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Rare τ decays from B factory

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Recent results and the current situation concerning the search for lepton-flavor-violating τ decays are presented. B-factories have successfully accumulated data samples of $> 10^9$ τ pairs, and have performed searches for 50 modes. In the searches, optimization for background reduction is important to obtain high sensitivity. The upper limit of the branching ratio was obtained to be $\sim$O(10^{-8}). The results have ruled out some parts of the parameter space for models beyond the Standard Model, such as the SUSY+seesaw mechanism. The upgraded B-factory can be expected to reach $\sim$O(10^{-10}).

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1. Introduction

Lepton-flavor-violation (LFV) phenomena in the charged lepton sector are clear evidence for new physics (NP) beyond the Standard Model (SM). The SM exactly forbids LFV. Even considering an extended SM that includes neutrino mixing, charged LFV is highly suppressed, because it occurs through a loop diagram with a tiny neutrino mass. The branching ratio (BR) is expected to be BR($\tau \to \mu\gamma$)<O(10^{-40}) [1]. On the other hand, many NP models include the LFV vertex naturally. Therefore, we could observe charged LFV decay as a clear NP signal. Furthermore, since the τ lepton is the heaviest charged lepton, it is expected to show strong coupling with NP, and has many possible LFV decay modes, which depend on the NP models. Thus, LFV searches with τ leptons opens a wide window to probe the NP effect.

LFV τ decays are predicted by many NP models. Some of them are summarized in Table 1. Normal NP models enhance the decay $\tau \to \mu\gamma$. Other modes, however, may be enhanced instead for some NP parameters. As shown in this table, many NP models allow a measurable BR of O(10^{-8}) within the parameter space.

Table 1: Theoretical predictions of the branching ratio for $\tau \to \mu\gamma$ and $\tau \to \mu\mu\mu$.

Model	$\tau \to \mu\gamma$	$\tau \to \mu\mu\mu$
SM + ν mixing [1]	10^{-40}	10^{-14}
SM + heavy ν_R [2]	10^{-9}	10^{-10}
Non-universal Z' [3]	10^{-9}	10^{-8}
SUSY SO(10) [4]	10^{-8}	10^{-10}
mSUGRA + seesaw [5]	10^{-7}	10^{-9}
SUSY Higgs [6]	10^{-10}	10^{-7}

2. Experiment

Recent results are being obtained by B-factory experiments, Belle and BaBar collaborations. The B-factories comprise asymmetric e^+e^- colliders with their center-of-mass energy on the Υ(4S) resonance, and a forward-backward asymmetric general-purpose detector, originally aiming to measure CP violations in B decay. They also act as a τ factory, since the cross-section of τ pair production (0.9 nb) is almost the same as that of $B\overline{B}$ production (1.1 nb). The integrated luminosity has currently reached more than 900 fb^{-1} at Belle and 500 fb^{-1} at BaBar; the detectors exhibit excellent vertex resolution and particle-identification ability [7],[8]. Because Belle and BaBar now collect 8.3×10^8 and 4.6×10^8 τ pairs, respectively, their sensitivity on the τ's LFV will reach BR$\sim$O(10^{-8}).

The analysis procedure in a quest for the LFV signal is basically similar over different decay modes. The following selection criteria are generally imposed to discriminate the signal from the dominant background (BG), such as generic $\tau\tau$ decays and $q\bar{q}$ processes. An event is divided into hemispheres along the thrust axis, as shown in Fig. 1. Requirements exist concerning low multiplicity for charged tracks and photons: exclusive decay modes at the signal τ-side; a single track, a small number of photons and the missing momentum carried away by neutrino(s) with a low missing mass-squared at the tagging τ-side.

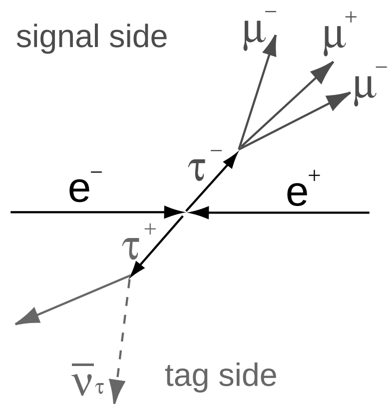

Figure 1: Schematic view of an event shape for $\tau \to \mu\mu\mu$.

The signal yield is evaluated in the $m_{\rm inv}$-ΔE distribution, where $m_{\rm inv}$ is the invariant mass of the signal candidate and ΔE is the energy difference of the candidate from the beam energy in the center-of-mass frame. The signal should distribute around $m_{\rm inv} = m_\tau$ and $\Delta E = 0$, and the BG events scatter broadly without any $m_{\rm inv}$ dependence. A so-called blind analysis is applied for avoiding any bias. In the beginning, the relevant $m_{\rm inv}$-ΔE signal region is blinded, and the BG yield in the signal region is estimated using the side-band data and/or Monte-Carlo samples. The number of signal events is then counted by unveiling the blind. The upper limit (UL) is calculated in most cases by applying the Feldman-Cousins method [9] when the expected BG is nearly to zero, or by the likelihood method employing probability density functions for the signal and BG when a non-negligible number of BG distributes with a $m_{\rm inv}$ and/or ΔE dependence.

We have optimized the selection criteria to obtain good sensitivity for signal discovery, because the sensitivity strongly depends on the BG level. Figure 2 shows the number of observed events ($N^{99}_{\rm obs.}$), which we need to state the 99% confidence level (CL) evidence, as a function of the number of expected BG ($N_{\rm BG}$). It tells us that better sensitivity for fewer $N_{\rm BG}$ is obtained, as long as the signal efficiency does not drop drastically. For example, when we reduce $N_{\rm BG}$ from 0.5 to 0.1, we can decrease $N^{99}_{\rm obs.}$ from 4 to 2. It is equal to an improvement of the effective efficiency by 2.

3. Current status of LFV searches

To improve the sensitivity using the current statistics, we need to efficiently remove the BG processes. The difficulty of reducing BG can be classified in the following order: $\tau \to \ell\ell\ell$, ℓh^0, $\ell hh'$ and $\ell\gamma$, where h^0 means a neutral hadron decaying into two charged mesons, and $h(h')$ is a charged meson. BG reduction is performed with the particle identification and the restriction of the invariant mass for the neutral hadron. Because of good lepton identification, the search for $\tau \to \ell\ell\ell$ can be applied to simple selection. In the current analysis, we optimize the selection criteria for each final state individually and introduce intelligent variables, such as the likelihood and neural net.

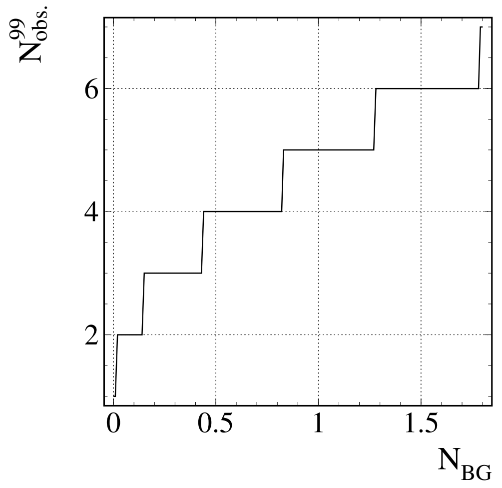

Figure 2: Number of observed events ($N^{99}_{\rm obs.}$) that we need for 99% confidence level evidence, as a function of the number of expected BG ($N_{\rm BG}$), evaluated by the POLE program [10] without systematic uncertainties of the signal efficiency and number of BG.

Recent results of searches for $\tau \to \ell\ell\ell$ were obtained by Belle and BaBar. BaBar has performed a search with 477 fb^{-1} data, and improved the lepton identification efficiency from that of a previous analysis. They observed zero events in the signal region for all modes, while the number of expected background events was $0.03-0.64$ events for each mode. The efficiency was $6.4-12.6$%. Their preliminary result is BR$<(1.8-3.3)\times 10^{-8}$ at the 90% CL. Belle analyzed a data sample of 782 fb^{-1}. The $m_{\rm inv}$-ΔE distributions are shown in Fig. 3. They observed zero events for all 6 possible modes, where the number of expected background events was $0.01-0.21$, and the efficiency was $6.0-11.5$%. The preliminary resulting UL of the BR is $(1.5-2.7)\times 10^{-8}$ at the 90% CL.

A search for $\tau \to \ell K_s$ has also been performed recently. Belle updated the analysis using the data of 671 fb^{-1}, and also searched for $\tau \to \ell K_s K_s$. The main background is from the process $e^+e^- \to q\bar{q}$, where q indicates the u,d,s and c quarks, which include K_s. They observed zero events for all modes with an efficiency of $5.08-10.7$%. The preliminary result of $\tau \to \ell K_s$ is BR$<(2.3-2.6)\times 10^{-8}$, while $\tau \to \ell K_s K_s$ BR$<(7.1-8.0)\times 10^{-8}$, at the 90% CL. BaBar also searched for $\tau \to \ell K_s$ with 469 fb^{-1} data, and the obtained result was BR$<(3.3-4.0)\times 10^{-8}$ at the 90% CL [11].

Belle and BaBar have shown results of a search for $\tau \to \ell V^0$, where V^0 indicates the vector mesons, and the decay modes are $\phi \to K^+K^-$, $\rho \to \pi^+\pi^-$, $K^*(892) \to K^+\pi^-$ and $\bar{K}^*(892) \to \pi^+K^-$. The MSSM model [12] predicts an enhancement. BaBar analyzed the 451 fb^{-1} data. The efficiency was $4.1-8.0$%, while the number of expected backgrounds was $0.68-2.76$. The dominant BG comes from the process $e^+e^- \to q\bar{q}$. They observed 16 events in total, and set the UL of BR($\tau \to \ell V^0$) to be $(2.6-19)\times 10^{-8}$ at the 90% CL [13]. Belle also updated the results using 543 fb^{-1} data and obtained a similar UL to be BR$<(5.9-10)\times 10^{-8}$ at the 90% CL [14].

Recently, BaBar updated the search for $\tau \to \ell\gamma$ using their final data set of 470 fb^{-1} on $\Upsilon(4S)$ 31 fb^{-1} on $\Upsilon(3S)$ and 15 fb^{-1} on $\Upsilon(2S)$, which corresponds to $(963\pm 7)\times 10^6$ τ decays. In the

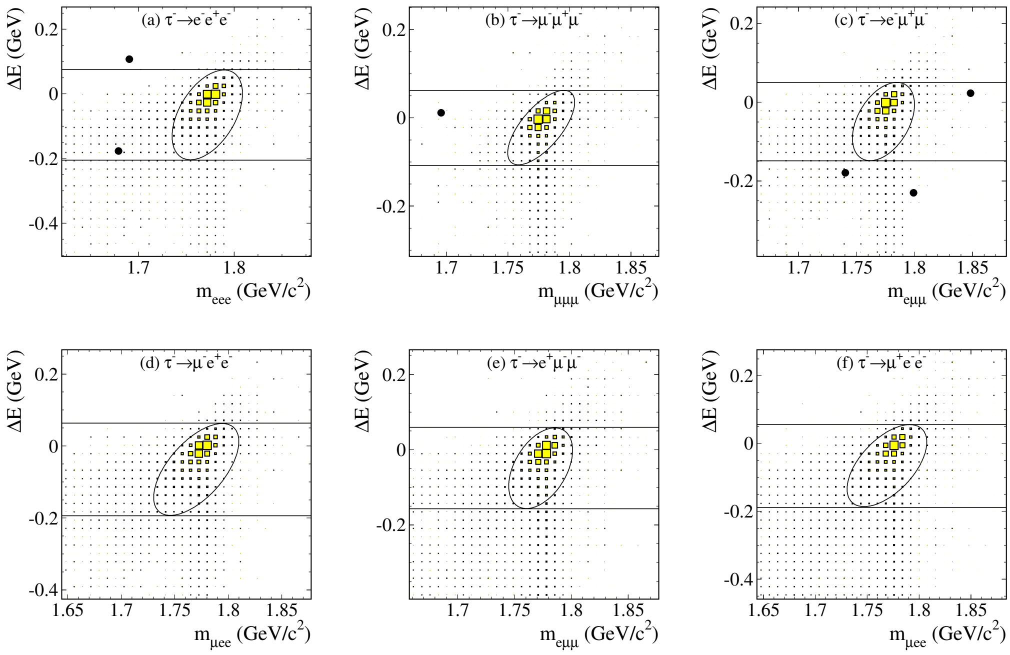

Figure 3: $m_{\rm inv}$-ΔE distributions for $\tau \rightarrow eee$ and $\tau \rightarrow \mu\mu\mu$ from the Belle analysis. The dots are data and yellow boxes indicate the expected signal distribution. The ellipse is the signal region.

analysis, new kinematic cuts and a neural-net discriminator were applied. The $m_{\rm inv}$-ΔE distributions are shown in Fig. 4. The efficiency was 6.1 and 3.9% for $\tau \rightarrow \mu\gamma$ and $e\gamma$, respectively. The number of expected backgrounds was 3.6 ± 0.7 and 1.6 ± 0.4. They observed two and zero events, and set the UL of BR to be $< 4.4 \times 10^{-8}$ for $\tau \rightarrow \mu\gamma$ and $< 3.3 \times 10^{-8}$ for $\tau \rightarrow e\gamma$ at the 90% CL [15].

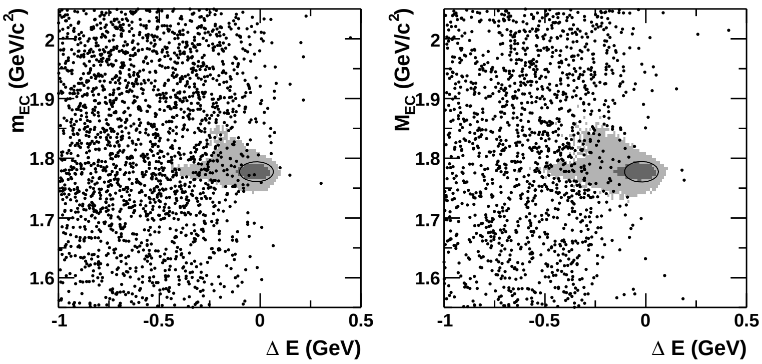

Figure 4: $m_{\rm inv}$-ΔE distributions for $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$ from the BaBar analysis. The dots are data and yellow boxes indicate the expected signal distribution. The ellipse is the signal region.

The current status of LFV searches is summarized in Fig. 5. B-factory experiments have reached a sensitivity of $\sim 10^{-8}$ branching ratio. The search for $\tau \rightarrow \ell\ell\ell$ sets the current most stringent UL. The experimental results have already ruled out some parts of the parameter space of, for instance, the mSUGRA + seesaw model and the SUSY Higgs model, given in Table 1. We can exclude the large $\tan\beta$ and small SUSY or the Higgs mass region.

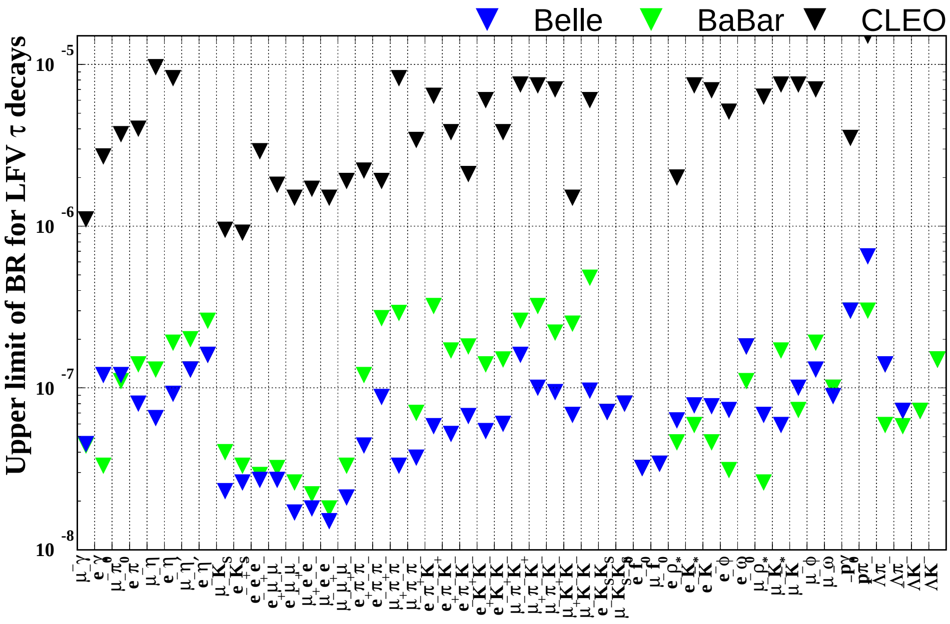

Figure 5: Current status of the search for LFV τ decays. Blue, green and black triangles show the results from Belle, BaBar and CLEO experiments, respectively.

The upgraded B-factory is planned to produce $> 10^{10}$ τ's, which is 10-times or more data than that of the current B-factory. The improvement in the sensitivity depends on the integrated luminosity, $\mathscr{L}$, and the BG situation. Figure 6 shows the history of the obtained UL of the BR as a function of the integrated luminosity, as well as the expected sensitivity extrapolating from the results. The BR of $\tau \to \ell\gamma$ will scale as $\sim 1/\sqrt{\mathscr{L}}$ because of the irreducible BG from $e^+e^- \to \tau^+\tau^-\gamma$ with $\tau \to \ell\nu\bar{\nu}$, while the BR of $\tau \to \ell\ell\ell$ will scale as $\sim 1/\mathscr{L}$ because the BG can be easily reduced by particle identification. Because of recent optimization of event selection, the expectation is improved as shown in Fig. 6. The LFV sensitivities will reach O($10^{-9\sim-10}$) at an integrated luminosity of 50 ab^{-1}.

4. Conclusion

Two B-factories, Belle and BaBar, have successfully obtained data samples of $> 10^9$ τ pairs. They investigated 50 LFV decay modes and observed no evidence so far. Presently, the UL on the BR is around $\sim$O(10^{-8}), such as BR($\tau \to \mu\gamma$)$< 4.4\times10^{-8}$, BR($\tau \to \mu\mu\mu$)$< 2.1\times10^{-8}$, etc. We are exploring some NP parameter space.

Optimization for BG reduction is important to improve the sensitivity. Recent analysis introduces a multi-variable discriminator, such as likelihood and a neural net, and an estimation of the signal yields with the likelihood. At the upgraded B-factory, the LFV sensitivity can be expected to reach BR$\sim$O(10^{-10}).

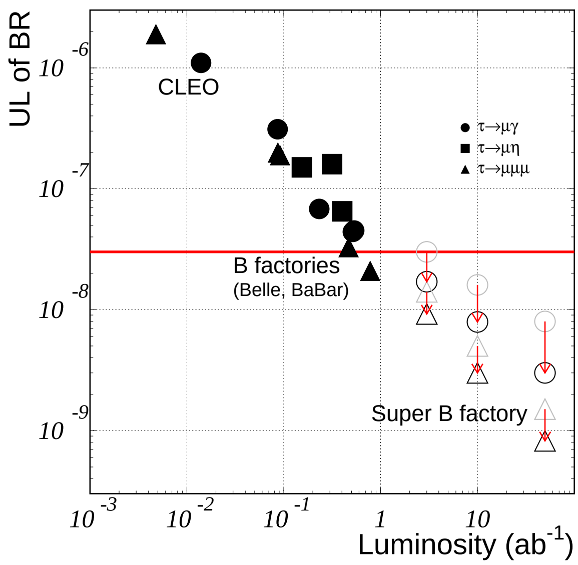

Figure 6: UL of the BR as a function of the integrated luminosity. Open marks indicate the present expectation at the upgraded B-factory, while light marks the old estimation using the situation at the 0.1 ab^{-1}.

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