The Mu2e Experiment at Fermilab

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Charged Lepton Flavor Violation

• Charged lepton flavor violation (CLFV) is extremely suppressed in the Standard Model (SM) due to sums over \((\Delta m_{ij}/M_W)^4\), for example \(\mu \rightarrow e\gamma\):

\[
\mathcal{B}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54}
\]

• SM rates of CLFV are below any conceivable experimental sensitivity → any detection of a signal is an unambiguous evidence for physics beyond the SM

• Searches for CLFV have a long history:

Most stringent limits for muon decays:

- **MEG**
  
  PRL 110, 201801 (2013)
  
  \[
  \mathcal{B}(\mu \rightarrow e\gamma) < 5.7 \times 10^{-13}
  \]

- **SINDRUM-II**
  
  EPJ C 47, 337 (2006)
  
  \[
  R_{\mu e}(\mu N \rightarrow eN \text{ on Au}) < 7 \times 10^{-13}
  \]
Sensitivity to Charged Lepton Flavor Violation

- Model-independent effective Lagrangian allowing for CLFV:
  \[ \mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{1 + \kappa} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)} \bar{\mu}_L \gamma_\mu e_L \left( \sum_{q=u,d} \bar{q}_L \gamma_\mu q_L \right) \]

- Two types of amplitudes contribute to CLFV:

  **Contact Terms**
  \[ \mu \to e\gamma \]
  \[ \mu N \to eN \]

  **Loops**
  \[ \mu \to e\gamma \]
  \[ \mu N \to eN \]

- \( \mu \to e\gamma \) and \( \mu N \to eN \) have complementary sensitivity to new physics
  → important to search for both processes

- Mu2e can probe at all \( \kappa \) and mass scales up to \( 10^4 \) TeV
Conversion of Muons to Electrons

- Mu2e searches for the neutrino-less $\mu^-$→$e^-$ conversion in the field of an atomic nucleus:
  - Coherent process
  - Kinematics of a two-body decay
    → mono-energetic electron
  - Lifetime muonic aluminum $\tau(1S)=864$ ns
  - Corrected for nuclear recoil and binding energy
    the signature is a single 105 MeV electron

- Observable: Ratio of $\mu^-$→$e^-$ conversion rate relative to muon capture by nucleus
  $$R_{\mu e} = \frac{\Gamma(\mu^- + A(Z, N) \rightarrow e^- + A(Z, N))}{\Gamma(\mu^- + A(Z, N) \rightarrow \nu_\mu + A(Z - 1, N))}$$

- Mu2e is designed to measure $R_{\mu e}$ with a single-event-sensitivity of $2.9 \times 10^{-17}$
  → sensitivity improvement of 4 orders of magnitude compared to SINDRUM-II
Background Processes

- The dominant irreducible background comes from the decay of bound muons
  - 39% of stopped muons decay in orbit (DIO)
  - recoil of the nucleus causes tail into the signal region
  - spectrum falls rapidly close to the endpoint

- Other backgrounds originate from:
  - radiative pion captures
  - beam-induced backgrounds
  - cosmic ray or antiproton induced backgrounds
The Mu2e Experiment

- Key components:
  - Intense 8 GeV proton beam
  - 3 superconducting solenoids (4.6T to 1T)
  - Muon stopping target, tracker and calorimeter

- Measurement principle:
  - Proton beam on tungsten target produces pions and muons
  - Muons are collected and propagated through s-shaped transport solenoid
  - Collimated low energy muons are stopped on an aluminum target
  - Trajectories and energies of electrons from muonic atoms are measured
Mu2e Timing Structure

- FNAL accelerator complex and Mu2e timing structure:
  - Utilize the pulsed structure of the proton beam and the lifetime of muonic atoms to suppress prompt backgrounds

Debuncher cycle 1695 ns

- Pions and muons arrive at target
- Prompt backgrounds, e.g. radiative pion captures
- Delayed processes: Conversion electrons
- Decay-in-orbit electrons

- Signal window
Tracker

• ≈20,000 straw tubes:
  - 5 mm diameter
  - 25 µm sense wire
  - 15 µm thick mylar walls
  - 80/20 Ar:CO₂

• 18 stations of straw chambers
  - 3 m long
  - low effective mass
  - insensitive to <53 MeV electrons

Tracker Momentum Resolution

Excellent momentum resolution better than a few hundred keV/c
Calorimeter

- Two disks placed behind the tracker
  - radii 36 to 70 cm
  - each disk: ≈800 BaF$_2$ crystals
  - crystals 3x3x20 cm (10 X$_0$)

- Each BaF$_2$ crystal is readout by 2 APDs
  - APDs tailored to discriminate between fast and slow scintillating components
  - unprecedented sensitivity in the UV
  - capable of high rates

- The calorimeter provides independent timing and energy measurements
  (resolution $\sigma(t)=0.5$ ns and $\sigma(E)/E=5\%$)

- The calorimeter contributes to particle identification and the trigger
Further Instrumentation

- Cosmic ray veto
  - Covers whole detector solenoid and downstream end of the transport solenoid
  - 4 layers of long scintillator strips with wavelength shifter and aluminum absorbers

- Muon stopping target monitor
  - measures delayed $\gamma$-rays from radioactive nuclei produced by nuclear muon captures
  - enables to determine the number of captured muons
  - important as normalization for $R_{\mu e}$
Background Estimates and Detection of the Signal

- Mu2e background estimates for 3 years of running:

| Category       | Background process                  | Estimated yield (events) |
|----------------|-------------------------------------|--------------------------|
| Intrinsic      | Muon decay-in-orbit (DIO)           | $0.199 \pm 0.092$        |
| Late Arriving  | Muon capture (RMC)                  | $0.000 \pm 0.000$        |
|                | Pion capture (RPC)                  | $0.023 \pm 0.006$        |
|                | Muon decay-in-flight ($\mu$-DIF)    | $<0.003$                 |
|                | Pion decay-in-flight ($\pi$-DIF$^*$) | $0.001 \pm 0.001$        |
|                | Beam electrons                      | $0.003 \pm 0.001$        |
| Miscellaneous  | Antiproton induced                  | $0.047 \pm 0.024$        |
| 25%            | Cosmic ray induced                  | $0.092 \pm 0.020$        |
|                | Total                               | $0.37 \pm 0.10$          |

- Reconstructed simulated momentum spectra assuming $R_{\mu e} = 10^{-16}$

Separation of conversion from DIO electrons due to excellent momentum resolution

$\rightarrow$ Signal is a peak over the background close to the endpoint
Current Status

- Mu2e received the DOE critical decision (CD-2/3b) approval in March 2015
  → the budget, timeline and baseline are fixed;
  i.e. for civil construction and magnet fabrication

- Testing of a transport solenoid coil prototype has started

- Construction of the detector building has started

- Preparations for DOE CD-3c “proceed with construction” review in early 2016

- The commissioning of the beam-line and detector are scheduled for 2020
Summary

• Mu2e will search charged lepton flavor violation at unprecedented sensitivity

• Mu2e has a $5\sigma$ discovery sensitivity to all $\mu\rightarrow e$ conversion rates greater than $2 \times 10^{-16}$ and probes effective mass scales of new physics up to the $10^4$ TeV scale

• Expected sensitivity is $R_{\mu e}(\mu N \rightarrow eN \text{ on Al}) < 6 \times 10^{-17}$ in 3 years running (improvement of 4 order of magnitude to previous experiments)

• Mu2e construction and next approval steps are proceeding on schedule

• Commissioning is scheduled for 2020
BACKUP
Prospects of Charged Lepton Flavor Violation

![Graph showing branching fraction upper limit from 1940 to 2030. The graph includes data points for various processes, such as $\mu \to e\gamma$, $\mu \to 3e$, and $\mu N \to eN$, with a factor 10,000 improvement indicated by an arrow.]

Phys. Rept. 352, 27 (2013)
Extinction Monitor

- Extinction defined as number of protons striking the production target between beam pulses to the number of protons striking during the beam pulses.

- For Mu2e an extinction of about $10^{-10}$ is required to reduce the backgrounds induced by out of time particles to an acceptable level.

- An extinction monitor will estimate the overall performance by monitoring the beam hitting the primary target.