Results and prospects on lepton flavor violation at Belle/Belle II

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Abstract. We report the results and prospects on the τ lepton flavor violation at Belle and Belle II. This is a contribution to NUFACT11, XIIth International Workshop on Neutrino Factories, Super beams and Beta beams, 1-6 August 2011, CERN and University of Geneva.

1. Introduction

A charged-lepton-flavor violation (cLFV) is one of the clear signatures for the new physics (NP) since the cLFV is forbidden in the SM and its probability is very small even if the neutrino oscillations are taken into account. In particular, a tau-lepton-flavor violation (τ LFV) is promising because the tau lepton is expected to have a strong coupling to the NP by reason of its heaviest mass among the leptons. In addition, the tau lepton has many possible τ LFV modes: not only merely lepton-flavor-violating process but also a lepton-number- or baryon-number-violating process. In order to reveal the structure of the NP, the information from these τ LFV modes, such as a magnitude relation for the branching fractions, will help us. Since a B-factory is also a τ-factory, the KEKB/Belle experiment is a good place to search for the τ LFV decays. In addition, since the superKEKB/Belle II experiment is planned, where forty times larger luminosity (8×10^{35} cm^{-2}s^{-1}) is expected, the τ LFV search on the new experiment is also important.

Here, we report the recent results using around a 1000 fb^{-1} data sample obtained by the Belle collaboration and the future prospects evaluated by the Belle II collaboration.

2. Method

All searches for LFV τ decays follow a similar procedure. We search for $\tau^+\tau^-$ events in which one τ (signal side) decays into an LFV mode under study, while the other τ (tag side) decays into one charged particle and any number of additional photons and neutrinos (for example, see Fig. 1 (left)). To search for exclusive LFV-decay modes, we select low multiplicity events with zero net charge, and separate an event into two hemispheres (signal and tag) using a thrust axis. The backgrounds in such searches are dominated by $q\bar{q}$ ($q = u, d, s, c$), generic $\tau^+\tau^-$, two-photon, $\mu^+\mu^-$ and Bhabha events. To obtain a good sensitivity, we optimize the event selection using particle identification and kinematic information for each mode separately. Because every τ LFV decay is a neutrinoless one, the information from missing tracks is very powerful to reject the background from generic $\tau^+\tau^-$ events. After signal selection criteria are applied, signal
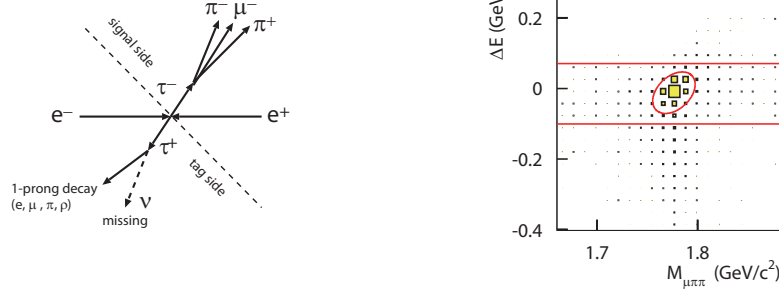
Figure 1. Topology for the signal event, where the signal decay is $\tau \to \mu\pi\pi$. (left) Resulting distribution for the signal events on the $M_{\mathrm{inv}} - \Delta E$ plane. (right) The size of boxes shows the magnitude of the density for the signal events, the red ellipse indicates the $\pm 3\sigma$ signal region and the region between the two red lines is defined as the $\pm 5\sigma_{\Delta E}$ side-band region for the background estimation.

candidates are examined in the two-dimensional space of the invariant mass, M_{inv}, and the difference of their energy from the beam energy in the CM system, ΔE. A signal event should have M_{inv} close to the τ-lepton mass and ΔE close to 0 as shown in Fig. 1(right). We blind a region around the signal region in the $M_{\mathrm{inv}} - \Delta E$ plane so as not to bias our choice of selection criteria. The expected number of background events in the blind region is first evaluated, and then the blind region is opened and candidate events are counted. By comparing the expected and observed numbers of events, we either observe a τ LFV decay or set an upper limit (UL) by applying counting approach. [1]

3. Results
Here, since the number of the pages is limited, we show the recently obtained results only.

3.1. $\tau \to \ell h h'$ $(\ell = e, \mu, \ h = \pi, K)$
Although $\tau^- \to \ell^- h^+ h'^-$ violates only the lepton flavor, $\tau^- \to \ell^+ h^- h'^-$ violates the lepton number as well. Here, we search for 8 modes of $\tau^- \to \ell^- h^+ h'^-$ and 6 modes of $\tau^- \to \ell^+ h^- h'^-$. The former ones are expected to be enhanced by the Higgs-mediated model while the latter are motivated by the Majorana neutrino model.

We have updated the analysis for these modes with the 854 fb^{-1} data sample. Main backgrounds come from $\tau \to \pi\pi\pi\nu$ for $\ell = \mu$ and $\tau \to \pi\pi^0\nu$ for $\ell = e$, where the photon,

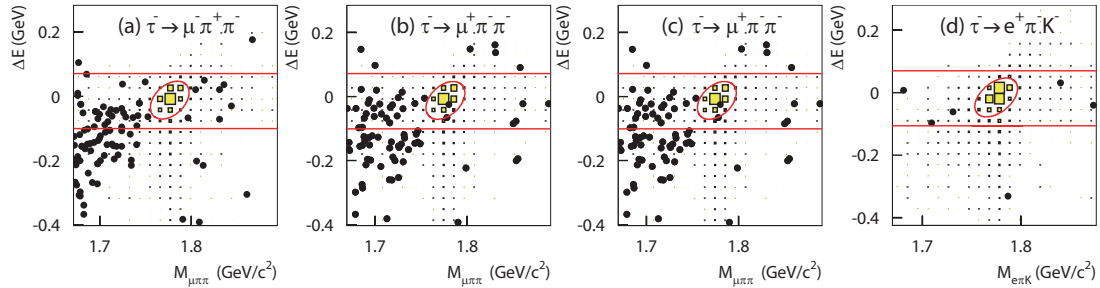**Figure 2.** Resulting plots on the $M_{\mathrm{inv}} - \Delta E$ plane for $\tau^- \to \mu^-\pi^+\pi-$ (a), $\tau^- \to \mu^+\pi^-\pi^-$ (b), $\tau^- \to \mu^-\pi^+K^-$ (c) and $\tau^- \to e^+\pi^-K^-$ (d). Here, black dots show the data and yellow boxes indicate the density for the signal events.

Table 1. Summary of ULs for recently updated mode. The signal efficiency (ε), the number of expected background events (N_{BG}) estimated from the sideband data, the total systematic uncertainty (σ_{syst}), the number of observed events in the signal region (N_{obs}), 90% CL UL on the number of signal events including systematic uncertainties (s_{90}) and 90% CL UL on the branching fraction for each individual mode.

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	s_{90}	$\mathcal{B}$ (10^{-8})
$\tau^- \to \mu^- \pi^+ \pi^-$	5.83	0.63 ± 0.23	5.3	0	1.87	2.1
$\tau^- \to \mu^+ \pi^- \pi^-$	6.55	0.33 ± 0.16	5.3	1	4.02	3.9
$\tau^- \to e^- \pi^+ \pi^-$	5.45	0.55 ± 0.23	5.4	0	1.94	2.3
$\tau^- \to e^+ \pi^- \pi^-$	6.56	0.37 ± 0.18	5.4	0	2.10	2.0
$\tau^- \to \mu^- K^+ K^-$	2.85	0.51 ± 0.18	5.9	0	1.97	4.4
$\tau^- \to \mu^+ K^- K^-$	2.98	0.25 ± 0.13	5.9	0	2.21	4.7
$\tau^- \to e^- K^+ K^-$	4.29	0.17 ± 0.10	6.0	0	2.28	3.4
$\tau^- \to e^+ K^- K^-$	4.64	0.06 ± 0.06	6.0	0	2.38	3.3
$\tau^- \to \mu^- \pi^+ K^-$	2.72	0.72 ± 0.27	5.6	1	3.65	8.6
$\tau^- \to e^- \pi^+ K^-$	3.97	0.18 ± 0.13	5.7	0	2.27	3.7
$\tau^- \to \mu^- K^+ \pi^-$	2.62	0.64 ± 0.23	5.6	0	1.86	4.5
$\tau^- \to e^- K^+ \pi^-$	4.07	0.55 ± 0.31	5.7	0	1.97	3.1
$\tau^- \to \mu^+ K^- \pi^-$	2.55	0.56 ± 0.21	5.6	0	1.93	4.8
$\tau^- \to e^+ K^- \pi^-$	4.00	0.46 ± 0.21	5.7	0	2.02	3.2
$\tau^- \to \Lambda \pi^-$	4.80	0.21 ± 0.15	8.2	0	2.26	2.8
$\tau^- \to \bar{\Lambda} \pi^-$	4.39	0.31 ± 0.18	8.2	0	2.17	3.0
$\tau^- \to \bar{\Lambda} K^-$	4.11	0.31 ± 0.14	8.6	0	2.17	3.1
$\tau^- \to \Lambda K^-$	3.16	0.42 ± 0.19	8.6	0	2.08	4.2

that is a daughter of π^0, converts to $e^+ e^-$. To reduce them, $\tau \to \pi\pi\pi\nu$ veto, using $M_{\pi\pi\pi}$, and γ-conversion veto are newly introduced for $\mu\pi K$ modes and $\ell = e$ modes, respectively. As a result, we have found 1 event for $\mu^+ \pi^- \pi^-$ and $\mu^- \pi^+ K^-$ modes while no events are observed in the other modes. Since this is consistent with the expected number of the backgrounds, we set the UL on the branching fraction. The evaluated numbers to set the UL and the number of observed events in the signal region are summarized in Table 1. The ULs for this mode are the most sensitive. (preliminary)

3.2. $\tau \to \Lambda h$ ($h = \pi, K$)
This mode violates the lepton number (L) as well as the baryon number (B): $\tau^- \to \bar{\Lambda} h^-$ conserves ($B - L$) while $\tau^- \to \Lambda h^-$ violates ($B - L$). Some GUTs can make ($B - L$) conserving decays while a more complicated model is necessary to induce ($B - L$) violating decays.

   We have searched for these decays with the 906 fb^{-1} data sample. Main backgrounds come from $\tau \to \pi K_S^0 \nu$ and $q\bar{q}$ ($q = u, d, s$) events having Λ and π. In the former background, K_S^0 is misidentified as Λ. This can be rejected by K_S^0 veto using $M_{\pi\pi}$. On the other hand, the latter is likely to have a proton as a charged track on the tag side because of the baryon number conservation. Therefore, we veto the proton for the tag-side track. As a result, no events are observed for each mode; no excess is found for the signal. Thus, we set the UL on the branching fraction. The obtained numbers are summarized in Table 1. We obtain the most stringent ULs. (preliminary)

4. Future Prospect
The superKEKB/Belle II experiment is planned to collect 50-times larger luminosity than the KEKB/Belle, i.e., a 50 fb^{-1} data sample will be accumulated.

   LFV sensitivity depends on the remaining background level. In the case where there is a
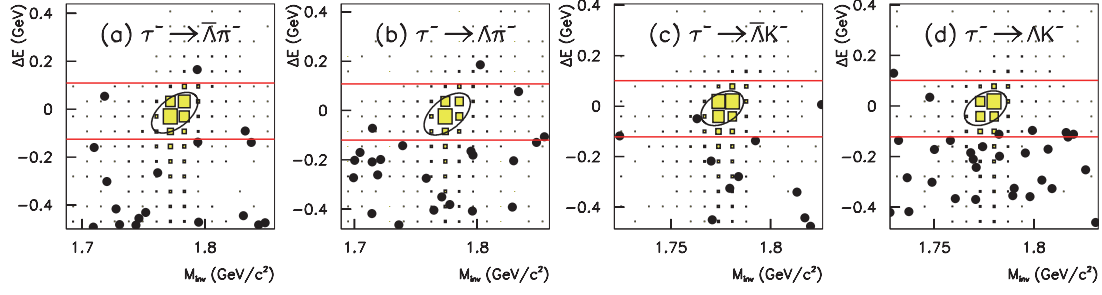
Figure 3. Resulting plots on the $M_{\mathrm{inv}} - \Delta E$ plane for $\tau^- \to \mu^- \pi^+ \pi^-$ (a), $\tau^- \to \mu^+ \pi^- \pi^-$ (b), $\tau^- \to \mu^- \pi^+ K^-$ (c) and $\tau^- \to e^+ \pi^- K^-$ (d). Here, black dots show the data and yellow boxes indicate the density for the signal events.

large (negligibly small) remaining background, such as that in the $\tau \to \mu\gamma$ ($\tau \to \ell\ell\ell$) analysis, the sensitivity is scaled as $1/\sqrt{\mathcal{L}}$ ($1/\mathcal{L}$), where $\mathcal{L}$ means a luminosity. Therefore, the accessible branching fractions for $\tau \to \mu\gamma$ and $\tau \to \ell\ell\ell$ at the superKEKB/Belle II are $O(10^{-8 \sim -9})$ and $O(10^{-9 \sim 10})$, respectively.

5. Summary

We have searched for 46 major modes of lepton flavor violating τ decays with the 1000 fb^{-1} data sample. The current status of the τ LFV searches in $B-$factory experiments is summarized in Fig. 4. No evidence for these decays is observed and we set 90% CL ULs on the branching fractions at the $O(10^{-8})$ level. The sensitivity for the LFV search is 100 times improved in comparison with CLEO's one due to the effective background rejection and increase of the data sample. In the future experiment, i.e., the superKEKB/Belle II experiment, the sensitivity will reach $O(10^{-9--10})$ with a 50 ab^{-1} data sample.
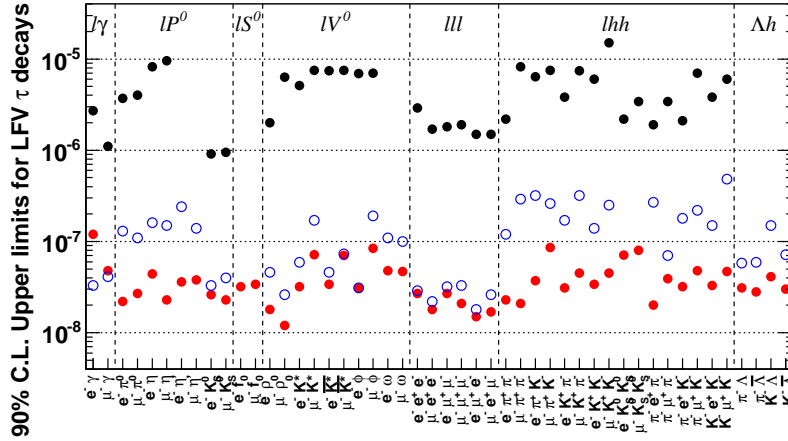

Figure 4. Current 90% CL ULs for the branching fraction of τ LFV mode. Red, blue and black circles shows Belle, BaBar and CLEO results, respectively.

References

[1] Feldman G J and Cousins R D 1998 *Phys. Rev. D* **57** 3873.