Searching for Muon to electron conversion:
The Mu2e experiment at Fermilab

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WIN 2017

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Mu2e: the basics

- Mu2e will search for neutrinoless conversion of a muon to an electron in a nuclear environment:

  \[ \mu^- N \to e^- N \]

- This would violate **charged lepton flavor**, something that has never been seen before

- Any detection of charged lepton flavor violation would be an unambiguous sign of new physics! (SM contribution is < $10^{-50}$)
History of $\mu \rightarrow e\gamma$, $\mu N \rightarrow eN$, and $\mu \rightarrow 3e$

Mu2e goal is a $10^4$ improvement!
Charged Lepton Flavor Violation

- Many models of new physics predict contributions to CLFV:

### Supersymmetry

\[ \tilde{\chi}_i^0 \]

\[ \mu^- \rightarrow l^- e^- \]

### Compositeness

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

### Leptoquark

\[ \mu^- \rightarrow d e^- \]

### Heavy Neutrinos

\[ \mu^- \rightarrow W e^- \]

### Second Higgs Doublet

\[ \mu^- \rightarrow H e^- e^- \]

### Heavy Z’

Anomalous Z Coupling

\[ \mu^- \rightarrow \gamma, Z, Z' \]
CLFV Effective Lagrangian

\[ \mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(1+\kappa)^2} \bar{\mu} R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)^2} \bar{\mu}_L \gamma_\mu e_L \left( \sum_{q=u,d} \bar{q}_L \gamma^\mu q_L \right) \]

- **loop**: \( \kappa \ll 1, \mu N \rightarrow eN \) and \( \mu \rightarrow e\gamma \)
- **contact**: \( \kappa \gg 1, \mu N \rightarrow eN \) only

- Complementary to LHC: can probe mass scales up to \( 10^4 \) TeV
Measuring $\mu$ to e conversion

Measure the ratio of conversions to muon captures:

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

- Signal of CLFV conversion is single monoenergetic electron
- Backgrounds:
  - Beam related: $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+ e^-$
  - Cosmic rays: $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$
  - Muon Decay in orbit: $\mu^- N \rightarrow e^- N \nu_\mu \bar{\nu}_e$
Backgrounds: Decay in orbit \( (\mu^- N \rightarrow e^- N \nu_\mu \bar{\nu}_e) \)

- Muon decay electron energy much lower than from conversion

\[
E_e(\text{max}) = \frac{m_\mu^2 + m_e^2}{2m_\mu} \approx 52.8 \text{ MeV}
\]
Backgrounds: Decay in orbit ($\mu^- N \rightarrow e^- N\nu_\mu\bar{\nu}_e$)

- Muon decay electron energy much lower than from conversion
- Recoil off nucleus pushes tail all the way up to conversion peak
Backgrounds: Decay in orbit \( (\mu^- N \rightarrow e^- N \nu_\mu \bar{\nu}_e) \)

- Need to measure energy precisely to reject this background
- Maximize resolution while minimizing energy loss in detector materials
The Mu2e Experiment at Fermilab

- Stop a lot more muons! $O(10^{18})$
- Use timing to reject beam backgrounds
  - Pulsed proton beam 1.7 $\mu$s between pulses
  - Pions decay with 26 ns lifetime
  - Muons capture on Aluminum target with 864 ns lifetime

$$E_0 = m_\mu c^2 - (B.E.)_{1S} - E_{\text{recoil}} = 104.96 \text{ MeV}$$
The Mu2e Collaboration

Over 200 scientists from 37 institutions in 6 countries
Mu2e Proton Beam

- 8 GeV 8 kW proton beam using protons from booster
- Resonantly extracted to get pulses of $4 \times 10^7$ protons separated by $1.7 \, \mu s$
- Runs simultaneously with NOVA
Proton extinction between beam pulses allows us to reject RPC events \((\pi^- \text{ Al} \rightarrow \text{Mg}^* + \gamma)\)

- 700 ns delay followed by 1 \(\mu\)s livegate
- Extinction factor (ratio of out-of-time protons to in-time protons) of \(10^{-10}\) is needed
Mu2e experimental setup

- Consists of three superconducting solenoids:
  - Production Solenoid (PS)
  - Transport Solenoid (TS)
  - Detector Solenoid (DS)
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Production Target and Solenoid produce slow muon beam in the reverse direction of the proton beam

- Protons hit production target and produce pions, decay to muons
- Magnetic mirror traps and redirects back to TS
Transport Solenoid sign selects charged particles
• Muons stop on thin aluminum foils, are captured or decay
  ● Decay products emitted isotropically
  ● Graded field directs electrons back through detector elements in helical path
  ● Flat field in straw tracking volume
• High precision straw tracker for momentum measurement
• Electromagnetic calorimeter for PID
Straw Tracker provides the energy measurement to reject DIO background

~21,000 low mass straw tubes in vacuum

- 5 mm diameter, 15 μ thick walls
- 80/20 ArCO2 gas mixture
- instrumented on both ends - measure:
  - drift time to get radial position (≈ 100μm resolution)
  - time difference between ends to get position along straw (≈ 4cm resolution)
  - pulse size to identify highly ionizing proton hits
Straw Tracker provides the energy measurement to reject DIO background

- 18 stations, each containing 12x 120° panels for stereo measurement
- Blind to DIO electron momentum peak and beam flash
- Expected resolution better than 200 keV/c
8 straw tracker prototype used to tune simulation and verify expected resolution

- Prototype also used to develop/test electronics and DAQ/firmware

Pixel detectors used to determine cosmic ray track position
8 straw tracker prototype used to tune simulation and verify expected resolution

**Drift Radius Residual [mm]**

-8 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1

Arbitrary Unit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>N electrons per ionization</td>
<td>$&lt; N &gt;= 2$</td>
<td>NIMA 301, 202(1991)</td>
</tr>
<tr>
<td>Energy per ionization electron</td>
<td>39 eV</td>
<td>NIST (27-100 eV) and G4</td>
</tr>
<tr>
<td>Avg. Straw Gain</td>
<td>70k</td>
<td>Prototype (PAM, $^{55}$Fe)</td>
</tr>
<tr>
<td>Threshold Value</td>
<td>12 mV</td>
<td>Prototype (DVM, $^{55}$Fe)</td>
</tr>
<tr>
<td>Threshold Noise</td>
<td>3 mV</td>
<td>Spice Sim. (V. Rusu)</td>
</tr>
<tr>
<td>Shaping Time</td>
<td>22 ns</td>
<td>Prototype ($^{55}$Fe)</td>
</tr>
</tbody>
</table>
Mu2e Detector Simulation

- Detailed Geant4 simulation of full detector
- Simulate from production target forward (including backgrounds)
- Response tuned to data and detector prototype measurements

1 μs selection window after beam flash
Mu2e Detector Simulation

Hits selected by track finder within ±50 ns selection window around potential track

- Detailed Geant4 simulation of full detector
- Simulate from production target forward (including backgrounds)
- Response tuned to data and detector prototype measurements
Track Reconstruction

- Filter background hits (protons / Compton electrons)
- Least squares helix fit, followed by iterative Kalman Filter track fit
Calorimeter

- Two annular disks separated by half a “wavelength” (70cm) of electron’s helical path
  - Maximize probability to hit at least one disk
- Each disk contains 860 CsI crystals read out by SiPMs
- 5% energy, 0.5 ns time, 1 cm position measurement independent of straw tracker
- Provides particle ID for track rejection
Calorimeter prototype agrees with simulation

- 3x3 matrix of undoped CsI crystals 3x3x20 cm$^3$
- Tested under 80 to 120 MeV electron beam
- Energy response (7%) and time resolution (110 ps) meet specifications
Stopping Target Monitor measures capture rate

- Muons cascade to 1s state emitting x-rays
- HPGe detector monitor these x-rays to measure capture rate
- Normalization of measurement $R_{\mu e} = \frac{\mu^- + A(Z, N) \rightarrow e^- + A(Z, N)}{\mu^- + A(Z, N) \rightarrow \nu_\mu + A(Z-1, N)}$
Stopping Target Monitor measures capture rate

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- Normalization of measurement \( R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)} \)
Cosmic ray veto

- Expect cosmic rays to produce 1 conversion-like event per day
- 4 overlapping layers of scintillator, read out on both ends with SiPMs
- Covers entire DS, half of TS, better than $10^{-4}$ inefficiency
### Expected backgrounds for 3 year run

<table>
<thead>
<tr>
<th>Category</th>
<th>Background process</th>
<th>Estimated yield (events)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic</td>
<td>Muon decay-in-orbit (DIO)</td>
<td>0.199 ± 0.092</td>
</tr>
<tr>
<td></td>
<td>Muon capture (RMC)</td>
<td>0.000 ± 0.004</td>
</tr>
<tr>
<td>Late Arriving</td>
<td>Pion capture (RPC)</td>
<td>0.023 ± 0.006</td>
</tr>
<tr>
<td></td>
<td>Muon decay-in-flight (μ-DIF)</td>
<td>&lt;0.003</td>
</tr>
<tr>
<td></td>
<td>Pion decay-in-flight (π-DIF)</td>
<td>0.001 ± &lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Beam electrons</td>
<td>0.003 ± 0.001</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>Antiproton induced</td>
<td>0.047 ± 0.024</td>
</tr>
<tr>
<td></td>
<td>Cosmic ray induced</td>
<td>0.082 ± 0.018</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>0.36 ± 0.10</td>
</tr>
</tbody>
</table>

- Fewer than \(\sim 0.5\) background events expected over entire run
- \(3.6 \times 10^{20}\) protons on target over 3 years \(\rightarrow \sim 10^{18}\) stopped muons
Sensitivity

- Single event sensitivity: $R_{\mu e} < 3 \times 10^{-17}$
- Typical SUSY prediction of $10^{-15} \rightarrow \sim 50$ signal events
Civil construction
Mu2e is fully approved! Moving ahead on schedule
Backup
- Joint project by Mu2e and COMET
- Measure particles emitted after muon capture on Al
Beam structure
# Beam requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Value</th>
<th>Requirement</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total protons on target</td>
<td>$4.7 \times 10^{20}$</td>
<td>$\geq 4.7 \times 10^{20}$</td>
<td>protons</td>
</tr>
<tr>
<td>Time between beam pulses</td>
<td>1695</td>
<td>$&gt; 864$</td>
<td>nsec</td>
</tr>
<tr>
<td>Maximum variation in pulse separation</td>
<td>$&lt; 1$</td>
<td>10</td>
<td>nsec</td>
</tr>
<tr>
<td>Spill duration</td>
<td>43.1</td>
<td>$&gt; 20$</td>
<td>msec</td>
</tr>
<tr>
<td>Beamline Transmission Window</td>
<td>230</td>
<td>$&lt; 250$</td>
<td>nsec</td>
</tr>
<tr>
<td>Transmission Window Jitter (rms)</td>
<td>$&lt; 5$</td>
<td>$&lt; 10$</td>
<td>nsec</td>
</tr>
<tr>
<td>Out-of-time extinction factor</td>
<td>$1.6 \times 10^{-12}$</td>
<td>$\leq 10^{-10}$</td>
<td>protons/pulse</td>
</tr>
<tr>
<td>Average proton intensity per pulse</td>
<td>$3.9 \times 10^{7}$</td>
<td>$&lt; 5.0 \times 10^{7}$</td>
<td>protons/pulse</td>
</tr>
<tr>
<td>Maximum Pulse to Pulse intensity variation</td>
<td>50</td>
<td>50</td>
<td>%</td>
</tr>
<tr>
<td>Target rms spot size</td>
<td>1</td>
<td>0.5 – 1.5</td>
<td>mm</td>
</tr>
<tr>
<td>Target rms beam divergence</td>
<td>0.5</td>
<td>$&lt; 4.0$</td>
<td>mrad</td>
</tr>
</tbody>
</table>
## Systematics

<table>
<thead>
<tr>
<th>Effect</th>
<th>Uncertainty in DIO background yield</th>
<th>Uncertainty in CE single-event-sensitivity ($\times 10^{-17}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC Statistics</td>
<td>±0.02</td>
<td>±0.07</td>
</tr>
<tr>
<td>Theoretical Uncertainty</td>
<td>±0.04</td>
<td>-</td>
</tr>
<tr>
<td>Tracker Acceptance</td>
<td>±0.002</td>
<td>±0.03</td>
</tr>
<tr>
<td>Reconstruction Efficiency</td>
<td>±0.01</td>
<td>±0.15</td>
</tr>
<tr>
<td>Momentum Scale</td>
<td>+0.09, -0.06</td>
<td>±0.07</td>
</tr>
<tr>
<td>$\mu$-bunch Intensity Variation</td>
<td>±0.007</td>
<td>±0.1</td>
</tr>
<tr>
<td>Beam Flash Uncertainty</td>
<td>±0.011</td>
<td>±0.17</td>
</tr>
<tr>
<td>$\mu$-capture Proton Uncertainty</td>
<td>±0.01</td>
<td>±0.016</td>
</tr>
<tr>
<td>$\mu$-capture Neutron Uncertainty</td>
<td>±0.006</td>
<td>±0.093</td>
</tr>
<tr>
<td>$\mu$-capture Photon Uncertainty</td>
<td>±0.002</td>
<td>±0.028</td>
</tr>
<tr>
<td>Out-Of-Target $\mu$ Stops</td>
<td>±0.004</td>
<td>±0.055</td>
</tr>
<tr>
<td>Degraded Tracker</td>
<td>-0.013</td>
<td>+0.191</td>
</tr>
<tr>
<td>Total (in quadrature)</td>
<td>+0.10, -0.08</td>
<td>+0.35, -0.29</td>
</tr>
</tbody>
</table>
Tracker Occupancy

Hits / micro-pulse / ns vs Hit Time (ns)

- Primary Proton, $\int = 1266$
- Stopping Target Proton, $\int = 706$
- Photon, $\int = 596$
- Neutron, $\int = 522$
- OOT Muon, $\int = 295$
- DIO, $\int = 33$
- Total $\int = 3418$

(only simulate hits > 300 ns)
SUSY model constraints

![Graph showing SUSY model constraints](image)

- **PMNS case**
- **CKM case**
- **SINDRUM II (Ti)**
- **Mu2e (Al)**

**SUSY GUT** \(\tan(\beta) = 10\)

SUSY model constraints

[Graphs showing scatter plots with logarithmic axes and data points colored blue, red, and green, indicating different experimental results and constraints.]
Tracker prototype

Drift time (ns)

Track position (mm)

Straw 1
Straw 2
Straw 3
Straw 4
Straw 5
Straw 6

Straw measurement
Pixel measurement
Extinction Monitor located downstream of production target
Extinction Monitor located downstream of production target

Scintillators coupled to PMTs for triggering and additional timing information

Silicon pixels for fast, high resolution tracking

Spectrometer Magnet:
Repurposed dipole magnet bends out low energy elections generated by muons stopping in the upstream silicon
## Types of CLFV measurements

<table>
<thead>
<tr>
<th>Process</th>
<th>Current Limit</th>
<th>Next Generation exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu \eta$</td>
<td>BR $&lt; 6.5 \times 10^{-8}$</td>
<td>$10^{-9} - 10^{-10}$ (Belle II, LHCb)</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \gamma$</td>
<td>BR $&lt; 6.8 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \mu \mu$</td>
<td>BR $&lt; 3.2 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$\tau \rightarrow eee$</td>
<td>BR $&lt; 3.6 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$K_L \rightarrow e\mu$</td>
<td>BR $&lt; 4.7 \times 10^{-12}$</td>
<td></td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ e^- \mu^+$</td>
<td>BR $&lt; 1.3 \times 10^{-11}$</td>
<td></td>
</tr>
<tr>
<td>$B^0 \rightarrow e\mu$</td>
<td>BR $&lt; 7.8 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+ e\mu$</td>
<td>BR $&lt; 9.1 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$\mu^+ \rightarrow e^+ \gamma$</td>
<td>BR $&lt; 4.2 \times 10^{-13}$</td>
<td>$10^{-14}$ (MEG)</td>
</tr>
<tr>
<td>$\mu^+ \rightarrow e^+ e^+ e^-$</td>
<td>BR $&lt; 1.0 \times 10^{-12}$</td>
<td>$10^{-16}$ (PSI)</td>
</tr>
<tr>
<td>$\mu^- N \rightarrow e^- N$</td>
<td>$R_{\mu e} &lt; 7.0 \times 10^{-13}$</td>
<td>$10^{-17}$ (Mu2e, COMET)</td>
</tr>
</tbody>
</table>
Determining model with CLFV

Previous experiments: SINDRUM II

- Beam backgrounds reduced by degrader
  - Pions have half the range in CH$_2$ compared to muons
- Limit: $7 \times 10^{-13}$ (90% confidence) on Au
Previous experiments: SINDRUM II

Class 1 events: prompt forward removed

Class 2 events: prompt forward
Achieving required beam extinction

- Beam from delivery ring starts with $10^{-4}$ extinction
- 2 AC dipoles coupled with collimators expected to bring extinction to $10^{-12}$
More prototypes

Cosmic ray veto

3x3 CsI crystals matrix

TS prototype module