Constraints on Muon Decay Parameters from Neutrino Mass[1]

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Abstract. We use experimental limits on the neutrino mass to derive model-independent upper bounds on various muon decay parameters. We find that the bounds obtained in this way are improved by more than three orders of magnitude over current experimental limits.

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INTRODUCTION

The discovery of neutrino mass has led to new connections between Standard Model (SM) and non-SM phenomena (for example, see Refs. [1] and [4]). One of these connections is between neutrino mass and muon decay. By analyzing the mixing of chirality-changing operators that contribute to both processes, we can use upper bounds on the neutrino mass to place upper bounds on some μ-decay parameters.

MICHEL PARAMETERS

The Michel parameters are a way of parameterizing contributions to μ-decay from physics beyond the SM. Depending on the details of the process being examined there can be as many as ten parameters (excluding radiative decay) describing muon decay. Physically, they represent the energy and angular distributions and the longitudinal and transverse polarizations of the outgoing electrons in μ-decay.

Muon decay can be described with the four-fermion interaction [2],

$$\mathscr{L} = \frac{4G_{\mathrm{F}}}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T \\ \alpha,\beta=R,L}} g^{\gamma}_{\alpha\beta} \bar{e}_{\alpha} \Gamma^{\gamma} \nu^{n}_{e} \bar{\nu}^{m}_{\mu} \Gamma_{\gamma} \mu_{\beta} \ , \tag{1}$$

where G_{F} is the Fermi coupling constant, fixed by the muon lifetime, and in the coupling constants $g^{\gamma}_{\alpha\beta}$, $\gamma = S, V, T$ indicates scalar, vector, and tensor interactions and $\alpha, \beta = R, L$ are the chiralities of the charged leptons. The chiralities n and m of the neutrinos are determined by the values of γ, α, and β. In the SM, $g^{V}_{LL} = 1$, and the remaining gs

[1] Work done in collaboration with Jennifer E. Kile, Michael Ramsey-Musolf, and Peng Wang.

are zero. Interestingly, in many extensions to the SM these other coupling constants are nonzero.

The Michel parameters are bilinear combinations of the μ-decay coupling constants $g^{\gamma}_{\alpha\beta}$. Several parameterizations of the Michel parameters exist, and to avoid confusion we will quote our results in terms of these gs, which can be directly compared with other studies ([3, 4]).

CONNECTING μ-DECAY AND ν MASS

We use the minimally extended SM with gauge-singlet right-handed Dirac neutrinos. A basis of operators up to dimension six that contribute both to μ-decay and ν mass and are invariant under $SU(2)_L \times U(1)_Y$ is:

$$\begin{aligned} \mathcal{O}_{ff} &= \varepsilon^{ij}\bar{L}_i l_R \bar{L}_j \nu_R & \qquad \mathcal{O}_B &= g_1 \bar{L}\tilde{\phi}\sigma^{\mu\nu}\nu_R B_{\mu\nu} \\ \mathcal{O}_{\tilde{V}} &= i\bar{l}_R\gamma^{\mu}\nu_R\phi^{\dagger}D_{\mu}\tilde{\phi} & \qquad \mathcal{O}_M^{(6)} &= \bar{L}\tilde{\phi}\nu_R\,(\phi^{\dagger}\phi) \\ \mathcal{O}_W &= g_2\bar{L}\tau^a\tilde{\phi}\sigma^{\mu\nu}\nu_R W^a_{\mu\nu} & \qquad \mathcal{O}_M^{(4)} &= \bar{L}\tilde{\phi}\nu_R \end{aligned}$$

By using a set of gauge-invariant operators, the contributions to m_ν from scales lying between the electroweak scale at $\upsilon = 246\,\mathrm{GeV}$ and the scale of new physics (typically $\Lambda \approx 1\,\mathrm{TeV}$) can be taken into account. While all of the chirality-changing operators above contribute to neutrino mass, only the operators $\mathcal{O}_{ff}$, $\mathcal{O}_{\tilde{V}}$, and $\mathcal{O}_W$ contribute to μ-decay. The remaining dimension-six operators mix with these at one loop under dimensional regularization and must be taken into account. In addition, there is mixing of the dimension-six operators $\mathcal{O}_{ff}$ and $\mathcal{O}_{\tilde{V}}$ with the dimension-four mass operator $\mathcal{O}_M^{(4)}$. This contribution is estimated using dimensional analysis.

The various operators above (those contributing to μ-decay) will contribute to different coupling constants. For example, the mixing of the operator $\mathcal{O}_{ff}$ with the dimension-four mass operator $\mathcal{O}_M^{(4)}$ gives an estimate of the upper bound on $g^{S,T}_{RL,LR}$, while mixings among the dimension-six operators (see Fig. 1 for an example) give upper bounds on $g^{V}_{RL,LR}$. Notice that these chirality-changing operators, and hence m_ν, put no constraints on the α, $\beta = RR$, LL coupling constants in $g^{\gamma}_{\alpha\beta}$.

IMPLICATIONS FOR THE TWIST EXPERIMENT

In Table 1, bounds on $g^{\gamma}_{\alpha\beta}$ obtained from the operator mixing analysis are compared with bounds from two previous studies: a recent global analysis [3] that includes new and more precise measurements of six parameters from the TWIST experiment and PSI, and bounds from the theoretical analysis in [4].

A degenerate neutrino mass spectrum with $m_\nu = 1\,\mathrm{eV}$ was used in our calculations. Since the upper limit on the gs is proportional to neutrino mass, a smaller bound on m_ν would result in tighter limits on $g^{S,V,T}_{RL,LR}$.

The upper limits on the gs on columns four and five are at least two orders of magnitude smaller than those in the third column and at least three orders of magnitude

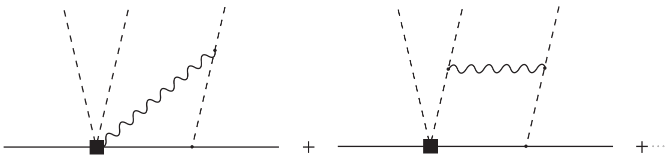

FIGURE 1. Mixing of $\mathcal{O}_V$ into $\mathcal{O}_M^{(6)}$.

TABLE 1. Upper bounds on μ-decay coupling constants $g^{\gamma}_{\alpha\beta}$ from two recent studies (second and third columns), and this work (fourth and fifth columns). A $-$ indicates that this g is not constrained by a mixing of this dimensionality.

$g^{\gamma}_{\varepsilon\mu}$	**Global Analysis[3]**	**Ref. [4]**	$4D$	$6D$
g^S_{LR}	< 0.088	10^{-4}	10^{-7}	–
g^S_{RL}	< 0.417	10^{-2}	10^{-5}	–
g^V_{LR}	< 0.036	10^{-4}	10^{-6}	10^{-6}
g^V_{RL}	< 0.104	10^{-2}	10^{-4}	10^{-4}
g^T_{LR}	< 0.025	10^{-4}	10^{-7}	–
g^T_{RL}	< 0.104	10^{-2}	10^{-5}	–

smaller than the bounds from the recent global analysis. One implication of our stronger constraints on the g coupling constants is that at current experimental sensitivities, any deviation from the SM values of $g^{S,V,T}_{RL,LR} = 0$ would have to result from fine-tuning in order to overcome the limits set by a Dirac neutrino mass.

CONCLUSIONS

We have presented results from a model-independent analysis connecting upper limits on the neutrino mass to the Michel parameters, which describe contributions to μ-decay from beyond the SM. The resulting constraints are much smaller than current experimental limits. Since the bounds on $g^{S,V,T}_{RL,LR}$ are directly proportional to the neutrino mass, smaller limits on m_ν will decrease these upper bounds.

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