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Mu2e-II
Letter of Interest for Snowmass 2021

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An observation of Charged Lepton Flavor Violation (CLFV) would be unambiguous evidence for physics beyond the Standard Model. The Mu2e and COMET experiments, under construction, are designed to push the sensitivity to CLFV in the $\mu \rightarrow e$ conversion process to unprecedented levels. Whether conversion is observed or not, there is a strong case to be made for further improving sensitivity, or for examining the process on additional target materials. Mu2e-II is a proposed upgrade to Mu2e, with at least an additional order of magnitude in sensitivity to the conversion rate over Mu2e. The approach and challenges for this proposal are summarized. Mu2e-II may be regarded as the next logical step in a continued high-intensity muon program at FNAL.

Charged Lepton Flavor Violation (CLFV) provides an extremely sensitive window into new-physics scenarios, capable of indirectly probing new particle masses far beyond both existing and planned colliders. The observation of CLFV would provide clear evidence for particles beyond the Standard Model. Many well-motivated models predict testable CLFV rates involving muons, which lend themselves to incredibly precise measurements. We propose to search for the muon to electron conversion process with a significantly improved discovery potential over currently planned projects. This idea has already been outlined in a previous expression of interest [1].

The plan is to continue a search for the CLFV process $\mu \to e$ conversion (e.g., [2, 3]) in the field of a nucleus as an evolution of the Mu2e experiment [4] at FNAL, which we call Mu2e-II. The anticipated single event sensitivity (SES) of Mu2e is

$$R_{\mu e} \equiv \frac{\Gamma(\mu^- N(A,Z) \to e^- N(A,Z)}{\Gamma(\mu^- N(A,Z) \to \nu_\mu N(A,Z-1)^*)} = 3 \times 10^{-17} \tag{1}$$

for scattering on an aluminum nucleus. The current best limit is from SINDRUM II on gold, $R_{\mu e} < 7 \times 10^{-13}$ [5]. In addition to Mu2e, the COMET collaboration is preparing their apparatus at J-PARC, with planned SES of 3×10^{-15} for Phase-I and $\mathcal{O}(10^{-17})$ for Phase-II [6]. The DeeMe collaboration, also at J-PARC, is preparing for a SES of up to 10^{-14} on carbon [7]. The aim of Mu2e-II is a further order of magnitude improvement in sensitivity to $\mu \to e$ conversion over Mu2e.

Along with $\mu^- \to e^-$ conversion there are other new-physics signatures that can be investigated in Mu2e-II [8]. One popular example is the $\Delta L = 2$ CLFV process $\mu^- \to e^+$ [9, 10], which generates an approximately monoenergetic positron. A precise measurement of the decay-in-orbit background tail can furthermore reveal other signatures, such as a $\mu \to eX$ decay involving an ultralight new boson X [11, 12].

Construction of the present Mu2e experiment is nearing completion, with data-taking beginning in 2023 and extending for several years beyond. If a signal for $\mu \to e$ conversion is found, it will be essential to improve the search to help understand the nature of the BSM physics. This can be done by changing the target material, comparing an aluminum target to other targets [13, 14]. We note also that the best existing limit for $\mu^- \to e^+$ is on titanium [15], and we include this option. On the other hand, if neither COMET nor Mu2e finds a signal (or they disagree!) it will be important to improve sensitivity and push the search for new physics to a higher mass scale. We thus regard Mu2e-II as the next logical step following Mu2e in a future CLFV program with intense muon beams at FNAL.

Mu2e-II relies on the existence of a more powerful source of protons, the PIP-II linac [16], under construction at Fermilab. This will provide $\sim 1.4 \times 10^9$ 800 MeV protons/pulse for Mu2e-II, compared with 3.9×10^7 8 GeV protons/pulse at Mu2e, with 1.7 μs pulse spacing. The H^- beam is extracted directly from the linac (with additional RF to handle the beam load), stripped of electrons and transported in a new beamline to match the Mu2e beamline. The delivery ring and resonant extraction are no longer used, removing one source of radiation hazard and providing for a much more stable beam intensity as well as flexibility in time structure. Another improvement is that narrower pulses, $\sim$ 100 ns, can be delivered, compared with $\sim$250 ns for Mu2e.

We note that the efficiency to produce muons is comparable, for a given beam power, at 800 MeV and 8 GeV. The factor of ten gain in sensitivity and discovery reach over Mu2e is achieved by a combination of higher intensity and higher duty factor (both for a running period of 3 years, corresponding to 3.7×10^{20} protons-on-target in Mu2e).

There are a number of challenges to handling the more powerful beam and reducing backgrounds sufficiently to achieve the greater sensitivity. The R&D is, in several cases, already in progress.

The accelerator [17] delivers 100 kW, of which over 20 kW is deposited as heat in the target. This is too much to remove radiatively, as is done for Mu2e. Thus various alternatives are under investigation [18]. Further, the lower momentum beam has increased curvature in the solenoidal field around the target. A curved target is needed in order to optimize the muon rate.

Mu2e-II, like Mu2e, uses a pulsed proton beam to eliminate a limiting background of SINDRUM [5]. After the beam hits the target, produced pions decay to muons, which propagate to the stopping target [19] and are eventually captured in atoms. There is a quiet time between beam pulses when the spray of particles from proton interactions with the production target has stopped. It is during this time that the search for conversion electrons is done. However, protons outside of the main beam pulse can produce backgrounds. Thus, the "extinction" of protons during this period is very important. For Mu2e, the extinction must be kept to a level 10^{-10}. The requirement becomes 10^{-11} for Mu2e-II. A combination of techniques is used to obtain this suppression in Mu2e, and similar techniques are available to Mu2e-II. The PIP-II linac pulse is narrower than the Mu2e resonantly extracted beam, aiding in the extinction.

The more intense beam means that radiation and shielding must be re-evaluated. While the delivery ring is no longer an issue, the M4 beam line, production solenoid and associated shielding, as well as downstream components and Mu2e building shielding may all need significant alteration. An advantage of Mu2e-II is that the 800 MeV proton energy is below anti-proton production threshold, eliminating a potentially problematic background.

The Mu2e tracker is a straw tube chamber with 15 μm aluminized mylar straws. It is crucial to discriminating the monochromatic conversion signal from backgrounds such as muon decays in atomic orbit in the stopping target. The key requirement is on the momentum resolution; for the improved sensitivity of Mu2e-II, the resolution must be about a factor two better than Mu2e. This requires a new chamber, along with re-optimization of other sources of multiple scattering. Ideas are being explored [20], and R&D is already underway on the possibility of reducing the thickness of straws for a new straw chamber solution.

The Mu2e calorimeter, used for particle identification, triggering, and as a cross check on the tracker momentum, consists of 1348 CsI crystals read out by SiPMs [21]. CsI has a moderate scintillation light decay time, of the order of 30-40 ns. This is marginal for the higher rates at Mu2e-II so alternatives are needed [22]. Especially promising is the use of BaF_2, which has a very fast (sub-nanosecond) component at around 220 nm. Unfortunately, it also has a very slow component at longer wavelength, and R&D has begun on suppressing the slow component by doping with dopants such as yttrium and developing "solar-blind" readout [23–28].

Cosmic rays are a major background consideration and their rejection is crucial to obtaining the desired sensitivity. The higher running duty factor means about a factor of three greater livetime for Mu2e-II compared with Mu2e. The scintillator-based Mu2e cosmic ray veto (CRV) system is not sufficient for Mu2e-II. Additional shielding and different materials can help, but the unavoidable gaps in the Mu2e CRV counters around the solenoids are a limitation. A new geometry to close these gaps is required. R&D is needed to develop and optimize the system, but we are also considering new technology (such as RPCs) [29].

Mu2e-II will have an order of magnitude higher data rate than Mu2e, as well as higher dosing of the front-end electronics. Thus, there are also challenges for the trigger and data acquisition, and an R&D program is planned to investigate possible approaches [30–33].

As a natural evolution of Mu2e, Mu2e-II provides the nearest-term next step in a possible major muon future program at FNAL. With the powerful PIP-II accelerator at 800 MeV and the infrastructure of the Fermilab Muon Campus, it is both logical and compelling to consider a forefront future CLFV program at Fermilab. Other LOIs address such longer-term facilities towards this goal (e.g., [34–38]).

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