Letter of Interest: rare muon decays and light new physics

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Abstract: Rare muon decays can be used to search for a variety of light new physics. Generic examples are axion-like particles (ALPs), dark photons, leptophilic scalars, heavy neutral leptons ... The new particles can escape the detector, resulting in a missing energy signature, or decay into SM particles, resulting in either prompt or displaced vertex signatures in the detector. The aim of this letter is to collect the possible new physics signatures in rare muon decays, and assess the new physics scenarios that would generate them. This may motivate future experimental efforts in the next generation of high intensity muon facilities.

Probes of the Standard Model (SM) based on rare processes with charged leptons are set to improve substantially in the next decade. The muon beam experiments MEG II [1], Mu3e [2, 3], COMET [4] and Mu2e [5] will collect unprecedented datasets using $\mathcal{O}(10^{15}-10^{17})$ muons each. The standard New Physics (NP) targets for these experiments are rare lepton flavor violating (LFV) transitions of the muon: $\mu \to e\gamma$, $\mu \to eee$, and $\mu \to e$ conversion. The results of these searches are usually interpreted in terms of dimension-6 NP operators, suppressed by the heavy NP scale Λ so that the corresponding LFV branching ratios scale as $\text{BR} \propto 1/\Lambda^4$. Assuming $\mathcal{O}(1)$ Wilson coefficients for the dimension-6 operators the reach on the scale Λ is expected to exceed 10^8 GeV during the next decade [6].

Qualitatively new NP signatures are possible, however, if the NP is light and weakly coupled to the SM. This is the case for dark sectors having new dark states below the muon mass. The light dark states might have LFV couplings with the SM or not.

- The LFV couplings of a light dark sector state are generated by heavy new physics. Integrating out the heavy new physics leads to both the dimension-6 NP operators mentioned above, as well as the LFV couplings of light NP to the SM. The presence of a light dark sector state gives an extra phenomenological handle, through which much higher NP physics scales can be probed. An example is the LFV decay $\mu \to ea$, where a is a light axion-like particle (ALP). This decay is induced by a dimension-5 operator suppressed by the ALP decay constant f_a. The projected bounds one the $\mu \to ea$ branching ratio, $\text{BR} \propto 1/f_a^2$, translate to a reach on f_a that could exceed 10^{10} GeV, assuming $\mathcal{O}(1)$ flavor violating couplings [7]. These scales are among the highest scales that can be probed with ground-based experiments and are well above the present astrophysical constraints induced by the coupling of the light ALP to electrons. LFV transitions of the muon can then teach us something about axion solutions to the strong CP problem in a region where the axion can be a DM candidate or even about scenarios where the lepton number is spontaneously broken.

- Even if the light dark sector does not have flavor violating couplings, future high intensity muon facilities can probe unexplored parameter space. Particularly interesting is the case where the light dark sector states decay back into the SM, giving a spectacular signature in muon decays. An example is the dark photon production in $\mu \to e\nu\bar{\nu}\gamma_d$ transition, which gives a final state $\mu \to 3e + \text{MET}$ for a dark photon decaying back to electron-positron pairs. A projection for this final state at Mu3e was obtained in [8]. These type of light dark sector states are generically motivated in the context of light DM freeze-out, but may also explain the observed anomalies in the muon magnetic moment [9] and the ^{8}Be nuclear transitions [10, 11].

The search strategies depend on how the light dark sector states decay. The possible signatures are then classified in terms of the number of electrons/positrons, photons and the invisible energy in the final states. The examples in Table 1 are obtained by considering the $\mu \to \text{SM}+X_{\text{NP}}$ decays where X_{NP} can be a new heavy neutral lepton N, an ALP a or a dark photon γ_d, while on the SM side we restrict the discussion to decays that have up to 3 SM particles in the final state. Furthermore, for the 3 body SM final state we only consider the $\mu \to e\nu_\mu\bar{\nu}_e + X_{\rm NP}$ transition, which is the decay with the smallest SM multiplicity that does not involve LFV. More exotic possibilities with more visible SM particles are also possible, for instance from dark showers, and it would be interesting to explore how well these can be constrained in rare muon decays. So far only three SM branching ratios of the muons have been measured: $\mu \to e\nu\bar{\nu}$, $\mu \to e\gamma\nu\bar{\nu}$ and $\mu \to 3e\nu\bar{\nu}$. These constitute an irreducible SM background for the BSM rare decay searches. The backgrounds for most of the new physics final states are therefore reducible and are dominated by accidental coincidences of different muon decays due to the pile up.

Missing energy. Quite generically, the decays to feebly interacting particles would result in missing energy in the detector (inv). The two-body decays, $\mu \to ea$ and $\mu \to e\gamma_d$, where a and γ_d are stable on detector time scales, both lead to $\mu \to e$+inv signature. The distinguishing feature of such decays is a line in the e energy (or equivalently, a line at m_{a,γ_d} in the missing mass distribution) on top of the smooth distribution from $\mu \to e\nu\bar{\nu}$ decays. Conversely, the $\mu \to eN\bar{\nu}$ decays lead to a modification of the missing mass distribution from the one expected from the SM $\mu \to e\nu\bar{\nu}$ decay, which is very challenging to observe given the large SM backgrounds. The use of polarized muon decays has been proven to be helpful in reducing the SM background if the ALP couplings have a right-handed component [7, 12]. Similar ideas might be fruitful to pursue in other physics cases.

Alternatively, an extra handle on the SM background could be given by the presence of an extra photon in the final state, $\mu \to ea\gamma$ and $\mu \to e\gamma_d\gamma$ are examples. For this final state the challenge is to design an electron-photon trigger at MEGII inspired by the one designed at Crystal Box [13] with a rate below 200 Hz and then perform a bump-hunt on the missing mass distribution. The final sensitivity of such a search compared to the one based on a single positron in the final state depends on the signal acceptance vs. the trigger efficiency, and is an interesting open question to be explored.

Prompt decays. For large enough couplings the light NP sector particles can decay promptly, potentially resulting in completely visible signatures. A prominent example is the dark photon bremsstrahlung $\mu \to e\nu\bar{\nu}\gamma_d$, followed by the $\gamma_d \to e^+e^-$ decay [8]. Other final states are possible via LFV couplings of γ_d. It would be interesting to understand in which scenarios prompt decays of light particles are consistent with indirect measurements such as $\mu \to e\gamma$, $\mu \to 3e$, etc..., since generically these force the dark sector couplings to the SM to be small.

Displaced vertices. A significant part of the parameter space is expected to lead to displaced decays inside the detector. These require rethinking the present experimental techniques used in rare muon experiments, in order to take full advantage of such unique signatures of NP, while understanding fully the SM backgrounds.

In conclusion, the rare muon decays provide a very rich set of possible search strategies for light NP. Extending the present experimental program to fully exploit the potential of such exotic decay modes may well lead to surprise discoveries. Large parts of the parameter space are expected to not yet be excluded by other searches, and at the same time to be theoretically motivated. We plan to provide a more detailed study of these opportunities as part of the Snowmass process.

signature	$\mu \to e X_{\rm NP}$	$\mu \to e\gamma X_{\rm NP}$	$\mu \to e\nu X_{\rm NP}$	$\mu \to e\nu\bar{\nu} X_{\rm NP}$
$\mu \to e + \text{inv}$	$a\vert_{\rm inv}, \gamma_d\vert_{\rm inv}$	–	$N\vert_{\rm inv}$	$a\vert_{\rm inv}, \gamma_d\vert_{\rm inv}$
$\mu \to 3e$	$a, \gamma_d \to e^+e^-$	–	–	–
$\mu \to e\,2\gamma$	$a \to \gamma\gamma$	–	–	–
$\mu \to e\gamma + \text{inv}$	$a, \gamma_d \to \gamma + \text{inv}$	$a\vert_{\rm inv}, \gamma_d\vert_{\rm inv}$	$N \to \gamma + \text{inv}$	$a, \gamma_d \to \gamma + \text{inv}$
$\mu \to 3e\,\gamma$	$a \to e^+e^-\gamma$	$a, \gamma_d \to e^+e^-$	–	–
$\mu \to e + 3\gamma$	$\gamma_d \to 3\gamma$	$a \to \gamma\gamma$	–	–
$\mu \to e2\gamma + \text{inv}$	$a, \gamma_d \to \gamma\gamma + \text{inv}$	$N \to \gamma + \text{inv}$	–	$a \to 2\gamma$
$\mu \to 3e + \text{inv}$	$a, \gamma_d \to e^+e^- + \text{inv}$	–	$N \to e^+e^-\nu$	$a, \gamma_d \to e^+e^-$

Table 1. Common signatures expected in the $\mu \to X_{\rm NP}X_{\rm SM}$ decays, where $X_{\rm NP}$ is for illustration taken to be either a (pseudo)scalar a, a dark vector, γ_d, or a heavy neutral lepton N.

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