Muon to electron conversion
and the Mu2e experiment
at Fermilab

S. Miscetti, INFN LNF, ITALY
on behalf of the Mu2e Collaboration
The Mu2e Collaboration

~230 Scientists from 37 Institutions

Argonne National Laboratory, Boston University, Brookhaven National Laboratory, University of California Berkeley, University of California Irvine, California Institute of Technology, City University of New York, Joint Institute of Nuclear Research Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionali di Frascati, University of Houston, Helmholtz-Zentrum Dresden-Rossendorf, University of Illinois, INFN Genova, Lawrence Berkeley National Laboratory, INFN Lecce, University Marconi Rome, Institute for High Energy Physics Protvino, Kansas State University, Lewis University, University of Liverpool, University College London, University of Louisville, University of Manchester, University of Minnesota, Muons Inc., Northwestern University, Institute for Nuclear Research Moscow, Northern Illinois University, INFN Pisa, Purdue University, Novosibirsk State University/Budker Institute of Nuclear Physics, Rice University, University of South Alabama, University of Virginia, University of Washington, Yale University

S.Miscetti @ HEP-2017 : The Mu2e experiment

July 8 2017
Talk Layout

- The Physics
  - CLFV processes and BSM reach
  - Muonic Atom processes: Conversion/capture
- Mu2e experimental technique
- Mu2e Detector Layout
- Status of Mu2e experiment
- Conclusions
CLFV processes

✓ Muon-to-electron conversion is a **charged lepton flavor violating process (CLFV)** similar but complementary to other CLFV processes as $\mu \rightarrow e \gamma$ and $\mu \rightarrow 3e$, $\tau \rightarrow \mu \gamma$, $\tau \rightarrow 3e$, $3\mu$ ...

✓ The Mu2e experiment searches for **muon-to-electron conversion** in the coulomb field of a nucleus: $\mu$ Al $\rightarrow$ e$^-$ Al

✓ CLFV processes are **strongly suppressed** in the Standard Model
  - In principle, not forbidden due to neutrino oscillations
  - In practice $\text{BR}(\mu \rightarrow e \gamma) \sim 10^{-54}$ is negligible in the SM!

✓ **New Physics could enhance CLFV rates to observable values**

✓ Muon channels are ideal for CLFV search: clean topologies, large rates
Current best limits:

**MEG-2016**

$BR(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$

**SINDRUM-1988**

$BR(\mu \rightarrow 3e) < 1 \times 10^{-12}$

**SINDRUM-II 2006**

$R_{\mu e} < 6.1 \times 10^{-13}$

**MU2E GOAL**

$R_{\mu e} = 6 \times 10^{-17}$
CLFV: Muon channels discovery plane

\[ L_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)} \Lambda^2 \bar{\mu} R \sigma_{\mu \nu} e_L F_{\mu \nu} + \frac{\kappa}{(1 + \kappa)} \Lambda^2 \bar{\mu} L \gamma^\mu \mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L) \]

**LOOP TERM**

\( \kappa \ll 1 \)

**CONTACT TERM**

\( \kappa \gg 1 \)

All limits are at 90\% CL

\[ R_{\mu e} = \frac{\Gamma(\mu^- + N(A, Z))}{\Gamma(\mu^- + N(A, Z) \to \text{all muon capture})} \leq 6 \times 10^{-17} \text{ (90\% CL)} \]

Probing mass scales \( \lambda \approx 2000\text{~to~}10000 \text{ TeV} \), significantly above the direct reach of LHC.
Mu2e physics reach & goal

Sensitivity reach:
10^4 improvement with respect to previous muon to electron conversion experiment (Sindrum-II)

Test of Physics BSM:
A. de Gouvêa, P. Vogel, arXiv:1303.4097

Models which can be probed also by μ→eγ searches

Direct coupling between quarks and leptons, better accessed by μN→eN
Mu2e experimental Technique

- Low momentum $\mu$ beam ($< 100$ MeV/c)
- High intensity “pulsed” rate
  \[ \rightarrow 10^{10}/s \text{ muon stop on Al target} \]
- Formation of muonic atoms that can make a:

**Decay in Orbit (DIO)**

- (BR=39%)

**Muon Capture Process**

- (BR=61%)

**Conversion Process**

The conversion process results in a clear signature of a single electron, CE, with a mono-energetic spectrum close to the muon rest mass.

\[ E_e = m_\mu c^2 - (\text{B.E.})_{1S} - E_{\text{recoil}} = 104.96 \text{ MeV} \]
Mu2e backgrounds

- Intrinsic – scale with number of stopped muons
  - $\mu$ Decay-in-Orbit (DIO)
  - Radiative muon capture (RMC)

- Cosmic-ray induced

- Late arriving – scale with number of late protons
  - Radiative pion capture (RPC)
  - $\pi N \rightarrow \gamma N', \gamma \rightarrow e^+e^-$ and $\pi N \rightarrow e^+e^- N'$
  - $\mu$ and $\pi$ decay-in-flight (DIF)

- Miscellaneous
  - Anti-proton induced
    produce pions when they annihilate in the target ..
    antiprotons are negative and they can be slow!
DIO background

- Electron energy distribution from the decay of bound muons follows a modified-Michel spectrum:

  → Presence of atomic nucleus and momentum transfer create a recoil tail with a fast falling slope close to the endpoint

  → To separate DIO endpoint from CE line we need a high Resolution Spectrometer

Beam structure $\rightarrow$ prompt background

The trick is ... muonic atomic lifetime $>$ prompt background
Need a pulsed beam to wait for prompt background to reach acceptable levels $\Rightarrow$ Fermilab provides the beam we need!
Muon Beam-line and solenoids

Production Target / Solenoid (PS)
- 8 GeV Proton beam strikes target, producing mostly pions
- Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons

Transport Solenoid (TS)
Selects low momentum, negative muons
Antiproton absorbers in the mid-section

Target, Detector and Solenoid (DS)
- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- CRV to veto Cosmic Rays event

→ Heat and radiation shielding
→ Tungsten target.
Mu2e @ on campus: civil constructions done
Mu2e Solenoids

- 75 km of superconducting cable procured and tested.
- Solenoids’ designs completed
- TS fabrication has begun at ASG Superconducting in Genova (Italy).
- PS, DS fabrication started at GA (USA).
Mu2e apparatus: CE trajectories

“The Mu2e tracker and calorimeter systems”
See S.Giovannella @ Detector session
## Mu2e apparatus: the tracker system

<table>
<thead>
<tr>
<th>2x48 Straw tubes on a panel</th>
<th>One station 2 planes</th>
<th>Tracker Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
</tbody>
</table>

**Low mass straw drift tubes design:**
- 20000 straws
- 5 mm diameter, 33 – 117 cm length
- 15 µm Mylar wall, 25 µm Au-plated W wire
- 80:20 Ar:CO₂ @ 1 atm
- Dual-ended readout
- Momentum resolution core < 180 keV for 105 MeV electrons.
- dE/dX capability to distinguish e/p

![Image](image4.png)
**Calorimeter provides:**

- PID: $e/\mu$ separation
- $\times$ seeding for track finder
- $\times$ standalone EMC trigger
- with O(5%) energy resolution
- and < 500 ps timing resolution

- Two disks, of 674+674 square pure CsI crystals, each one readout with two custom large area UV-extended SiPMs
- Analog FEE directly mounted on SiPM, WD on crates
- Calibration/Monitoring with 6 MeV radioactive source, MIPs and laser system
Cosmic Rays are one of two largest backgrounds → high efficiency (0.9999) veto needed
✓ Composed of 4 layers of overlapping scintillator bars (3 out of 4 coincidence used)
✓ 2 WLS fibers (1.4 mm diameter) per counter, 1-side readout with 2x2 mm² SIPMs.
✓ CRV covers all DS and part of TS area
Mu2e expectation with full simulation

Discovery sensitivity accomplished with 3 years of running and suppressing backgrounds to < 0.4 event total

Upper Limit < 6 x 10^{-17} @ 90% C.L.
Mu2e schedule

3 years run expected 2022-2025
Conclusions

The Mu2e experiment:

• Improves sensitivity on conversion exp. by a factor of $10^4$

• Provides *discovery capability* over wide range of New Physics models

• Is complementary to LHC, heavy-flavor, dark matter, and neutrino experiments

• Is progressing on schedule... will begin commissioning in 2021

• Start discussing about Mu2e-II
ADDITIONAL INFORMATION
Fermilab accelerator scheme for Mu2e

- **Booster**: batch of $4 \times 10^{12}$ protons every $1/15^{th}$ second

- Booster “batch” is injected into the Recycler ring

- Batch is re-bunched into 4 bunches

- These are extracted one at a time to the Debuncher/Delivery ring

- As a bunch circulates, protons are extracted to produce the desired beam structure

- **Produces bunches of $\sim 3 \times 10^7$ protons each, separated by 1.7 µs (debuncher ring period)**
Other CLFV Predictions

<table>
<thead>
<tr>
<th>ratio</th>
<th>LHT</th>
<th>MSSM (dipole)</th>
<th>MSSM (Higgs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{Br(\mu^-\rightarrow e^-e^+e^-)}{Br(\mu^-\rightarrow e^-\gamma)}$</td>
<td>0.02...1</td>
<td>$\sim 6 \cdot 10^{-3}$</td>
<td>$\sim 6 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$\frac{Br(\tau^-\rightarrow e^-e^+e^-)}{Br(\tau^-\rightarrow e^-\gamma)}$</td>
<td>0.04...0.4</td>
<td>$\sim 1 \cdot 10^{-2}$</td>
<td>$\sim 1 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$\frac{Br(\tau^-\rightarrow \mu^-\mu^+\mu^-)}{Br(\tau^-\rightarrow \mu^-\mu^-\gamma)}$</td>
<td>0.04...0.4</td>
<td>$\sim 2 \cdot 10^{-3}$</td>
<td>0.06...0.1</td>
</tr>
<tr>
<td>$\frac{Br(\tau^-\rightarrow e^-\mu^+\mu^-)}{Br(\tau^-\rightarrow e^-\gamma)}$</td>
<td>0.04...0.3</td>
<td>$\sim 2 \cdot 10^{-3}$</td>
<td>0.02...0.04</td>
</tr>
<tr>
<td>$\frac{Br(\tau^-\rightarrow e^-\mu^-\mu^-)}{Br(\tau^-\rightarrow e^-\gamma)}$</td>
<td>0.04...0.3</td>
<td>$\sim 1 \cdot 10^{-2}$</td>
<td>$\sim 1 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$\frac{Br(\tau^-\rightarrow e^-e^+e^-)}{Br(\tau^-\rightarrow e^-\gamma)}$</td>
<td>0.8...2.0</td>
<td>$\sim 5$</td>
<td>0.3...0.5</td>
</tr>
<tr>
<td>$\frac{Br(\tau^-\rightarrow \mu^-\mu^+\mu^-)}{Br(\tau^-\rightarrow \mu^-\mu^-\gamma)}$</td>
<td>0.7...1.6</td>
<td>$\sim 0.2$</td>
<td>5...10</td>
</tr>
<tr>
<td>$\frac{R(\mu Ti\rightarrow eTi)}{Br(\mu^-\rightarrow e^-\gamma)}$</td>
<td>$10^{-3} \ldots 10^2$</td>
<td>$\sim 5 \cdot 10^{-3}$</td>
<td>0.08...0.15</td>
</tr>
</tbody>
</table>

Table 3: Comparison of various ratios of branching ratios in the LHT model ($f = 1$ TeV) and in the MSSM without [92,93] and with [96,97] significant Higgs contributions.

- Relative rates Conversions/MEG are model dependent
- Measure ratios to pin-down theory details
These are SuSy benchmark points for which LHC has discovery sensitivity. Some of these will be observable by MEG/Belle-2. All of these will be observable by Mu2e.
A typical Mu2e event: Calo track seeding

500 - 1695 ns window

± 50 ns around conversion electron

Search for tracking hits with time and azimuthal angle compatible with the calo clusters ( |ΔT| < 50 ns ) \( \Rightarrow \) simpler pattern recognition
Mu2e Expected Background (TDR)

(assuming ~ 10 GHz muon stops, 6x10^{17} stopped muons in 6x10^{7} s of beam time)

<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 (0.09)</td>
</tr>
<tr>
<td></td>
<td>Radiative µ Capture</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Radiative π Capture</td>
<td>0.023</td>
</tr>
<tr>
<td></td>
<td>Beam electrons</td>
<td>0.003(0.001)</td>
</tr>
<tr>
<td>Late Arriving</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>0.047 (0.024)</td>
</tr>
<tr>
<td></td>
<td>Cosmic Ray induced</td>
<td>0.082(0.018)</td>
</tr>
<tr>
<td>Total Background</td>
<td></td>
<td>0.36 (0.10)</td>
</tr>
</tbody>
</table>

Discovery sensitivity accomplished by suppressing backgrounds to < 0.5 event total

Upper Limit < 6 x 10^{-17} @ 90% C.L.
# Mu2e Expected Background (CD3 +)

(assuming ~ 10 GHz muon stops, $6 \times 10^{17}$ stopped muons in $6 \times 10^7$ s of beam time)

<table>
<thead>
<tr>
<th>Category</th>
<th>Source</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>µ Decay in Orbit</td>
<td></td>
<td>0.14 (0.11)</td>
</tr>
<tr>
<td>Intrinsics</td>
<td>Radiative µ Capture</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Radiative π Capture</td>
<td>0.025(0.003)</td>
</tr>
<tr>
<td></td>
<td>Beam electrons</td>
<td>2.5E-4</td>
</tr>
<tr>
<td></td>
<td>µ Decay in Flight</td>
<td>&lt;0.003</td>
</tr>
<tr>
<td>Late Arriving</td>
<td>π Decay in Flight</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Anti-proton induced</td>
<td>0.047(0.024)</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>Cosmic Ray induced</td>
<td>0.247(0.055)</td>
</tr>
<tr>
<td></td>
<td>Total Background</td>
<td>0.46(0.11)</td>
</tr>
</tbody>
</table>

Discovery sensitivity accomplished by suppressing backgrounds to < 0.5 event total

Upper Limit $< 6 \times 10^{-17}$ @ 90% C.L.
(WhatNext?) Mu2e → Mu2e-II

Project-X re-imagined to match Budget constraints:

1) PIP-2 plans:
   - 1 MW at LNBF at start (2025)
   - 2 MW at regime at LNBF
   - x 10 at Mu2e

Projectx-docdb.fnal.gov/cgi-bin/
ShowDocument?docid=1232
CLVF-snowmass → Arxiv.1311.5278
Mu2e-2 → Arxiv.1307.1168v2.pdf

2) Depending on the beam Structure available:
   - study Z dependence if signal is observed

3) If no signal is observed
   Use x 10 events in Mu2e-II

Some R&D and modifications of detector and shielding → $BR < 6 \times 10^{-18}$
Out of Time proton $\rightarrow$ Extinction Method

Proton extinction between pulses $\rightarrow$ # protons out of beam/# protons in pulse

achieving $10^{-10}$ is hard; normally get $10^{-2} - 10^{-3}$

- Internal (momentum scraping) and bunch formation in Accumulator
- External: oscillating (AC) dipole
  - high frequency (300 KHz) dipole with smaller admixture of 17th harmonic (5.1 MHz)
- Sweep Unwanted Beam into collimators

Calculations based on accelerator models that take into account collective effects
Shows that this combination gets $\sim 10^{-12}$
Extinction Monitor

- Thin foils in the Delivery Ring → Mu2e production target transport line (fast feedback)
- Off-axis telescope looking at the production target (slow feedback - timescale of hours)

Spectrometer based on ATLAS pixel detector

Reach a $10^{-10}$ extinction sensitivity in an hour or so
Cosmic Rays are a problem

Interacts with Al target, emits electron that mimics signal

• This happens once per day!