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 fb^{-1} of data to date. Recent results from Belle II with a focus on BSM searches, including the first evidence for the $B^+ \to K^+\nu\bar{\nu}$ decay, search for a lepton-flavor violating τ 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 Belle experiment operated from 1999 to 2010. Belle II aims at collecting an integrated luminosity of 50 ab^{-1}. In the Run 1 operation from 2019 to 2022, SuperKEKB achieved the world's highest luminosity of 4.7×10^{34} cm^{2}s^{-1}. After 1.5 year long shutdown (LS1), SuperKEKB resumed its operation in January 2024. As of October 2024, Belle II accumulated 530 fb^{-1} of data.

A large number of B mesons, charm and τ are produced at SuperKEKB. Precise measurements of their decays provide information of New Physics (NP) beyond the Standard Model (SM). Recent results from Belle II, with a focus on BSM (physics beyond the Standard Model) searches are reported below[1].

2 $B^+ \to K^+\nu\bar{\nu}$

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

[1] Charge conjugate modes are implied unless explicitly stated. First and second uncertainties are statistical and systematic.

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 with $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ process.

Belle II searched for the $B^+ \to K^+\nu\bar{\nu}$ decay using 365 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 simulatied data to combine various quantities for background suppression. Various control samples, including $B^+ \to J/\psi K^+$ where J/ψ 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 distriution in bins of a BDT and $q^2_{\rm rec}$ (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 $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (2.4 \pm 0.5\,^{+0.5}_{-0.4}) \times 10^{-5}$ with the significance of 3.5σ. The result shows the first evidence of $B^+ \to K^+\nu\bar{\nu}$ and is 2.7σ away from the SM prediction.

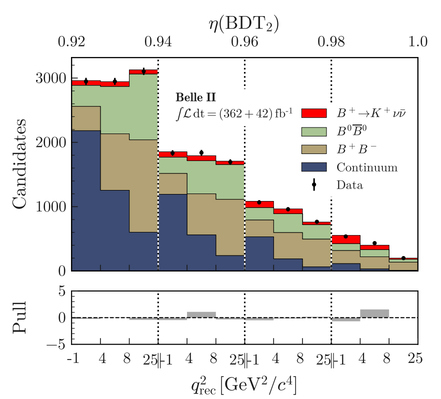

Fig. 1. Distribution in bins of a BDT variable ($\eta(\mathrm{BDT}_2)$) and $q^2_{\rm rec}$ in ITA analysis [4]

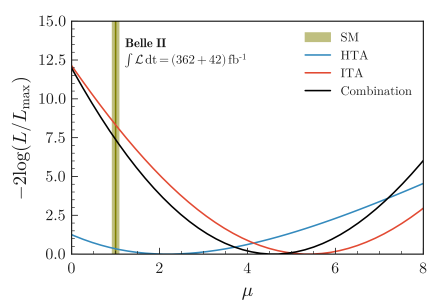

Fig. 2. Likelihood distribution of ITA, HTA and combined results. The signal strength μ is the signal branching fraction relavtive to the SM expectation.

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

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

New Belle II analysis with a data of 365 fb^{-1} uses the hadronic tag method. The analysis is divided into 4 categories based on the charged particles from τ: $\ell\ell$, $\ell\pi$, $\pi\pi$ and ρX ($\ell = e, \mu$ and $X = \ell, \pi$). The signal is extacted using background suppression variable η(BDT) copomposed from the extra energy, q^2, the invariant mass of a system of K^* and a track from τ and so on. No signal is seen and the upper limit of $\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3}$ 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 $B^0 \to K^0_S\tau\ell$

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

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

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

LFV decays can be also searched for by the decays of other mesons. Belle searched for $B_s \to \ell\tau$ using a data of 121 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 $B_s \to \ell_1^-\tau^+$ $(\to \ell_2^+\bar{\nu}_\tau\nu_{\ell_2})$ with $\overline{B}{}^0_s$ tagged by the decay $\overline{B}{}^0_s \to D_s^+\ell_3^-(X')\bar{\nu}_{\ell_3}$, where X' stands for any particles or their combinations. Here, the charge of ℓ_1 is required to be the same as that for ℓ_3 to reduce combinatorial background, though the opposite charge combination can also occur due to B_s mixing.

Large background is suppressed using BDT. The distribution of the BDT output is shown in Fig. 3. The signal is characterized by a primary lepton ℓ_1 that has the c.m. momentum p_1^* of around 2.4 GeV. Figure 4 shows the p_1^* distribution for $B_s \to e\tau$. By counting the number of signal candidates, we obtain $\mathcal{B}(B_s \to e^-\tau^+) < 14 \times 10^{-4}$ and $\mathcal{B}(B_s \to \mu^-\tau^+) < 7.3 \times 10^{-4}$. This is the first measurement of $B_s \to e\tau$. The limit for the muon mode is not competitive to LHCb.

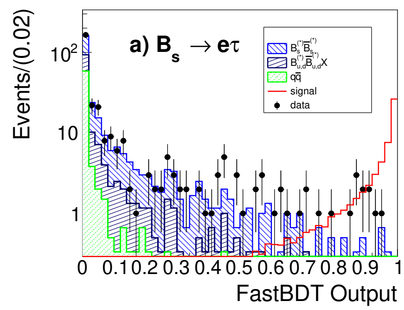

Fig. 3. The distribution of the BDT output for $B_s \to e^- \tau^+$ [7]

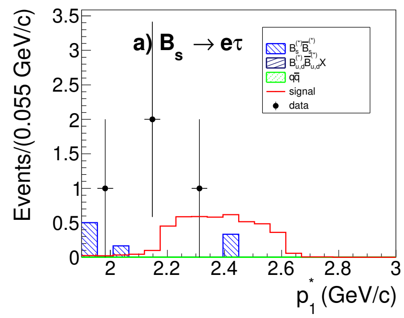

Fig. 4. The p_1^* distribution for $B_s \to e^- \tau^+$ [7]

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

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

Search for τ LFV is an important topic at Belle II. The cross section of $e^+e^- \to \tau^+\tau^-$ is around 0.9 nb; therefore Run1 data (424 fb^{-1} taken at or near $Y(4S)$) of Belle II contains 389 million τ-pairs, and one or two order larger τ sample is expected in future. There are many possible LFV τ 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}.

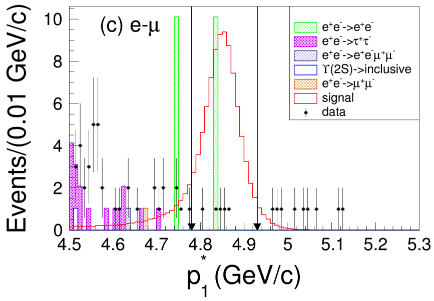

Fig. 5. The p_1^* distribution for $\Upsilon(2S) \to e^-\tau^+$ with $\tau^+ \to \mu^+\nu\bar{\nu}$ [8]

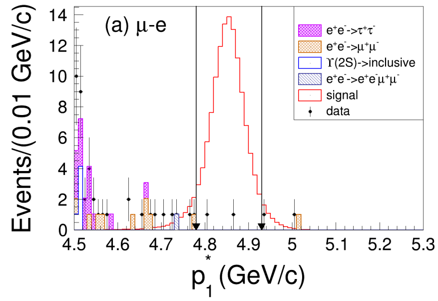

Fig. 6. The p_1^* distribution for $\Upsilon(2S) \to \mu^-\tau^+$ with $\tau^+ \to e^+\nu\bar{\nu}$ [8]

Recently, Belle II reported the result on the search for $\tau^- \to \mu^-\mu^+\mu^-$ [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 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 1.9×10^{-8} for the branching fraction of $\tau^- \to \mu^-\mu^+\mu^-$, which is the world most stringent.

7 $e^+e^- \to \pi^+\pi^-\pi^0$

Recently, the muon anomalous magnetic moment $a_\mu = (g_\mu - 2)/2$ draws much attention due to a 5σ discrepancy between the SM prediction and the experimental measurement. Major theoretical uncertainty comes from the Hadronic Vacuum Polarization (HVP) term, where the experimental input of the cross section of $e^+e^- \to$ 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 $e^+e^- \to pi^+\pi-$, but Belle II first measured the cross $e^+e^- \to pi^+\pi - \pi^0$, using data of 191 fb^{-1} [10].

The signal is $e^+e^- \to \pi^+\pi^-\pi^0\gamma_{\rm ISR}$, where $\gamma_{\rm ISR}$ is the ISR photon with the energy above ~ 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 $e^+e^- \to \pi^+\pi^-\pi^0\gamma_{\rm ISR}$ and $e^+e^- \to K^+K^-\gamma_{\rm ISR}$. Precise efficiency corrections are performed for various items including the trigger, tracking, ISR photon and π^0 efficiency.

The obtained contribution of $e^+e^- \to \pi^+\pi^-\pi^0$ at leading order in HVP, to a_μ 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

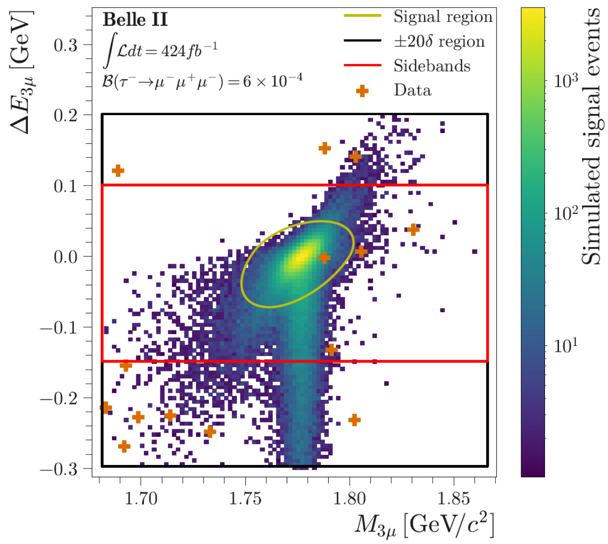

Fig. 7. Scatter plot on $M_{3\mu}$ and $\Delta E_{3\mu}$ plane for $\tau^- \to \mu^-\mu^+\mu^-$ [9]

result is 2.5σ higher from the past measurements. The next target of Belle II is to measure a_μ for $e^+e^- \to \pi^+\pi^-$ with 0.5% precision.

8 Summary

Although the accumulated integrated luminosity is still smaller than Belle, Belle II has improved the analysis techinique 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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