 7 shows the two dimensional distribution on the invariant mass ( $M_{3\mu}$ ) and energy difference to the beam energy ( $\Delta E_{3\mu}$ ). We observe one event in the signal region with the expectation of  $0.50^{+1.4}_{-0.5}$  events. We set the upper limit of  $1.9 \times 10^{-8}$  for the branching fraction of  $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ , which is the world most stringent.

## 7 $e^+e^- \rightarrow \pi^+\pi^-\pi^0$

Recently, the muon anomalous magnetic moment  $a_\mu = (g_\mu - 2)/2$  draws much attention due to a  $5\sigma$  discrepancy between the SM prediction [10] and the experimental measurement [11]. Major theoretical uncertainty comes from the Hadronic Vacuum Polarization (HVP) term, where the experimental input of the cross section of  $e^+e^- \rightarrow \text{hadrons}$  plays an important role to improve the precision. Belle II can measure the energy dependence of the cross section using events with initial-state radiation (ISR). The largest contribution is from  $e^+e^- \rightarrow p_i^+\pi^-$ , but Belle II first measured the cross  $e^+e^- \rightarrow p_i^+\pi^-\pi^0$ , using data of  $191 \text{ fb}^{-1}$  [12].

The signal is  $e^+e^- \rightarrow \pi^+\pi^-\pi^0\gamma_{\text{ISR}}$ , where  $\gamma_{\text{ISR}}$  is the ISR photon with the energy above  $\sim 5$  GeV. In this case, the energy of the hadronic system is between. 0.4 and 3.5 GeV. The main background components are from  $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0\gamma_{\text{ISR}}$  and  $e^+e^- \rightarrow K^+K^-\gamma_{\text{ISR}}$ . Precise efficiency corrections are performed for various items including the trigger, tracking, ISR photon and  $\pi^0$  efficiency.

The obtained contribution of  $e^+e^- \rightarrow \pi^+\pi^-\pi^0$  at leading order in HVP, to  $a_\mu$  is  $a_\mu^{3\pi} = (48.91 \pm 0.23 \pm 1.07) \times 10^{-10}$  in the 0.52–1.8 GeV energy range. This result is  $2.5\sigma$  higher than past measurements. The next target of Belle II is to measure  $a_\mu$  for  $e^+e^- \rightarrow \pi^+\pi^-$  with 0.5% precision.



**Fig. 7.** Scatter plot on  $M_{3\mu}$  and  $\Delta E_{3\mu}$  plane for  $\tau^- \rightarrow \mu^- \mu^+ \mu^-$  [9]

## 8 Summary

Although the accumulated integrated luminosity is still smaller than Belle, Belle II has improved the analysis technique and has obtained results with the world's best sensitivity. Belle II plans to increase the luminosity and more analyses on the study of the BSM are expected.

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