LEPTON FLAVOUR VIOLATION

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A review of current experimental lepton flavour violation studies involving μ and τ decays is presented. Prospects for future experiments are also discussed.

1 Introduction

Historically, searches for lepton flavour violation (LFV) have had a tremendous impact on the field of particle physics, both when it was seen (in the neutrino sector [1]) and unseen (in the charged lepton sector [2]). Around the time that the muon was established to be a lepton, and not the Yukawa meson [3], Hinks and Pontecorvo at Chalk River began searching for evidence of transitions of a charged lepton of one flavour into another via the emission of a photon [4]. Failure to observe this decay ruled out a model of the muon being an excited electron. In 1957 the lack of a flavour-changing neutral current in the lepton sector together with a "leptonic GIM" argument was used to establish the existence of two neutrino flavours [5,6,7]. Also in the 1950's experimenters began searching for LFV in other processes. The first $\mu^- N \to e^- N$ neutrinoless muon nuclear capture experiments [8,9] and searches for $\mu^- \to e^- e^+ e^-$ date from that era.

Since that time, the upper limits on branching fractions or conversion probabilities have fallen ten orders of magnitude from the percent level limits of the first studies to the "state-of-the-art" upper limit of $\mathcal{B}(\mu \to e\gamma) < 1.2 \times 10^{-11}$ from MEGA/LAMPF [10]. By the 1970's searches for μ-e LFV in meson decays had also been performed and, in fact, new limits on LFV from kaons [11] and b-mesons [12] are being presented at this conference.

With the discovery of the τ-lepton in 1974, a new LFV window opened and searches for a variety of lepton flavour violating decays were undertaken by the MARK-II, ARGUS and CLEO collaborations. These studies helped establish the SM description of the τ lepton: like its lighter cousin, is also is *not* an excited muon or electron and the existance of a third type of neutrino could be deduced. Clearly, the non-observation of LFV in the charged sector over the years has yielded critical input to the development of the standard model (SM).

In the neutral leptonic sector, however, a different story unfolds: by the beginning of the 21^{st} century LFV has been established with the discovery of neutrino mixing [1]. In fact, we even have some knowledge of parts of the neutrino mixing matrix (θ_{12} and θ_{23}) and plans for experiments to measure some of the unknown parts. For example, the T2K experiment is preparing to measure θ_{13}, as discussed at this conference [13] and long-term plans to measure CP violation in this sector are underway. The observation of LFV in this sector has generated a new field of exploration.

The SM, when extended to include finite mass differences from neutrino mixing, allows for $\mu - e$, $\tau - e$ and $\tau - \mu$ mixing at the one-loop level, but it is suppressed by a factor of $(m_\nu^2/m_W^2)^2$, which, for example, gives an expectation of $\mathcal{B}(\tau \to \mu\gamma) \sim \mathcal{O}(10^{-54})$, which is many orders of magnitude below any conceivable experimental sensitivity. As a consequence, this essentially non-existant SM background ensures that LFV in the charged sector is an unambiguous signature of new physics. This is very useful, in fact, since many SM extensions predict observable LFV in the charged sector. For example, if a see-saw mechanism is responsible for the small ν masses, it is natural to expect large LFV in the charged sector. In SO(10) inspired SUSY models there are regions of parameter space that allow for LFV above the existing limits [14].

2 The LFV Programme Motivation

Needless to say, LFV predictions are very model dependent with specific models and parameters giving LFV process rates characteristic of those models. Generally speaking, we don't expect a single LFV process to provide sufficient information to nail down the underlying mechanism responsible for LFV, or even identify a particular model uniquely. Nonetheless, a strategy of combining results from many different, and varied measurements, is envisioned as the scientific programme that will move our understanding forward. For example, all the $\mu - e$ LFV processes should be measured along with all τ LFV channels because many models have strong connections between the expected rates of the various channels. Consquently, the $\mu \to e\gamma$ measurements need to be augmented, for example, by $\tau \to \mu\gamma$ as well as $\tau \to e\gamma$ studies. Progress will be made by interpreting these results in the context of those of other measurements, including LFV decays of K and B mesons, neutrino oscillation measurements, g-2 and electric dipole moment measurements, and, naturally, searches for new particles at the energy frontier of LHC. Eventually precision measurements at a future ILC will also play an important role in this programme.

A very important step in the charged sector LFV component of these studies is to be realized later this year as the MEG experiment at Paul Scherrer Institut in Zurich takes first data [15]. This project, which involves collaborators from Japan, Italy, Switzerland, Russia and the United States, aims at a $\mu \to e\gamma$ branching fraction sensitivity of 10^{-13} which is 100 times lower than the existing MEGA limit. The detectors are currently being built and installed with the first physics run slated for autumn 2007.

Since the MEGA results were publised in 1999, new LFV results from charged lepton decays have come from studies of the third-generation lepton, which is the focus of the remainder of this paper. The LFV decays of the τ have been studied at e^+e^- colliders where the τ leptons are most copiously pair-produced in an experimentally clean environment. The luminosities available at the e^+e^- machines limit the number of τ leptons produced and thereby determine the sensitivity to τ LFV decays. Despite the unprecendented $10^{34} cm^{-1} s^{-1}$ luminosities attained the e^+e^- B-factories, these luminosity-limited sensitivities are still typically 1000 times weaker than the MEGA $\mu \to e\gamma$ upper limit. Given that reality, one may wonder if studies of τ decays bring anything new to the table. The answer is yes: many SM extensions predict very sizable enhancements of the τ LFV decays relative to the μ LFV processes. These usually originate from strong dependencies of the couplings on the masses of the leptons involved, so that a LFV process involving a τ-μ transition, which involves a 1777 MeV mass lepton converting to a 106 MeV lepton, may be greatly enhanced relative to a process involving a $\mu - e$ transition which converts a 106 MeV lepton to a 0.5 MeV lepton. Consequently, one encounters theories with predictions of $\mathcal{B}(\tau \to \mu\gamma)$, for example, that have parameters being constrained by the existing experimental bounds.

Equally important is the model dependence of the expected rates for different τ LFV decays and the relations between these rates. For example, in a supersymmetric seesaw model there is an expectation that the specific relative rates of $\mathcal{B}(\tau \to \mu\gamma) : \mathcal{B}(\tau \to \mu\mu\mu) : \mathcal{B}(\tau \to \mu\eta)$ are dependent on the model parameters [16,17]. Because we do not know what lies beyond the SM, it is unknown which LFV decay mode will be first discovered and therefore it is critical that all LFV modes be probed. Limits, or (preferably) a discovery and measurement, will better constrain theories in a manner that complements well the potential discoveries at the LHC.

3 The τ LFV Experiments

In recent years, only the Babar and Belle experiments have been providing new results on LFV in τ decays. These operate at two different e^+e^- "B-factories" both tuned to a centre-of-mass energy of 10.58 GeV: at the $\Upsilon(4S)$ resonance, and just above the threshold for producing open beauty. Babar operates at the PEP-II B-factory at SLAC, running the e^- beam at 9 GeV and e^+ beam at 3.1 GeV. By 1 January 2007 Babar had written more that 400 fb^{-1} of data to tape. Belle, operating at the KEKB B-factory in Japan, which collides an 8 GeV e^- beam with a 3.5 GeV e^+ beam, has recorded an integrated luminosity of approximately 700 fb^{-1}. The Babar [18] and Belle [19] detectors are remarkably similar with the major difference being in the technology used to identify charged particles: Belle uses a threshold Cherenkov detector together with time-of-flight and tracker dE/dx, whereas Babar mainly relies on a ring-imaging Cerenkov detector augmented by the dE/dx in the trackers. With a total of 1.1 ab^{-1} and the $e^+e^- \to \tau^+\tau^-$ cross-section of 0.919 nb [20], the world sample of τ-leptons produced at the e^+e^- colliders now exceeds 10^9 which allows for experimental probing of LFV processes at the $\mathcal{O}(10^{-7})$ to $\mathcal{O}(10^{-8})$ levels.

The general analysis approach is to select τ-pair events with the appropriate charged-particle topology, removing non-τ events with an impact as minimal as possible on the signal efficiency. This is accomplished by dividing the candidate event into hemispheres in the centre-of-mass in which each hemisphere contains either the τ^+ or τ^- decay products. Each hemisphere is then considered a possible candidate for the LFV decay under consideration. Unlike SM τ-decays which have at least one neutrino, the LFV decay products have a combined energy in the centre-of-mass equal to the energy of the τ, approximately equal to the beam energy in the centre-of-mass, $\sqrt{s}/2$, and a mass equal to that of the τ. A two dimensional signal box in $E_{\ell X}$ *vs.* $M_{\ell X}$ is therefore used to separate the signal from the SM τ-decay backgrounds. The distribution of $\Delta_E = E_{\ell X} - \sqrt{s}/2$ for the signal peaks near zero and typically has a standard deviation of around 50 MeV. When a beam energy constrained mass is employed and the γ constrained to come from the same primary vertex as the charged particles in the event, then a resolution on $M_{\ell X}$ of 9 MeV is achieved.

The analyses are optimized to give the best "expected upper limit" using Monte Carlo simulations of the signal and backgrounds. The Monte Carlo simulation of the signal is used to determine the signal efficiency (ϵ), which typically lies between 2% and 10%, depending on the channel under study. A generic analysis of a τ LFV decay pocesses roughly the following efficiency components: trigger (90%), acceptance/reconstruction (70%), charged-particle hemisphere topology (1-vs-1 or 1-vs-3: 70%), paricle identification (50%), other non-signal box requirements (50%), $E_{\ell X}$ *vs.* $M_{\ell X}$ signal box requirements (50%). The cummulative efficiencies, starting with the trigger and acceptance/reconstruction efficiency of 63%, decreases to 44% once topology requirements are imposed, to 22% with particle ID requirements, to 11% as other non-signal box requirements are imposed, and finally to ∼5% once it is enforced that the events fall within signal-box.

The expected number of background events ($N_{\rm bkd}$) are normally estimated using the distribution shapes from the Monte Carlo simulation with background normalization obtained from the data in the regions outside the signal box in the ($E_{\ell X}$–$M_{\ell X}$) plane. These analyses are "blind" in the sense that the physics analysts have no knowledge of the data in the signal region as the optimization and systematic studies are undertaken. Once these steps are complete, the data in the signal region is "unblinded" and the analyst sees the number of events observed in the signal box ($N_{\rm obs}$) and either learns of a discovery, or - as has been the case to date - sets an upper limit on the process.

$N_{\rm obs}$ together with $N_{\rm bkd}$ then gives the number of signal events ($N_{\rm sig}$): if $N_{\rm obs}$-$N_{\rm bkd}$ is consistent with zero, an upper limit on $N_{\rm sig}$ is established. Schematically, the 90%CL branching ratio upper limit is then obtained from:

$$\mathcal{B}_{90}^{UL} = \frac{N_{90}^{UL}}{2N_{\tau\tau}\epsilon} = \frac{N_{90}^{UL}}{2\mathcal{L}\sigma_{\tau\tau}\epsilon} \tag{1}$$

Table 1: Summary of 90%CL Upper Limits on Selected LFV τ decays. An asterix($*$) indicates a preliminary result. h and h$'$ denotes a charged pion or kaon. Banerjee's combination of a subset of these channels is also included - note that for the combined results only, the limits are in units of 10^{-8}.

Channel	Belle [21,24,25,26]		Babar [22,27,28,29,30]		Babar+Belle [23]	
	BF(10^{-7})	$\mathcal{L}(fb^{-1})$	BF (10^{-7})	$\mathcal{L}(fb^{-1})$	BF (10^{-8})	$\mathcal{L}(fb^{-1})$
$\mu\gamma$	0.5*	535	0.7	232	1.6	767
$\mu\pi^0$	1.2*	401	1.1	339	5.8	740
$\mu\eta$	0.7*	401	1.5	339	5.1	740
$\mu\eta'$	1.3*	401	1.4	339	5.3	740
$e\gamma$	1.2*	535	1.1	232	9.4	767
$e\pi^0$	0.8*	401	1.3	339	4.4	740
$e\eta$	0.9*	401	1.6	339	4.5	740
$e\eta'$	1.6*	401	2.4	339	9.0	740
$\ell\ell\ell$	2$\rightarrow$4	87	1$\rightarrow$3	92		
$\ell hh'$	2$\rightarrow$16	158	1$\rightarrow$5	221		

where $N_{\tau\tau} = \mathcal{L}\sigma_{\tau\tau}$ is the number of τ-pairs produced in e^+e^- collisions; $\mathcal{L}$ is the integrated luminosity and $\sigma_{\tau\tau}$ is the τ-pair production cross section. In practice, if $N_{\rm bkd}$ is sufficiently large (more than approximately two or three), $N_{\rm sig}$ and $N_{\rm bkd}$ are determined from a fit to the $M_{\ell X}$ distribution after removing events outside the $E_{\ell X}$ signal region.

4 The τ LFV Results

Experimentally, LFV decays can be conveniently classified as $\tau \rightarrow \ell\gamma$, $\tau \rightarrow \ell_1\ell_2\ell_3$ and $\tau \rightarrow \ell h$ where ℓ is either an electron or muon and h represents a hadronic system (*e.g.*, π^0, η, η', K^0_S, *etc.*)

The most recent $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$ results were reported by Belle at ICHEP last summer[21]. The $\tau \rightarrow \mu\gamma$ ($\tau \rightarrow e\gamma$) analyses have a 5.1% (3%) signal efficiency within a 2σ elliptical signal region in the $M_{\ell\gamma} - E_{\ell\gamma}$ plane. After performing a 2D unbinned extended maximum likelihood fit for the number of signal events and background events, Belle finds -3.9 (-0.14) signal events and 13.9(5.14) background events in the $\tau \rightarrow \mu\gamma$ ($\tau \rightarrow e\gamma$) analysis. Therefore the 90%CL upper limits on the number of signal events for $\tau \rightarrow \mu\gamma$ ($\tau \rightarrow e\gamma$) is 2.0 (3.34) events. These yield upper limits of $\mathcal{B}(\tau \rightarrow \mu\gamma) < 4.5 \times 10^{-8}$ and $\mathcal{B}(\tau \rightarrow e\gamma) < 1.2 \times 10^{-7}$.

Babar has very recently published new results on LFV decays involving the π^0, η and η' pseudoscalars: $\tau \rightarrow \ell\pi^0$, $\tau \rightarrow \ell\eta$ and $\tau \rightarrow \ell\eta'$ where ℓ is separately identified as either an electron or muon[22]. In these analyses both of the $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow 3\pi$ η decay modes are used for the $\tau \rightarrow \ell\eta$ analyses. In the $\tau \rightarrow \ell\eta'$ analyses, the $\eta' \rightarrow 2\pi\eta$ and $\eta' \rightarrow 2\pi\gamma$ modes were included. The expected background per channel is between 0.1 and 0.3 events. Summing over all ten modes, the total expected background within the signal regions is 3.1 events whereas 2 events in total were observed. The results of these searches and a selection of searches for other key LFV decays in data from Babar and Belle are summarized in Table 1. At the Tau2006 conference in Pisa, Swagato Banerjee presented a frequentist combination of these measurements[23] which are also included in the table.

5 Future Prospects for τ LFV Searches

Belle has funding secured that will enable it to collect 1 ab^{-1} of data and Babar, which will stop data taking at the end of September 2008, is expected to collect 940 fb^{-1} of data. The estimated physics reach of these data based on projections from existing analyses depends on how the background is treated. We express the experimental reach in terms of the 'expected 90%CL upper limit' and, for brevity's sake, refer to this as the 'sensitivity'. In the absence of signal, for large N_{bkd}, $N_{90}^{UL} \sim 1.64\sqrt{N_{bkd}}$ whereas for small N_{bkd} a value for N_{90}^{UL} is obtained using the method described in [31]. So, for $N_{bkd} \sim 0$, $N_{90}^{UL} \sim 2.4$. Reducing the background below a handful of events doesn't greatly improve the expected limit if significant efficiency is lost in the process, which is why it is common to see experiments reporting the expected backgrounds to be small (i.e. a few events), but rarely below 0.1 of an event.

A "worst-case scenario" is obtained if identical analyses to those published by Babar and Belle are repeated, as is, on the increased data sample: in that case the expectations then simply scale as $\sim \sqrt{N_{\mathrm{bkd}}}/\mathcal{L}$, which for large N_{bkd} scales as $1/\sqrt{\mathcal{L}}$. A "best case" scenario would take the current expected limit and scale linearly with the luminosity. This is equivalent to a statement that analyses can be developed maintaining the same efficiency and backgrounds as the current analyses.

For $\tau \to \ell\gamma$, there is an "irreducible background" from $\tau \to \ell\nu\nu + \gamma(\mathrm{ISR})$ in which the photon from initial state radiation can be combined with a lepton to form a candidate that accidentally overlaps with the signal region in the $E_{\ell X}$–$M_{\ell X}$ plane. It is "irreducible" in the sense that it arises from $e^+e^- \to \tau^+\tau^-$ process with a well measured μ and γ in one of the τ hemispheres. In the existing Babar analyses, these events account for approximately one fifth of the total background. Scaling with this irreducible background only, one has an expected upper limit for $\mathcal{B}(\tau \to \ell\gamma)$ of between 1 and $2{\times}10^{-8}$ from a complete combined Babar and Belle data set. That Banerjee's combined limit on $\mathcal{B}(\tau \to \mu\gamma)$ is already at this level is a consequence of a downward statistical flucttutation in the expected background.

The situation for the other LFV decays, $\tau \to \ell_1\ell_2\ell_3$ and $\tau \to \ell h$, is even more promising, since these modes do not suffer from the aforementioned backgrounds from ISR. In this case, one can project sensitivities assuming N_{bkd} comparable to backgrounds in existing analyses for approximately the same efficiencies. These yield expected limits at the 10^{-8} level with the complete Babar+Belle data set.

It should also be mentioned that there are proposals [32] for Super B flavour factories which will generate up to a 100 fold increase in the size of the τ sample compared to those expected from the existing B-factories. If such a facility is built, one will be probing LFV decays of the τ at the $\mathcal{O}(10^{-9\to-10})$ level.

6 Summary

Lepton flavour violation in the decays of charged letpons is an extremely clean means of searching for evidence of physics beyond the SM. Until now, there has been no evidence of LFV in either the $\mu \to e\gamma$ decay nor in any of a number of $\tau \to \mu X$ or $\tau \to eX$ decays, where X is a photon, meson or set of mesons. Recent results from Babar and Belle have pushed the upper limits on the braching fractions of these decays of the τ into the 10^{-8} zone and the parameter space in some beyond-the-SM theories is being constrained. As there is still much data yet to be collected and analysed by the B-factory experiments, we look forward to continuing progress on this front over the next two years.

With physics data from MEG to come online this autumn, we also look forward to progress on the $\mu \to e\gamma$ front, ultimately, with sensitivities at the $\mathcal{O}(10^{-13})$ level being reached. In the more distant future, if Super B flavour factories move forward, sensitivities to some τ LFV modes will approach the $\mathcal{O}(10^{-10})$ level. Probing LFV at these tiny levels will provide critical information about the nature of the beyond-the-SM theories in a manner that is complementary to that from direct production of new particles at the LHC.

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References

1. B. T. Cleveland *et al.*, *Astrophys. J.* **496**, 505 (1998);
   Y. Fukuda *et al.*, Super-Kamiokande Collaboration, *Phys. Rev. Lett.* **81**, 1562 (1998);
   Q. R. Ahmad *et al.*, SNO Collaboration, *Phys. Rev. Lett.* **89**, 011301 (2002) ;
   M. H. Ahn *et al.*, K2K Collaboration, *Phys. Rev. Lett.* **90**, 041801 (2003).
2. W-M Yao *et al.*, Particle Data Group, *J. Phys. G: Nucl. Part. Phys.* **33**, 1 (2003).
3. Conversi, M., E. Pancini, and O. Piccioni, *Phys. Rev.* **71**, 209 (1947).
4. Hincks, E.P. and B. Pontecorvo, *Phys. Rev. Lett.* **73** (1948);
   Hincks, E.P. and B. Pontecorvo, *Canadian J. Res.* **28A**, 29 (1950).
5. Pontecorvo, B., *J. Exptl. Theoret. Phys. (U.S.S.R.)* **33**, 549 (1957) [translation: *Soviet Phys. - JETP* **6**, 429 (1958)].
6. Nishijima, K., *Phys. Rev.* **108**, 907 (1957).
7. Feinberg, G., *Phys. Rev.* **110**, 1482 (1958).
8. Lagarrigue, A., and C. Peyrou, *Acad. Sci., Paris, C. R.* **234**, 873 (1952).
9. Steinberger, J., and H.B. Wolfe, *Phys. Rev.* **100**, 1490 (1955).
10. Brooks, M.L., *et al.*, *Phys. Rev. Lett.* **83**, 1521 (1999).
11. Nguyen, H. (KTeV Collaboration), these proceedings.
12. Bechtle, P. (Babar Collaboration), these proceedings.
13. Yokoyama, M. (T2K Collaboration), these proceesings.
14. Calibbi L., Faccia, A, and Masiero, A., PRD **74**, 116002 (2006).
15. Mori, T., (MEG Collaboration), *Proceedings of the 9th International Workshop on Tau Lepton Physics (Tau 06)*, Pisa, Italy, (2006).
16. Babu, K.S. and Kolda, C., *Phys. Rev. Lett.* **89**, 241802 (2002).
17. Sher, M., *Phys. Rev.* D **66**, 057301 (2002).
18. Aubert, B. *et al.,* (Babar Collaboration) *Nucl. Instrum. Methods* A **479**, 1-116 (2002).
19. Abashian, A. *et al.*, (Belle Collaboration) *Nucl. Instrum. Methods* A **479**, 117 (2002).
20. Banerjee, Sw., Pietrzyk, B., Roney, J.M., Was, Z., arXiv:0706.3235 [hep-ph].
21. Abe, K. *et al.*, (Belle Collaboration), arXiv:hep-ex/0609049v1.
22. Aubert, B. *et al.*, (Babar Collaboration) *Phys. Rev. Lett.* **98**, 061803 (2007).
23. Banerjee, Sw., hep-ex/0702017, in *Proceedings of the 9th International Workshop on Tau Lepton Physics (Tau 06)*, Pisa, Italy, (2006).
24. Abe, K. *et al.*, (Belle Collaboration), arXiv:hep-ex/0609013v2.
25. Yusa, Y. *et al.*, (Belle Collaboration), PLB **589**, 103 (2004).
26. Yusa, Y. *et al.*, (Belle Collaboration), PLB **639**, 159 (2006).
27. Aubert, B. *et al.*, (Babar Collaboration), PRL **92**, 121801 (2004).
28. Aubert, B. *et al.*, (Babar Collaboration), PRL **95**, 191801 (2005).
29. Aubert, B. *et al.*, (Babar Collaboration), PRL **95**, 041802 (2005).
30. Aubert, B. *et al.*, (Babar Collaboration), PRL **96**, 041801 (2006).
31. Cousins, R.D. and Highland, V.L., NIMA **320**, 331-335 (1992).
32. *The Discovery Potential of a Super B Factory*, SLAC-R-709 (2004); *Letter of Intent for KEK Super B Factory*, KEK Report 2004-4 (2004); *SuperB: A High-Luminosity Asymmetric e+ e- Super Flavor Factory. Conceptual Design Report*, SLAC-R-856, INFN-AE-07-02, LAL-07-15 (2007).