Tau-Mu Flavor Violation  
and the Scale of New Physics  

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Abstract. Motivated by the strong experimental evidence of large $\nu_\mu - \nu_\tau$ neutrino oscillations, we study existing constraints for related $\mu - \tau$ flavor violation. Using a general bottom-up approach, we construct dimension-6 effective fermionic operators whose coefficients encode the scale of new physics associated with $\mu - \tau$ flavor violation, which is a piece in the puzzle of the origin of neutrino oscillations. We survey existing experimental bounds on this scale, which arise mostly from $\tau$ and $B$ decays. In many cases the new physics scale is constrained to be above a few TeV. We also discuss the operators which are either weakly constrained or, at present, subject to no experimental bounds.  

INTRODUCTION  

In the past few years there has been a wealth of exciting results from solar, atmospheric, reactor and accelerator neutrino experiments [1] which provide strong evidence for neutrino oscillations. The atmospheric neutrino experiments point in particular to maximal $\nu_\mu - \nu_\tau$ mixing. In Ref. [2] we investigated bounds on related $\mu - \tau$ flavor violation in the charged lepton sector. This, together with other studies of lepton flavor violation, for example $\mu - e$ mixing, complements what we learn from neutrino oscillations and will help in eventually achieving an understanding of lepton flavor dynamics.  

In order to carry out a systematic study, we use a model-independent effective operator approach. We consider an effective theory containing the Standard Model (SM) at dimension-4 and a class of dimension-6 four-fermion lepton flavor-violating operators of the form  

$$O_{\mu \tau} = \frac{4\pi}{\Lambda^2} (\mu \Gamma \tau) (\bar{q} \alpha \Gamma q) \beta. \tag{1}$$  

Here $\alpha$ and $\beta$ are flavor indices and $\Gamma$ denotes any of the four Dirac structures $\Gamma = 1, \gamma_5, \gamma^\mu, \gamma_5 \gamma^\mu$. This effective interaction paramaterizes new physics effects associated with $\mu - \tau$ flavor-violation below an ultraviolet cutoff scale, $\Lambda$. As illustrated schematically in Fig. 1, such dimension-6 operators could be generated, for example, from exchange of new gauge bosons or scalar (pseudoscalar) particles in the underlying theory at the scale $\Lambda$. A careful discussion of the construction of these operators is given in Ref. [2].  

In Ref. [2] we also considered purely leptonic effective interactions of the form $\frac{4\pi}{\Lambda^2} (\bar{\mu} \Gamma \tau) (\bar{\nu} \Gamma \nu) \beta$. Updated bounds using the latest upper limits from Belle [3] on the branching fractions for decays such as $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ are given in Ref. [4].
PHENOMENOLOGICAL CONSTRAINTS

Light quarks: $\tau$ decays

Experimental searches for lepton flavor violating (LFV) $\tau$ decay modes give strong bounds on many operators involving light quarks. The most recent experimental results\(^1\) for branching ratios for $\tau$ decay to $\mu$ and pseudoscalar or vector mesons are given in Refs. [3, 5, 6]. In order to obtain bounds\(^2\) on $\Lambda$, we calculate the appropriate matrix element of the effective operator leading to each decay using vacuum insertion and standard results for the hadronic matrix elements of the light quark bilinear current densities.

One $b$ quark: $B$ decays

The operators in Eq. (1) with $\Gamma = \gamma^5$, $\gamma^\mu \gamma^5$ and with quark-antiquark combinations $\bar{b}d$ and $\bar{b}s$ will give decays of $B$ and $B_s$ to $\mu \tau$. We calculate this width using vacuum insertion and a Heavy Quark Effective Theory estimate of $|\langle 0 | \bar{q} \gamma^5 b | B \rangle|$. The experimental upper limits are $\text{Br}(B^0 \to \mu \tau) < 8.3 \times 10^{-4}$ [5] and $\text{Br}(B_s \to \mu \tau) < 10\%$ (a conservative estimate based on the observed $B_s$ lifetime). Similarly, the operators with $\Gamma = 1$, $\gamma^\mu$ give the decays $B \to \pi \mu \tau, K \mu \tau$ which we calculate using a quark model estimate for the form factors in the heavy-light meson matrix elements. There is no experimental data at present on these branching ratios so we take conservative estimates $\text{Br}(B \to \pi \mu \tau, K \mu \tau) < 5\%$, which give $\Lambda > 2.5$ TeV.

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\(^1\) The speaker thanks Jon Urheim for drawing her attention to these new results [6, 3] in his talk “Rare tau decays: an experimental review” at this conference.

\(^2\) We considered only one operator in Eq. (1) at a time, so treated the operators $\bar{\mu} \Gamma \tau \bar{d} \Gamma \bar{s} + H.c.$ and $\bar{\mu} \Gamma \tau \bar{s} \Gamma \bar{d} + H.c.$ independently and, using the new experimental limits [3] on the branching ratio for $\tau \to \mu K_s$, quote strong bounds on each one. If these operators occur with the same coefficients then their contributions to $\tau \to \mu K_s$ would actually cancel (up to presumably small CP violating effects).
Loop-induced processes

We found that it is hard to constrain all operators $O_{\mu \tau}$ with heavy quarks directly from tree-level processes. Hence we consider one-loop processes which induce effective light-quark vertices via insertions of the relevant heavy quark operators, for example diagrams with $W^{\pm}$ exchange as shown in Fig. 2. As an example we see that through this mechanism, if the quarks in the loop are $c$ and $\bar{c}$ then the final state quarks can be $s$ and $\bar{s}$. This means that the operator $\bar{\mu} \Gamma \tau \bar{c} \Gamma c$ can lead to an amplitude at one loop for $\tau$ decay to $\mu$ and an $\bar{s}s$ state such as the $\phi$ vector meson. Other operators for which the strictest bounds come from similar one-loop processes are given in Table 2.

SUMMARY AND DISCUSSION

We have presented a survey based on Ref. [2] of existing constraints on flavor violation in the charged lepton sector due to effective interactions of the type $\frac{4\pi}{\Lambda^2} (\bar{\mu} \Gamma \tau)(\bar{q} \Gamma q \bar{\beta})$. Most of our lower bounds on the scale of new physics responsible for these lepton flavor-violating operators come from $\tau$ and $B$ decays at tree or one-loop level and are of order 1-10 TeV. A complete summary of our results is given in Table 2.

It will be interesting to further apply the bounds presented in this study to constrain specific new physics scenarios which can generate the $\mu - \tau$ flavor violating interactions of the kind we have analyzed. We note that as ongoing experimental searches for rare $\tau$ decay modes reach higher levels of precision almost half of the bounds listed in Table 2 will become more stringent. Searches for $\mu \tau$ in charmonium and bottomonium decays may help to constrain some of the operators for which we could at present find no limits. Also we expect searches for $B_s \rightarrow \mu \tau$ and for $B$ decays to ($\mu \tau$ + meson) to improve the values listed in Table 2 for operators involving one $b$ quark. It would also be interesting to look for the decay $t \rightarrow \mu \tau + \text{jet}$ at top-quark factories.
TABLE 1. Bounds at 90% C.L. on four-Fermi flavor-violation operators discussed in text. Asterisk indicates that no bounds have been found, otherwise we list the process which gives the strongest bound.

| Bound | 1 | $\gamma_5$ | $\gamma_6$ | $\gamma_5\gamma_6$ |
|-------|---|-------------|-------------|------------------|
| $\bar{u}u$ | 2.6 TeV | 12 TeV | 12 TeV | 11 TeV |
| | ($\tau \to \mu \pi^+ \pi^-$) | ($\tau \to \mu \pi^0$) | ($\tau \to \mu \rho$) | ($\tau \to \mu \pi^0$) |
| $d\bar{d}$ | 2.6 TeV | 12 TeV | 12 TeV | 11 TeV |
| | ($\tau \to \mu \pi^+ \pi^-$) | ($\tau \to \mu \pi^0$) | ($\tau \to \mu \rho$) | ($\tau \to \mu \pi^0$) |
| $s\bar{s}$ | 1.5 TeV | 9.9 TeV | 14 TeV | 9.5 TeV |
| | ($\tau \to \mu K^+ K^-$) | ($\tau \to \mu \eta$) | ($\tau \to \mu \phi$) | ($\tau \to \mu \eta$) |
| $\bar{s}d$ | 2.3 TeV | 24.3 TeV | 13 TeV | 23.6 TeV |
| | ($\tau \to \mu K^+ \pi^-$) | ($\tau \to \mu K_{s}$) | ($\tau \to \mu K^+$) | ($\tau \to \mu K_{s}$) |
| $b\bar{d}$ | 2.2 TeV | 9.3 TeV | 2.2 TeV | 8.2 TeV |
| | ($B \to \tau \mu \pi$) | ($B \to \tau \mu \pi_0$) | ($B \to \tau \mu \pi_0$) | ($B \to \tau \mu \pi_0$) |
| $b\bar{s}$ | 2.6 TeV | 2.8 TeV | 2.6 TeV | 2.5 TeV |
| | ($B \to K \mu \tau$) | ($B_s \to K \mu \tau$) | ($B \to K \mu \tau$) | ($B_s \to K \mu \tau$) |
| $\bar{i}c$ | 190 GeV | 190 GeV | 310 GeV | 310 GeV |
| | ($\tau \to \mu \tau$) | ($\tau \to \mu \tau$) | ($\tau \to \mu \tau$) | ($\tau \to \mu \tau$) |
| $\bar{i}u$ | 190 GeV | 190 GeV | 650 GeV | 650 GeV |
| | ($\tau \to \mu \tau$) | ($\tau \to \mu \tau$) | ($\tau \to \mu \tau$) | ($\tau \to \mu \tau$) |
| $\bar{c}u$ | * | * | 550 GeV | 550 GeV |
| | | | ($\tau \to \mu \phi$) | ($\tau \to \mu \phi$) |
| $\bar{c}c$ | * | * | 1.1 TeV | 1.1 TeV |
| | | | ($\tau \to \mu \phi$) | ($\tau \to \mu \phi$) |
| $b\bar{b}$ | * | * | 180 GeV | * |
| | | | ($\tau \to \mu \tau$) | ($\tau \to \mu \tau$) |
| $\bar{t}t$ | * | * | 75 GeV | 120 GeV |
| | | | ($B \to \mu \tau$) | ($B \to \mu \tau$) |

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