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Lepton flavor violation with displaced vertices

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ABSTRACT

If light new physics with lepton-flavor-violating couplings exists, the prime discovery channel might not be $\ell \to \ell' \gamma$ but rather $\ell \to \ell' X$, where the new boson X could be an axion, majoron, familon or Z' gauge boson. The most conservative bound then comes from $\ell \to \ell' + \text{inv}$, but if the on-shell X can decay back into leptons or photons, displaced-vertex searches could give much better limits. We show that only a narrow region in parameter space allows for displaced vertices in muon decays, $\mu \to eX, X \to \gamma\gamma, ee$, whereas tauon decays can have much more interesting signatures.

1. Introduction

The Standard Model (SM) brings with it the accidental conservation of baryon number B and individual lepton numbers $L_{e,\mu,\tau}$. The linear combination $B + \sum_\alpha L_\alpha$ is broken at a non-perturbative level [1] and the differences $L_\alpha - L_\beta$ are clearly violated by neutrino oscillations [2]. Despite of that, we have yet to observe a lepton-flavor-violating (LFV) process involving *charged* leptons, which is, without additional assumptions, decoupled from neutrino oscillations and thus a perfect signature of new physics [3].

Assuming new particles with LFV couplings much heavier than the energies in question allows one to use an effective-field-theory approach with higher-dimensional operators, which typically make $\mu \to e\gamma$, $\mu \to 3e$ or μ–e conversion (Table 1) the best processes to detect LFV in the μ–e sector (see e.g. Ref. [4,5]). This conclusion no longer holds if new particles with LFV couplings exist that are *lighter* than the muon. Examples for these are plentiful, be it light gauge bosons Z' [6–11] or light (pseudo-)scalars, e.g. familons, majorons or axion(-like) particles [12–24]. The usually considered processes listed above are then typically heavily suppressed, making the two-body decay $\mu \to eX$ the prime search channel. The signature here depends on the decay channels of X:

1. If X decays invisibly, for example into neutrinos or dark matter, only the mono-energetic electron can be searched for on top of the continuous Michel spectrum, with limits on $\text{BR}(\mu \to eX)$ of order 10^{-5} [25] and 10^{-6} [26], depending on m_X and the chirality. The emission of an additional photon can help to further reduce background, leading to $\text{BR}(\mu \to e\gamma X) < 10^{-9}$ [27,28].
2. If X decays into visible particles, e.g. $X \to e^+e^-$ or $X \to \gamma\gamma$, much better limits could be obtained as long as the decay happens *inside* of the detector. This typically involves a reconstruction of the displaced vertex (DV) of $X \to$ vis and thus different cuts and triggers than usual. We stress that the signatures are background-free both due to their LFV nature and the DV.

Table 1
LFV processes in the muon sector with current (90% C.L.) and future limits on branching ratios. Limits involving a new light boson X depend on its mass, lifetime, and branching ratios, see references and text for details.

Process	Current	Future
$\mu \to e$ conv.	$\mathcal{O}(10^{-12})$ [33]	10^{-17} [34,35]
$\mu \to e\gamma$	4.2×10^{-13} [36]	4×10^{-14} [37]
$\mu \to e\bar{e}e$	1.0×10^{-12} [38]	10^{-16} [39]
$\mu \to e\gamma\gamma$	7.2×10^{-11} [40]	–
$\mu \to e\gamma X, X \to \text{inv}$	$\mathcal{O}(10^{-9})$ [27,28]	–
$\mu \to eX, X \to \text{inv}$	$\mathcal{O}(10^{-5})$ [25]	10^{-8} [41]
$\mu \to eX, X \to ee$	$\mathcal{O}(10^{-11})$ [42]	$< 10^{-14}$
$\mu \to eX, X \to \gamma\gamma$	$\mathcal{O}(10^{-10})$ [28,43]	10^{-11} [43]

Similar considerations hold for LFV τ decays, which allow for many more visible DV channels, including $X \to$ hadrons. *Invisible* $\tau \to \ell X$ decays have been studied at ARGUS [29] (see also older limits in Refs. [30,31]), and are under investigation at Belle [32].

LFV decays *with DV* are only possible in certain kinematical regions, e.g. $2m_e < m_X < m_\mu - m_e$ for $\mu \to eX, X \to ee$, and furthermore require the X decay length to be larger than the experi-

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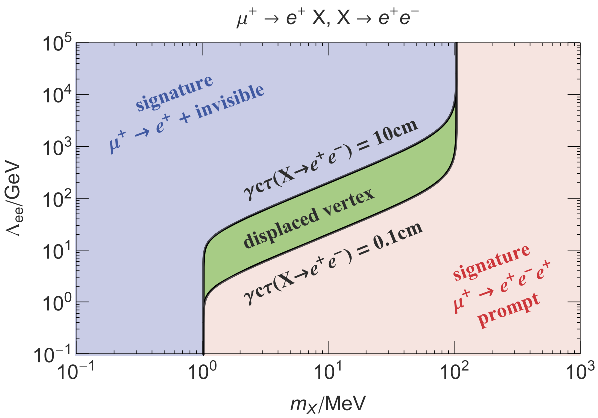

Fig. 1. Signatures of $\mu \to eX$, $X \to ee$ depending on X mass and Xee coupling strength. For $m_X < 2m_e$ or if X decays outside of the detector, the signature is mainly $\mu \to e + \text{inv}$ (blue region). For $m_X > m_\mu - m_e$ or if the X decay length $c\tau$ is smaller than the vertex resolution, the signature is just prompt $\mu \to 3e$ (red region). In between, a region with detectable displaced $X \to ee$ vertex exists (green), which of course depends on the detector geometry and acceptance. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mental vertex resolution and smaller than the detector. This leaves a sliver of testable parameter space where limits can be put on $\text{BR}(\mu \to eX, X \to ee)$, illustrated in Fig. 1 (see later for details). Since sub-GeV particles X with couplings to leptons or photons are strongly constrained by other experimental searches, it is not obvious that there is viable parameter space for LFV DV. As we will see below, there is only a small feasible region for muon decays, whereas tauon decays are much less constrained and can have a plethora of interesting signatures.

The focus of this letter will be these LFV decays with DV. Existing work is scarce; we are not aware of any analyzes for τ, but there is an old limit from SINDRUM on $\text{BR}(\mu \to eX, X \to ee)$ of order 10^{-11} [42] and a thesis within the MEG collaboration on $\text{BR}(\mu \to eX, X \to \gamma\gamma)$ with a limit of order 10^{-11} [43]. We expect Mu3e [39] to vastly improve at least the SINDRUM limit, and encourage searches for these kind of LFV τ decays at B factories.

2. Framework

We focus our analysis on pseudo-Goldstone bosons X,[1] whose couplings to SM leptons $\ell_{e,\mu,\tau}$ can be conveniently parametrized as [17]

$$\begin{aligned}\mathcal{L}_X &= \frac{\partial_\mu X}{\Lambda}\bar{\ell}_\alpha \gamma^\mu (g^V_{\alpha\beta} + g^A_{\alpha\beta}\gamma^5)\ell_\beta \\ &= -i\frac{X}{\Lambda}\bar{\ell}_\alpha (g^V_{\alpha\beta}(m_\alpha - m_\beta) + g^A_{\alpha\beta}(m_\alpha + m_\beta)\gamma^5)\ell_\beta\,,\end{aligned} \tag{1}$$

with some effective scale Λ and hermitian (anti-hermitian) coupling matrix g^A (g^V), to be assumed real in the following. In the second line we have integrated by parts and used the equations of motion, which is justified for on-shell particles. In the case of leptonic familons [12–14], Λ corresponds to the scale of the broken global flavor symmetry and the matrix structure of $g^{A,V}$ is determined by the symmetry generators [17]. However, these couplings arise even in simple unflavored singlet-majoron models at one-loop level [16] and depend on seesaw parameters [24]; in fact, measuring these majoron couplings could make it possible to reconstruct the seesaw parameters without having to detect the heavy neutrinos. Diagonal as well as off-diagonal couplings to charged leptons are thus a generic part of many models and in particular relevant for neutrino-mass models with global symmetries.

We assume the mass of X, m_X, to be an independent parameter. It proves convenient to define the scales

$$\Lambda_{\alpha\beta} \equiv \Lambda/\sqrt{(g^V_{\alpha\beta})^2 + (g^A_{\alpha\beta})^2}\,. \tag{2}$$

The LFV two-body decays then take the form

$$\begin{aligned}\Gamma(\ell_\alpha \to \ell_\beta X) = {}& \frac{m_\alpha^3}{16\pi\Lambda^2}\sqrt{\left(1-r_X^2\right)^2 + r_\beta^4 - 2r_\beta^2\left(1+r_X^2\right)} \\ &\times \left[\left((g^A_{\alpha\beta})^2 + (g^V_{\alpha\beta})^2\right)\left(1-r_\beta^2\right)^2\right. \\ &\left. - \left((g^V_{\alpha\beta})^2(1-r_\beta)^2 + (g^A_{\alpha\beta})^2(1+r_\beta)^2\right) r_X^2\right],\end{aligned} \tag{3}$$

with $r_{\beta,X} \equiv m_{\beta,X}/m_\alpha$. For $m_{\beta,X} \ll m_\alpha$, this is simply $m_\alpha^3/(16\pi\Lambda^2_{\alpha\beta})$. The boson decay is given by

$$\Gamma(X \to \ell_\alpha \bar{\ell}_\alpha) = \frac{m_X}{2\pi}(g^A_{\alpha\alpha})^2\frac{m_\alpha^2}{\Lambda^2}\sqrt{1-\frac{4m_\alpha^2}{m_X^2}}\,, \tag{4}$$

$$\Gamma(X \to \ell_\alpha \bar{\ell}_\beta + \bar{\ell}_\alpha \ell_\beta) \simeq \frac{m_X}{4\pi}\frac{m_\alpha^2}{\Lambda^2_{\alpha\beta}}\left(1-\frac{m_\alpha^2}{m_X^2}\right)^2, \tag{5}$$

the last equation being valid for $m_\beta \ll m_\alpha$.

The decay $X \to \gamma\gamma$ induced by a fermion loop is typically suppressed, but of course becomes the dominant decay channel for $m_X < 2m_e$ [47]. We will simply assume an effective photon coupling [2],

$$\mathcal{L} \supset -\frac{g_{\gamma\gamma}}{4} X F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \Rightarrow \quad \Gamma(X \to \gamma\gamma) = \frac{g_{\gamma\gamma}^2 m_X^3}{64\pi}\,, \tag{6}$$

with field-strength tensor $F_{\mu\nu}$ and its dual $\tilde{F}^{\mu\nu} = \frac{1}{2}F_{\alpha\beta}\epsilon^{\mu\nu\alpha\beta}$. The coupling $g_{\gamma\gamma}$ with mass dimension -1 could be generated by a triangle anomaly analogous to axions or via mixing with the longitudinal Z component as in majoron models [24,48]. In addition to the decay into leptons and photons one could easily imagine invisible decays (into neutrinos or additional new light particles) or decays into hadrons (for sufficiently heavy X). To simplify the analysis we will neglect these channels.

The relevant quantity for DV is the decay length in the laboratory frame, in which X is typically boosted. For LFV with muons (e.g. MEG or Mu3e), the muon is stopped before it decays into eX, so X has the following momentum in the lab frame

$$|\boldsymbol{p}_X| = \frac{\sqrt{(m_\mu^2 - (m_e + m_X)^2)(m_\mu^2 - (m_e - m_X)^2)}}{2m_\mu}\,, \tag{7}$$

leading to the boosted decay length [2]

$$\gamma c\tau = \frac{c|\boldsymbol{p}_X|}{m_X \Gamma_X}\,. \tag{8}$$

Now $P(x) = \exp(-x/\gamma c\tau)$ is the probability for X to travel a distance x without decaying. Note that the inclusion of additional X decay channels can only *shorten* the decay length, rendering the decay more prompt and reducing the rate by $1 - \text{BR}(X \to \text{inv})$.

[1] Vector bosons Z' will behave similar to pseudoscalars since for light Z' only the longitudinal component is produced in $\ell_\alpha \to \ell_\beta Z'$ [10]. The main difference is then in the Z' decay, which in particular does not allow for $\gamma\gamma$. Light CP-*even* scalars look qualitatively similar and will typically mix with the Higgs boson, leading to additional couplings [44–46].