Mu2e Experiment at Fermilab

Chicago

Wilson Hall

Mu2e

g-2

Yuri Oksuzian, BLV 2017
We've discovered that quarks and neutrinos mix

- Do charged lepton flavors mix as well?

Mu2e will search for neutrino-less, coherent muon conversion into an electron

\[ \mu^- + N \rightarrow e^- + N \]

- Neutrino-less \( \mu \rightarrow e^- \) conversion is Charge Lepton Flavor Violation (CLFV)

\[ \mu \rightarrow e\gamma, \mu \rightarrow 3e, \tau \rightarrow e\gamma, \tau \rightarrow \mu\gamma... \]

- In the SM, \( \mu \rightarrow e^- \) occurs at the rate of \(< 10^{-50}\)

  - Signal observation at Mu2e is unambiguous sign of new physics
What do we measure?

Mu2e will measure the ratio of $\mu \rightarrow e^-$ conversions to the number of muon captures by Al nuclei:

$$R_{\mu e} = \frac{\Gamma(\mu^- + (A, Z) \rightarrow e^- + (A, Z))}{\Gamma(\mu^- + (A, Z) \rightarrow \nu_{\mu} + (A, Z-1))}$$
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$E_{e^-} = 104.96$ MeV
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Dominant background $\text{BR} = 39\%$
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- Mu2e single event sensitivity: $R_{\mu e} = 2.4 \times 10^{-17}$
  - Expect 4 events at $R_{\mu e} = 10^{-16}$
  - Expect 40 events at $R_{\mu e} = 10^{-15}$
- Expected limit: $R_{\mu e} = 7 \times 10^{-17} \text{ at } 90\% \text{ CL}$
- Mu2e needs to stop $\sim 10^{18}$ muons
  - $3.6 \times 10^{20}$ protons on target (POT) over 3 years
- Need to keep background small and well understood
  - Total expected background 0.4 events
History of CLFV Searches

R. H. Bernstein and P. S. Cooper, Phys. Rept. 532 (2013) 27

- $\mu \rightarrow e\gamma$
- $\mu \rightarrow 3e$
- $\mu N \rightarrow eN$

Year

10^{-19} 10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4}


Mu2e, COMET

10^{-4}
\[ L = \frac{m_\mu}{(\kappa+1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L \sum_{q=u,d} \bar{q}_L \gamma_\mu q_L \]

**Effective CLFV Lagrangian**

- **Magnetic moment type operator**
- **Contact term operator**

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<thead>
<tr>
<th>State</th>
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Mu2e Physics Reach

Effective CLFV Lagrangian

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Magnetic moment type operator

Supersymmetry

Heavy neutrinos

Two Higgs Doublets

Contact term operator

Compositeseness

Leptoquarks

Heavy Z’
Mu2e proton beam

- Mu2e will recycle the existing accelerator infrastructure
- **Booster** provides batches of 8 GeV protons to recycler
- **Recycler** divides proton batches into 4 smaller bunches
- **Delivery ring** gets 1 out of 4 bunches from recycler
- Mu2e gets the **proton beam** pulses from delivery ring every 1695 ns
- Mu2e runs simultaneously with NOvA
  - Using spare Booster batches
  - NOvA POT is unaffected by Mu2e
1. Protons hit production target to produce $\pi^-$
   - $\pi^-/\mu^-$ are reflected toward the transport solenoid

2. Transport Solenoid delivers $\pi^-/\mu^-$ to Detector Solenoid
   - Selects particle’s momentum and charge
   - Avoids direct line of sight

3. Muons stop on the Al Stopping Target
   - 1,000 POT $\to$ 4(2) muons reach(stop on) the target
   - Conversion electron momentum and energy are measured in the tracker and calorimeter
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**Mu2e apparatus**

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Pulsed beam

- Prompt background: particles produced by proton pulse which interact almost immediately when they enter the detector
- Muons travel with pions. Pions produce background when captured on target
  \[ \pi^- N \rightarrow \gamma N^* \rightarrow e^+ e^- N^* \]
- Other examples of prompt backgrounds: beam electrons, \( \mu/\pi \) decay in flight
- Solution: Suppress prompt backgrounds by employing a delayed signal window
- Delivery ring revolution period of 1695 ns is well matched for \( \tau^{\text{Al}} = 864 \) ns
  - 50% of muons decay/captured in the signal window
Out-of-time Protons

- Out-of-time protons can give rise to prompt backgrounds in the signal window.
- RF structure in Delivery ring and sweeping AC dipole in front of PS will suppress out-of-time protons by >10^{-10}.
- Only 1 in 10 billion POT will be outside of the main pulse.

**Out-of-time protons: 10^{-10}**

**Signal window**

- POT pulse
- $\pi^-$ arrival/decay time ($\times 1M$)
- $\mu^-$ arrival time ($\times 400$)
Trajectories of Michel electrons in the Mu2e tracker for different energies. The tracker is designed to intercept only a small fraction of the significant flux of electrons from muon decays-in-orbit. The vast majority of electrons from muon decay in orbit are below 60 MeV in energy (Figure 3.4). Only electrons with energies greater than about 53 MeV, representing a very small fraction of the rate (about 3%), will be observed in the tracker. Lower energy electrons will curl in the field of the Detector Solenoid and pass unobstructed through the hole in the center of the tracker. This is illustrated in Figure 4.12.
- Long tail from Michel peak. Signal is smeared
- Need good momentum resolution
  - 100 KeV momentum resolution is achievable

### Simulation

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
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<tbody>
<tr>
<td>Total POT</td>
<td>$3.6 \times 10^{20}$</td>
</tr>
<tr>
<td>$\mu$- stops</td>
<td>$6.7 \times 10^{17}$</td>
</tr>
<tr>
<td>Signal $R_{\mu e}$</td>
<td>$1 \times 10^{-16}$</td>
</tr>
<tr>
<td>Signal yield</td>
<td>3.5 evt</td>
</tr>
<tr>
<td>DIO yield</td>
<td>0.2 evt</td>
</tr>
</tbody>
</table>

**Reconstructed $e^-$ Momentum**

**Signal Window**

$103.75 < p < 105.00$ MeV/c
- Low mass straw drift tubes
- 5 mm diameter straws
  - 12 $\mu$m Mylar walls
  - Filled with Ar/CO$_2$
- 25 $\mu$m tungsten wires

- 100 Straws = Panel; 6 Panel = Plane; 2 Planes = Station; 18 Station = Tracker
Mu2e expects 1 signal-like event per day induced by cosmic rays.
Cosmic Ray Veto (CRV) consists of 4-layer scintillating counters.
CRV needs to reject 99.99% of cosmic rays:
- Covering 327 m²
- Operating in a high radiation environment

- Area: 327 m²
- 86 modules of 6 lengths
- 5,504 counters
- 11,008 fibers
- 19,840 SiPMs
- 310 Front-end Boards
Calorimeter

- Two disks of CsI scintillating crystals
  - Radiation hard, good time (110 ps) and energy (5%) resolution
- Provides precise timing, PID, seed for tracking and triggering
- Muon rejection x200 with 96% electron efficiency

- Tracker
- Calorimeter

- 2 disks (radius = 37-66 cm)
- 1400 crystals (3x3x20 cm$^3$)
- 2800 SiPMs
### Background processes

<table>
<thead>
<tr>
<th>Category</th>
<th>Source</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic</td>
<td>μ Decay in Orbit</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Radiative μ Capture</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Late Arriving</td>
<td>Radiative π Capture</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Beam electrons</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td></td>
<td>μ Decay in Flight</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td></td>
<td>π Decay in Flight</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>Anti-proton induced</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Cosmic Ray induced</td>
<td>0.08</td>
</tr>
<tr>
<td>Total Background</td>
<td></td>
<td>0.36</td>
</tr>
</tbody>
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- All these backgrounds can be controlled to the level of <1 event
Mu2e Status

- Successfully passed DOE reviews
- Detector hall construction is complete
- Detector construction starts next year
- Solenoid installation in 2019
- Commissioning in 2020
Mu2e R&D/Prototypes Efforts

Yuri Oksuzian
Mu2e experiment at Fermilab
Mu2e Collaboration

200 scientists, 37 institutions
Summary

- Mu2e has a great discovery potential and can reveal new physics
  - Improves over previous conversion experiments by 4 orders of magnitude and probes new physics mass scales of $10^4$ TeV
  - Provides discovery capability over wide range of new physics models
  - Complementary to LHC and other experiments

- Experimental design is mature and on schedule to start commissioning in 2020

- Technical Design Report

- Experiment web site
  - [http://mu2e.fnal.gov](http://mu2e.fnal.gov)