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, $\Delta m_\nu^4/m_W^4$. 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 *BABAR* 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 *BABAR* collaboration has ended data-taking in April 2008, collecting about $531\,\text{fb}^{-1}$ of data, and has completed its data analysis on about its full data sample for the most interesting LFV channels, $\tau \to (\mu/e)\gamma$ and $\tau \to 3\ell$, 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 $1040\,\text{fb}^{-1}$ 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 $\tau \to (\mu/e)\gamma$.

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 ($\sqrt{s} \approx 10.58\,\text{GeV}$). 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 $10-20\,\text{MeV}$. The experimental resolution in the final state energy is around $40\,\text{MeV}$.

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

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

Table 1: Search for $\tau \to \ell P^0$, $P^0 = \pi^0, \eta, \eta'$, efficiencies (Eff.), expected number of background events ($N_{\mathrm{BG}}^{\mathrm{exp}}$), 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.

by counting for each background source how many Monte Carlo simulated events survive the selection procedure. For some background sources, such as Bhabha and two-photon events, it is too resource-demanding or otherwise inconvenient to produce large enough simulated samples: in these cases properly selected data control samples are used to estimate the background. The selection procedure is optimized without looking at data where the LFV signal is expected, to avoid the experimenter bias; *BABAR* usually optimizes the selection to obtain the lowest expected 90% CL upper limit in case there is no signal, while Belle usually optimizes in order to be able to detect the smallest possible tau LFV branching fraction with 99% CL evidence.

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

Belle has presented preliminary results on a search for $\tau \to \ell P^0$, $P^0 = \pi^0, \eta, \eta'$ [11], which updates a 2007 publication based on about $400\,\mathrm{fb}^{-1}$ [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, $\eta \to \gamma\gamma$, $\pi^+\pi^-\pi^0$ and $\eta' \to \pi^+\pi^-\eta$, $\rho^0\gamma$. 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 $(2.2 - 4.4)\times 10^{-8}$ 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 $\tau \to \ell V^0$, $V^0 = \rho, K^{*0}, \omega, \phi$ on a sample of $854\,\mathrm{fb}^{-1}$ of data [14], updating on former published results based on $543\,\mathrm{fb}^{-1}$ [15]. No evidence for a signal has been found, as well as in the *BABAR* searches on the same channels that were based on $451\,\mathrm{fb}^{-1}$ 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 $\tau \to \mu\rho$. Table 2 reports the established 90% CL upper limits.

Mode ($\tau \to$)	Eff.(%)	$N_{\text{BG}}^{\text{exp}}$	UL ($\times 10^{-8}$)	Mode ($\tau \to$)	Eff.(%)	$N_{\text{BG}}^{\text{exp}}$	UL ($\times 10^{-8}$)
$e\rho$	7.6%	0.29 ± 0.15	1.8	eK^{*0}	4.4%	0.39 ± 0.14	3.2
$\mu\rho$	7.1%	1.48 ± 0.35	1.2	μK^{*0}	3.4%	0.53 ± 0.20	7.2
$e\phi$	4.2%	0.47 ± 0.19	3.1	$e\overline{K^{*0}}$	4.4%	0.08 ± 0.08	3.4
$\mu\phi$	3.2%	0.06 ± 0.06	8.4	$\mu\overline{K^{*0}}$	3.6%	0.45 ± 0.17	7.0
$e\omega$	2.9%	0.30 ± 0.14	4.8	$\mu\omega$	2.4%	0.72 ± 0.18	4.7

Table 2: Search for $\tau \to \ell V^0$, $V^0 = \rho, K^{*0}, \omega, \phi$, efficiencies (Eff.), expected numbers of background events ($N_{\text{BG}}^{\text{exp}}$), 90% CL upper limit on the branching fraction (UL) for each mode.

4. Search for the tau decay into three leptons

Both BABAR and Belle have published in 2010 results on searches for $\tau \to 3\ell$ [18, 19]. BABAR 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 ($\tau^- \to$)	Belle Eff.(%)	Belle $N_{\text{BG}}^{\text{exp}}$	Belle UL ($\times 10^{-8}$)	BABAR Eff.(%)	BABAR $N_{\text{BG}}^{\text{exp}}$	BABAR UL ($\times 10^{-8}$)
$e^- e^+ e^-$	6.0	0.21 ± 0.15	2.7	8.6	0.12 ± 0.02	3.4
$e^- e^+ \mu^-$	9.3	0.04 ± 0.04	1.8	8.8	0.64 ± 0.19	3.7
$e^- \mu^+ e^-$	11.5	0.01 ± 0.01	1.5	12.6	0.34 ± 0.12	2.2
$e^- \mu^+ \mu^-$	6.1	0.10 ± 0.04	2.7	6.4	0.54 ± 0.14	4.6
$\mu^- e^+ \mu^-$	10.1	0.02 ± 0.02	1.7	10.2	0.03 ± 0.02	2.8
$\mu^- \mu^+ \mu^-$	7.6	0.13 ± 0.06	2.1	6.6	0.44 ± 0.17	4.0

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

5. Future prospects

The *B*-factories BABAR 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 ($\propto 1/\sqrt{\mathcal{L}}$). By optimizing the event

selection for the larger datasets, however, the sensitivity to tau LFV will improve at a faster pace, up to $\propto 1/\mathscr{L}$ 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 Super*B* collaboration has recently produced a physics report [24] where the sensitivities for the search for LFV in $\tau \to (e/\mu)\gamma$ and $\tau \to 3\ell$ are estimated.

The last published *BABAR* results on $\tau \to (\mu/e)\gamma$ [25] are extrapolated to the Super*B* 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 Super*B* detector project with respect to *BABAR* will however provide a better sensitivity than the $\propto 1/\sqrt{\mathscr{L}}$ extrapolation. The Super*B* 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 Super*B* sensitivity for $\tau \to \mu\gamma$ is determined to be $2.4 \cdot 10^{-9}$ as 90% CL upper limit and $5.4 \cdot 10^{-9}$ for a 3σ signal evidence. For the $\tau \to e\gamma$ the two figures are $3.0 \cdot 10^{-9}$ and $6.8 \cdot 10^{-9}$, respectively.

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

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