μ–e conversion and the Mu2e experiment at Fermilab

Eleonora Diociaiuti on behalf of the Mu2e collaboration
Tor Vergata University & LNF INFN
The collaboration

> 220 scientists from 38 institutions

Argonne National Laboratory, Boston University, 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 Nazionale di Frascati, University of Houston, Helmholtz-Zentrum Dresden-Rossendorf, INFN Genova, Institute for High Energy Physics, Protvino, Kansas State University, Lawrence Berkeley National Laboratory, INFN Lecce, University Marconi Rome, Lewis University, University of Liverpool, University College London, University of Louisville, University of Manchester, University of Michigan, University of Minnesota, Muon Inc., Northwestern University, Institute for Nuclear Research Moscow, INFN Pisa, Northern Illinois University, Purdue University, Rice University, Sun Yat-Sen University, University of South Alabama, Novosibirsk State University Budker Institute of Nuclear Physics, University of Virginia, University of Washington, Yale University
Outline

• Physics goal:
  - CLFV processes
  - Muonic atom related processes
• The Mu2e experiment:
  - the technique
  - the experimental setup
• Current status of construction
Charged Lepton Flavour Violation

- CLFV processes are forbidden in the Standard Model
- If the neutrino oscillations are included in a Minimal extension of the SM, CLFV processes are strongly suppressed \( (\Delta M_\nu^4/M_W^4 \sim 10^{-50}) \)
- Different New Physics models predict rates observable for the current/next CLFV experiments

<table>
<thead>
<tr>
<th>Process</th>
<th>Upper limit</th>
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<tbody>
<tr>
<td>( \mu^+ \to e^+\gamma )</td>
<td>&lt; 4.2 \times 10^{-13}</td>
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<tr>
<td>( \mu^+ \to e^+e^-e^- )</td>
<td>&lt; 1.0 \times 10^{-12}</td>
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<tr>
<td>( \mu^- N \to e^- N )</td>
<td>&lt; 7 \times 10^{-13}</td>
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<tr>
<td>( \mu^+e^- \to \mu^-e^+ )</td>
<td>&lt; 8.3 \times 10^{-11}</td>
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<td>( \tau \to e\gamma )</td>
<td>&lt; 3.3 \times 10^{-8}</td>
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<tr>
<td>( \tau^- \to \mu\gamma )</td>
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<td>( \tau^- \to e^-e^+e^- )</td>
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<td>( \pi^0 \to \mu e )</td>
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<td>( K_L^0 \to \mu e )</td>
<td>&lt; 4.7 \times 10^{-12}</td>
</tr>
<tr>
<td>( K^+ \to \pi^+\mu^+e^- )</td>
<td>&lt; 1.3 \times 10^{-11}</td>
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- Any observation will be a clear evidence of Physics Beyond the SM (BSM)
- Muons ideal for CLFV searches
  - High intensity beams
  - Clean topologies
Muon CLFV - time line

Current best limits:
BR(μ→eγ) < 4.2 × 10^{-13} MEG ’16
BR(μ→3e) < 1 × 10^{-12} SINDRUM ’98
R_{μe} < 7 × 10^{-13} SINDRUM-II 2006
R_{μe} ~ 8 × 10^{-17} Mu2e goal
Mu2e Design

PRODUCTION SOLENOID
- 8 Gev Protons hitting the target and producing mostly $\pi$
- Graded magnetic field reflects slow forward $\pi$

TRANSPORT SOLENOID
- Selection and transport of low momentum $\mu^-$
- Antiproton absorber in the mid-section

DETECTOR SOLENOID
- Capture $\mu$ on the Al target
- Momentum measurement in the tracker and energy reconstruction with calorimeter
- CRV to veto cosmic rays events
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Experimental technique

**Mu2e will look for coherent muon conversion into a muonic atom**

\[ \mu^- \text{Al} \rightarrow e^- \text{Al} \]

- Low momentum \( \mu \) beam (<100 MeV/c)
- High intensity pulsed rate
  - \( 10^{10} \mu/s \) stopped on Al
- Stopped \( \mu^- \) captured in atomic orbits
  - Cascade in the \( 1s \) state (~fs)

**Conversion process**

**Background**

**Normalisation**

**Signal**

**Mu2e will measure:**

\[
R_{\mu e} = \frac{\mu^- + N(A, Z) \rightarrow e^- + N(A, Z)}{\mu^- + N(A, Z) \rightarrow \nu\mu + N(A, Z - 1)} < 8.4 \times 10^{-17}
\]
Main backgrounds

- **Intrinsic** (*scales with the stopped μ*)
  - Muon decay in obit
    \[ \mu^- + Al \rightarrow e^- + \bar{\nu}_e + \nu_\mu + Al \]
  - Radiative μ capture
    \[ \mu^- + Al \rightarrow \nu_\mu + \gamma + Mg \]

- **Cosmic Rays**

- **Late arriving from prompt processes** *(scales with number of late protons)*
  - Radiative π capture
    \[ \pi^-N \rightarrow \gamma N^*, \gamma \rightarrow e^+e^- \]
    \[ \pi^-N \rightarrow e^+e^-N^* \]
  - μ/π decay in flight

- **Antiproton annihilation**
Main backgrounds

- **Intrinsic** \((scales\ with\ the\ stopped\ \(\mu\))
  - Muon decay in orbit
    \[ \mu^- + Al \rightarrow e^- + \bar{\nu}_e + \nu_\mu + Al \]
  - Radiative \(\mu\) capture
    \[ \mu^- + Al \rightarrow \nu_\mu + e^- + M_g \]

- **Cosmic Rays**

- **Late arriving from prompt processes** \((scales\ with\ number\ of\ late\ protons)\)
  - Radiative \(\pi\) capture
    \[ \pi^- N \rightarrow e^+ e^- N^* \]
    \[ \pi^- N \rightarrow e^+ e^- N^* \]
  - \(\mu/\pi\) decay in flight

- **Antiproton Annihilation**

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[Equations and graphs related to the content are shown.]
Minimising the main backgrounds

• The design of the Mu2e experiment is **optimised for the observation of CE events**.

• To get rid of low momentum particles ($p<57$ MeV) the tracker and the calorimeter presents a hole in the central part

• Muonic atomic life ($\tau = 864$ ns) $>>$ prompt backgrounds

• Narrow pulsed proton beam

• delayed signal window starting 700 ns after the initial proton pulse
The Detectors

**Aluminum target**
34 Al foils; the material choice is a compromise between the $\mu$ life time and $E_{ce}$

**Tracker**
~20k straw tubes; low mass detector with high performances ($\sigma <200$ keV/c)

**Calorimeter**
2 disks of CsI crystals; used for Particle Identification; $\sigma_E <10\%$

**Proton absorber**
made of high-density polyethylene; designed in order to reduce proton flux on the tracker and minimize energy loss

**Muon Beam Stop**
several concentric cylindrical structures of stainless steel and high density polyethylene; absorbs beam particles at the end of DS
Tracker

- 3 m long, 1.4 diameter in a 1 T uniform B field
- 18 stations made of 20k straw drift tubes:
  - 5 mm diameter, 15 μm Mylar walls
  - Ar:CO$_2$ (80:20) with HV~1500V

σ$_p$<180 keV/c @(100 MeV/c)
σ$_t$~ 1 ns
σ$_x$~100μm
Calorimeter

- 2 disks filled with 674 pure CsI crystals (34x34x200 mm$^3$) each
- Inner/outer radii: 35.1/66 cm
- Disk separation ~ 75 cm
- Crystal read-out by 2 UV-extended SiPMs
- Analog FEE and electronics in near-by electronics crates
- Work in vacuum and B = 1T
- PID: e/μ separation
- EMC seed track finder
- Standalone trigger

$\sigma_E < 10\%$ (100 MeV/c)
$\sigma_t \sim 500$ ps
$\sigma_x \leq 1$ cm
Cosmic Ray Veto

- CRs main source of backgrounds
  - 1 fake CE event per day
- CRV cover whole DS and part of TS
- passive shield and active veto
  - Four layers of extruded polystyrene scintillator counters with embedded wavelength shifting fibers, read out with SiPMs
- excellent muon veto efficiency (99.99%)
Mu2e sensitivity

Discovery sensitivity accomplished with 3 years of run and background suppression to <0.4 event total

5σ discovery @ 7 events

Mu2e simulation
3.6 × 10^{20} POT

Conversion $R_{\mu e} = 2 \times 10^{-16}$

Total background (stat+syst)

DIO background

Other backgrounds
Status of construction - Solenoids

• Conductor construction completed
• Winding procedure of the PS and DS started
• 1/2 TS completed and the modules are now under test
Status of the construction - Tracker

• Straws production completed
• Panel production will start in August
• preparing for a beam test @ Fermilab in the fall
Status of the construction - Calorimeter

- Test beam on a large size prototype
  - good energy and time resolution
- QA on SiPMs completed
- 1100/1400 crystals tested
  - end of test 10-2019
- Slice test of the whole electronics chain completed
- board design being upgraded to include rad-hard components
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Status of the construction - CRV

• Di-counter production started June 2018
  - Half production is done
• pre-production modules completed
• pre-production module tested
• analysis ongoing

First module being vacuum bagged.
Conclusion

• The Mu2e experiment is a discovery experiment looking for the CLFV process of a coherent conversion of muon into electron
• Mu2e will improve the sensitivity on conversion experiment of ~ 4 orders of magnitude up to 10000 TeV mass scale
• It provides discovery capabilities over a wide range on NP model
• Construction phase: 2017-2020
• Installation in 2021
• Commissioning phase will begin in 2022
• Start thinking about Mu2e-II —> increase x10 the intensity and the sensitivity
Spares
Muon CLFV - BSM theory

\[ L_{CLFV} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma^\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L) \]
Interval searches
**SUSY benchmark point**


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</table>

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models. ⭐⭐⭐⭐ signals large effects, ⭐⭐ visible but small effects and ⭐ implies that the given model does not predict sizable effects in that observable.
Proton beam

• Mu2e will use 8 GeV protons from the Booster
• Mu2e will repurpose much of the Tevatron anti-proton complex to instead produce muons
• Mu2e will collect data \textit{simultaneously} with NOvA and short baseline program
• 5% loss
We obtain model discriminating power on underlying physics mechanism by comparing CLFV rates on different stopping targets.

Model Discrimination

- Vector Z-penguin
- Vector γ-penguin
- Dipole e.g. SUSY GUTS
- Scalar e.g. SUSY SeeSaw
**Prompt background**

**Radiative pion capture:**
Non-decayed pion reaches stopping target, is radiatively captured, then photon converts:

\[ \pi^- N \rightarrow \gamma N \]
\[ \gamma \rightarrow e^- e^+ \]

The electron can have momentum in signal window, and mimic conversion event.

Simply wait until their rates are lowered before initiating live window to look for signal.
A typical event

- Search for tracking hits with time and azimuthal angle compatible with the calorimeter clusters (\(|\Delta T| < 50 \text{ ns}\)) → **simpler pattern recognition**
### Background summary

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

- 3 years at \(1.2 \times 10^{20}\) protons/year (8 kW beam power)
- Expect <0.5 background event in 3 years
competitor experiments @ J-Park

- Al target:
  - SES : $3 \times 10^{-15}$ (Phase I)
  - SES : $2 \times 10^{-15}$ (Phase II)
- Phase I is now under construction
- Directly measure the muon beam with prototypes of Phase-II detector.

- Graphite target: SES<$10^{-13}$
- SiC target: SES<$10^{-15}$
- Construction of detector system completed:
  - spectrometer from TRIUMF
  - tracker
Calorimeter TB

Large size prototype: 51 crystals coupled to 102 sensors

- Goals:
  - Test performances
  - Test integration and assembly procedures
  - Operate under vacuum, low temperature and irradiation test

- e- beam (60-120)MeV
  - Orthogonal and tilted (~50°) configuration
  - Readout: 1 GHz CAEN digitizers (DRS4 chip), 2 boards x 32 channels
Mu2e signal?

- A next-generation Mu2e experiment makes sense in all scenarios:
  - Push sensitivity or
  - Study underlying new physics
  - Will need more protons
  - Upgrade accelerator
  - **Snowmass** white paper, arXiv:1802.02599