Rare Decays of Tau Leptons: an Experimental Review

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I review the current experimental situation with regard to searches for rare decays of τ leptons. The recent progress in this area has been made by the BELLE and BaBar collaborations thanks to their impressive datasets and detection capabilities, attention to backgrounds, and careful statistical treatments of the data. After summarizing the present status, the review concludes with look at the future prospects for these searches.

1 Introduction

The τ lepton offers unique possibilities for searches for physics beyond the Standard Model (SM). By virtue of being a heavy lepton, neutrino-less decays to lighter charged leptons can be probed experimentally. These transitions are typically “lepton flavor violating” (LFV). That is, the additive quantum numbers \((L_e, L_\mu, L_\tau)\) associated with the three lepton flavors are not all conserved in these decays, in contrast with all observations of known interactions. Lepton flavor conservation is not associated with a known symmetry, and thus remains an unexplained aspect of the SM. In fact, LFV processes are natural features of many models for new physics.

By virtue of being the heaviest lepton, the τ has more LFV final states accessible than the other leptons. On the other hand, searches for lepton flavor violation in rare decays of muons, pions and kaons benefit by virtue that these particles can be produced in copious quantities. However, it is possible that, for example, LFV interactions that involve third generation particles are more prevalent, enhanced perhaps by mass-dependent couplings. A recent exploration of the constraints on the scale of new physics imposed by existing experimental limits on various processes involving τ-μ flavor violation [1] demonstrates the sensitivities that can be attained in searches for neutrino-less τ lepton decays.

In this talk, I report on recent experimental progress on rare τ lepton decays, focussing on neutrino-less channels that are forbidden in the SM. Time limitations prevent me from discussing the status of searches for SM-allowed, but highly-suppressed, channels (i.e., those such as \(\tau^- \to \pi^- \eta \nu_\tau\) in which \(G\)-parity is not conserved) where new physics might also appear.

2 The Classic Decay \(\tau^- \to \mu^- \gamma\)

The decay \(\tau \to \mu \gamma\) (see Fig. 1) is analogous to the \(\mu \to e \gamma\) decay that has been the subject of a number of dedicated experiments. The current 90% CL upper limit on the branching ratio,
\[ B(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11} \] from the MEGA experiment \cite{2}, is already quite impressive and future experiments are being planned \cite{3}. Considering models with mass-dependent couplings, comparable sensitivity to the new physics can be attained in \( \tau \rightarrow \mu\gamma \) at only the \( 10^{-6} - 10^{-8} \) level in branching fraction \cite{4}.

With \( \tau \)-pair production in \( e^+e^- \) collisions, experimenters have two main kinematic handles on \( \tau \rightarrow \mu\gamma \). First, the reconstructed \( \mu\gamma \) invariant mass \( M(\mu\gamma) \) must equal the \( \tau \) mass. Second, the deviation \( \Delta E = E_\mu + E_\gamma - E_{\text{beam}} \) where all quantities are evaluated in the \( e^+e^- \) CM frame, must be consistent with zero. The latter condition holds only approximately with the presence of initial state radiation (ISR). Additional requirements on the system recoiling against the \( \mu\gamma \) system can be placed to ensure that the event is compatible with being due to \( \tau \)-pair production.

Until recently, the most stringent limits on \( \tau \rightarrow \mu\gamma \) came from the CLEO-II experiment operating at the Cornell Electron Storage Ring (CESR) at energies in the \( \Upsilon \) energy region. An analysis in 1992 \cite{5} of 1.6 fb\(^{-1}\) of data (\( \sim 1.4 \times 10^6 \) produced \( \tau \)-pairs) yielded no candidate events and a 90\% CL upper limit of \( 4.2 \times 10^{-6} \) on \( B(\tau \rightarrow \mu\gamma) \).

This analysis was most recently updated in 1999 \cite{6} with a sample of \( N_{\tau\tau} \sim 12.6 \) million \( \tau \)-pairs, which yielded a limit of \( B(\tau \rightarrow \mu\gamma) < 1.1 \times 10^{-6} \), while six events were observed in the signal region in the \( \Delta E - M(\mu\gamma) \) plane, consistent with 5.5 \( \pm \) 0.5 expected background events. The improvement in the limit at a rate faster than \( 1/\sqrt{N_{\tau\tau}} \) despite the presence of background was facilitated by the use of an extended unbinned maximum likelihood fit (a “cut-and-count” analysis yielded a limit of \( 1.8 \times 10^{-6} \)).

In the past year, BaBar and Belle have investigated this decay, both with considerably larger data samples. From the CLEO experience, the immediate question is whether \( \tau \rightarrow \mu\gamma \) isn’t already background-limited. The two main background sources are (1) radiative \( \mu \)-pair events \( (e^+e^- \rightarrow \mu^+\mu^-\gamma) \), and (2) \( \tau \)-pair events in which one \( \tau \) decays to the common \( \mu\nu\bar{\nu} \) final state. In the latter case, a radiative photon can be emitted in the decay, and thus, if the neutrinos are soft enough, one is left with the same kinematics as in \( \tau \rightarrow \mu\gamma \) decay. Alternately, the muon from \( \tau \rightarrow \mu\nu\bar{\nu} \) can be combined with an ISR photon. The \( \tau \) backgrounds tend to give \( \Delta E \) values less than zero, while the \( \mu\mu\gamma \) background can yield \( \Delta E \) values greater than zero.

The preliminary BaBar analysis \cite{7}, presented at ICHEP and at the Tau Lepton Workshop in summer 2002, is based on a sample of 56 million \( \tau \)-pairs. A fully “blind” analysis was carried out, with signal and background control regions excluded from the determination of selection criteria. With careful attention to suppression of the \( \mu\mu\gamma \) background, the total residual background was estimated based on extrapolation from sideband regions in the data to be \( 7.8 \pm 1.4 \) events, with an acceptance for \( \tau \rightarrow \mu\gamma \) decays of (5.2 \( \pm \) 0.5) \% (the acceptance for the CLEO cut-and-count analysis of \( \sim 12.7\% \)). The background estimation method was
validated by Monte Carlo simulations of background processes, as well as through comparisons of estimated yields in sideband regions with observed yields.

The final event sample from the BaBar analysis is shown in the left plot in Fig. 2. The signal region contains 13 events, a yield higher than, but consistent with, the background estimation. The 90% CL upper limit on the $\tau \to \mu \gamma$ yield of 11.5 events leads to a limit $\mathcal{B}(\tau \to \mu \gamma) < 2.0 \times 10^{-6}$, actually less stringent than the CLEO limit. This is due to the lower detection efficiency and the apparent upward fluctuation in the background.

![Figure 2: Left plot: Final sample of selected events in the BaBar $\tau \to \mu \gamma$ analysis, plotted as $M_{EC}(\mu \gamma)$ vs. $\Delta E$, where $M_{EC}(\mu \gamma)$ is the beam energy constrained $\mu \gamma$ mass. The $\tau \to \mu \gamma$ signal region is indicated by the distorted ellipse. Right plot: The corresponding selected sample from Belle, plotted as $\Delta E$ vs. $M(\mu \gamma)$ (the 'raw' $\mu \gamma$ mass). The boxes represent the distribution from $\tau \to \mu \gamma$ Monte Carlo events, and the signal region is indicated by the ellipse. The different orientations of the ellipses in the two plots reflects the different correlations of the two variants of $\mu \gamma$ mass with $\Delta E$ for signal events.](image)

A preliminary Belle analysis [8] of $\tau \to \mu \gamma$, based on $N_{\tau \tau} = 29.7$ million, was also presented at the Tau 2002 Workshop. The final event sample is shown as the right plot in Fig. 2. This analysis lacked some of the nice features of the BaBar analysis, namely the ‘blind’ approach and the attention to suppression of the $\mu \mu \gamma$ backgrounds. On the other hand, careful studies of the backgrounds, including the use of identified $\mu \mu \gamma$ events in the data to estimate this background, and a higher detection efficiency (9.0%) are strong elements of the Belle analysis.

Unlike BaBar, the Belle analysis was not ‘unlucky’ with regard to the observed yield in the signal region: one candidate event is observed while the background expectation was $2.5 \pm 0.6$ events. This leads to an upper limit on the $\tau \to \mu \gamma$ yield of 4.1 events and $\mathcal{B}(\tau \to \mu \gamma) < 6 \times 10^{-7}$, a considerable improvement over the CLEO limit.

Since this conference, Belle has presented an updated analysis [9], based on 86.3 fb$^{-1}$ ($N_{\tau \tau} \sim$...
In this update, Belle has adopted a blind analysis approach similar to that of BaBar, and also employs a likelihood analysis similar to that of CLEO. In an enlarged signal region (a box of dimension $\pm 3\sigma$ in both $M(\mu\gamma)$ and $\Delta E$), 19 events are observed with an expected background of 20.2. The result is $B(\tau \rightarrow \mu\gamma) < 3.2 \times 10^{-7}$.

### 3 Searches for Other Neutrino-less Decays

Other neutrino-less channels of the type $\tau \rightarrow 3$ leptons (illustrated in Fig. 3) and $\tau \rightarrow e/\mu+$hadrons are also of great interest, potentially being sensitive to different interactions than $\tau \rightarrow \mu\gamma$. Like $\tau \rightarrow \mu\gamma$ these violate separate lepton number conservation, and in some cases (such as $\tau^{-} \rightarrow e^{+}\pi^{-}\pi^{-}$) fail to conserve total lepton number. The decays $\tau \rightarrow 3$ leptons are analogous to $\mu \rightarrow eee$, while the decays with hadrons are analogous to LFV decays of kaons as well as $\mu \rightarrow e$ conversion in a nuclear field, for all of which stringent limits exist [10].

![Figure 3: Possible diagram for $\tau \rightarrow eee$, mediated by a heavy neutral boson $X$.](image)

Prior to the asymmetric $B$-factories, the most sensitive searches for many ($\sim 32$) neutrino-less decay modes of the types described above had been carried out by CLEO [11, 12] yielding typical branching fraction limits in the range $1 \rightarrow 8 \times 10^{-6}$. Belle has presented preliminary results [13] on eight channels based on 48.6 fb$^{-1}$ of data, the results for which are shown in Table 1. Since this conference, Belle has also presented results [14] on the decay $\tau \rightarrow \mu\eta$, motivated by the suggestion [15] that the rate for this channel might be enhanced relative to other LFV $\tau$ decays. The 90% CL limit obtained is $B(\tau \rightarrow \mu\eta) < 3.4 \times 10^{-7}$.

### 4 Summary

The experimental search for $\tau$ lepton decays decays forbidden in the Standard Model continues to be an active area of research. The present scene is dominated by the $B$-factories, in particular by preliminary results from Belle where impressive sensitivities at the few $\times 10^{-7}$ level have already been attained. We can expect steady progress from both BaBar and Belle in the coming years. However, several points are worth noting:

- The $\tau \rightarrow \mu\gamma$ decay suffers serious background issues. With the hope that the two experiments will increase their data samples by at least a factor of five over the next several
Table 1: The 90% C.L. upper limits on branching fractions for $\tau$ lepton decays to the final states shown.

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<td>$e^-e^+e^-$</td>
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<td>$2.7 \times 10^{-7}$</td>
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<tr>
<td>$\mu^-\mu^+\mu^-$</td>
<td>$1.9 \times 10^{-6}$</td>
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<td>$e^-\mu^+\mu^-$</td>
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<td>$\mu^-e^+e^-$</td>
<td>$1.7 \times 10^{-6}$</td>
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<td>$e^+\mu^-\mu^-$</td>
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<td>$\mu^+e^-e^-$</td>
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<td>$e^-K_s^0$</td>
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<td>$\mu^-K_s^0$</td>
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years, additional work will be needed if the sensitivity for this decay is to reach below the $10^{-7}$ level.

- The importance of a ‘blind’ analysis approach cannot be overstated, particularly in the situation where there are many decay modes being explored. I found it interesting to note that in the Belle analyses [8, 13] where such an approach was not used, the observed yields, summed over related channels, were consistently lower than the background expectations. For example, in the $\tau \rightarrow 3$ leptons samples the total number of events in each signal region was zero while the summed background expectation was $1.7 \pm 0.6$ events. In the $\tau \rightarrow K_s^0$+ lepton analysis, zero events were observed while $3.7 \pm 0.7$ were expected. Together, these results appear to be improbable, and so one’s confidence in the integrity of the reported limits might have been buoyed had a blind approach been employed.

The question of the future beyond the current $B$-factory era is a more uncertain one. Substantial upgrades to the existing facilities to “super-B-factory” status are being considered, however the prospects for further progress in rare $\tau$ decays is not clear in light of the background issues. Detector and data analysis strategy issues are paramount in understanding these prospects.

Rare $\tau$ decay studies have so far come ‘for free’ as part of the larger program of heavy quark and lepton physics accessible with high-luminosity $e^+e^-$ colliders. A dedicated rare $\tau$ decay experiment may have to be considered, as already has been done in the case of rare muon and kaon decay searches, if significant progress is to continue.


References


[4] For a discussion of interesting theoretical prospects for $\tau \rightarrow \mu \gamma$, see R. Kitano, presentation at CIPANP 2003, Conference on the Intersections of Particle and Nuclear Physics, New York, May 2003.


