The Mu2e Experiment at Fermilab*

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Abstract

The Mu2e Experiment at Fermilab will search for the coherent, neutrinoless conversion of a muon to an electron in the field of an atomic nucleus. Such charged lepton flavor violating events have never been observed, but are predicted to occur in many Beyond the Standard Model scenarios at rates accessible to our experiment. I outline the physics and key issues for the experiment, our progress on design and construction to date, and prospects for the future.

INTRODUCTION

The Mu2e effort holds a prominent place in the near term future of the U.S. High Energy Physics program. In fact, the recent report of the Particle Physics Project Prioritization Panel (P5) - which advises the U.S. Government on HEP community priorities - advises completion of the Mu2e Experiment under all budget scenarios considered [1]. With a project baseline cost of $270 million, this involves a significant investment of available resources; why, then, this level of interest?

Although charged lepton flavor violation (CLFV) has never been observed experimentally, we know that it must occur: neutrino flavor oscillations coupled with loops guarantees the existence of CLFV; see Figure 1. However, even with the most optimistic parameter values in the PMNS neutrino mixing matrix U, the Standard Model rate prediction is tiny

$$\mathrm{Br}(\mu \to \mathrm{e}\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{k=2,3} U^*_{\mu k} U_{\mathrm{e}k} \frac{\Delta m^2_{1k}}{M^2_{\mathrm{W}}} \right|^2 < 10^{-54} \; .$$

There is no conceivable experiment which could observe a branching ratio this small. While this initially seems disappointing, it is a major opportunity in disguise as *any* experimental observation of CLFV becomes incontrovertible evidence for new physics Beyond the Standard Model (BSM)!

Searches for CLFV have a long and distinguished history of guiding both theorists and experimentalists in elucidating the foundations of particle physics. For at least seventy years, there has been a long line of experiments searching for violations in both meson and lepton decays. Early non-observation of $\mu \to \mathrm{e}\gamma$ at the 10% level laid rest to the notion that the muon was simply an electromagnetic excitation of the electron [2]. Later, the non-observation of the same signal at the 10^{-8} level proved that muon and electron neutrinos were distinct species [3].

Today, CLFV searches form their own cottage industry: there are numerous ongoing searches in many meson and tau channels at the LHC, while there are a number of significant efforts worldwide in muon decays. A large number of these efforts were represented at this workshop. In $\mu \to \mathrm{e}\gamma$, the MEG search at PSI has pushed down nearly to the limits of their sensitivity [4], while the Mu3e developments at PSI promise a very sensitive search for $\mu^+ \to \mathrm{e}^+\mathrm{e}^+\mathrm{e}^-$ [5]. Neutrinoless conversion provides perhaps the most promising avenue for large sensitivity improvements, with at least three ongoing efforts at advanced stages of development: DeeMee [6] and COMET [7] at the JPARC, and the Mu2e Experiment at Fermilab [8].

The conversion experiments have a major kinematic advantage over MEG and Mu3e: in the latter experiments, the signal electrons of interest of hard to distinguish from the bulk of electrons from the vast background of Michel electrons from normal muon decay. In contrast, because the conversion signal comes from the two body decay of a heavy muonic atom, the signal electrons are monochromatic with an energy roughly that of the muon mass. This puts the signal well above the vast bulk of the background, and just beyond the high energy recoil tail from normal muon decay in orbit (DIO). Herein lies the advantage of the conversion channel, and the experiments are designed to take advantage of this kinematic separation.

In terms of accessing new physics, the conversion process has an additional advantage, as it can be driven by more different types of physics than other channels. For instance, because of the final state photon, the $\mu \to \mathrm{e}\gamma$ channel can only be driven by dipole type interactions in the low energy effective theory. By contrast, conversion can be driven by both dipole interactions and four fermion processes. This gives the conversion process signficantly deeper reach into heretofore unexplored energy regimes. In Figure 3, we show the reach of

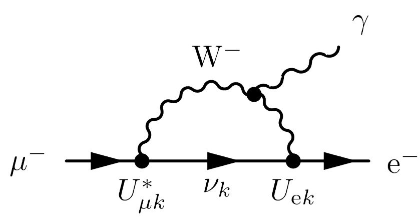


FIG. 1: A Standard Model source of charged lepton flavor violating $\mu \to \mathrm{e}\gamma$ arises from neutrino flavor oscillations within loops; these events have an unmeasurably small branching ratio.

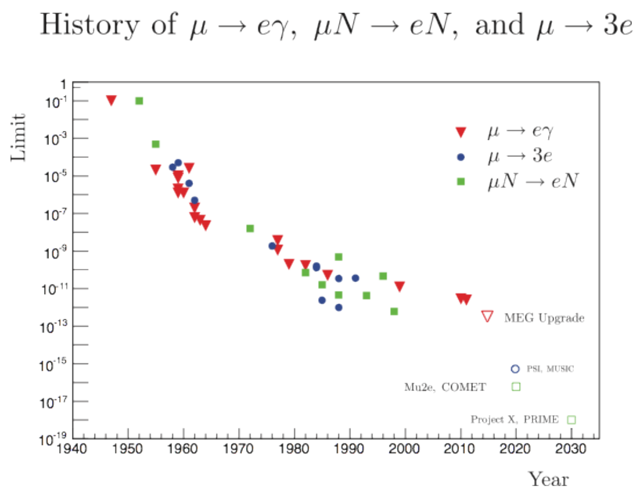


FIG. 2: The history of CLFV searches in muon decay stretch over seventy years and many decades in rate.

both MEG and Mu2e in terms of the model of de Gouvêa and Vogel [9]. This model has two terms in the CLFV Lagrangian, corresponding to dipole and four fermi interactions, and the dimensionless parameter κ interpolates between the dipole and fermi limits

$$\mathcal{L}_{\mathrm{cLFV}} = \frac{1}{\kappa+1}\frac{m_\mu}{\Lambda^2}\bar{\mu}_R\sigma_{\alpha\beta}\mathrm{e}_L F^{\alpha\beta} + \frac{\kappa}{\kappa+1}\frac{1}{\Lambda^2}\bar{\mu}_L\gamma_\alpha\mathrm{e}_L\left(\bar{\mathrm{u}}_L\gamma^\alpha\mathrm{u}_L + \bar{\mathrm{d}}_L\gamma^\alpha\mathrm{d}_L\right) ,$$

where Λ is the scale of the new physics contributions. Because amplitudes scale as the Lagrangian, and rates scale with the square of the amplitudes, the conversion rate scales with the fourth power of Λ. By improving the sensitivity to conversion by four orders of magnitude, both COMET and Mu2e will improve our energy reach by an order of magnitude compared to the SINDRUM-II experiment [10] across the entire parameter space, to perhaps as high as 10^4 TeV, well in excess of processes directly accessible at even the LHC.

THE DESIGN OF MU2E

The known atomic, nuclear, and particle physics processes of the negatively charged muon drive the design of the experiment. For a high statistics search, we must bring a large quantity of muons to rest in a stopping target that can be observed by a precision detector. Negative muons are brought to rest in the stopping target by well understood electromagnetic scattering and energy loss processes, thermalize, and are captured into atomic orbitals of the target atoms. They act like heavy electrons and rapidly cascade to the $1s$ ground state

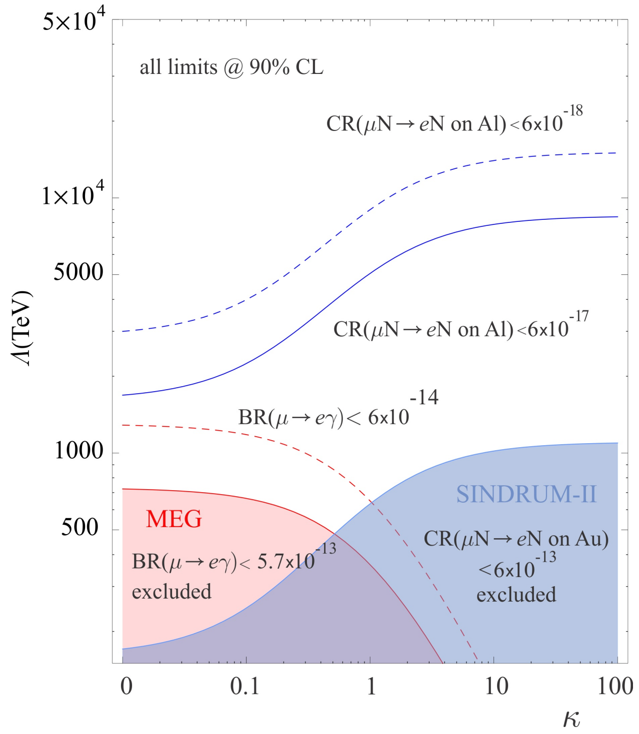


FIG. 3: Here we plot the sensitivity in terms of new physics energy scale reach for the model of de Gouvêa and Vogel; the left side of the plot corresponds to dipole transition dominated CLFV physics, while the right side corresponds to fermi contact interactions.

through a series of well understood level transitions, with the corresponding emission of well-characterized hard photons. Once in the ground state, the muons will either perform a Michel-like Decay in Orbit (DIO), or capture on the nucleus. The ratio of DIO to capture depends on the target nucleus, and is well characterized for all interesting target materials; for aluminum in particular, this ratio is roughly 40:60.

The process of conversion itself produces a monochromatic electron with energy roughly the muon mass (slightly reduced of course by the small electron mass, atomic binding energy, and nuclear recoil). This signal energy is essentially identical to the endpoint for the rapidly falling DIO spectrum. DIO, of course, has a four body final state: the decay electron, the recoiling nucleus, and a pair of neutrinos. In the limit that the neutrinos are born at rest, the kinematics of DIO and conversion are the same. To conclusively observe any conversion events requires high intrinsic detector resolution, requiring an extremely low mass design to minimize the energy loss and multiple scattering leading to resolution smearing. Additionally, as the rate near the end point is many orders of magnitude below the rate at

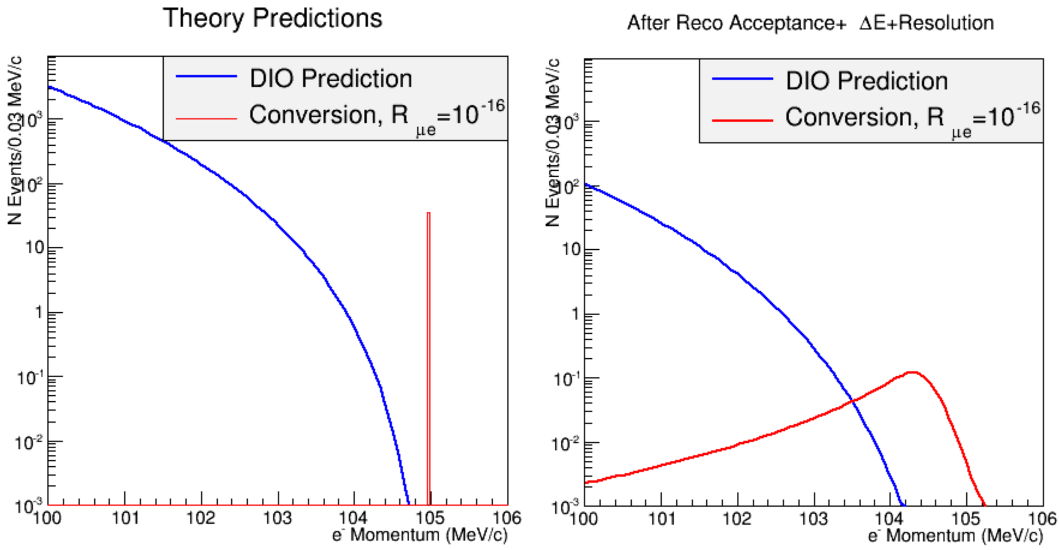


FIG. 4: A schematic illustration of the effects of resolution smearing on the observed spectrum of conversion event candidates; the left hand plot is the ideal physics case, while the right hand plot has the effects of detector physics included. It is clear that minimizing distortion of the signal peak requires a low mass detector system.

the Michel peak, there is a major issue with dynamic range that any detector must overcome.

In addition to the intrinsic DIO background, there are potentially severe backgrounds from beam sources, primarily pion capture products. Because of the physics processes involved, these backgrounds are prompt with the arrival of the beam particle. The standard solution to reducing such prompt contamination is a pulsed primary beam followed by a pause before opening the "live window" for data collection.

THE MU2E IMPLEMENTATION

The Mu2e Experiment is under construction at the Fermi National Accelerator Laboratory in Batavia, Illinois in the United States. Along with the Fermilab Muon $g-2$ Experiment, Mu2e will occupy the new Muon Campus facility close to Wilson hall, forming the core of a muon program for at least the next decade. Proton delivery to the Muon Campus has required modest upgrades to the accelerator complex, upgrades which are compatible with the continuation of the ongoing Fermilab neutrino program. For Mu2e, protons will be accelerated by the Booster ring to 8 GeV, and transported to the Recycler ring where they will be rebunched and stacked into the Delivery Ring (the former antiproton

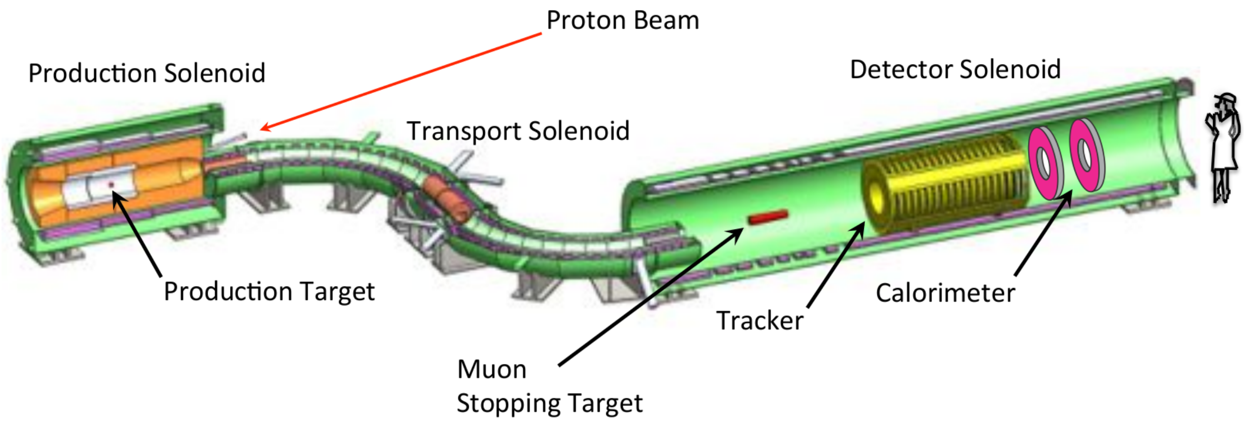
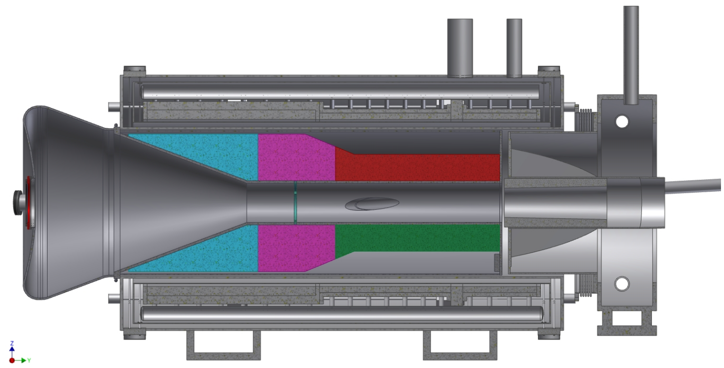


FIG. 5: The Mu2e Apparatus, showing cutaways of the three solenoids.



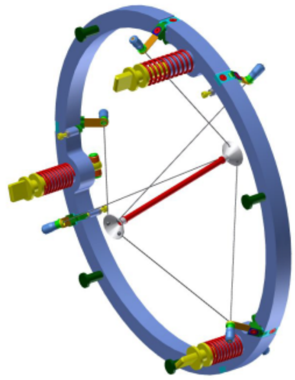


FIG. 6: The left-hand rendering shows the design of the Mu2e Production Solenoid; here, the TS is off to the right, and the proton beam enters from right, just above the centerline. The right-hand picture shows a blowup of the pion production target mounted in its "bicycle wheel" support structure.

Debuncher). Protons will be slow extracted for delivery to the Mu2e production target in a new experiment hall that is currently under construction. This full chain requires additional RF equipment in the Recycler, a reconfiguration of the Delivery Ring, as well as the construction of a new beamline from the Delivery Ring to the Mu2e experiment hall on the Muon Campus.

The Mu2e apparatus will separate the production of muons from observation of their decays; see Figure 5. Muons will be produced within the *Production Solenoid* (PS) and their decays will be observed by a suite of detectors within the *Detector Solenoid* (DS). An "S"-shaped *Transport Solenoid* (TS) will be responsible for muon beam transport between the other solenoids.

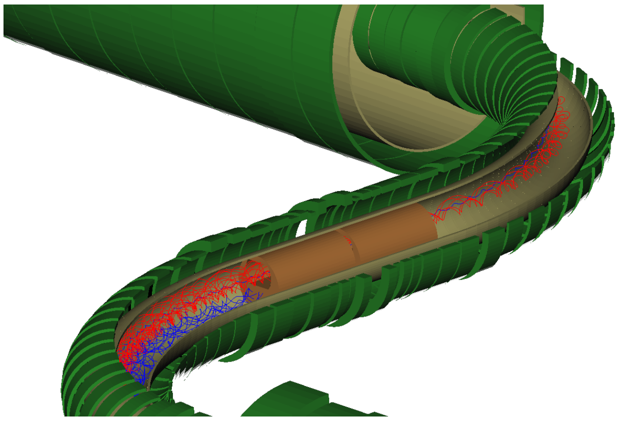


FIG. 7: The Mu2e Transport Solenoid contains an asymmetric collimator to eliminate the positively secondary beam; vertical drift in a curved solenoid separates particles of opposite charge, allowing us to sign select our beam.

The PS (see Figure 6) produces a backward moving muon beam to dramatically reduce beam related backgrounds. The proton beam enters slightly off axis, in the gap between the PS and TS. The production target is pencil-sized tungsten rod, held in place by a "bicycle wheel" support system, and cooled by direct radiation to the vacuum. The stainless steel vacuum vessel holding the production target is surrounded by a bronze and water heat and radiation shield to protect the PS superconducting coils from both heat load and radiation damage. The PS endcap provides windows for passing the spent beam to a downstream proton beam stop, along with a maintenance window to allow for target changes. Because of the heavy activation of the target and PS, target changes will be performed by a robotic remote handling system. The field in the PS is graded from 4.5 T at the proton-downstream end to 2.5 T at the entrance to the TS. This graded field acts both as a mirror increasing muon acceptance, as well as sweeping particles towards to TS to prevent long-lived storage of secondaries within the PS that could later escape and arrive in the DS during the live window.

The "S"-shaped solenoid TS sweeps muons from the PS to the DS. The field is also graded inside TS, again to ensure that particles do not become trapped in long-lived orbits. The solenoid is curved to ensure that there is no line-of-sight path between the production target and the detectors to reduce contamination by neutral particles. The entrance to and exit from the TS are occupied by collimators to define the acceptance of the channel. The most interesting aspect of this design is the effect a curved solenoid has on charged particle

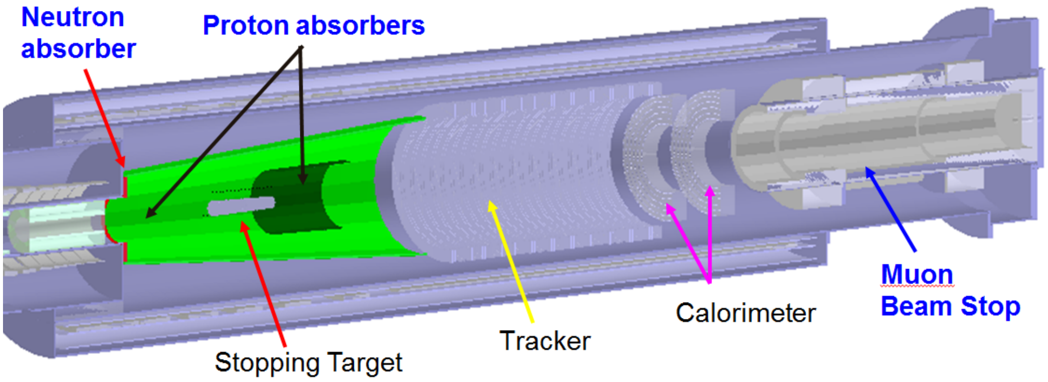


FIG. 8: A rendering of the Mu2e Detector Solenoid, showing the internal arrangement of muon stopping target foils, detectors, and supporting devices.

trajectories: charged particles drift in the non-bend direction (vertically in our case), with particles of opposite sign drifting in opposite directions. This naturally charge separates the beam in the vertical direction. We insert an asymmetric collimator in the central straight section to sign select on negative muons; see Figure 6. The recurved section past the central collimator moves the beam back on-axis at the entrance to the DS.

The Detector Solenoid forms the heart of the experiment; see Figure 8. As the beam enters the DS, it first encounters a series of aluminum stopping target foils. These are mounted within a graded magnetic field region; again, the grade reflects decay products towards the downstream end of the DS, increasing the acceptance of the detector systems. Beyond the stopping target, the field becomes uniform over the detector train. The primary measurement device is a low-mass, straw-tube electron tracker; with a wall thickness of only 15 μm, the tracker has a high-side resolution of less than 180 keV, thanks to the low mass design. The dynamic range issues are solved by simply not measuring electrons in the peak of the DIO distribution: the tracker has a central hole along its axis that passes particles below 55 MeV/c without measurement. Following the tracker is a scintillating crystal calorimeter, made from two annular disks. The calorimeter provides a redundant energy measurement to the tracker, as well as powerful particle ID capability, and independent trigger and track seeding capabilities. The final major component mounted within the DS is a muon beam stop, which intercepts and absorbs the beam particles that are not stopped by the target foils, and decay products below measurement threshold. A four layer scintillating plastic Cosmic Ray Veto system surrounds the top and sides of the DS to virtually eliminate cosmic ray muons that could fake conversion signals; to reduce the rate from one per day to less than 0.1 event during the three year duration of the experiment, this system must operate at a 99.99% detection efficiency.

While the bulk of the Mu2e experiment is designed for the detection of conversion events, that's only half the equation (literally!). To measure the conversion *rate* (or branching ratio), we have to normalize the number of conversion candidates to some proxy for the total number of muon stops. This is the job of the final detector, the *Stopping Target Monitor* (STM). The baseline design is for a High Purity Germanium detector that will view through very small solid angle the stopping target foils, and will count the characteristic atomic cascade transition x-rays. Given acceptance and efficiency measures for both the conversion event counting and the cascade x-ray counting, we can determine the ratio of conversions to nuclear capture events; our final result will be the *conversion ratio*

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

For a three year run, we expect less than half a background event in the signal window; our goal for single event sensitivity is 2.5×10^{-17}, a four order of magnitude improvement over the SINDRUM II result. For a conversion ration $R_{\mu\mathrm{e}} \sim 10^{-15}$, we will see fifty conversion events during the run.

RECENT PROGRESS AND FUTURE PROSPECTS

The Mu2e Project and Collaboration are making progress on design, reviews, procurement, and construction across the many subsystems comprising the experiment. Two significant milestones occurred in the spring of 2015: U.S. Department of Energy Critical Decision 2 approval of the project baseline design and cost, and Critical Decision 3b approval to begin construction of the experiment hall. The formal groundbreaking for that hall occurred during the Collaboration Meeting in April. The Project and Collaboration are working diligently to prepare for the many subsystem technical reviews leading up to the Critical Decision 3c review in early 2016, which will authorize construction of the rest of the experiment. The baseline schedule has commissioning slated for early 2021, followed by at least three years of data taking.

As mentioned earlier, because the Standard Model does not predict observable levels of

CLFV, the value of Mu2e is high whether or not we see a signal. In either case, a future extension of the experiment - Mu2e-II - is under active study. If we do see a signal in our first run, an upgraded experiment run with multiple different target materials could help elucidate the physics sources responsible for CLFV. If we do not see a signal in our first run, an upgrade will allow us to improve our sensitivity and probe higher energy scales. In either case, the result from Mu2e combined with other CLFV experiments and direct searches at the LHC will help point us in the right direction to define the next Standard Model.

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‡ URL: `http://mu2e.fnal.gov/`

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