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Search for Lepton Flavor Violation at B-factories

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Lepton flavor violation gives a good signature for new physics. We review recent searches for lepton flavor violation in τ and $\Upsilon(nS)$ decays at B-factories. In these searches, optimization for background reduction is important to obtain high sensitivity. No evidence for these decays is observed and 90% confidence level upper limits have been set on the branching fractions at the $O(10^{-8})$ and $O(10^{-6})$ level for τ and $\Upsilon(nS)$ decays, respectively.

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1. Introduction

Lepton-flavor-violating (LFV) decays of charged leptons are expected to have negligible probability even including neutrino oscillations in the Standard Model (SM). The branching fractions 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 the current experimental sensitivity [1, 2, 3, 4, 5]. 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 B-factory experiments. Therefore, an observation of LFV decay will be a clear signature for new physics beyond the SM. τ leptons are expected to be coupled strongly with new physics and have many possible LFV decay modes due to their large mass. Therefore, τ leptons are ideal objects to search for LFV decay.

SUSY, which is the most popular candidate among New Physics (NP) models, induces naturally 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

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

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 is 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 weak scale, LFV occurs via a Higgs-mediated LFV mechanism. If LFV occurs via a Higgs-mediated LFV mechanism, 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].

The ratios between theoretically predicted branching fractions of $\tau \to \mu\gamma$, $\tau \to \mu\mu\mu$, and $\tau \to \mu ee$ and maximum theoretical branching fraction of the $\tau \to \mu\gamma$ mode are summarized in Table 1. Since the ratio of the branching ratios allows to discriminate between new physics models, model-independent searches for various LFV modes are very important.

	SUSY+GUT	Higgs mediated	Little Higgs	Non-universal Z' boson
$\frac{\mathscr{B}(\tau \to \mu\mu\mu)}{\mathscr{B}(\tau \to \mu\gamma)}$	$\sim 2 \times 10^{-3}$	~ 0.1	$0.4 \sim 2.3$	20
$\frac{\mathscr{B}(\tau \to \mu ee)}{\mathscr{B}(\tau \to \mu\gamma)}$	$\sim 1 \times 10^{-2}$	$\sim 1 \times 10^{-2}$	$0.3 \sim 1.6$	~ 20
$\mathscr{B}(\tau \to \mu\gamma)$	$< 10^{-7}$	$< 10^{-10}$	$< 10^{-10}$	$< 10^{-9}$

Table 1: Ratios between the branching fractions of the $\tau \to \mu\gamma$ and $\tau \to \mu\ell\ell$ modes and the maximum theoretical branching fraction of the $\tau \to \mu\gamma$ mode in various NP models.

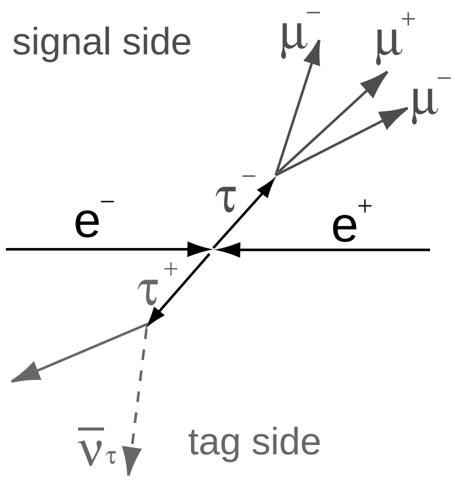

Figure 1: Event signature of LFV τ decay in case of $\tau \to \mu\mu\mu$ analysis

2. KEKB/Belle and PEP-II/BaBar

The KEKB is a e^+e^- asymmetric-energy collider operating at the center-of-mass (CM) energy corresponding to the $\Upsilon(4S)$ resonance. Experiments at the energy of $\Upsilon(4S)$ allow searches for LFV decays with a very high sensitivity since the cross section of $\tau^+\tau^-$ production is $\sigma_{\tau\tau} \simeq 0.9$ nb, close to that of $B\overline{B}$ production, $\sigma_{B\bar{B}} \simeq 1$ nb, and thus, $B-$factories are also excellent $\tau-$factories. The Belle detector [8] operating at the KEKB B-factory [9] accumulated about 9×10^8 τ pairs.

Similarly, the BaBar detector, described in more detail elsewhere [10], collected data at the PEP-II asymmetric-energy e^+e^- collider that operated at a CM energy of 10.58 GeV. Finally, a 557 fb^{-1} data sample has been accumulated before the PEP-II collider stopped running.

Both detectors at B-factories are the multipurpose detectors with good track reconstruction and particle identification ability.

3. Analysis 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 an 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 a signal- and tag-side into two hemispheres using a thrust axis. The backgrounds in such searches are dominated by $q\overline{q}$, 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. Typical event selection at Belle uses the relation between the missing momentum $p_{\rm miss}$ and missing mass squared $m^2_{\rm miss}$ since neutrinos are included in the tag side only in a signal event. This event selection is very effective to suppress background from generic $\tau^+\tau^-$ events.

After signal selection criteria are applied, signal candidates are examined in the two-dimensional space of the invariant mass, $M_{\rm inv}$, and the difference of their energy from the beam energy in the center-of-mass (CM) system, ΔE. A signal event should have $M_{\rm inv}$ close to the τ-lepton mass and ΔE close to 0. We blind a region around the signal region in the $M_{\rm inv} - \Delta E$ 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 LFV τ decay or set an upper limit by applying Bayesian, Friedman-Cousins or maximum likelihood approaches.

4. Results

4.1 $\tau^- \to \ell^-\gamma$

Belle have obtained upper limits for the branching fraction at the 90% confidence level $\mathscr{B}(\tau^- \to \mu^-\gamma) < 4.5 \times 10^{-8}$ and $\mathscr{B}(\tau^- \to e^-\gamma) < 1.2 \times 10^{-7}$ [11] using 535 fb^{-1} of data. The dominant background for these modes comes from generic $\tau\tau$ events where one τ decays into $\ell\nu\bar{\nu}$ with initial state radiation. Since many background events from $\tau\tau$ with initial state radiation remain, our sensitivity is limited.

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 this analysis, new kinematic cuts and a neural-net discriminator were applied. The $m_{\rm inv}$-ΔE distributions are shown in Fig. 2. The efficiency was 6.1 and 3.9% for $\tau \to \mu\gamma$ and $e\gamma$, respectively. The number of expected background events was 3.6 ± 0.7 and 1.6 ± 0.4. They observed 2 and 0 events, and set the UL of BR to be $< 4.4 \times 10^{-8}$ for $\tau \to \mu\gamma$ and $< 3.3 \times 10^{-8}$ for $\tau \to e\gamma$ at the 90% CL [12].

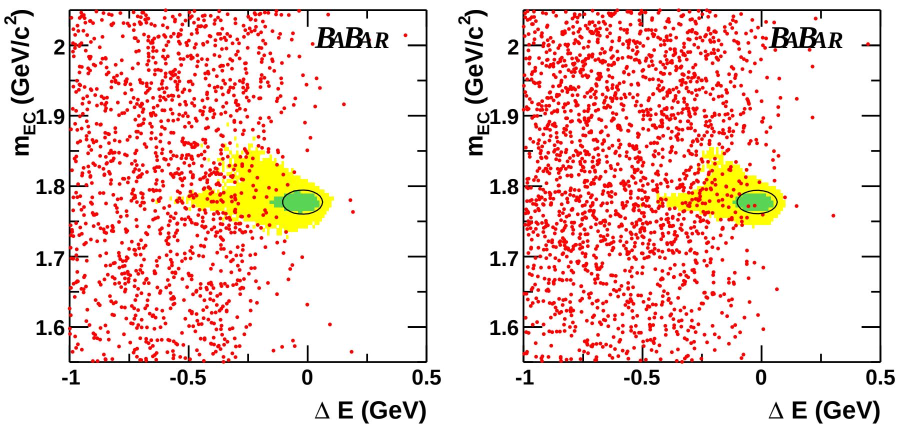

Figure 2: $m_{\rm inv}$-ΔE distributions for $\tau \to \mu\gamma$ and $\tau \to e\gamma$ from the BaBar analysis. Data are shown as dots and contours containing 90are shown as yellow- (green-) shaded regions.

4.2 $\tau^- \to \ell^-\ell^+\ell^-$

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 $e^-\mu^+e^-$.

BaBar has performed an updated search with 477 fb^{-1} data, and improved lepton identification efficiency from 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 result is BR$< (1.8 - 3.3) \times 10^{-8}$ at the 90% C.L. [13].

In the previous analysis, Belle reached 90% C.L. upper limits on the branching fractions in the range $(2.0 - 4.1) \times 10^{-8}$ [14], based on about 543 fb^{-1} of data. Belle updated this analysis using 782 fb^{-1}. For the signal region, we use an elliptical region which contains 90% of signal events in the $M_{\rm inv} - \Delta E$ plane. The signal efficiencies are kept in the range of (6.0-11.5)%. Belle observes no events after event selection in the signal region for all modes while the expected background is less than 0.2 events. No evidence for these decays is observed and we set 90% C.L. upper limits on the branching fractions between (1.5-2.7)$\times 10^{-8}$ [15]. Belle improves the best previous upper limits by factors from 1.3 to 1.6.

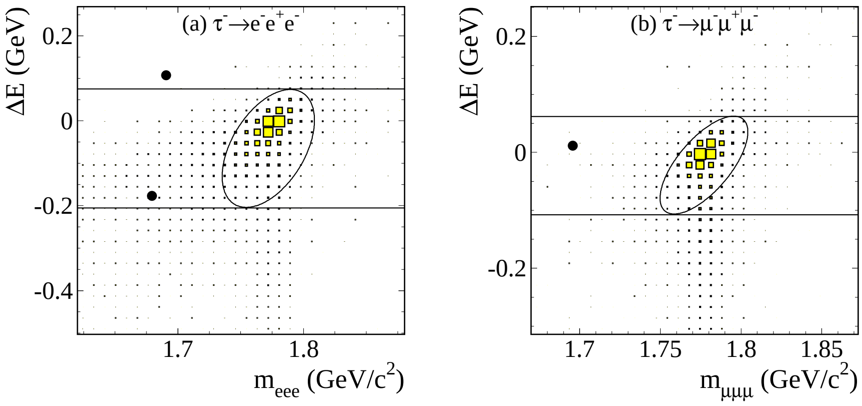

Figure 3: Scatter-plots in the $M_{\rm inv} - \Delta E$ plane in the (a) $\tau^- \to e^- e^+ e^-$ and (b) $\tau^- \to \mu^- \mu^+ \mu^-$ modes at Belle. The data are indicated by the solid circles. The filled boxes show the MC signal distribution with arbitrary normalization. The elliptical signal regions shown by a solid curve are used for evaluating the signal yield.

4.3 $\tau^- \to \ell h h'$

Belle and BaBar have also searched for various $\ell h h'$ (where h, $h' = \pi^\pm$ or $K^\pm$) modes including lepton number violation with the range of upper limits of the order of 10^{-7} [16, 17]. Belle recently updated a search for these modes using 671 fb^{-1} of data. Belle observes no events in the signal region after event selection except the $\tau^- \to \mu \pi K$ and $\tau^- \to e^+ \pi^- \pi^-$ modes while the expected background is less than 1.3 events. For the $\tau \to \mu \pi K$ modes, we observed a few events in the signal region which is consistent with the expected number of background events. For the $\tau^- \to e^+ \pi^- \pi^-$ modes, we observed one event in the signal region. Therefore, no evidence for these decays is observed, and we set upper limits on the branching fractions at 90% C.L.: $\mathscr{B}(\tau^- \to e h h') < (4.4 - 8.8) \times 10^{-8}$ and $\mathscr{B}(\tau^- \to \mu h h') < (3.3 - 16) \times 10^{-8}$ [18]. These results improve upon previously Belle published upper limits by factors of 1.6 to 8.8 [16].

4.4 $\tau \to \ell K_S^0$ and $\ell K_S^0 K_S^0$

Previously, Belle obtained 90% confidence level (C.L.) upper limits for $\tau^- \to \ell^- K_S^0$ branching fractions ($\mathscr{B}$) using 281 fb^{-1} of data; the results were in the range (4.9–5.6) $\times$ 10^{-8} [19]. The BaBar collaboration has recently used 469 fb^{-1} of data to obtain 90% C.L. upper limits in the range (3.3–4.0) $\times$ 10^{-8} [20]. Belle updates searches for the LFV decays $\tau^- \to \ell^- K_S^0$ based on 671 fb^{-1} with K_S^0 reconstructed from $\pi^+\pi^-$. No signal in either mode was found, so Belle obtained the following 90% C.L. upper limits on the branching fractions: $\mathscr{B}(\tau^- \to e^- K_S^0) < 2.6 \times 10^{-8}$ and $\mathscr{B}(\tau^- \to \mu^- K_S^0) < 2.3 \times 10^{-8}$ These results improve the search sensitivity by factors of 2.2 and 2.1 for eK_S^0 and μK_S^0, respectively, compared to our previous published limits [21].

For the $\ell K_S^0 K_S^0$ modes, the best 90$\mathscr{B}(\tau^- \to e^- K_S^0 K_S^0) < 2.2 \times 10^{-6}$ and $\mathscr{B}(\tau^- \to \mu^- K_S^0 K_S^0) < 3.4 \times 10^{-6}$ were set by CLEO using 13.9 fb^{-1} of data [22]. Belle used 671 fb^{-1} for this search. No evidence for a signal was found in either of the decay modes, and we set the following upper limits for the branching fractions: $\mathscr{B}(\tau^- \to e^- K_S^0 K_S^0) < 7.1 \times 10^{-8}$ and $\mathscr{B}(\tau^- \to \mu^- K_S^0 K_S^0) < 8.0 \times 10^{-8}$ [21]. These results improve the search sensitivity by factors of 31 and 43 for $eK_S^0 K_S^0$ and $\mu K_S^0 K_S^0$, respectively, compared to previous limits from CLEO [22].

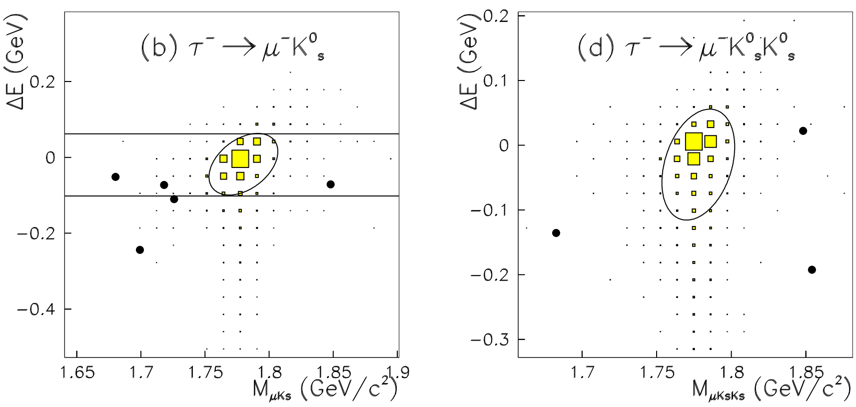

Figure 4: Scatter-plots in the $M_{\rm inv} - \Delta E$ plane corresponding to the $\pm 20\sigma$ area for the $\tau^- \to \mu^- K_S^0$ (left) and $\tau^- \to \mu^- K_S^0 K_S^0$ (right) modes at Belle, respectively. The data are indicated by the solid circles. The filled boxes show the MC signal distribution with arbitrary normalization. The elliptical signal regions shown by a solid curve are used for evaluating the signal yield.

4.5 $\Upsilon(nS) \to \ell^\pm \tau^\mp$ $(n = 2, 3)$

Here, we discuss LFV bottomonium decays $\Upsilon(nS) \to \ell^\pm \tau^\mp$ $(n = 2, 3)$. Various NP models predict such decays via the flavor-changing neutral currents with, e.g., R-parity violating and large $\tan\beta$ SUSY scenarios, leptoquarks and so on.

The signature for such events is two oppositely charged particles, which consist of a primary lepton as electron and muon, and a lepton or a pion from τ decay. Thus the experimental signature is: $\Upsilon(nS) \to \ell^\pm \tau^\mp (\to \ell \nu\nu, \pi\nu)$. To suppress background, the events are rejected if two leptons have the same flavor for a primary lepton and a lepton from τ decay.

An extended unbinned maximum likelihood fits are performed to the distribution of the variable, $x = p_1/E_B$, where p_1 is the momentum of a primary lepton at the CM system and E_B is the beam energy. The signal x is expected to peak around ~ 0.97 while the distribution from $\tau\tau$ background is smooth near zero at $x \to 0.97$ and the distribution from Bhabha and $\mu\mu$ is peaking around $x \sim 1$. Each PDF is determined from MC and data. Figure 5 shows maximum likelihood fit results for the leptonic $e\tau$ channel in $\Upsilon(3S)$ data. The signal yield is consistent with no signal-hypothesis within $\pm 1.8\sigma$ for all modes. Therefore, the upper limits at 90% C.L. are determined using the Bayesian method. The upper limits at 90% C.L. for each mode are shown in Table 2 and are $O(10^{-6})$ [23]. The results for the $\mathscr{B}(\Upsilon(nS) \to e^{\pm}\tau^{\mp})$ modes are the first searches while improving the sensitivity with respect to the previous upper limits on $\mathscr{B}(\Upsilon(nS) \to \mu^{\pm}\tau^{\mp})$[24].

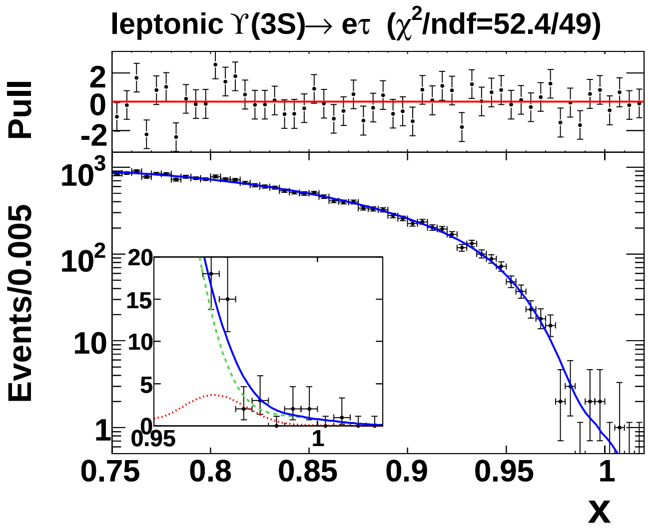

Figure 5: Maximum likelihood fit results for the leptonic $e\tau$ channel in $\Upsilon(3S)$ data. The red dotted line represents the signal PDF, the green dashed line represents the sum of all background PDFs and the solid blue line represents the sum of these components. The inset shows a close-up of the region $0.95 < x < 1.02$. The top plot shows the normalized residuals (data − fit)/σ_{data} (pull).

Model	UL(10^{-6})
$\mathscr{B}(\Upsilon(2S) \to e^{\pm}\tau^{\mp})$	< 3.2
$\mathscr{B}(\Upsilon(2S) \to \mu^{\pm}\tau^{\mp})$	< 3.3
$\mathscr{B}(\Upsilon(3S) \to e^{\pm}\tau^{\mp})$	< 4.2
$\mathscr{B}(\Upsilon(3S) \to \mu^{\pm}\tau^{\mp})$	< 3.1

Table 2: 90% C.L. uppper limits on the branching fractions $\mathscr{B}$ for $\Upsilon(nS) \to \ell^{\pm}\tau^{\mp}$.

5. Future Prospect

LFV sensitivity depends on the remaining background level. For the $\tau \to \mu\gamma$ mode, there is large remaining background from $\tau\tau$ event with initial state radiation. In this case, the expected

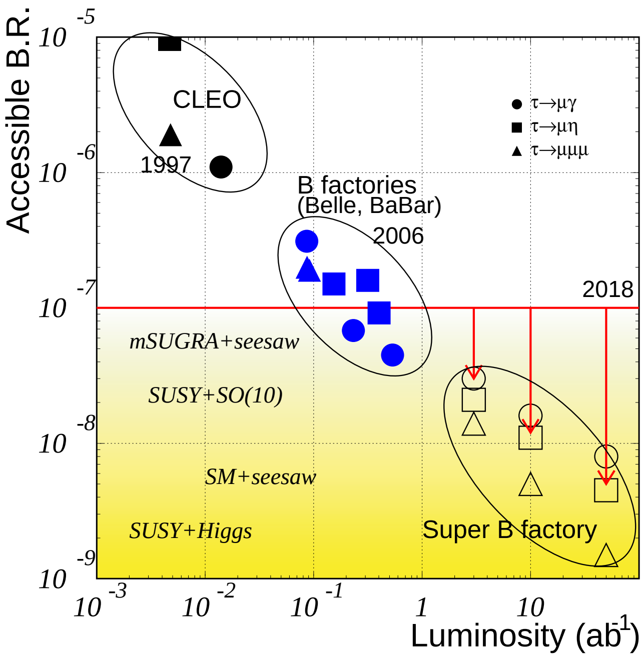

Figure 6: Branching fraction of LFV decay as a function of the integrated luminosity as well as the expected sensitivity extrapolating from the results.

branching fraction of $\tau \to \mu\gamma$ is scaled as $1/\sqrt{\mathscr{L}}$. On the other hand, the remaining background events for the $\tau \to \ell\ell'\ell''$ and ℓ+meson modes are expected to be negligible at 10 ab^{-1}. Therefore, the expected branching fractions of these modes scale linearly with luminosity from current upper limits. Figure 6 shows the history of the obtained UL of the branching fractions as a function of the integrated luminosity, as well as the expected sensitivity extrapolating from the results. A Super $B-$factory is planned to collect more than 10-times larger luminosity than the current one. Therefore, the expected branching fraction of $\tau \to \mu\gamma$ at the Super $B-$factory is $O(10^{-8\sim 9})$ while the expected branching fractions of $\tau \to \ell\ell\ell$ and ℓ+meson are $O(10^{-9\sim 10})$.

6. Summary

We have searched for all major modes of lepton-flavor-violating τ decays using $> 10^9$ τ pairs of data collected at the B-factories as the Belle detector at the KEKB asymmetric-energy e^+e^- collider and the BaBar detector at the PEP-II 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 from τ decays, shown in Table 3. We also set 90% confidence level upper limits on the branching fractions at the $O(10^{-6})$ level, from $\Upsilon(nS)$. These more stringent upper limits can be used to constrain the space of parameters in various models beyond the SM.

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τ^- decay mode	Belle		BaBar	
	$\mathscr{B}, 10^{-8}$	# of $\tau^+\tau^-$	$\mathscr{B}, 10^{-8}$	# of $\tau^+\tau^-$
$\mu^-\gamma$	4.5 [11]	492M	4.4 [12]	482M
$e^-\gamma$	12 [11]	492M	3.3[12]	482M
$\mu^-\eta, \mu^-\eta', \mu^-\pi^0$	6.5-13 [25]	369M	11-20 [26]	312M
$e^-\eta, e^-\eta', e^-\pi^0$	8.0-16 [25]	369M	14-26 [26]	312M
$\ell^-\ell'^-\ell''^+$	1.5-2.7 [14]	719M	1.8-3.3 [13]	430M
μ^-hh'	3.4-16 [18]	617M	7-44 [17]	203M
e^-hh'	4.4-8.7 [18]	617M	12-32 [17]	203M
$\ell^- f_0(980)(\to \pi^+\pi^-)$	3.2-3.4 [27]	617M	–	–
μ^-V^0	6.8-13 [29]	499M	8-18 [30]	414M
e^-V^0	6.3-7.3 [29]	499M	3.1-5.6 [30]	414M
$\mu^-K_S^0$	2.3 [21]	617M	4.0 [20]	431M
$e^-K_S^0$	2.6 [21]	617M	3.3 [20]	431M
$\mu^-K_S^0K_S^0$	8.0 [21]	617M	–	–
$e^-K_S^0K_S^0$	7.1 [21]	617M	–	–

Table 3: Summary for upper limits of branching fraction of lepton-flavor-violating τ decay

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