Lepton Flavor Violation and Rare Tau Decays*

Clemens A. Heusch

Santa Cruz Institute for Particle Physics
University of California, Santa Cruz, CA 95064

Abstract

We point out that the good statistics promised by the proposed Tau-Charm Factory for tau lepton pair production close to threshold, in combination with the high purity of the tagged sample, opens a window onto new physics phenomena: lepton flavor violation involving the third family of basic fermions may have uniquely interesting implications not accessible in interactions under scrutiny elsewhere.

1. Introduction

Rare decays are a window onto interactions not dominant under customary conditions. Rare lepton decays involving flavor change are therefore sensitive to interactions not permitted by our successful low-energy phenomenology, the "Standard Model" of particle interactions.

We expect this model to break down upon very close scrutiny at present energies, or else at very high energies. Lepton flavor conservation has therefore been tested to great accuracy where experimentally accessible - mostly at low momentum transfers, and in the lower two families of elementary fermions.

The emergence of the experimental chance to study the charged third-family lepton with good statistical sensitivity in a Tau-Charm Factory[1)] opens up new doors to sensitive searches for Beyond-the-Standard-Model Interactions in a sector not much hemmed in by well-understood regularities: in fact, we do not understand the third-family of fermions at all, its two isospin-up states have never yet been observed, but hidden beyond slowly improving upper ($m(\nu_\tau) < 35$ MeV/c^2), and lower ($m(t) > 60$-80 GeV/c^2) bounds. There may be a message in the non-saturation of the inclusive one-prong branching fraction by the known exclusive channels. Furthermore, there is no tight check yet for the V-A structure of the weak interaction governing τ decay.

It is therefore only natural that we turn our interest to the one possibility that we know of, of producing background-free samples of tagged third-family fermions for a close study: a number of models for the ultimately needed enlargement of the presently evident $SU_{3C} \times SU_2 \times U_1$ group structure predict the existence of new gauge bosons with mass - or generation - dependent couplings. Recent results on the Z° width[2)] make us doubt that there is likely to be a fourth family of fundamental fermions: looking at rare τ decays may therefore be our best bet to find novel features that will point our way beyond known phenomenology. In clearly identified final states, one or a few events can establish a new interaction. It is in this spirit that we present the following remarks on aspects of lepton flavor changing phenomena in τ lepton decay[3)].

2. Practical Matters

The appearance of New Physics is usually associated with a new energy scale Λ, which may coincide with the rest mass of the (gauge) boson mediating the new interaction.

Lowest-order operator phenomenology[4] then suggests a set of practical rules[5] that are useful to keep in mind when hunting down lepton flavor violating effects that are to be seen as tell-tale signs for this new interaction:

- $\sigma_{new}, \; \Gamma_{new} \sim S, Q^2$

Since we expect to see effects due to new boson exchanges, Q^2 is the operative measure. This implies that τ decay is much more promising than μ decay from the point of view of $Q^2 (\tau \rightarrow X\nu) \approx (1 \text{ GeV/c})^2$, or

$$\frac{Q^2 (\tau \text{ decay})}{Q^2 (\mu \text{ decay})} \approx 300$$

- $$\sigma_{new}, \; \Gamma_{new} \sim \frac{1}{\Lambda^4}$$

or to improve our Λ sensitivity by an order of magnitude, our branching fraction has to be pursued to a level 10^4 times more exacting.

- Mass- and family- specific couplings favour tests involving the heaviest possible lepton (quark) of the highest generation:

  τ, b decays favored.

- Couplings include mixing angles: we tend to favor neighboring families:

  $$\Gamma(\tau \rightarrow \mu \ldots) > \Gamma(\tau \rightarrow e \ldots), \text{ etc.}$$

- Specific couplings of E_6-based string models prefer up-quark-to-charged-lepton, down-quark-to-neutral-lepton couplings, rule out up-to-neutral matrix elements.

$$\left.\begin{array}{l}(u,c,t) \bullet (e,\mu,\tau) \\ (d,s,b) \bullet (\nu, \ldots)\end{array}\right\} \text{ favored}$$

$$\left.\begin{array}{l}(u,c,t) \bullet (\nu, \ldots) \\ (d,s,b) \bullet (e,\mu,\tau)\end{array}\right\} \text{ suppressed}$$

- Watch for specific sub-processes on the quark level: $\Delta L_i \neq 0$ may still permit $\Delta G = 0$ in the presence of quarks (substructure models).

- Helicity, mass suppression have to be minded.

These criteria, as motivated by various specific models as well as on general grounds, make τ decays involving hadrons a particularly attractive place to watch out for lepton-flavor-violating indicators of NEW PHYSICS phenomena.

Add to that the fact that, while rare μ decays and rare K decays have been studied to great precision, but that τ decays have been investigated to the $< 10^{-4}$ level, (see Table 1), and the motivation for searches in this system becomes all the more compelling. Table I also points out the generation structure of the sub-process of interest.

TABLE I

Searches for Rare τ Decays (Particle Data Book 1988)

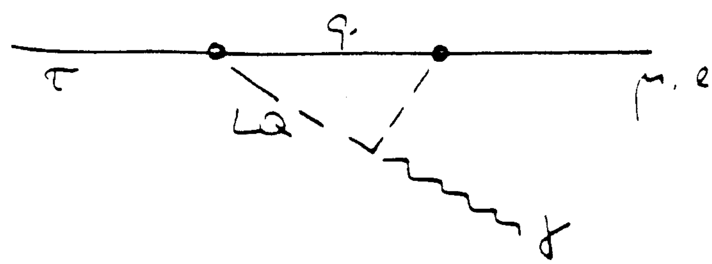
Decay mode	Q[GeV/c]	ΔG	Limit	Remarks
$\tau \to e\gamma$	0.9	2	$\sim 4 \times 10^{-5}$	Permitted if massive ν, but doubly weak
$\to \mu\gamma$	"	1	6×10^{-4}	
$\to e^+e^-e$	"	2	3×10^{-5}	
$\to e^+e^-\mu$	"	1	"	
$\to e\mu^+\mu^-$	0.8	2	"	
$\to \mu^+\mu^-\mu$	"	1	"	
$\to \rho^\circ e$	0.5	2	4×10^{-5}	
$\to \rho^\circ \mu$	"	1	"	
$\to \pi^\circ e$	0.8	2	2×10^{-3}	most likely leptoquark mediated
$\to \pi^\circ \mu$	"	1	8×10^{-4}	
$\to K^\circ e$	0.6	2	1.3×10^{-3}	
$\to K^\circ \mu$	"	1	1×10^{-3}	

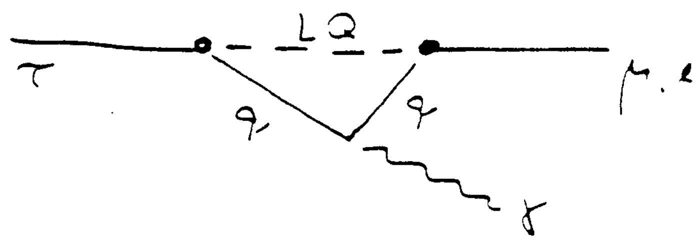
3. Specific Rare Decay Channels of Interest

While presently known evidence in lepton (μ,τ) decay is compatible with lepton universality and a universal V-A structure of the weak interaction, we can ask ourselves what specific modes exist for breaking this pattern.

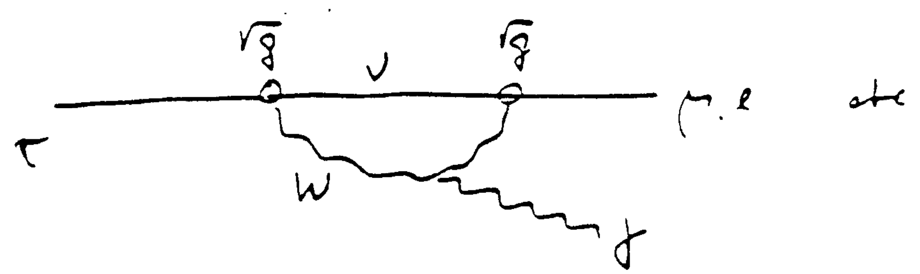
As examples, we mention flavor-breaking Higgs coupling and leptoquark exchange that will mediate flavor-changing decays.

For the radiative τ decays into μ and e, leptoquarks may contribute *via* the loop diagrams

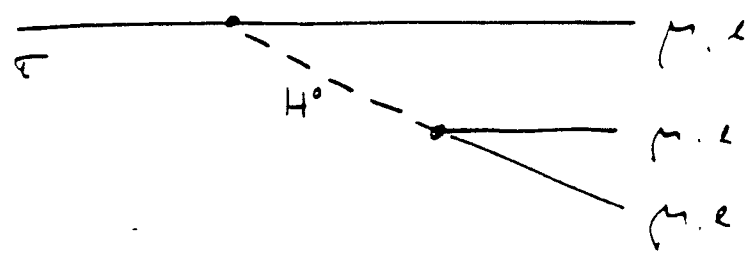




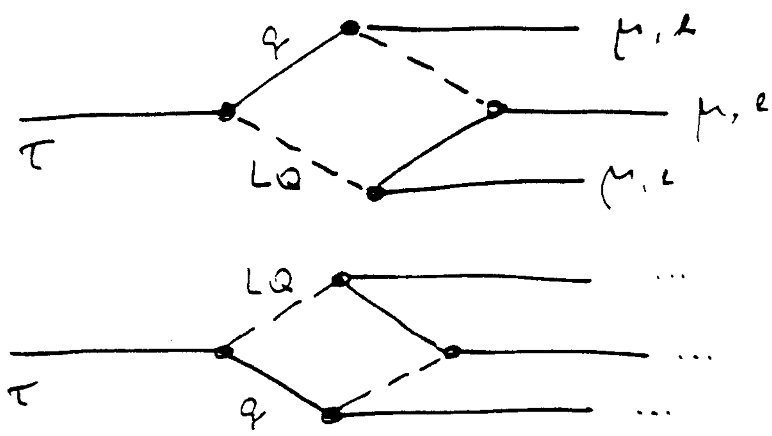
Our lack of information on $(g-2)_\tau$ makes these diagrams with their unknown generation specific couplings worth watching out for. In a Standard Model extension with massive neutrinos, these processes occur by W exchange; but they are doubly weak, and therefore beyond experimental accessibility.



Similarly, τ decays into three leptons can be mediated by non-minimal Higgs exchange

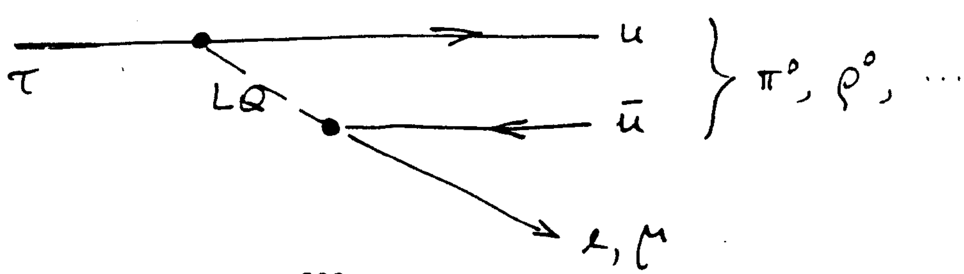


or by one-loop diagrams involving leptoquarks:



and similar diagrams involving mixing of mass-degenerate E_6 - based leptoquarks D, D^c.[6,7])

For semileptonic decays, we do not even need loops to find leptoquark-induced flavor change: take the diagram



Present limits of order 10^{-4} for all processes of the type

$$\tau \rightarrow \pi^{\circ}\mu, \quad \pi^{\circ}e, \quad \rho^{\circ}\mu, \quad \rho^{\circ}e, \quad \eta\mu, \ \ldots$$

are not sufficient to test for such effects; an expected improvement to the 10^{-7} level may well make a decisive difference. Note that tagged samples may also permit searches for the equivalent modes

$$\tau \rightarrow K^{\circ}\mu, \quad K^{\circ}e; \quad \phi\mu, \quad \phi e; \ \ldots..$$

which are "smoking gun" tests for the existence of charge -2/3 leptoquarks[7)].

We also note that generation-(or mass)-specific couplings natural to Higgs or leptoquark exchange can lead to lepton non-universality by way of introducing different Cabibbo angles in τ decay. A precise measurement of the ratio

$$\frac{\tau^{\pm} \rightarrow \pi^{\pm}\nu}{\tau^{\pm} \rightarrow K^{\pm}\nu}$$

is therefore of considerable interest: the appropriate decay widths

$$\Gamma(\tau \rightarrow \{{}^{\pi l}_{K l}\}) \sim \frac{(f\pi, fK)^2}{m_\tau^2} \quad \frac{g_3^2\, g_{1,2}^2}{m_{LQ}^4}$$

(where the g_i are the generation-specific couplings to Higgs particles or leptoquarks) may lead to noticeable effects if systematic uncertainties can be minimized.

4. Strategies for a Tau/Charm Factory

From the above it becomes clear that a successful search will need to be based on the assumptions that

- the rates have to be maximized,
- backgrounds have to be suppressed as far as possible by a clever choice of kinematics,
- an optimal detector will help to provide a clear sample of "tagged" τ events.

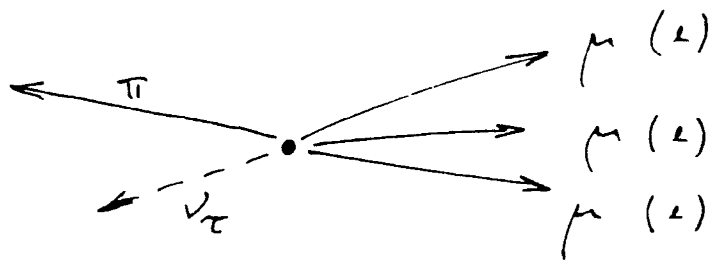
We have recently pointed out [8] that running closely above threshold for the process

$$e^+e^- \rightarrow \tau^+\tau^- ,$$

but below $D\bar{D}$ production threshold, we can use the decay modes $\tau(\rightarrow \pi\nu, K\nu;$ 11.5%) for background-free tagging of τ pairs. Including the modes $\tau \rightarrow \rho\nu$, $\tau \rightarrow 3\pi\nu$ (23.8%), we arrive at a 35% tagging efficiency for a clean sample of τ's to be studied. As an example, take the process

$$\tau \rightarrow \mu\mu\mu, \quad eee$$

which can be seen to be representative for a number of other channels. J.J. Gomez-Cadenas[9] did a Monte Carlo study of this process using the $\tau \rightarrow \pi\nu$ tag:



With the selection criteria

- 4 charged tracks at $|\cos\theta| \leq 0.9$,
- 3 identified μ's, one identified π,
- no neutrals seen in calorimeter,
- $\vec{P}_{miss}$, E_{miss} compatible with the 5 - body final state configuration,

we find a background-free $\tau \rightarrow 3\mu$ (or 3e) sample as shown in Fig. 1. This simulation is representative for other channels, which leads us to the conclusion that with an overall tagging effiency of some 50%, and an assumed τ/charm factory luminosity on the level of the 10^{33} cm^{-2} sec^{-1} foreseen for the facility, we can reach sensitivities defined by the product

$N\tau$ (year)	*	BR (tag)	*	eff. (tag) .
7×10^7		3×10^{-1}		0.5

In a year of full-luminosity running, we should therefore expect to be sensitive to lepton flavor violating effects of order 10^{-7}. That, it turns out, is a level which is compatible with seeing a signal in the framework of a number of reasonable expectations concerning Standard Model extensions. Quantitative aspects of these expectations will be published elsewhere.

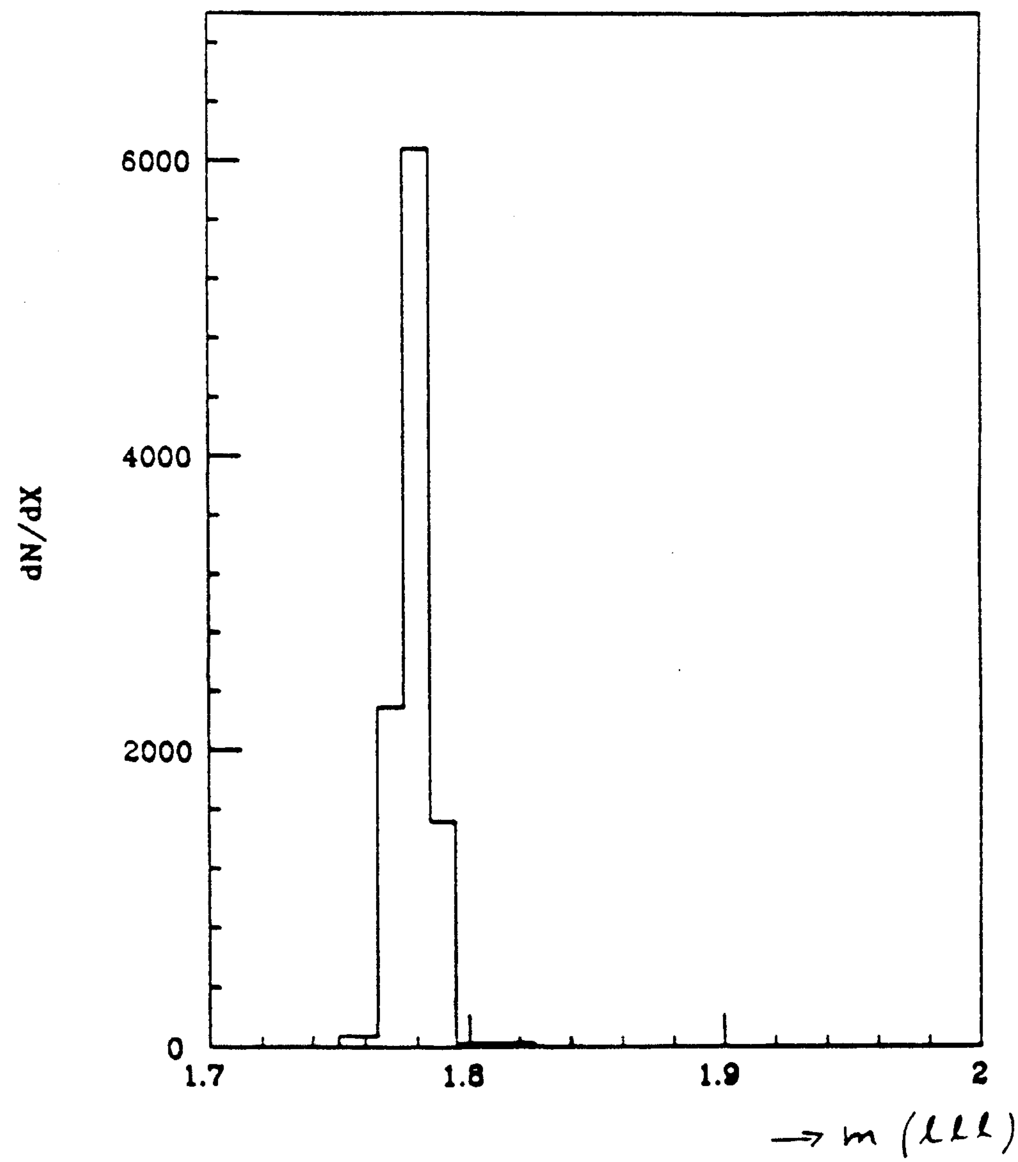


Fig. 1
A beautiful, background-free signal in the m(3e) distribution

References

1. The Tau/Charm Factory concept is described in detail in these proeeedings.
2. MARK II Collaboration at the SLC; presentation by G. Feldman at the Lepton-Photon Symposium, Stanford (1989).
3. For a fuller and broader treatment of the present status of lepton flavor violation, see C.A. Heusch, Proc. XII. Int. Workshop on Weak Interactions and Neutrinos, P. Singer ed. (Nucl. Phys., to be published).
4. W. Buchmüller, D. Wyler, Nucl. Phys. B268, 621 (1986)
5. These are elaborated in Ref. 3.
6. B. Campbell et al; Int. J. Mod. Phys. A2, 831 (1987).
7. C.A. Heusch, Proc. Rencontre des Physique de la Vallée d'Aoste, to be published, SCIPP 89/21 (1989).
8. J.J. Gomez-Cadenas, C.A. Heusch, A. Seiden, Particle World 1 (to be published, 1989).
9. J.J. Gomez-Cadenas, private communication.
10. J.J. Gomez-Cadenas and C.A. Heusch, to be published.