Search for Lepton-Flavor-Violating Tau Decays at the $B$-factories

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Both the $B$-factories $BaBar$ and Belle have ended data-taking and have mostly completed the data analysis aimed at searching Lepton Flavor Violation in Tau decays. No evidence of LFV in tau decays has been found yet. We review in the following the experimental upper limits that have been set.

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1. Introduction

The observation of neutrino oscillations implies that Lepton Flavor Violation (LFV) must happen in the interactions and decays of the charged leptons. Within the Standard Model (SM), however, LFV decays of charged leptons are heavily suppressed with respect to the dominant processes by the fourth power of the small ratio between the neutrino mass differences and the $W$ mass, $\frac{\Delta m_\nu^2}{m_W^4}$. On the other hand, most models beyond the SM, such as Supersymmetry, Grand Unification or Extra Dimensions, naturally include additional lepton-flavor-violating processes, which can produce observable tau decay rates with LFV, even when the model parameters are constrained with the available experimental data [1, 2, 3, 4, 5, 6, 7, 8, 9].

In the past, the CLEO collaboration has searched for LFV in tau decays without finding any evidence, and has set 90% CL upper limits around $10^{-6}$ for the corresponding tau branching fractions. In the last decade, the $\bar{B}A\bar{B}A R$ and Belle $B$-factories collaborations have extensively searched for LFV in tau decays, exploiting two orders of magnitude larger samples of $e^+e^-$ annihilation data at and around the $\Upsilon(4S)$ peak, with a sensitivity for tau LFV branching fractions up to about $10^{-8}$.

The $\bar{B}A\bar{B}A R$ collaboration has ended data-taking in April 2008, collecting about 531 fb$^{-1}$ of data, and has completed its data analysis on about its full data sample for the most interesting LFV channels, $\tau \rightarrow (\mu/e)\gamma$ and $\tau \rightarrow 3\ell$, and on samples close to it full data samples for the other channels.

The Belle collaboration has ended data taking in June 2010, collecting about 1040 fb$^{-1}$ of data, has recently produced results on some tau LFV searches using most of its complete dataset, and is updating to its final dataset the most complex searches, such as $\tau \rightarrow (\mu/e)\gamma$.

We report in the following on the most recent $B$-factories results, and we refer the reader to the HFAG group 2010 report [10] for a comprehensive status of tau LFV searches.

The typical search for LFV tau decays selects candidate $\tau^+\tau^-$ events where one tau decays into the most common final states, while the other one decays into a neutrinoless final state with a specific particle content. With respect to $q\bar{q}$ events, $\tau^+\tau^-$ events have fewer tracks and are more collimated around the thrust axis in the $e^+e^-$ center-of-mass (CM) reference frame. Candidate events from di-lepton final states are recognized because their total energy is close to the $e^+e^-$ energy, while for candidate $\tau^+\tau^-$ pairs a significant share of the energy escapes undetected with one or two neutrinos of the non-LFV tau decay. Finally, two-photon events can be recognized because their total energy is smaller than for $\tau^+\tau^-$ events, with zero net transverse momentum and with a larger imbalance of momentum along the beams in the $e^+e^-$ CM system.

While standing in the CM system, both tau decay products cluster in two relatively collimated cones around the thrust axis, aligned with their respective tau directions. Since the LFV tau decay is neutrinoless, the particles in its hemisphere have an invariant mass that matches the tau mass within the experimental resolution and a total energy that matches half the $e^+e^-$ energy ($\sqrt{s} \approx 10.58$ GeV). The experimental resolution in the invariant mass can be improved by constraining the total energy to half the event energy and by recovering Bremsstrahlung radiation that is close enough to the final state tracks, obtaining a resolution of $10–20$ MeV. The experimental resolution in the final state energy is around 40 MeV.

Selected candidates whose energy and invariant mass match the expected values are counted to detect evidence for a signal exceeding the expected background. The background is estimated
Table 1: Search for $\tau \rightarrow \ell P^0$, $P^0=\pi^0, \eta, \eta'$, efficiencies (Eff.), expected number of background events ($N_{BG}^{exp}$), 90% CL upper limits on the branching fractions (UL), where (comb.) indicated the combined upper limit when combining all examined modes of the eta mesons decay.

| Mode ($\tau \rightarrow$) | Eff.(%) | $N_{BG}^{exp}$ | UL ($\times 10^{-8}$) | Mode ($\tau \rightarrow$) | Eff.(%) | $N_{BG}^{exp}$ | UL ($\times 10^{-8}$) |
|--------------------------|--------|----------------|---------------------|--------------------------|--------|----------------|---------------------|
| $\mu \eta (\rightarrow \gamma \gamma)$ | 8.2 | $0.63 \pm 0.37$ | 3.6 | $e \eta (\rightarrow \gamma \gamma)$ | 7.0 | $0.66 \pm 0.38$ | 8.2 |
| $\mu \eta (\rightarrow \pi \pi \pi^0)$ | 6.9 | $0.23 \pm 0.23$ | 8.6 | $e \eta (\rightarrow \pi \pi \pi^0)$ | 6.3 | $0.69 \pm 0.40$ | 8.1 |
| $\mu \eta$(comb.) | 2.3 | - | 4.4 | $e \eta$(comb.) | - | - | - |
| $\mu \eta(\rightarrow \pi \pi \eta)$ | 8.1 | $0.00 \pm 0.16$ | 10.0 | $e \eta(\rightarrow \pi \pi \eta)$ | 7.3 | $0.63 \pm 0.45$ | 9.4 |
| $\mu \eta(\rightarrow \gamma \rho^0)$ | 6.2 | $0.59 \pm 0.41$ | 6.6 | $e \eta(\rightarrow \gamma \rho^0)$ | 7.5 | $0.29 \pm 0.29$ | 6.8 |
| $\mu \eta'(\rightarrow \pi \pi \eta)$ | 4.2 | $0.64 \pm 0.32$ | 2.7 | $e \eta'(\rightarrow \pi \pi \eta)$ | 4.7 | $0.89 \pm 0.40$ | 2.2 |
| $\mu \pi^0$(comb.) | 3.8 | - | 4.4 |

2. Search for the tau decay into a lepton and neutral pseudoscalar meson

Belle has presented preliminary results on a search for $\tau \rightarrow \ell P^0$, $P^0=\pi^0, \eta, \eta'$ [11], which updates a 2007 publication based on about 400 fb$^{-1}$ [12] (BaBar also published results on a similar sample [13]). All searches did not find any evidence of a LFV signal.

In the most recent Belle analysis, the eta mesons have been searched on two decay modes each, $\eta \rightarrow \gamma \gamma$, $\pi^+\pi^-\pi^0$ and $\eta' \rightarrow \pi^+\pi^-\eta$, $\rho^0\gamma$. The selection has been further optimized and reports a signal efficiency 1.5 higher with less than one expected background event for each mode. The 90% CL upper limits on the branching fraction are $(2.2-4.4)\times10^{-8}$ and are detailed in Table 1.

3. Search for the tau decay into a lepton and neutral vector meson

Belle has presented preliminary results on searches for $\tau \rightarrow \ell V^0$, $V^0=\rho, K^{*0}, \omega, \phi$ on a sample of 854 fb$^{-1}$ of data [14], updating on former published results based on 543 fb$^{-1}$ [15]. No evidence for a signal has been found, as well as in the BaBar searches on the same channels that were based on 451 fb$^{-1}$ of data [16, 17].

The selection has been improved, and on average the signal efficiency has been increased by 20%, while maintaining the expected background at around one event or less for all channels. Backgrounds have been studied in higher detail and it was found that two-photon and radiative Bhabha processes constitute a non-negligible background for $\tau \rightarrow \mu \rho$. Table 2 reports the established 90% CL upper limits.
lists the 90% CL upper limits. Scale as the inverse square root of the integrated luminosity (\(\propto \frac{1}{\sqrt{L}}\)) followed, just repeating the B can be kept under control, as it appears possible especially if the nano-beams design option is substantial advancement of the experimental sensitivity to the tau LFV. If the machine backgrounds that within the next ten years the proposed super flavor factories BelleII [22] and SuperB [23] will collect about 100 times larger samples of \(e^+e^-\) annihilations around the \(\Upsilon(4S)\) peak, permitting a substantial advancement of the experimental sensitivity to the tau LFV. If the machine backgrounds can be kept under control, as it appears possible especially if the nano-beams design option is followed, just repeating the B factories analyses unchanged will provide 90% CL upper limits that scale as the inverse square root of the integrated luminosity (\(\propto 1/\sqrt{L}\)). By optimizing the event

| Mode (\(\tau \rightarrow \)) | Eff.(%) | \(N_{BG}^{exp}\) | UL \((\times 10^{-8})\) | Mode (\(\tau \rightarrow \)) | Eff.(%) | \(N_{BG}^{exp}\) | UL \((\times 10^{-8})\) |
|-----------------------------|--------|----------------|----------------|-----------------------------|--------|----------------|----------------|
| \(e^-\mu^+\mu^-\)         | 10.1   | 0.02 \pm 0.02 | 1.7            | \(\mu^-\mu^+\mu^-\)      | 7.6    | 0.13 \pm 0.06 | 2.1            |
| \(e^+\mu^-\mu^-\)         | 6.1    | 0.10 \pm 0.04 | 2.7            | \(e^-\mu^-\mu^-\)        | 6.1    | 0.10 \pm 0.04 | 2.7            |
| \(e^-\mu^+\mu^-\)         | 11.5   | 0.01 \pm 0.01 | 1.5            | \(e^-\mu^-\mu^-\)        | 11.5   | 0.01 \pm 0.01 | 1.5            |
| \(e^-e^+e^-\)             | 6.0    | 0.21 \pm 0.15 | 2.7            | \(\mu^-e^+e^-\)          | 9.3    | 0.04 \pm 0.04 | 1.8            |
| \(e^-e^-\mu^-\)           | 9.3    | 0.04 \pm 0.04 | 1.8            | \(e^-\mu^+e^-\)          | 11.5   | 0.01 \pm 0.01 | 1.5            |
| \(\mu^-e^+\mu^-\)         | 10.1   | 0.02 \pm 0.02 | 1.7            | \(\mu^-\mu^+\mu^-\)      | 7.6    | 0.13 \pm 0.06 | 2.1            |
| \(\mu^-\mu^-\mu^-\)       | 7.6    | 0.13 \pm 0.06 | 2.1            | \(\mu^-\mu^+\mu^-\)      | 7.6    | 0.13 \pm 0.06 | 2.1            |

Table 2: Search for \(\tau \rightarrow 3\ell\), Belle and BABAR efficiencies (Eff.), expected numbers of background events \((N_{BG}^{exp})\), 90% CL upper limit on the branching fraction (UL) for each mode.

4. Search for the tau decay into three leptons

Both \(B\bar{B}\) and Belle have published in 2010 results on searches for \(\tau \rightarrow 3\ell\) [18, 19]. \(B\bar{B}\) has examined 486 fb\(^{-1}\) of data, most of its dataset, and has considerably improved the previously published result [20], based on 221 fb\(^{-1}\), by using improved reconstruction software, especially regarding particle identification, where for instance the muon efficiency has increased from 66% to 77%, and by more carefully optimizing the event selection. Belle has updated a former search based on 535 fb\(^{-1}\) of data [21] to 782 fb\(^{-1}\), maintaining a selection with a similar efficiency and high background suppression, with at most 0.2 events expected in all channels. Both experiments found no evidence for LFV in all channels, Table 3 lists the 90% CL upper limits.

| Mode (\(\tau \rightarrow \)) | Eff.(%) | BABAR \(N_{BG}^{exp}\) | UL \((\times 10^{-8})\) | Belle \(N_{BG}^{exp}\) | UL \((\times 10^{-8})\) |
|-----------------------------|--------|----------------|----------------|----------------|----------------|
| \(e^-e^+e^-\)             | 6.0    | 0.12 \pm 0.02 | 3.4            | 2.7            | 8.6            |
| \(e^-e^-\mu^-\)           | 9.3    | 0.64 \pm 0.19 | 3.7            | 1.8            | 8.8            |
| \(e^-\mu^+e^-\)           | 11.5   | 0.34 \pm 0.12 | 2.2            | 1.5            | 12.6           |
| \(e^-\mu^-\mu^-\)         | 6.1    | 0.54 \pm 0.14 | 4.6            | 2.7            | 6.4            |
| \(\mu^-e^+\mu^-\)         | 10.1   | 0.03 \pm 0.02 | 2.8            | 1.7            | 10.2           |
| \(\mu^-\mu^+\mu^-\)       | 7.6    | 0.44 \pm 0.17 | 4.0            | 2.1            | 6.6            |

Table 3: Search for \(\tau \rightarrow 3\ell\), Belle and BABAR efficiencies (Eff.), expected numbers of background events \((N_{BG}^{exp})\), 90% CL upper limit on the branching fraction (UL) for each mode.

5. Future prospects

The \(B\)-factories \(B\bar{B}\) and Belle have both ended data-taking and are close to complete tau LFV searches with a sensitivity for branching fractions up to about \(10^{-8}\), a two orders of magnitude improvement with respect to the previously existing limits set by CLEO. There are good prospects that within the next ten years the proposed super flavor factories BelleII [22] and SuperB [23] will collect about 100 times larger samples of \(e^+e^-\) annihilations around the \(\Upsilon(4S)\) peak, permitting a substantial advancement of the experimental sensitivity to the tau LFV. If the machine backgrounds can be kept under control, as it appears possible especially if the nano-beams design option is followed, just repeating the \(B\) factories analyses unchanged will provide 90% CL upper limits that scale as the inverse square root of the integrated luminosity (\(\propto 1/\sqrt{L}\)). By optimizing the event
selection for the larger datasets, however, the sensitivity to tau LFV will improve at a faster pace, up to $\propto 1/L$ for those searches that are background-free, i.e. whose candidate selection can be optimized to retain the B-factories efficiencies while at the same time suppressing backgrounds to expect at most one background event in the signal region. The SuperB collaboration has recently produced a physics report [24] where the sensitivities for the search for LFV in $\tau \rightarrow (e/\mu)\gamma$ and $\tau \rightarrow 3\ell$ are estimated.

The last published $\text{BaBar}$ results on $\tau \rightarrow (\mu/e)\gamma$ [25] are extrapolated to the SuperB expected luminosity assuming that the analysis is background-dominated, i.e. that the background cannot be further suppressed at constant signal efficiency. Improvements in the SuperB detector project with respect to BaBar will however provide a better sensitivity than the $\propto 1/\sqrt{L}$ extrapolation. The SuperB detector will have better tracking resolution, to compensate for the smaller boost, and its beam spot will be smaller: both features improve the resolution on the energy-constrained invariant mass and on the energy. Improvements are also expected in the photon acceptance. The SuperB sensitivity for $\tau \rightarrow \mu\gamma$ is determined to be $2.4 \times 10^{-9}$ as 90% CL upper limit and $5.4 \times 10^{-9}$ for a 3σ signal evidence. For the $\tau \rightarrow e\gamma$ the two figures are $3.0 \times 10^{-9}$ and $6.8 \times 10^{-9}$, respectively.

The last published $\text{BaBar}$ analysis on $\tau \rightarrow 3\ell$ [18] is re-optimized for the SuperB design integrated luminosity of 75 ab$^{-1}$, disregarding further gains from detector improvements, and the SuperB LFV sensitivity is determined to be in the range $2.3 - 8.2 \times 10^{-10}$ as 90% CL upper limits and $1.2 - 4.0 \times 10^{-9}$ for a 3σ signal evidence.

References

[1] J. R. Ellis, M. E. Gomez, G. K. Leontaris, S. Lola, and D. V. Nanopoulos, Charged lepton flavour violation in the light of the Super-Kamiokande data, Eur. Phys. J. C14 (2000) 319–334, [hep-ph/9911459].

[2] J. R. Ellis, J. Hisano, M. Raidal, and Y. Shimizu, A new parametrization of the seesaw mechanism and applications in supersymmetric models, Phys. Rev. D66 (2002) 115013, [hep-ph/0206110].

[3] A. Masiero, S. K. Vempati, and O. Vives, Seesaw and lepton flavour violation in SUSY SO(10), Nucl. Phys. B649 (2003) 189–204, [hep-ph/0209303].

[4] T. Fukuyama, T. Kikuchi, and N. Okada, Lepton flavor violating processes and muon g-2 in minimal supersymmetric SO(10) model, Phys. Rev. D68 (2003) 033012, [hep-ph/0304190].

[5] G. Cvetic, C. Dib, C. S. Kim, and J. D. Kim, On lepton flavor violation in tau decays, Phys. Rev. D66 (2002) 034008, [hep-ph/0202212].

[6] C.-x. Yue, Y.-m. Zhang, and L.-j. Liu, Non-universal gauge bosons Z' and lepton flavor-violation tau decays, Phys. Lett. B547 (2002) 252–256, [hep-ph/0209291].

[7] A. Dedes, J. R. Ellis, and M. Raidal, Higgs mediated B(s,d)0 $\rightarrow$ mu tau, e tau and tau $\rightarrow$ 3mu, e mu mu decays in supersymmetric seesaw models, Phys. Lett. B549 (2002) 159–169, [hep-ph/0209207].

[8] A. Brignole and A. Rossi, Lepton flavour violating decays of supersymmetric Higgs bosons, Phys. Lett. B566 (2003) 217–225, [hep-ph/0304081].

[9] E. Arganda and M. J. Herrero, Testing supersymmetry with lepton flavor violating tau and mu decays, Phys. Rev. D73 (2006) 055003, [hep-ph/0510405].
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[10] The Heavy Flavor Averaging Group, Averages of b-hadron, c-hadron, and tau-lepton Properties, arXiv:1010.1589.

[11] K. Hayasaka, Recent Tau Decay Results at B Factories – Lepton Flavor Violating Tau Decays, arXiv:1010.3746.

[12] Belle Collaboration, Y. Miyazaki et. al., Search for lepton flavor violating tau- decays into l- eta, l- eta' and l- pi0, Phys. Lett. B648 (2007) 341–350, [hep-ex/0703009].

[13] BaBar Collaboration, B. Aubert et. al., Search for Lepton Flavor Violating Decays $\tau^\pm \rightarrow \ell^\pm \pi^0$, $\ell^\pm \eta$, $\ell^\pm \eta'$, Phys. Rev. Lett. 98 (2007) 061803, [hep-ex/0610067].

[14] K. Hayasaka, “Search for Lepton Flavour Violating tau decay and lepton-number violation B decay at Belle.” Talk given at the 35th International Conference on High Energy Physics, Paris, July, 2010.

[15] Belle Collaboration, Y. Nishio et. al., Search for lepton-flavor-violating $\tau \rightarrow \ell V^0$ decays at Belle, Phys. Lett. B664 (2008) 35–40, [arXiv:0801.2475].

[16] BaBar Collaboration, B. Aubert et. al., Search for Lepton Flavor Violating Decays $\tau^\pm \rightarrow \ell^\pm \omega$ ($\ell = e, \mu$), Phys. Rev. Lett. 100 (2008) 071802, [arXiv:0711.0980].

[17] BaBar Collaboration, B. Aubert et. al., Improved limits on lepton flavor violating tau decays to l phi, l rho, l K* and l K*bar, Phys. Rev. Lett. 103 (2009) 021801, [arXiv:0904.0339].

[18] BaBar Collaboration, J. P. Lees et. al., Limits on tau Lepton-Flavor Violating Decays in three charged leptons, Phys. Rev. D81 (2010) 111101, [arXiv:1002.4550].

[19] K. Hayasaka et. al., Search for Lepton Flavor Violating Tau Decays into Three Leptons with 719 Million Produced Tau+Tau- Pairs, Phys. Lett. B687 (2010) 139–143, [arXiv:1001.3221].

[20] BaBar Collaboration, B. Aubert et. al., Search for lepton flavor violation in the decay $\tau^- \rightarrow \ell^- \ell^+ \ell^-$, Phys. Rev. Lett. 92 (2004) 121801, [hep-ex/0312027].

[21] Belle Collaboration, Y. Miyazaki et. al., Search for Lepton Flavor Violating tau Decays into Three Leptons, Phys. Lett. B660 (2008) 154–160, [arXiv:0711.2189].

[22] T. Aushev et. al., Physics at Super B Factory, arXiv:1002.5012.

[23] M. Bona et. al., SuperB: A High-Luminosity Asymmetric e+ e- Super Flavor Factory. Conceptual Design Report, arXiv:0709.0451.

[24] T. Abe et. al., Belle II Technical Design Report, arXiv:1011.0352.

[25] BaBar Collaboration, B. Aubert et. al., Searches for Lepton Flavor Violation in the Decays tau -> e gamma and tau -> mu gamma, Phys. Rev. Lett. 104 (2010) 021802, [arXiv:0908.2381].