Theory challenges and opportunities of Mu2e-II: Letter of Interest for Snowmass 2021

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Searches for lepton flavor violation are extremely sensitive to physics beyond the Standard Model. Several experiments are going to probe uncharted parameter space in the near future; notably, the Mu2e experiment is aiming to improve sensitivity to $\mu^- \to e^-$ conversion in nuclei by several orders of magnitude over existing limits. Mu2e-II marks a potential upgrade of Mu2e with another order-of-magnitude increase in sensitivity. This remarkable reach will make Mu2e(-II) an important experiment to probe new physics, not only via $\mu^- \to e^-$ conversion, but potentially also via $\mu^- \to e^+$ conversion or $\mu^- \to e^- X$ decays involving a light new boson X. Theory challenges of this project include comparing the sensitivity of different experiments to a given model, evaluating possible stopping targets to maximize complementarity, and understanding the unavoidable muon-decay-in-orbit background at this unprecedented precision.

Introduction. Lepton flavor violation (LFV) has been identified long ago as an excellent probe of physics beyond the Standard Model (SM) [1]. Several experiments will soon increase the sensitivity in many channels by orders of magnitude. In the muon sector, the most promising LFV signatures are $\mu \to e\gamma$ (probed by the MEG II experiment [2]), $\mu \to ee\bar{e}$ (Mu3e [3]), and μ-to-e conversion in nuclei (DeeMe [4], COMET [5], and Mu2e [6]). Mu2e in particular aims to reach a $\mu^- + {}^{27}_{13}\mathrm{Al} \to e^- + {}^{27}_{13}\mathrm{Al}$ single-event sensitivity of 3×10^{-17}, roughly four orders of magnitude beyond existing bounds [6, 7]. The potential upgrade Mu2e-II at FNAL aims to improve Mu2e's sensitivity by yet another order of magnitude [8, 9].

Theoretical motivations. Theoretical motivation for LFV is plentiful [10]; most notably, the observation of neutrino oscillations already proved that lepton flavor is not conserved! The absence of LFV in the SM is accidental because of the minimal particle content. Extending the SM by new particles then often leads to LFV unless new symmetries are imposed [11]. Such extensions are well motivated as explanations for neutrino masses or the hierarchy problem and might even be linked to hints for new physics in the muon's magnetic moment [12, 13] or in leptonic B-meson decays [14, 15]. Correspondingly, the non-observation of LFV at upcoming experiments would put strong constraints on many models, including supersymmetric extensions, and provide critical information about our fundamental understanding of nature [10].

Mu2e(-II)'s reach makes it indirectly sensitive to very heavy new particles. In an effective-field-theory approach heavy particles match onto non-renormalizable operators that are suppressed by powers of a scale Λ that is related to the large masses. For example, a single dimension-six LFV operator $\bar{e}\gamma^\alpha P_L \mu\, \bar{d}\gamma_\alpha d/\Lambda^2$ would induce a μ-to-e conversion rate in aluminium of order [16]

$$\frac{\Gamma(\mu^- \mathrm{Al} \to e^- \mathrm{Al})}{\Gamma(\mu \text{ capture})} \simeq 3 \times 10^{-18} \left(\frac{1.5 \times 10^7\,\mathrm{GeV}}{\Lambda} \right)^4 ,$$

which means that Mu2e-II is sensitive to new particles as heavy as 10^4 TeV, far out of reach of any currently proposed collider! Mu2e-II will of course also be sensitive to many other operators and models and provide information complementary to the results of Mu3e and MEG II [16, 17]. In the event of an observation of LFV in any of these experiments the others will help to pin down the underlying new physics responsible for it.

Stopping target. Mu2e(-II) will use ${}^{27}_{13}\mathrm{Al}$ as a stopping target, but can also study conversions in a different material in case a signal is observed. This requires dedicated studies to analyze not only the ideal experimental properties a target should have (such as the effective muon lifetime and capture rate) but also to maximize complementarity with the aluminium target. Using different target materials opens the possibility to probe the (A, Z) and nuclear-spin dependence of the μ-to-e conversion rate and thus distinguish underlying models.

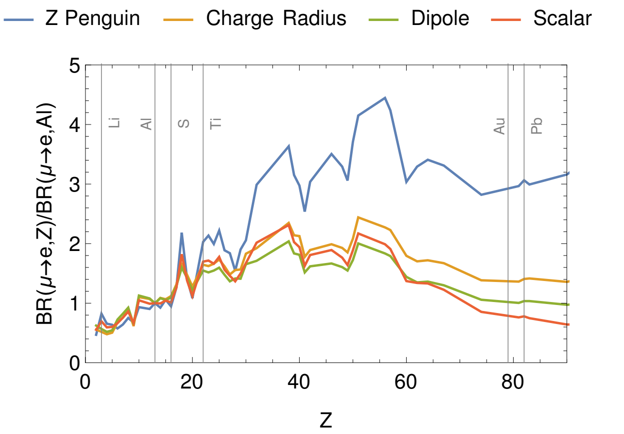

FIG. 1: Z dependence of $\mu \to e$ conversion rates for some example scenarios taken from Refs. [18, 20].

Calculations of the Z-dependence of different operators have been performed, e.g. in Refs. [18, 19]. Dedicated studies on how to distinguish new physics operators with different targets can be found in Refs. [17, 20], concluding that it is best to study one light (e.g. Al) and one heavy nucleus (e.g. Pb or Au), as shown in Fig. 1. In Mu2e(-II) such heavy nuclei are difficult because the muon lifetime goes down drastically (from 864 ns in Al to 75 ns in Pb [21]) and thus worsens the pion background. Using two *light* nuclei still allows to distinguish operators but requires better precision [20]. Ref. [17] points out that Lithium ${}^{7}_{3}\mathrm{Li}$ as a second target still has good discriminatory power despite being light, making it a worthwhile target candidate to study in better detail.

Most studies focus on coherent spin-independent (SI) $\mu \to e$ conversion, featuring a welcome $\sim A^2$ enhancement in the rate. However, there exist μeqq operators that lead to spin-*dependent* (SD) conversion [22, 23]. Including higher-order corrections these operator will always also induce SI $\mu \to e$ conversion that can then often dominate due to the A^2 enhancement. Still, it is in principle possible that SD dominates over SI, a possibility that can be studied using target nuclei of different spin. Aluminium carries spin $J = 5/2$ and is thus sensitive to both SI and SD processes. In case of a positive signal on Al one would then need to measure $\mu \to e$ on a light nucleus with different spin in order to distinguish SD from SI [23]; heavy nuclei are unlikely to be sensitive to SD because the higher-order—but A^2-enhanced—SI effects should dominate. Titanium is a good choice here because it is light and comes in isotopes of different spin. ${}^{48}_{22}\mathrm{Ti}$ has spin 0 and a natural abundance of 74%; SI operators would induce roughly the same rate as in Al, whereas SD would lead to a vanishing rate. In the latter case, one could enrich the target with ${}^{47}_{22}\mathrm{Ti}$ or ${}^{49}_{22}\mathrm{Ti}$, both of which carry spin. In the former case, one should go for a heavy target nucleus in order to distinguish different SI operators.

Decay-in-orbit calculation. $\mu \to e$ conversion in nuclei produces approximately monoenergetic electrons with $E_{\rm conv} = m_\mu - E_{\rm binding} - E_{\rm recoil}$, where $E_{\rm binding}$ and $E_{\rm recoil}$ are small energy corrections due to the muon's binding energy and nuclear recoil, respectively. While this is seemingly far away from the typical electron energies of the competing $\mu \to e\nu\nu$ decay in orbit (DIO), nuclear-recoil effects ensure that this SM decay distribution has a tail up to $E_{\rm conv}$, providing an irreducible background in Mu2e(-II). Precise calculations are necessary in order to predict and understand this background DIO spectrum near the endpoint in order to choose the optimal signal window. Such calculations exist [24–28], most importantly for aluminium, but might be lacking sufficient precision for other target nuclei. Higher-order effects should also be consistently incorporated into the theoretical predictions for the $\mu \to e$ conversion signal.

Extending the physics case. Although the main target of Mu2e-II will undoubtedly be the measurement of $\mu^- \to e^-$ conversion in nuclei, it is important to assess the capability of the experiment to address different processes, given the large number of stopped muons ($\sim 10^{19}$) that it will observe.

$\mu^- \to e^+$ conversion. In addition to $\mu^- \to e^-$ conversion, Mu2e(-II) is also sensitive to the lepton-*number*-violating process $\mu^- \to e^+$ [29]. These processes are mediated by even higher dimensional operators and therefore much more suppressed, to the point where it seems difficult to find models with testable rates [30–33]. There seem to be no dedicated studies evaluating the best target material for $\mu^- \to e^+$ conversion.

$\mu \to eX$. Every decay channel of a muon in orbit comes with a distribution tail of electron energies up to $E_{\rm conv}$. This allows Mu2e(-II) to probe non-standard muon decay channels, as long as they are not too suppressed, for example the decay $\mu \to eX$ with a light new boson X that would escape the detector unseen. The current bounds on this decay are rather weak, still allowing for $\text{BR}(\mu \to eX) \simeq 5 \times 10^{-5}$ for an ultralight X with left-handed couplings [34, 35]. These bounds can be improved by Mu3e [36] or MEG II [34], but even Mu2e(-II) could have some sensitivity due to the large number of collected muons. $\mu \to eX$ plus nuclear recoil leads to an electron spectrum with tail up to $E_{\rm conv}$ and a different *shape* ($(E_e - E_{\rm conv})^3$ compared to the standard $(E_e - E_{\rm conv})^5$) [37–39]. For $m_X > 0$ the *endpoint* is different, too (Fig. 2). If Mu2e(-II) can measure the DIO spectrum precisely enough it may be sensitive to the unusual shape coming from the $\mu \to eX$ decay.

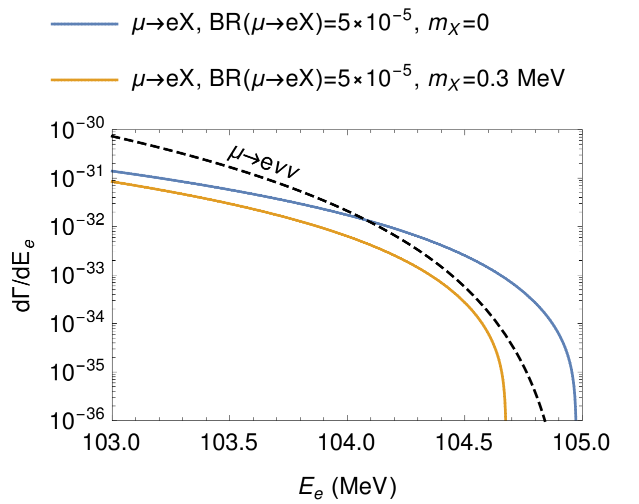

FIG. 2: The tail of $\mathrm{d}\Gamma(\mu \to e\nu\nu)/\mathrm{d}E_e$ (black, dashed) near the endpoint [27]. Following Ref. [37] we also show the tail of $\mathrm{d}\Gamma(\mu \to eX)/\mathrm{d}E_e$ corresponding to $\text{BR}(\mu \to eX) = 5 \times 10^{-5}$ (just below the current limit [34, 35]) for two values of m_X.

Summary. Mu2e and Mu2e-II will provide remarkable sensitivity to lepton flavor violation via μ-to-e conversion in nuclei. It is of utmost importance to match these experimental efforts on the theory side by providing precision calculations, guidance and motivation for the choice of target, and by exploring other new-physics scenarios that can be probed in these experiments.

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