PROCEEDINGS OF SCIENCE

Probing BSM with High-Multiplicity Muon Decays

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We discuss a class of exotic muon decay signatures that extend beyond the well-studied lepton flavor-violating channels such as $\mu \to e\gamma$ and $\mu \to 3e$. We focus on rare processes featuring final states with $2m + 1$ electrons and n photons, exploring their theoretical origin and experimental relevance. Our analysis begins in the framework of the Standard Model Effective Field Theory (SMEFT), where we examine the conditions under which an EFT description remains valid for such processes. We then identify the minimal single-particle EFT interactions capable of inducing these decays and investigate explicit ultraviolet completions that give rise to the relevant operators. Finally, we present a simple numerical study assessing the experimental prospects for observing these muon decay channels.

The European Physical Society Conference on High Energy Physics (EPS-HEP2025)
7-11 July 2025
Marseille, France

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 ISSN 1824-8039 . Published by SISSA Medialab.

PoS(EPS-HEP2025)425

$e\backslash\gamma$	**0**	**1**	**2**	**3**	**4**
1	e	$e\gamma$	$e2\gamma$	$e3\gamma$	$e4\gamma$
3	$3e$	$3e\gamma$	$3e2\gamma$	$3e3\gamma$	...
5	$5e$	$5e\gamma$	$5e2\gamma$	...	
7	$7e$	$7e\gamma$	...		
9	$9e$	...			

Table 1: Overview of exotic muon decay channels, organized by the number of charged leptons (rows) and photons (columns) in the final state. The standard cLFV modes ($\mu \to e$ conversion, $\mu \to e\gamma$, and $\mu \to 3e$) are shown in black. Decays containing one additional building block (e^+e^- pair or photon) are highlighted in red, those with two in blue, and those with three in green. Each entry may also involve missing energy, while final-state tracks can be either prompt or displaced.

1. Introduction

Charged-lepton flavor violation (cLFV) offers one of the most powerful probes of new physics beyond the Standard Model (SM). In the SM, individual lepton flavors are conserved in muon and tau decays up to tiny corrections proportional to neutrino masses, making any observation of cLFV a clear signal of new dynamics. The three golden channels $\mu \to e\gamma$, $\mu \to 3e$, and $\mu^- A \to e^- A^{(*)}$ are currently being explored with unprecedented precision at MEG II, Mu3e, Mu2e, and COMET [1, 2]. By the end of the decade, sensitivities to branching ratios as low as $\mathcal{O}(10^{-15})$ are expected, corresponding within the SMEFT framework to new-physics scales up to $\Lambda \sim 10^8$ GeV [3–6]. Yet, new physics might also manifest through light states rather than heavy ones. If a light boson couples feebly to leptons, processes such as $\mu \to ea$, $\mu \to e\gamma\gamma$, or $\mu \to 3e+\text{inv}$ can probe decay constants far above the SMEFT reach, even approaching 10^{14} GeV. These *exotic* muon decays open a qualitatively new window, sensitive to both the flavor structure and the mass scale of hidden sectors. In this work we follow a signature-driven approach, classifying all possible exotic final states in terms of a finite set of building blocks, in particular e^+e^- pairs, extra photons, and invisible particles, as summarized in Table 1. Several of these signatures, particularly those with higher multiplicity, remain unexplored both theoretically and experimentally. Our goal is to identify the corresponding effective operators and benchmark models, highlighting their complementarity to the golden cLFV modes and their relevance for upcoming searches at MEG II, Mu3e, Mu2e, and COMET.

2. EFT Approach to High-Multiplicity Decays

Our effective-field-theory (EFT) analysis distinguishes two qualitatively different regimes. When all new states are heavier than the electroweak scale ($\langle H \rangle = v_{\text{ew}}/\sqrt{2}$), they can be integrated

Signature	$\mathcal{L}_{\text{SMEFT}} \supset$	**Λ [GeV]**
$\mu \to e\gamma$	$\frac{y_\mu}{16\pi^2}\frac{1}{\Lambda^2}(\bar{\ell}_2\sigma^{\mu\nu}e_1)HB_{\mu\nu}$	3×10^5
$\mu \to 3e$	$\frac{1}{\Lambda^2}(\bar{\ell}_2\gamma^\mu\ell_1)(\bar{\ell}_1\gamma_\mu\ell_1)$	2×10^6
$\mu \to 5e$	$\frac{y_\mu}{\Lambda^6}(\bar{\ell}_1\gamma^\mu\ell_1)^2(\bar{\ell}_2He_1)$	5
$\mu \to 3e\gamma$	$\frac{1}{16\pi^2}\frac{1}{\Lambda^4}(\bar{\ell}_2\gamma^\mu\ell_1)(\bar{\ell}_1\gamma^\nu\ell_1)B_{\mu\nu}$	30
$\mu \to e2\gamma$	$\frac{y_\mu}{16\pi^2}\frac{1}{\Lambda^4}(\bar{\ell}_2He_1)B_{\mu\nu}B^{\mu\nu}$	80
$\mu \to e3\gamma$	$\frac{1}{16\pi^2}\frac{1}{\Lambda^4}(\bar{\ell}_2\gamma^\mu\overleftrightarrow{D}^\nu\ell_1)B_{\mu\rho}B^\rho_\nu$	20
$\mu \to 3e2\gamma$	$\frac{1}{\Lambda^4}(\bar{\ell}_2\gamma^\mu\overleftrightarrow{D}^\nu\ell_1)(\bar{\ell}_1\gamma_\mu\overleftrightarrow{D}_\nu\ell_1)$	40

Table 2: Representative SMEFT operators contributing to rare muon decays and the corresponding probed scales Λ. For the golden modes $\mu \to e\gamma$ and $\mu \to 3e$, the quoted sensitivities follow from the projected bounds $\text{BR}(\mu \to e\gamma) \sim 6\times10^{-14}$ and $\text{BR}(\mu \to 3e) \sim 10^{-16}$. For higher-multiplicity modes, Λ is estimated assuming $\text{BR}(\mu \to e + X) < 10^{-15}$.

out, leading to local dimension-6 SMEFT operators that mediate charged-lepton flavor violation.[1] The second regime arises when light, gauge-singlet particles are kinematically accessible, i.e. $m_X < m_\mu - m_e$. In this case, we extend the EFT below the electroweak scale by including explicit light fields coupled to SM currents through gauge-invariant higher-dimensional operators. Such setups naturally give rise to exotic muon decays with additional leptons, photons, or missing energy. Throughout, we adopt $\text{BR}(\mu \to e + X) < 10^{-15}$ as an illustrative benchmark sensitivity. Standard-Model backgrounds to these rare signatures are extremely suppressed. Higher-multiplicity muon decays originate only from QED radiation, scaling rapidly with the number of emitted photons or e^+e^- pairs, e.g. $\text{BR}(\mu \to 5e2\nu) \sim \mathcal{O}(10^{-10})$. This renders exotic channels with hard visible particles or little missing energy particularly promising discovery modes for new physics.

2.1 SMEFT

We first consider the case in which all new particles are heavier than the electroweak scale, so that they can be integrated out and their effects described by local dimension-6 and higher SMEFT operators. Examples of operators generating exotic muon decays along with the effective scales they probe are summarized in Table 2, where ℓ, e, and H denote the SM lepton doublets, right-handed leptons, and Higgs doublet, respectively. Two broad classes emerge: operators producing purely leptonic final states and those that additionally yield photons. The dominant experimental sensitivity always arises from processes in which all visible particles originate directly from the SMEFT vertex. Dalitz conversions or extra radiative emissions are suppressed by $\mathcal{O}(\alpha/\pi) \sim 10^{-3}$ and therefore subleading. For instance, the dipole operator $(\bar{e}\sigma^{\mu\nu}\mu)F_{\mu\nu}$ induces $\mu \to e\gamma$ as well

[1] An intermediate regime, characterized by $m_\mu < m_X < v_{\text{ew}}$, implies that a full SMEFT description breaks down but the new particle X cannot be produced in muon decays. An example of such scenario can be found in UV completions featuring off-shell ALP [7].

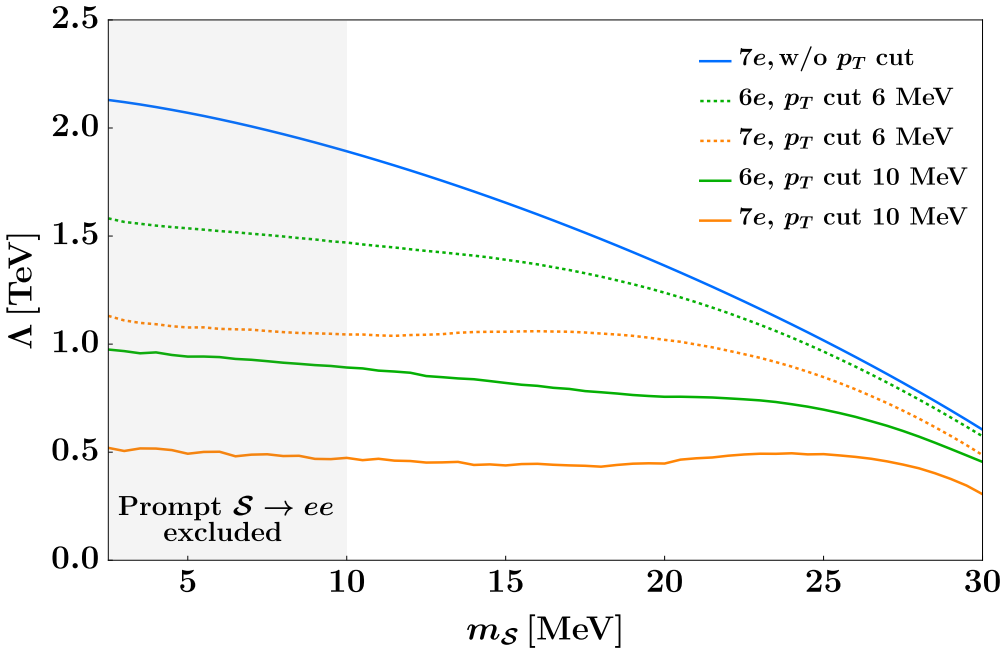

Figure 1: Sensitivity to the effective scale Λ for the scalar $\mathcal{S}$ and the interaction given by Eq. (1) with $n = 3$ corresponding to the decay $\mu \to e + 3\mathcal{S}$ with $\mathcal{S} \to 2e$ ($7e$ final state). The curves show the values of Λ yielding BR $\times$ acceptance $= 10^{-15}$ as a function of $m_{\mathcal{S}}$, for different kinematic selections requiring six or seven reconstructed leptons. The shaded region $m_{\mathcal{S}} \lesssim 10\,\text{MeV}$ is excluded by beam-dump searches [8].

as $\mu \to 3e$ through $\gamma^* \to e^+e^-$, but the latter rate is down by this factor. Consequently, higher-multiplicity decays stemming from QED radiation, such as $\mu \to 5e$, remain well below the expected sensitivities of BR $\sim 10^{-15}$ assumed for our benchmarks.

2.2 SMEFT$_X$

The presence of light new particles drastically modifies the EFT picture. We consider the simplest extension of the SMEFT that includes a single light, gauge-singlet field X, giving rise to the light-particle EFT framework denoted as SMEFT$_X$. In this case, exotic muon decays no longer originate from high-dimensional contact interactions, but rather from the production and subsequent decay of the on-shell state X. The resulting final states can therefore exhibit higher multiplicities or displaced vertices, depending on the lifetime of X. We focus on four representative realizations in which X is a scalar $\mathcal{S}$, pseudoscalar $\mathcal{P}$, fermion N, or vector V. The corresponding operators, which couple X to the SM leptons, are of lower dimension than the SMEFT operators generating analogous final states. Consequently, the same signatures $\mu \to (ne)(m\gamma)$ probe much higher underlying scales than in SMEFT. This also changes the radiative relations between processes: diagrams obtained by closing the e^+e^- legs are now further suppressed by the small couplings of X to electrons, while closing X lines in loops can yield additional, though model-dependent, constraints.

As a concrete realization of the SMEFT$_X$ framework, we first consider the case where the Standard Model is supplemented by a light scalar field $\mathcal{S}$. Such a state can couple to the charged-lepton sector through Yukawa-like interactions or through scalar insertions dressing higher-dimensional

cLFV operators. In both cases, the presence of $\mathcal{S}$ allows for multi-particle final states in muon decays that cannot be described within the ordinary SMEFT. A minimal example involves Yukawa-type operators of the form

$$\mathcal{L}_{\text{eff}} \supset \frac{C_{\mathcal{S}}^{(n)}}{\Lambda^n}(\bar{\ell}_2 H e_1)\mathcal{S}^n + \text{h.c.}\,, \tag{1}$$

which induce $\mu \to e + n\,\mathcal{S}$ transitions. Assuming couplings $C_{\mathcal{S}}^{(n)} \sim y_\mu$, the branching ratio scales as

$$\text{BR}(\mu \to e + n\,\mathcal{S}) \sim \frac{y_\mu^2\, v_{\text{ew}}^6}{(16\pi^2)^{n-2}} \frac{m_\mu^{2n-6}}{\Lambda^{2n}}\,. \tag{2}$$

If $\mathcal{S}$ decays promptly to $2e$ or 2γ, this process directly produces high-multiplicity final states such as $\mu \to 3e$, $\mu \to 5e$, or $\mu \to 7e$. For branching-ratio sensitivities of order 10^{-15}, the corresponding effective scales exceed the electroweak scale for $n = \{1, 2, 3\}$, motivating the restriction to a few emitted scalars. At larger n, the average lepton momenta drop to the $O(10\,\text{MeV})$ range, approaching current detector thresholds. Figure 1 summarizes the sensitivity to the effective scale Λ associated with the scalar interaction in Eq. (1), taking $n = 3$. The dependence on the scalar mass $m_{\mathcal{S}}$ is shown for different kinematic selections, assuming $C_{\mathcal{S}}^{(3)} = y_\mu$ and a benchmark sensitivity of BR $\times$ acceptance $= 10^{-15}$.

3. Example of Benchmark Model

As a concrete UV realization of the light-particle EFT, we consider a gauged $U(1)_{\mu-e}$ symmetry under which the Standard Model leptons carry vector-like charges $[\ell_1] = [e_1] = -[\ell_2] = -[e_2] = -1$ and $[\ell_3] = [e_3] = 0$. The model is supplemented by a scalar field Φ with charge $[\Phi] = +2/n$, whose vacuum expectation value (VEV) v_Φ spontaneously breaks the symmetry, giving mass to the new gauge boson V_μ, which can be expressed as $m_V = g_V v_\Phi$. For the small couplings of interest, $g_V \ll 1$, the corresponding symmetry-breaking scale satisfies $v_\Phi \gg m_\mu$. The scalar excitation of Φ, denoted as φ, is assumed to be light, with $m_\varphi \ll v_\Phi$.

The relevant lepton-flavor-violating interactions arise from higher-dimensional operators of the form

$$-\mathcal{L} \supset \sum_{i=e,\mu} \hat{y}_{ii}\, \bar{\ell}_i H e_i + y_5^{e\mu}\left(\frac{\Phi^\dagger}{\Lambda}\right)^n (\bar{\ell}_1 H e_2) + y_5^{\mu e}\left(\frac{\Phi}{\Lambda}\right)^n (\bar{\ell}_2 H e_1) + \text{h.c.}\,, \tag{3}$$

which generate off-diagonal entries in the charged-lepton mass matrix once H and Φ acquire VEVs. In the small-mixing limit, the induced rotations lead to flavor-violating couplings of both the gauge boson V_μ and the scalar φ to the charged leptons. The resulting effective interactions are

$$\mathcal{L}_V \supset 2 g_V \theta_{L,R}\, \bar{e}_{L,R} \not{V} \mu_{L,R} + \text{h.c.} \qquad \text{and} \qquad \mathcal{L}_\varphi \supset n \frac{m_\mu}{v_\Phi} \theta_{L,R}\, \bar{e}\, P_{R,L} \mu + \text{h.c.}\,,$$

where $\theta_{L,R} \simeq (y_5^{e\mu,\mu e}/y_\mu)(v_\Phi/\sqrt{2}\Lambda)^n$. Additionally, these interactions lead to the decays $\mu \to eV$ and $\mu \to e\varphi$, with branching ratios [7]

$$\text{BR}(\mu \to eV) = \frac{1}{4\pi}\frac{m_\mu}{\Gamma_\mu} g_V^2 (\theta_L^2 + \theta_R^2)\,, \qquad \text{BR}(\mu \to e\varphi) = \frac{1}{16\pi}\frac{m_\mu}{\Gamma_\mu}\left(n\frac{m_\mu}{v_\Phi}\right)^2 (\theta_L^2 + \theta_R^2)\,. \tag{4}$$

For $m_V \ll m_\mu/2$ and $m_\varphi < m_\mu - m_e$, the $\mu \to e\varphi$ channel dominates, yielding signatures such as $\mu \to 5e$ via $\mu \to e\varphi$, followed by $\varphi \to 2V$ and $V \to 2e$. In contrast, when the φ mode is kinematically forbidden, $\mu \to eV$ leads to the $\mu \to 3e$ final state. For the simplest case $n = 1$, these processes probe scales as high as $\Lambda \gtrsim 3 \times 10^{14}\,\text{GeV}$ for branching-ratio sensitivities near 10^{-15}. This example demonstrates how even weakly coupled light states in well-motivated gauge extensions can translate into exceptionally high sensitivity to the underlying new-physics scale.

4. Conclusions

The ongoing and planned high-precision muon experiments at PSI, Fermilab, and J-PARC are testing one of the fundamental organizing principles of the Standard Model, namely the conservation of charged-lepton flavor. While the current experimental program is largely centered on the golden channels $\mu \to e\gamma$, $\mu \to 3e$, and $\mu \to e$ conversion, several other exotic muon decay topologies can provide complementary and potentially background-free probes of new physics. Our EFT analysis demonstrates that such high-multiplicity or multi-photon signatures are difficult to generate within the standard SMEFT framework, where all new particles are heavy and integrated out. In contrast, once a light state is present in the spectrum, as in the SMEFT$_X$ setup, the exotic muon decays become a powerful window into very high energy scales. Depending on the decay topology and the properties of the light particle, branching-ratio sensitivities at the level of 10^{-15} can correspond to effective scales exceeding 10^{13}–10^{14} GeV.

We illustrated these ideas through several benchmark realizations, including scenarios with light scalars and new gauge bosons. In particular, the gauged $U(1)_{\mu-e}$ model exemplifies how spontaneous symmetry breaking can give rise to flavor-violating couplings and characteristic decay cascades such as $\mu \to e\varphi$ and $\mu \to eV$. These mechanisms lead to distinctive multi-lepton signatures, most notably $\mu \to 5e$ and $\mu \to 7e$, signatures that may become accessible in forthcoming muon experiments. Overall, our findings emphasize the need to broaden the experimental search program beyond the established cLFV modes. Systematic searches for exotic muon decays, particularly those with high multiplicities or displaced vertices, provide a unique and largely unexplored avenue to probe feebly interacting sectors and to test the flavor structure of new physics well above the energy reach of current colliders.

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