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

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Charged Lepton Flavor Violation (CLFV) has never been observed

- Standard model CLFV contribution is undetectably small ($< 10^{-50}$)
- Any detection of charged lepton flavor violation would be an unambiguous sign of new physics!
Muon searches reach the smallest branching ratio limits on CLFV processes

<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 \text{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}) (Mu3e)</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>
Muon conversion can probe mass scales up to $10^4$ TeV (assuming unit coupling)

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

- **loop:** $\kappa \ll 1$, $\mu N \rightarrow eN$ and $\mu \rightarrow e\gamma$
- **contact:** $\kappa \gg 1$, $\mu N \rightarrow eN$ only
- Mass scale reach makes these measurements complementary to LHC

Derived from A. de Gouvea, P. Vogl, Prog. Part. Nucl. Phys. 71 (2013) 75
Basics of a Muon conversion experiment

Measure the ratio of conversions to muon nuclear 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
Anything that can produce a $\sim 105$ MeV electron is a background to a $\mu$ to e conversion search.

- Muon Decay in orbit: $\mu^- N \rightarrow e^- N \nu_\mu \overline{\nu}_e$
- Beam related: $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+ e^-$
- Cosmic rays: $\mu^- \rightarrow e^- \nu_\mu \overline{\nu}_e$
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- Beam related: $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+ e^-$ (Delayed event window)
- Cosmic rays: $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ (Active veto)
The Mu2e Experiment at Fermilab

- Aim is $10^4$ improvement in sensitivity
  - Greatly increase muon production
  - Reduce backgrounds
  - High resolution detector that can survive event rate
Pulsed proton beam allows us to reject radiative pion capture events ($\pi^- + \text{Al} \rightarrow \text{Mg}^* + \gamma$)

- 8 GeV 8 kW proton beam from Fermilab booster
- Resonantly extracted to get pulses of $4 \times 10^7$ protons separated by 1.7 $\mu$s
- 700 ns delay followed by 1 $\mu$s livegate
- Must have very few protons outside of pulse (ratio to in-pulse $< 10^{-10}$)
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

- Tungsten production target
- Magnetic mirror traps and redirects back to TS
Transport Solenoid sign selects charged particles

\[ \mu^- \]

\[ \mu^+ \]
Detector solenoid directs electrons to detector elements

- Muons stopped on thin aluminum foils, again graded field for magnetic mirror
- Constant field in tracking volume
- High precision straw tracker in vacuum
- Electromagnetic calorimeter for PID
Straw Tracker designed to survive beam flash while providing resolution better than 200 keV/c

- 18 stations, each containing $12 \times 120^\circ$ panels for stereo measurement
Straw Tracker designed to survive beam flash while providing resolution better than 200 keV/c

- Blind to DIO electron momentum peak and beam flash
Straw Tracker designed to survive beam flash while providing resolution better than 200 keV/c

- \(~21,000\) low mass straw tubes in vacuum
- 5 mm diameter, 15 \(\mu m\) thick mylar walls
- 25\(\mu m\) tungsten wire at 1425V
- 80:20 ArCO\(_2\)
8 straw tracker prototype used to tune simulation and verify expected resolution.

- **Transverse Resolution**
  - FWHM = 283 μm

- **Longitudinal Resolution**
  - σ = 43.4 mm

- **Efficiency**
  - ε = 0.950
Reconstruction using tuned simulation shows we expect tracker to meet momentum resolution requirements. 

1. µs selection window after beam flash

Hits selected by track finder within ±50 ns selection window

- Helix fit followed by iterative Kalman Filter track fit

momentum resolution at start of tracker (simulation)

Core width = 159 keV/c
Calorimeter provides particle ID for track rejection

- 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 674 undoped CsI 34x34x200 mm³ crystals read out by SiPMs
- 0.5 ns time, 5% energy, 1 cm position measurement independent of straw tracker
- Seed for tracking algorithm
Large calorimeter prototype tested in electron beam at BTF in Frascati

- Prototype has 51 crystals, 102 SiPMs, 102 FEE boards
- Demonstrates energy and time resolution

![Image of calorimeter prototype]
Cosmic rays can produce dangerous background events

- Cosmic muon track can look like 105 MeV/c electron (mitigated by Calorimeter PID)
- Or - cosmic muon can decay inside the detector volume or knock out electron from stopping target → indistinguishable from signal
- Expect 1 such event per day
- Need highly efficient cosmic ray veto
Reject with efficiency cosmic ray veto

- 4 overlapping layers of scintillator, read out on both ends with SiPMs
  - Veto on 3-fold coincidence
- Covers entire DS, half of TS, better than $10^{-4}$ inefficiency

- Area: 327 m²
- 86 modules of 6 lengths
- 5,504 counters
- 11,008 fibers
- 19,840 SiPMs
- 310 Front-end Boards
CRV prototype counters tested with 120 GeV protons in Fermilab test beam
Expected backgrounds for $3.6 \times 10^{20}$ protons on target is 0.41 events

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<tr>
<th>Process</th>
<th>Expected event yield</th>
</tr>
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<tr>
<td><strong>Cosmic ray muons</strong></td>
<td>$0.21 \pm 0.02$ (stat) ± $0.06$ (syst)</td>
</tr>
<tr>
<td><strong>Muon decay in orbit</strong></td>
<td>$0.14 \pm 0.03$ (stat) ± $0.11$ (syst)</td>
</tr>
<tr>
<td>Antiprotons</td>
<td>$0.040 \pm 0.001$ (stat) ± $0.020$ (syst)</td>
</tr>
<tr>
<td>Pion capture</td>
<td>$0.021 \pm 0.001$ (stat) ± $0.002$ (syst)</td>
</tr>
<tr>
<td>Muon decay in flight</td>
<td>$&lt; 0.003$</td>
</tr>
<tr>
<td>Pion decay in flight</td>
<td>$0.001 \pm &lt; 0.001$</td>
</tr>
<tr>
<td>Beam electrons</td>
<td>$(2.1 \pm 1.0) \times 10^{-4}$</td>
</tr>
<tr>
<td>Radiative muon capture</td>
<td>$0.000^{+0.004}_{-0.000}$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$0.41 \pm 0.13$ (stat+syst)</td>
</tr>
</tbody>
</table>
Mu2e expects a $10^4 \times$ increase in sensitivity

- Discovery reach ($5\sigma$): $R_{\mu e} \geq 2 \times 10^{-16}$
- Exclusion power (90% CL): $R_{\mu e} \geq 8 \times 10^{-17}$
Mu2e status: detector hall
Mu2e status: detector hall
Mu2e status: beamline

- Most beamline elements installed or being fabricated
- Prototype AC dipole and collimators for extinction system fabricated
- Resonant extraction sextupoles being fabricated
- Prototype remote target handling system tested
Mu2e status: transport solenoid

- Solenoid production at ASG (Genova) and Fermilab
- All coils have been wound
- 4/14 modules delivered, 2 fully tested

TS Coils at ASG
TS Test Facility at Fermilab
Two units assembled on warm bore. Alignment ongoing
Mu2e status: production/detector solenoid

- Solenoid production at General Atomics (Tupelo)
- First demonstration coil with two layers of 70 turns each successfully completed
- Winding of PS began in April
Mu2e status: tracker

- All straws manufactured
- 10/12 pre-production panels built using final production tooling, full production (1 per day) starting soon

Panel assembly at UMN

Vacuum tests at FNAL
Mu2e status: Calorimeter

- All SiPMs delivered, and QA completed
- 1134/1450 crystals delivered (SICCAS and Saint Gobain) and tested, expected completion October 2019
- Electronics vertical slice test completed
  - Upgrading to Rad hard components

Caltech and INFN
Mu2e status: CRV

- 1229/2736 di-counters produced
- 5 pilot production modules complete and tested

Module being vacuum bagged at UVA
Mu2e is under construction, expect physics data in 2023

- Begin commissioning beam line: mid 2021
- Begin commissioning detector: early 2022
- First physics data taking: early-mid 2023
- Anticipate 4-5 years of run time for full data set (including calibrations, etc.)
Mock data challenge: shows physics capability after $<1\%$ POT

**Mu2e simulation - Preliminary**

$2.44 \times 10^{18}$ POT

(approx. 5 days at nominal)

- $R_{\mu e} = 8 \times 10^{-14}$, order of magnitude below current limit
- Created mixed samples with randomized/hidden parameters
  - will be used to test analysis tools
Mock data challenge: shows physics capability after <1% POT

Mu2e simulation - Preliminary

2.44 x 10^{18} POT
(approx. 5 days at nominal)

With analysis cuts on time, track, PID, CRV, trigger

- \( R_{\mu e} = 8 \times 10^{-14} \), order of magnitude below current limit
- Created mixed samples with randomized/hidden parameters
  - will be used to test analysis tools
• Mu2e will search for muon to electron conversion, a CLFV process, with a sensitivity of $8 \times 10^{-17}$
  - $10^4$ improvement over current results
  - Sensitive to new physics, complementary to LHC and other CLFV measurements

• Prototypes and simulation demonstrating performance of detectors

• Construction underway: beamline, solenoids, detectors

• Currently undergoing mock data challenge

• Expect to start physics data taking in 2023
Backup
Mock data challenge sample creation

- Simulate signals and backgrounds with natural energy / time spectra
  - Signals only include conversion, DIO, RMC, RPC, cosmic rays
  - Events overlaid on top of beam backgrounds
- Randomly sample at expected normalizations into single mixed file
- Randomize Rue, Rup, RMC kMax, effective proton beam intensity
- For closed ensembles, MC information is removed and hidden
- Assume nominal beam intensity (3.9e7 protons per pulse) on average
Mock data challenge - cuts used in figure

- Track $t_0 > 700 \text{ ns and } < 1695 \text{ ns}$
- Track quality MVA $> 0.8$
- Track PID MVA $> 0.95$
- Track geometry cuts:
  - $0.57735 < \tan \lambda < 1.0$
  - $-80 < d_0 < 105$
  - $450 < d_0 + \frac{2}{\Omega} < 680$
- No CRV trigger within $-120 \text{ ns to } +50 \text{ ns}$
- No upstream track reconstructed
- Triggered
Many models of new physics predict large additional contributions to CLFV

**Supersymmetry**

Supersymmetry diagrams involving fermions and gauge bosons.

**Leptoquark**

Leptoquark diagrams involving leptons and quarks.

**Heavy Neutrinos**

Heavy neutrino diagrams involving muons and electrons.

**Second Higgs Doublet**

Second Higgs doublet diagrams involving top quarks and electrons.

**Heavy Z’**

Heavy Z’ diagrams involving muons, electrons, and gauge bosons.

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Kuno, Y. and Okada, Y. Rev. Mod. Phys. 73, 151 (2001)
Search for CLFV started as soon as lepton flavors were discovered
Search for CLFV started as soon as lepton flavors were discovered.
Previous experiment: 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 experiment: 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 $10^{-12}$
Extinction Monitor located downstream of production target
Extinction Monitor located downstream of production target

- Measure extinction at $10^{-10}$ to 10% in a few hours
Stopping Target Monitor measures capture rate for final normalization

- Muons cascade to 1s state emitting x-rays
- HPGe detector monitor these x-rays to measure capture rate
- Normalization of measurement: $R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)}$
Mu2e Status: Conductor

- Conductor production (75 km of cables) complete
In the future, we can learn more by switching targets or by increasing muon yield with PIP-II

- Expression of interest for Mu2e-II, using PIP-II to increase sensitivity by factor of 10 (arxiv.1802.02599)
- Joint project by Mu2e and COMET
- Measure particles emitted after muon capture on Al
Beam structure

[Diagram showing beam structure with timelines and intensity levels for Mu2e Batch, NOvA Batch, Recycler Ring, and Delivery Ring.]

- Time (15 Hz ticks)
- RR Intensity ($10^2$ particles)
- DR Intensity ($10^2$ particles)
- Main Injector Ramp
- 5 ms reset after each spill
RMC background

SO(10) SUSY GUT limits

• LHC accessible region: $m_0 < 5000$ GeV, $M_{1/2} < 1500$ GeV
LHC accessible region: \( m_0 < 5000 \text{ GeV}, M_{1/2} < 1500 \text{ GeV} \)
- mSUGRA PMNS (red), NUHM PMNS (green), CKM (blue), \( \tan \beta = 10 \) (left), \( \tan \beta = 40 \) (right)
Leptoquark limits from CLFV

\[ \lambda \]

\[ m_{\nu} [\text{TeV}] \]

\[ \text{NOT FAVORED BY NATURALNESS} \]

\[ \text{Br}(\mu \rightarrow e\gamma) = 10^{-14} \]

\[ \text{Br}(\mu \rightarrow e \text{ in Al}) = 10^{-16} \]

\[ \text{Br}(\mu \rightarrow e \text{ in Al}) = 10^{-17} \]
