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Lepton flavor violation including $\tau \to \mu\mu\mu$

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We review recent searches for lepton flavor violation in τ^- decays, based on about 1000 fb^{-1} of data, collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. No evidence for these decays is observed and we set 90% confidence level upper limits on the branching fractions at the O(10^{-8}) level.

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PoS(Beauty 2013)023

Model	$\mathscr{B}(\tau \to \mu\gamma)$	$\mathscr{B}(\tau \to 3\ell)$
SM+ν oscillation [1]	$< 10^{-40}$	$< 10^{-14}$
mSUGRA+Seesaw [2]	$< 10^{-7}$	$< 10^{-7}$
Non-universal Z$'$ [3]	$< 10^{-9}$	$< 10^{-8}$
SUSY SO(10) [4]	$< 10^{-8}$	$< 10^{-10}$
SUSY+Higgs [5]	$< 10^{-10}$	$< 10^{-7}$

Table 1: Theoretical prediction of the branching fraction of the $\tau \to \mu\gamma$ and $\tau \to 3\ell$ modes

1. Introduction

Lepton Flavor Violating (LFV) decays of the charged leptons are expected to have negligible probability even including neutrino oscillations in the Standard Model (SM). The branching ratios of $\tau \to \mu\gamma$ and $\tau \to$ three leptons including SM + neutrino oscillations are less than O(10^{-40}) and O(10^{-14}), respectively. However, many extensions of SM, such as supersymmetry (SUSY) and large extra dimensions, predict enhanced LFV decays with branching fractions close to current experimental sensitivity, shown in Table 1. With certain combinations of new physics parameters the branching fractions for LFV τ decays can be as high as 10^{-7}, which is already accessible in high-statistics $\mathscr{B}$-factory experiments. Therefore, an observation of LFV decay will be a clear signature for new physics beyond SM. Tau leptons are expected to be coupled strongly with new physics and have many possible LFV decay modes due to their large mass. Therefore, the τ lepton is an ideal place to search for LFV decays.

SUSY, which is the most popular candidate among the NP models, naturally induces LFV at one loop through slepton mixing. The $\tau^- \to \ell^-\gamma$ modes, where ℓ^- is either an electron or a muon, are important and have the largest branching fraction in the SUSY seesaw model. The predicted branching fraction of $\tau \to \mu\gamma$ is written as

$$\mathscr{B}(\tau \to \mu\gamma) = 3.0 \times 10^{-6} \times \left(\frac{tan\beta}{60}\right)^2 \left(\frac{1\ \text{TeV}}{M_{SUSY}}\right)^4, \tag{1.1}$$

where M_{SUSY} is the typical SUSY mass and $tan\beta$ is the ratio of two Higgs vacuum expectation values [6]. If M_{SUSY} is small and $tan\beta$ is large, this decay mode may be enhanced up to current experimental sensitivity.

If a typical SUSY mass is larger than $\sim$1 TeV, processes via one-loop contributions with SUSY particles are suppressed. When scalar leptons are much heavier than the weak scale, LFV occurs via the Higgs mediated LFV mechanism and τ^- leptons can decay into $\ell^- f_0(980)$ through a scalar Higgs boson. The decays $\ell^-\pi^0$, $\ell^-\eta$ and $\ell^-\eta'$ are mediated by a pseudoscalar Higgs boson, while $\ell^-\mu^+\mu^-$ can be mediated through both scalar and pseudoscalar Higgs bosons [7]

2. KEKB and Belle

The KEKB is a e^+e^- asymmetric-energy collider operated primarily at the center-of-mass energy corresponding to $\Upsilon(4S)$ resonance. Experiments at KEKB enabled searches for LFV τ

PoS(Beauty 2013)023

decays with very high sensititvity since the cross section of $\tau^+\tau^-$ production is $\sigma_{\tau\tau} = 0.9$ nb, close to that of $B\bar{B}$ production $\sigma_{B\bar{B}} = 1$ nb. Thus, $\mathscr{B}$-factories are also τ-factories. During the years of the Belle [8] operations (1999 – 2010) at the KEKB $\mathscr{B}$-factory [9] it has accumulated about 9×10^8 τ pairs. The Belle detector is a multi-purpose detector which has good track reconstruction and particle identification capability.

3. Method

All searches for LFV τ decays follow a similar pattern. We search for $\tau^+\tau^-$ events in which one τ(signal side) decays into a LFV mode under study, while the other τ(tag side) decays into one (or three) charged particles and any number of additional photons and neutrinos (for example, see Fig. 1.

To search for exclusive decay modes, we select low multiplicity events with zero net charge, and separate the signal- and tag-side into two hemispheres using a thrust axis. The background in such searches is dominated by $q\bar{q}$, generic $\tau^+\tau^-$, two-photon, $\mu^+\mu^-$ and Bhabha events. To obtain good sensitivity, we optimize the event selection using particle identification and kinematic information for each mode separately. Signal candidates are examined in the two-dimensional space of the invariant mass, M_{inv}, and the difference of their energy from beam energy in the center-of-mass (CM) system, ΔE. Signal events should have M_{inv} close to the τ-lepton mass and ΔE close to 0. We blind a region around the signal region in the $M_{inv} - \Delta E$ plane so as not to bias our choice of selection criteria (see Fig. 2). 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 number of events, we either observe a LFV τ decay or set an upper limit by applying Bayesian, Feldman-Cousins or maximum likehood approaches.

4. Results

4.1 $\tau^- \to \ell hh'$.

Belle and BaBar have searched for various $\tau^- \to \ell hh'$ decays (where $h, h' = \pi^\pm$ or $K^\pm$) with lepton flavor and lepton number violation ($\tau^- \to \ell^- h^- h'^+$ and $\tau^- \to \ell^+ h^- h'^-$). Analysis of Belle is based on 854 fb^{-1} of data while the study of BaBar used data corresponding to 221 fb^{-1} of integrated luminosity.

In these analysises Belle has to apply tighter selection as, for example, missing information (see Fig. 3), to suppress background. And after event selection, Belle observed one event in the signal region for $\tau^- \to \mu^+\pi^-\pi^-$ and $\tau^- \to e^+\pi^-K^-$ modes while no events are found for the other modes. In each case, the number of events, observed in the signal region, is consistent with the expected number of background events. Therefore, no evidence for these decays is observed, and we set upper limits on the branching fractions at 90% C.L.: $\mathscr{B}(\tau \to ehh') < (2.0 - 3.7) \times 10^{-8}$ and $\mathscr{B}(\tau \to \mu hh') < (2.1 - 8.6) \times 10^{-8}$ [10]

In the BaBar study the upper limits for the branching fractions of the decays $\tau \to \ell^- h^- h'^+$ and $\tau \to \ell^+ h^- h'^-$ were set in the range (7.0 – 48.0)$\times 10^{-8}$ [11].

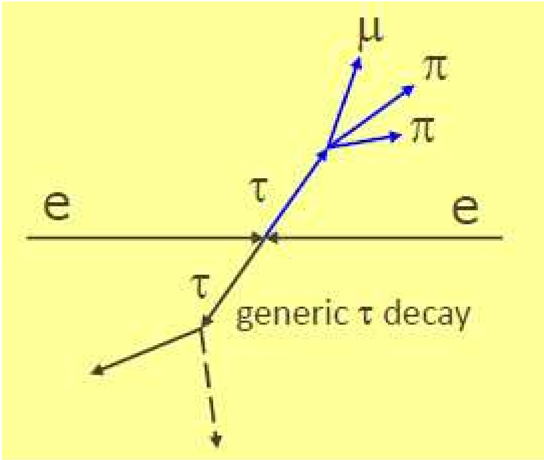

Figure 1: Event topology of LFV τ decay in case of $\tau \to \mu\pi^+\pi^-$ analysis

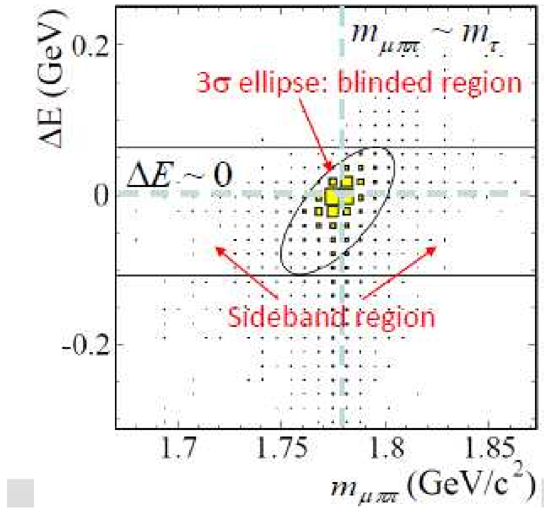

Figure 2: Distributions in the $M_{inv} - \Delta E$ plane correspond to the $\pm 20\sigma$ area for the $\tau \to \mu\pi^+\pi^-$ mode. The data are indicated by the solid squares. The filled boxes show the MC signal distribution with arbitrary normalization. The elliptical region shown is used for evaluating the signal yield while sideband is used to estimated background yeild.

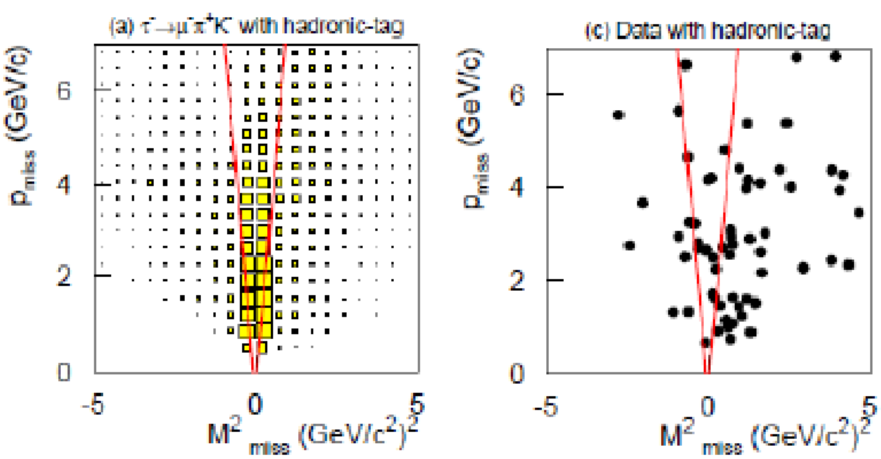

Figure 3: Distributions of p_{miss} vs. m^2_{miss} show the signal MC($\tau^- \to \mu^-\pi^+K^-$) (left) and data (right) for hadronic tag. Selected regions are indicated by lines.

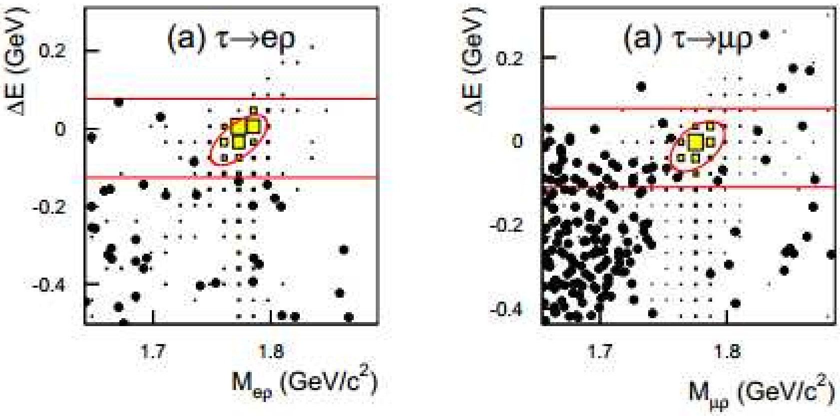

Figure 4: $M_{inv} - \Delta E$ distributions for the $\tau^- \to e^-\rho$(left) and $\tau^- \to \mu^-\rho$(right) modes from the Belle analysis. Data and signal MC events are shown as dots and histogram.The elliptical signal regions shown by a solid curve are used for evaluating the signal yield.

4.2 $\tau^- \to \ell^- V^0$.

We carry out a search for one charged lepton ℓ^- and one vector meson V^0: ϕ, $K^\star(892)$, $\bar{K}^\star(892)$, ρ and ω, based on 854 fb^{-1} of data and set upper limits in the range $(1.2-8.4)\times10^{-8}$ [12] (see, for example, Fig. 4). The BaBar collaboration has also published 90% C.L. upper limits in the range $(2.6 - 19)\times10^{-8}$ using 451 fb^{-1} of data [13] for all of the above $\tau^- \to \ell^- V^0$ decays except for $\tau^- \to \ell^-\omega$ for which 384 fb^{-1} of data were used [14].

4.3 $\tau^- \to \ell^-\ell^+\ell^-$.

The following τ^- decays into three leptons are considered: $e^-e^+e^-$, $\mu^-\mu^+\mu^-$, $e^-\mu^+\mu^-$, $\mu^-e^+e^-$, $\mu^-e^+\mu^-$ and $e^-\mu^+e^-$. We use 782 fb^{-1} of data for this search. Since each decay mode has different background, the event selection is optimized mode by mode. The signal efficiencies are kept in the range (6.0 – 11.5)%. We observed no events after event selection in the signal region for all modes, while expected background is less than 0.2 events. Therefore, no evidence for these decays is observed and we set 90% confidence levels on the branching fractions between $(1.5-2.7)\times10^{-8}$ [15]. The branching fraction of $\tau^- \to \mu^+e^-e^-$ is the most stringent upper limit ($< 1.5\times10^{-8}$) among current LFV τ decays. The BaBar detector has also studied the same $\tau \to \ell\ell\ell$ modes using 477 fb^{-1} of the data, and upper limits in the range $(1.8-3.3)\times10^{-8}$ [16] have been obtained.

5. Summary

Data samples, collected with the Belle and BaBar detectors, allowed one to perform a study of 48 τ LFV decay modes. Figure 6 shows the results for LFV τ decays studied with the Belle and BaBar detectors in comparison with those obtained with CLEO detector. As it can be seen from the plot, the upper limits for almost all modes reach O(10$^-$8). Analysis of $\tau \to \mu/e\gamma$ processes is on going and final results will be reported soon.

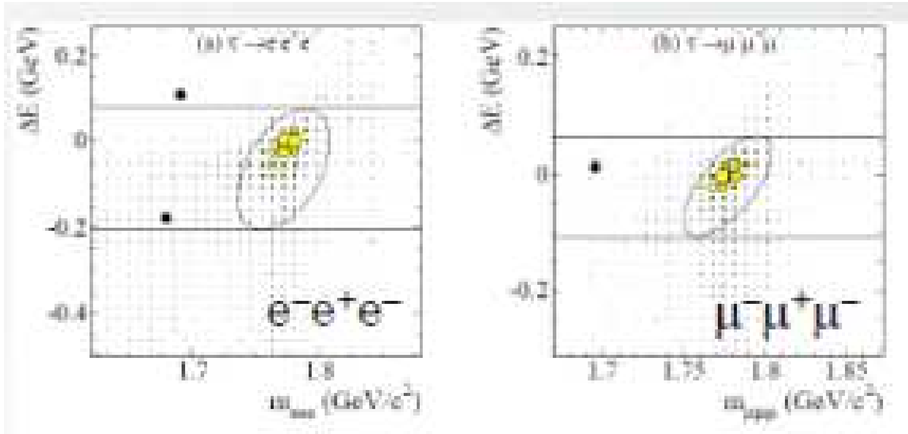

Figure 5: Distributions in the $M_{inv} - \Delta E$ plane corresponding to the $\pm 20\sigma$ area for the $\tau^- \to e^- e^+ e^-$(left) and $\tau^- \to \mu^- \mu^+ \mu^-$(right) modes respectively. The data are indicated by solid circles. The filled boxes show the MC signal distribution with arbitrary normalization. The elliptical signal regions shown by solid curve are used for evaluating the signal yield.

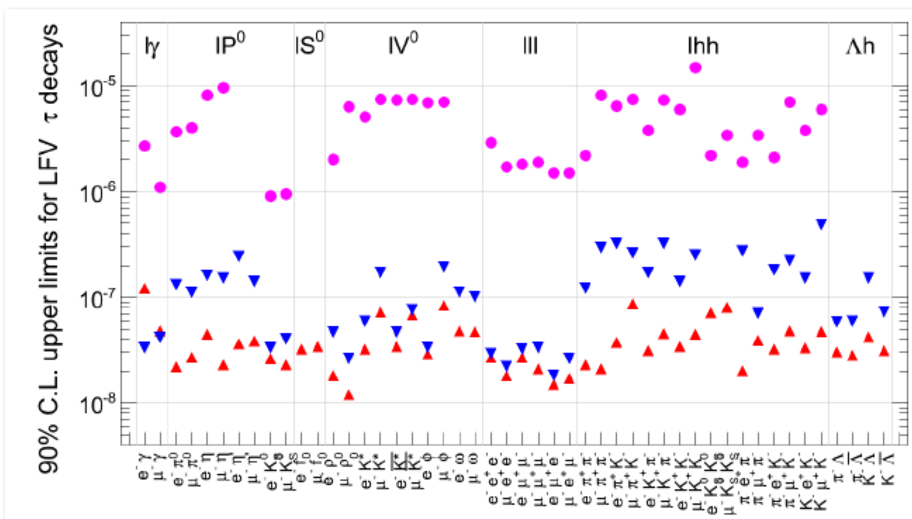

Figure 6: Summary of LFV τ decays studied with the Belle (triangles) and BaBar (inverted triangles) detectors in comparison with the CLEO (circles) results.

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