Mu2e Supporting Documentation

1 Introduction

Fermi National Accelerator Laboratory and the Mu2e Collaboration, composed of about 140 scientists from 26 Universities and Laboratories around the world, are collaborating on the design of a new facility to study charged lepton flavor violation using the existing Department of Energy investment in the Fermilab accelerator complex. Mu2e is an absolutely central initial step in the development of the Intensity Frontier program in the US and a continuation of the Mu2e physics program into the Project X era is part of Fermilab's longer-range plan. This program has broad interest that spans both the High Energy and Nuclear Physics communities.

Mu2e proposes to measure the rate of the neutrinoless, coherent conversion of muons into electrons in the field of a nucleus, relative to the rate of ordinary muon capture on the nucleus:

$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)}.$$

The conversion process is an example of charged lepton flavor violation (CLFV), a process that has never been observed experimentally. The current best experimental limit on muon-to-electron conversion, $R_{\mu e} < 7 \times 10^{-13}$ (90% CL), is from the SINDRUM II experiment [1]. With 3.6×10^{20} delivered protons Mu2e will probe four orders of magnitude beyond the SINDRUM II sensitivity, measuring $R_{\mu e}$ with a single event sensitivity of 2×10^{-17}. Observation of this process would provide unambiguous evidence for physics beyond the Standard Model and will either help to illuminate discoveries made at the LHC or will point to new physics beyond the reach of the LHC.

The conversion of a muon to an electron in the field of a nucleus occurs coherently, resulting in a monoenergetic electron near the muon rest energy that recoils off of the nucleus in a two-body interaction. This distinctive signature has several experimental advantages including the near-absence of background from accidentals and the suppression of background electrons near the conversion energy from muon decays.

2 Summary of the Physics Case for Mu2e

The discovery of the muon initiated a program of research in flavor physics that culminated in formation of the Standard Model. The flavor structure of the Standard Model in turn is closely linked to potential new physics at the TeV scale that is being explored at the LHC. Most new physics manifestations that we can envision will provide new sources of flavor phenomena, providing strong motivation for an aggressive program to address questions related to flavor. A deeper understanding of the open questions of flavor physics will require discoveries and measurements from complementary facilities at both the Energy and Intensity Frontiers.

2.1 Charged Lepton Flavor Violation

There is an active global program to search for CLFV processes using rare decays of muons, taus, kaons, and *B*-mesons. The ratio of rates among various CLFV processes is model dependent and varies widely depending on the underlying physics. Thus, it is important to pursue experiments sensitive to different processes in order to elucidate the mechanism responsible for CLFV effects. The most stringent limits on CLFV come from the muon sector because of the relative "ease" of producing an intense source of muons. Three rare muon processes stand out: $\mu^+ \rightarrow e^+ \gamma$, $\mu^+ \rightarrow e^+ e^+ e^-$ and $\mu^- N \rightarrow e^- N$. Searches for these processes have thus far yielded null results. The experimental limits (90% C.L.) are: $B(\mu^+ \rightarrow e^+ \gamma) < 2.4 \times 10^{-12}$ [2], $B(\mu^+ \rightarrow e^+ e^+ e^-) < 1.0 \times 10^{-12}$ [3], and $R_{\mu e}(Au) < 7 \times 10^{-13}$ (muon-to-electron conversion on gold) [1]. In this decade significant improvement is possible on all three modes.

The MEG experiment [2] at PSI has already reached a sensitivity of 2.4×10^{-12} and hopes to ultimately achieve $< 10^{-13}$ for the $\mu^+ \rightarrow e^+\gamma$ branching ratio, while the proposed COMET experiment [4] at JPARC and Mu2e [5] at Fermilab will each reach sensitivities of $10^{-16} - 10^{-17}$ on $R_{\mu e}(Al)$. It is important to note that muon-to-electron conversion and $\mu^+ \rightarrow e^+\gamma$ have complementary sensitivity to new physics effects and together provide a powerful constraint on the underlying physics. To illustrate this one can estimate the sensitivity of a given CLFV process in a model independent manner by adding lepton-flavor-violating effective operators to the Standard Model Lagrangian, where Λ is the mass scale of new physics and κ is an arbitrary parameter controlling the relative contribution of two classes of effective operators [6]

$$L_{CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)} \bar{\mu}_L \gamma_\mu e_L \left(\sum_{q=u,d} \bar{q}_L \gamma^\mu q_L \right).$$

If $\kappa << 1$, the first term, arising from loops with an emitted photon, is dominant. If the photon is real, one observes $\mu^+ \rightarrow e\,\gamma$. If $\kappa >> 1$, the second term, which includes contact terms and a variety of other processes not resulting in a photon, is dominant. Muon-to-electron conversion is sensitive to new physics regardless of the relative contributions of the first and second terms while $\mu^+ \rightarrow e^+\gamma$ is only sensitive to contributions from the first term. The new physics scale, Λ, to which these two processes are sensitive as a function of κ is shown in Figure 1.

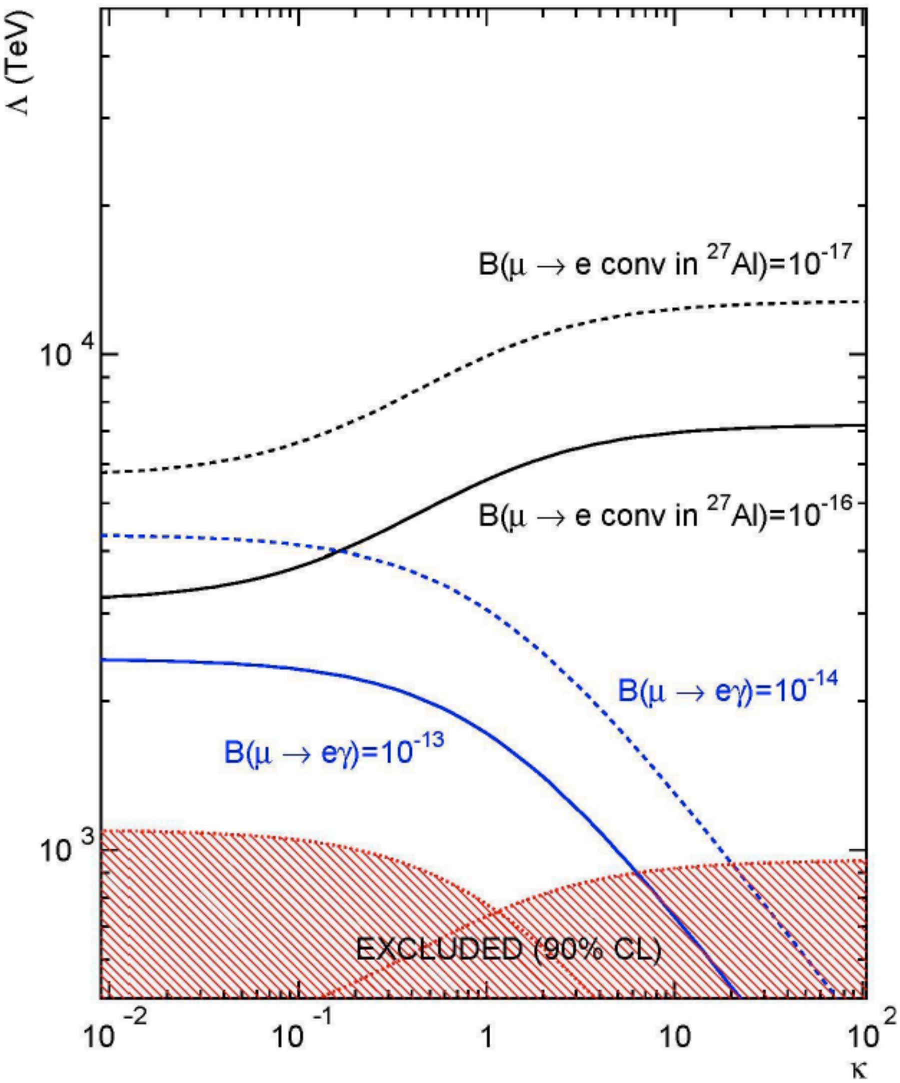

Figure 1. The sensitivity to the scale of new physics, Λ, as a function of κ, for a muon-to-electron conversion experiment with a sensitivity of 10^{-16} – 10^{-17} is compared to that for a muon-to-electron-gamma experiment with a sensitivity of 10^{-13} – 10^{-14}. See the text for a definition of κ. The excluded region of parameter space, based on current experimental limits, is shaded.

At their projected sensitivity, the MEG experiment will probe Λ values up to 2000 - 4000 TeV for κ << 1 scenarios, while having little sensitivity when κ >> 1. At the projected sensitivity of the Mu2e experiment, Λ values from 3000 to over 10,000 TeV for *all* values of κ will be probed. Figure 1 shows that a Mu2e experiment sensitive to rates in the range of 10^{-16} – 10^{-17} is interesting and important in all MEG scenarios. If MEG observes a signal, then Mu2e should also observe a signal, and the combined results can be used to simultaneously constrain Λ and κ, limiting which types of new physics models remain viable. On the other hand, a null result from MEG does not preclude a Mu2e discovery since the new physics may be dominated by interactions to which the $\mu^+ \rightarrow e^+\gamma$ process is blind.

An example of the complementary nature of these two processes in the context of a specific model is provided in Figure 2, which depicts a scan of parameter space for a Littlest Higgs Model with T-parity [7]. The different colored points refer to different choices for the structure of the mirror-lepton mixing matrix that gives rise to the CLFV effects. Combining results from MEG and Mu2e would severely constrain the allowed parameter space of this model and could distinguish between the Littlest Higgs Model and the Minimal Supersymmetric models in a transparent way, as the correlations between the two CLFV processes are significantly different in the two models. Several other specific examples are discussed in Ref. [8].

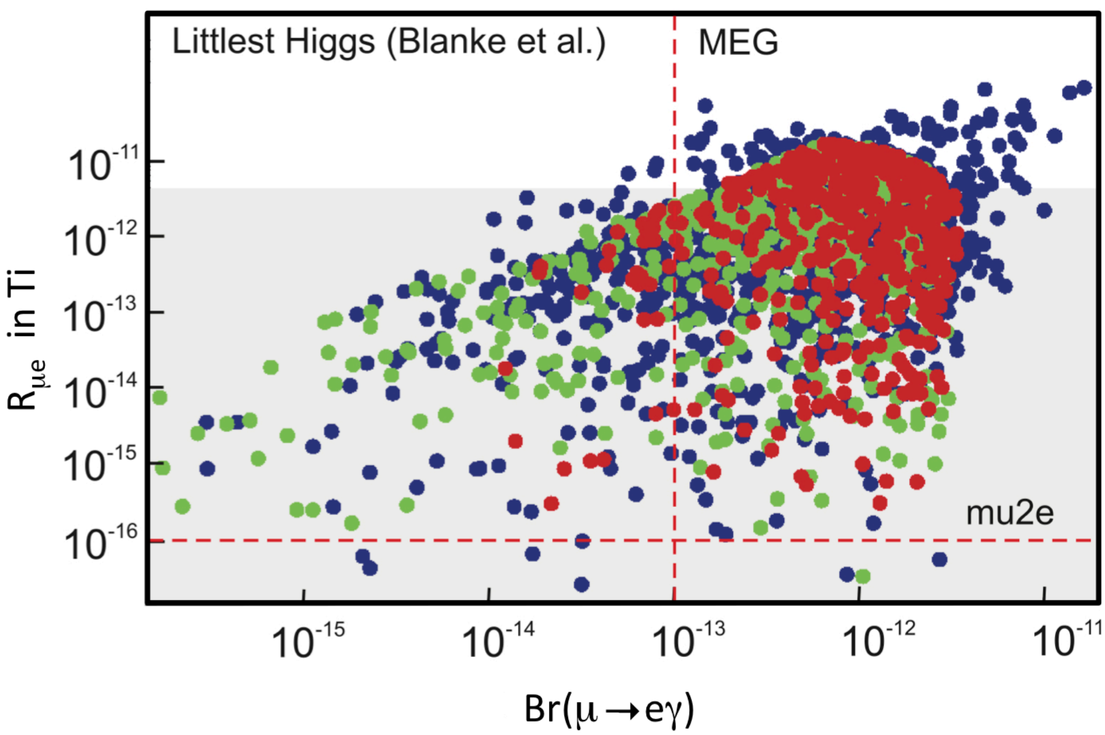

Figure 2. The predicted rate of muon-to-electron conversion is compared to the predicted branching ratio for $\mu \rightarrow e\gamma$ in the context of the Littlest Higgs model with T-parity [7]. The red points assume that a PMNS-like matrix describes the mixing matrix of the mirror leptons, while the green points assume that a CKM-like matrix describes the mixing. The blue points are a general scan of the parameters of the mirror-lepton mixing matrix. The shaded region is the parameter space not excluded by current CLFV results in conversion experiments.

2.2 Charged Lepton Flavor Violation in The LHC Era

By the time the next generation of CLFV experiments reach their target sensitivities, the LHC experiments are expected to have analyzed significant amounts of data collected at center-of-mass energies of 7 TeV or higher, thus exploring physics at the TeV scale. The HEP community is anxious to learn whether the LHC data reveals the new phenomena predicted by many new physics models. The importance and impact of pursuing next generation CLFV experiments is independent of what the LHC data might reveal over the next several years. As discussed above, these and other ultra-rare processes probe new physics scales that are orders of magnitude beyond the direct reach of the LHC and may offer the only evidence of new physics phenomena should it lie at high mass scales. A more optimistic scenario would assume new physics discoveries at the LHC *do* occur and ask how measurements of CLFV processes complement the LHC experiments. Most of the new physics scenarios for which the LHC has discovery potential predict rates for muon-to-electron conversion within the discovery range of Mu2e. Figure 2 shows one example, in the context of a specific new physics model, over a parameter space where the LHC has discovery potential. As discussed above, this is a Littlest Higgs with T-parity model and it is clear that the information provided by the CFLV measurements would help pin down where in the parameter space the new physics resides. Another example is given in Figure 3 that shows the predicted muon-to-electron conversion rate as a function of the universal gaugino mass at the GUT scale, $M_{1/2}$, in the context of an SO(10) SUSY GUT model [9]. The SUSY parameter space is explored for those scenarios for which the LHC has discovery sensitivity and the different color points correspond to different assumptions about the neutrino Yukawa couplings. Again, a measurement of the muon-to-electron conversion rate would significantly restrict the viable parameter space in a manner that the LHC experiments are unable to do. Only two specific models have been examined here but the results are representative of the power of muon-to-electron conversion. It is generally understood that an experiment sensitive to muon-to-electron conversion at the level of 10^{-16} to 10^{-17} would have discovery potential that overlaps the parameter space to which the LHC is sensitive and would help constrain that parameter space in a manner complementary to what the LHC experiments can accomplish on their own [8][9].

2.3 Mu2e at Project X

The first phase of Mu2e will begin taking data before the end of the decade with an 8 kW proton beam. Using the first stage of Project X, an increase in beam power by a factor of 3 to 5 could be achieved. Small, well-understood upgrades to the Mu2e apparatus are all that would be required to accommodate a beam power increase of this magnitude.

The motivation for increased beam power depends on results from the first phase of Mu2e. If no signal is observed then additional beam power can be applied to increase the sensitivity. If a signal is observed then there is significant physics motivation to repeat the muon-to-electron conversion rate measurement for different target nuclei [10]. There are significant differences in the Z dependences of the conversion rate for different theoretical models, so measurements in various nuclei are powerful discriminators.

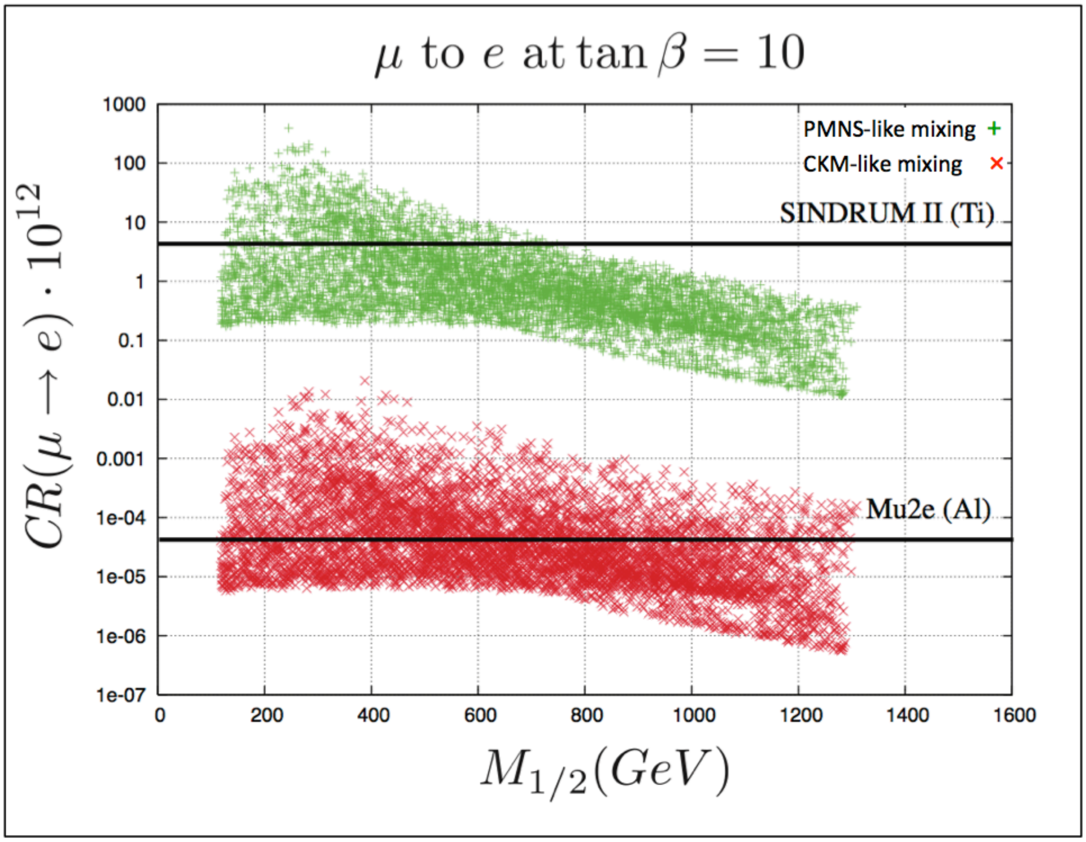

Figure 3. The predicted rate for muon-to-electron conversion in titanium for various scenarios in the context of the SUSY GUT model described in [9]. The SUSY parameter space explored corresponds to that for which the LHC has discovery sensitivity. The different colored points correspond to different assumptions about the neutrino Yukawa couplings.

2.4 Summary of the Physics Case for Mu2e

The physics case for a thorough investigation of Charged Lepton Flavor Violation has been made many times, in the references included in this document and elsewhere. Of the various potential CLFV processes, a search for muon-to-electron conversion would clearly have the greatest impact because of its broad physics reach and access to high mass scales, as described above. Additionally, Mu2e adds incisive input to our understanding of physics at the TeV scale and beyond in any scenario that develops in the next decade.

- If MEG observes a signal for $\mu^+ \to e^+\gamma$, Mu2e should also observe a signal. The combination of these two complimentary processes is a powerful discriminator between new physics models.
- If MEG does not observe a signal, Mu2e still has sensitivity to a broad array of new physics processes to which $\mu^+ \to e^+\gamma$ is blind.
- If new physics is discovered at the LHC, Mu2e could uniquely constrain the parameter space in a manner entirely complementary to what the LHC experiments can accomplish on their own. A null result from Mu2e at the proposed sensitivity would place severe restrictions on the nature of the underlying new physics mechanism.
- If new physics is not discovered at the LHC, Mu2e can probe new physics scales that are orders of magnitude beyond the direct reach of the LHC and may offer the only evidence of new physics phenomena should it lie at high mass scales.

Because of the importance that flavor physics plays in determining the nature of our universe, the window into detailed characteristics of potential new physics provided by studies of charged lepton flavor violation and the extraordinary mass scale accessible to muon-to-electron conversion experiments, the 2008 P5 panel strongly encouraged the DOE to proceed with Mu2e in all budget scenarios considered by the panel [11]. This was reaffirmed by P5 and HEPAP in 2010 [12]. On this basis we strongly believe that Mu2e is *absolutely central* to the goals of particle physics over the next decade.

3 Project Status and Construction Readiness

3.1 Project Scope

To achieve the Mu2e sensitivity goal a high intensity, low energy muon beam coupled with a detector capable of efficiently identifying 105 MeV electrons while minimizing background from conventional processes will be required. The muon beam is created by an 8 GeV, pulsed beam of protons striking a production target. The scope of work required to meet the scientific and technical objectives of Mu2e is listed below.

- Modify the accelerator complex to transfer 8 GeV protons with the requisite time structure from the Fermilab Booster to the Mu2e detector while the 120 GeV neutrino program is operating.
- Design and construct the Mu2e superconducting solenoid system (Figure 4).
- Design and construct the Mu2e detector (Figure 4) consisting of a tracker, a calorimeter, a stopping target monitor, a cosmic ray veto, an extinction monitor

- and the electronics, trigger and data acquisition required to read out, select and store the data.
- Design and construct a facility to house the Mu2e detector and the associated infrastructure. This includes an underground detector enclosure and a surface building to house necessary equipment and infrastructure that can be accessed while beam is being delivered to the detector.

3.2 Project Status

The Mu2e Project received CD-1 approval on July 11, 2012 after a series of internal and external technical, cost and schedule reviews. The most serious technical risk for the project is the large, complex set of procurements of superconducting solenoids that define the Project's critical path and concerns about beam losses.

The Mu2e Project is scheduled for CD-3a approval in early FY14. CD-3a will authorize procurement of conductor for the superconducting solenoids. This is a long lead item that is required before full construction of the solenoids can commence. CD-2/3b is scheduled for the middle of FY14. CD-3b will authorize construction of the Mu2e detector hall. Ground breaking is expected in the spring of 2014. Full CD-3 approval is expected by the middle of FY15. By this time all detector systems will have constructed and tested pre-production prototypes and will have passed construction readiness reviews.

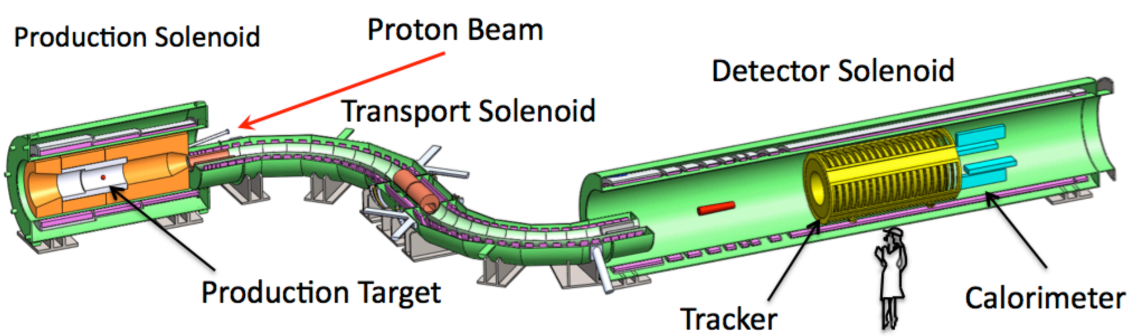

Figure 4. The Mu2e Detector. The cosmic ray veto, surrounding the Detector Solenoid, is not shown.

3.3 Construction Readiness

Mu2e R&D is now focused primarily on development of prototypes to validate performance and construction techniques. No R&D remains to address issues of technical viability. The solenoid system that drives the cost and schedule of Mu2e rely on conventional magnet technology. The tracker, calorimeter and cosmic ray veto are familiar technologies that are commonly deployed in HEP experiments. The accelerator work is similar to other upgrades of the Fermilab complex. Many technical challenges and risks remain, but they are related to execution rather than viability of the experiment.

Fabrication of conductor for the superconducting solenoids will begin in early FY14. R&D quantities of conductor have been procured for testing and prototypes and options are in place with vendors for procurement of production quantities. A well-developed plan to break ground on the detector hall in the middle of FY14 is in place and an A&E firm has been engaged to perform value engineering and develop the final set of construction drawings. Based on these considerations Mu2e falls into the category of being *ready to initiate construction* in 2014.

4 References

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