The Mu2e experiment at Fermilab: R&D, design and status

Eleonora Diociaiuti
LNF-INFN and Tor Vergata university
On behalf of the Mu2e collaboration
Outline

- Charged Lepton Flavour Violation (CLFV) processes
- Muon Conversion
- Mu2e experiment
- Conclusion
Charged Lepton Flavour Violation

- CLFV processes are strongly suppressed in the SM
  - Not forbidden due to the neutrino oscillation
  - Negligible (rate $\sim \Delta M^4/\langle M_W^4 \rangle < 10^{-50}$)

- Different models of New Physics (NP) predict rates observable at next generation CLFV experiments → An observation will be a clear evidence of Physics Beyond the Standard Model (BSM)

<table>
<thead>
<tr>
<th>Process</th>
<th>Current Limit</th>
<th>Next Generation exp</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \to \mu \eta$</td>
<td>BR &lt; 6.5 E-8</td>
<td></td>
</tr>
<tr>
<td>$\tau \to \mu \gamma$</td>
<td>BR &lt; 6.8 E-8</td>
<td></td>
</tr>
<tr>
<td>$\tau \to \mu \mu \mu$</td>
<td>BR &lt; 3.2 E-8</td>
<td></td>
</tr>
<tr>
<td>$\tau \to eee$</td>
<td>BR &lt; 3.6 E-8</td>
<td></td>
</tr>
<tr>
<td>$K_L \to e\mu$</td>
<td>BR &lt; 4.7 E-12</td>
<td></td>
</tr>
<tr>
<td>$K^* \to \pi^+e^-\mu^+$</td>
<td>BR &lt; 1.3 E-11</td>
<td></td>
</tr>
<tr>
<td>$B^0 \to e\mu$</td>
<td>BR &lt; 7.8 E-8</td>
<td></td>
</tr>
<tr>
<td>$B^+ \to K^* e\mu$</td>
<td>BR &lt; 9.1 E-8</td>
<td></td>
</tr>
<tr>
<td>$\mu^+ \to e^+\gamma$</td>
<td>BR &lt; 4.2 E-13</td>
<td>$10^{-14}$ (MEG)</td>
</tr>
<tr>
<td>$\mu^+ \to e^+e^-e^-$</td>
<td>BR &lt; 1.0 E-12</td>
<td>$10^{-16}$ (PSI)</td>
</tr>
<tr>
<td>$\mu N \to eN$</td>
<td>$\mathcal{R}_{\mu e} &lt; 7.0$ E-13</td>
<td>$10^{-17}$ (Mu2e, COMET)</td>
</tr>
</tbody>
</table>

- Muon channels are ideal for CLFV search
  - Clean topologies
  - Large rates
Muon CLFV - time line

\[ \mu \rightarrow e\gamma \]

\[ \mu \rightarrow 3e \]

\[ \mu N \rightarrow eN \]

Current best limits:
BR(\(\mu \rightarrow e\gamma\)) < \(4.2 \times 10^{-13}\) MEG 2016
BR(\(\mu \rightarrow 3e\)) < \(1 \times 10^{-12}\) SINDRUM 1998
\(R_{\mu e} < 6.1 \times 10^{-13}\) SINDRUM-II 2006
\(R_{\mu e} \sim 10^{-17}\) \textbf{Mu2e goal}

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

09/05/18
Muon CLFV – BSM theory

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

**LOOP TERM**

**CONTACT TERM**

Heavy Neutrinos

\[ |U_{\mu N}| U_{eN} |^2 \approx 8 \times 10^{-13} \]

Second Higgs Doublet

\[ g(H_{\mu e}) \approx 10^{-4} g(H_{\mu t}) \]

Supersymmetry

rate \( \approx 10^{-15} \)

Model which can be probed also by \( \mu \rightarrow e\gamma \) searches

Direct coupling between quarks and leptons, better accessed by \( \mu N \rightarrow eN \)

Heavy Z’ Anomalous Z Coupling

\[ M_{Z'} = 3000 \text{ TeV/c}^2 \]

Compositeness

\[ \Lambda_c \approx 3000 \text{ TeV} \]

M$_{\text{LQ}}$ = 3000 (\( \lambda_{\mu\mu} \lambda_{\phi\phi} \))$^{1/2}$ TeV/c$^2$
Mu2e physics reach

Muon conversion is a unique probe for physics BSM:

- Broad discovery sensitivity across all models
- Mass scale discovery up to $\sim 10000$ TeV, significantly above the direct reach of LHC
- Clear experimental signature: neutrinoless and mono-energetic electron:
  - $E_e = 104.96$ MeV
Experimental technique

Mu2e will look for coherent muon conversion into a muonic atom

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

- Generation of a \( \mu^- \) beam
  - Low momentum (<100 MeV/c)
  - High intensity “pulsed” rate
- Stop the beam in a Al target

Decay In Orbit (DIO) (BR=39%)

Muon Capture (BR=61%)

The conversion process results in a clear signature of a single electron (CE) with a mono-energetic spectrum close to the muon rest mass.
Mu2e sensitivity

- Measure the ratio of the $\mu$-e conversion wrt the conventional $\mu$ capture

$$R_{\mu e} = \frac{\mu^- + N(A, Z) \rightarrow e^- + N(A, Z)}{\mu^- + N(A, Z) \rightarrow \nu_{\mu} + N(A, Z - 1)} < 8.4 \times 10^{-17}$$

- To obtain a Single Event Sensitivity of $3 \times 10^{-17}$
  - $10^{18}$ stopped muons
  - High background suppression
Mu2e Design

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

**TRANSPORT SOLENOID**
- Selection and transportation of low momentum $\mu^-$

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

Some hits

Lower $P_T$

Larger $P_T$
Tracker

- 3 m long, 1.4 m diameter in a 1 T uniform B field
- Maximize/minimize the acceptance for CE/DIO
- ~20000 straw drift tubes organized into 18 stations, 2 planes per station
- Each straw is 5 mm diameter, with 25 µm sense wire, 15 µm Mylar wall

**Momentum resolution <170 keV/c (@100 MeV/c)**

**Timing resolution ~ 1 ns**

**Spatial resolution ~ 100 µm**
Electromagnetic Calorimeter

- Energy resolution < 5% (@ 100 MeV)
- Timing resolution < 0.5 ns
- Spatial resolution < 1 cm

- 2 annular disks with 674 CsI (30x30x200) mm³ crystals each
- Crystal read-out by 2 custom SiPMs
- Work in vacuum and B = 1T

- Acceptance optimized to observe conversion electron Ee~105 MeV
- PID and e/µ discrimination
- Help the track reconstruction
Cosmic Ray Veto (CRV)

- CR are the major source of background (1 fake CE event per day)
- CRV composed of 4 layers of overlapping scintillator
- CRV is placed around the DS and part of the TS
- Required efficiency 0.9999
Mu2e expectation with full simulation

Discovery sensitivity accomplished with 3 year of running and background suppression to <0.4 event total
Conclusions

- The Mu2e experiment is a discovery experiment looking for the CLFV event of a coherent conversion of muon into electron in the electric field of a nucleus.
- Mu2e will improve the sensitivity on conversion experiment of ~ 4 order of magnitude.
- It provides discovery capabilities over a wide range on NP model.
- Construction phase: 2017-2019
- Installation in 2020
- Commissioning phase will begin in 2021
- Start thinking about Mu2e-II ➔ increase the intensity x10 and the sensitivity.
These are SuSy benchmark point for which LHC has discovery sensitivity

Some of these will be observable by MEG/Belle-2

All of these will be observable by Mu2e

<table>
<thead>
<tr>
<th>Process</th>
<th>SPS 1a CKM $U_{e3} = 0$</th>
<th>SPS 1b CKM $U_{e3} = 0$</th>
<th>SPS 2 CKM $U_{e3} = 0$</th>
<th>SPS 3 CKM $U_{e3} = 0$</th>
<th>Future Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BR}(\mu \rightarrow e\gamma)$</td>
<td>$3.2 \cdot 10^{-14}$</td>
<td>$3.8 \cdot 10^{-13}$</td>
<td>$4.0 \cdot 10^{-13}$</td>
<td>$1.2 \cdot 10^{-12}$</td>
<td>$1.3 \cdot 10^{-15}$</td>
</tr>
<tr>
<td>$\text{BR}(\mu \rightarrow eee)$</td>
<td>$2.3 \cdot 10^{-16}$</td>
<td>$2.7 \cdot 10^{-15}$</td>
<td>$2.9 \cdot 10^{-15}$</td>
<td>$8.6 \cdot 10^{-15}$</td>
<td>$9.4 \cdot 10^{-18}$</td>
</tr>
<tr>
<td>$\text{CR}(\mu \rightarrow e\text{ in Ti})$</td>
<td>$2.0 \cdot 10^{-15}$</td>
<td>$2.4 \cdot 10^{-14}$</td>
<td>$2.6 \cdot 10^{-15}$</td>
<td>$7.6 \cdot 10^{-14}$</td>
<td>$1.0 \cdot 10^{-16}$</td>
</tr>
<tr>
<td>$\text{BR}(\tau \rightarrow e\gamma)$</td>
<td>$2.3 \cdot 10^{-12}$</td>
<td>$6.0 \cdot 10^{-13}$</td>
<td>$3.5 \cdot 10^{-12}$</td>
<td>$1.7 \cdot 10^{-12}$</td>
<td>$1.4 \cdot 10^{-13}$</td>
</tr>
<tr>
<td>$\text{BR}(\tau \rightarrow eee)$</td>
<td>$2.7 \cdot 10^{-14}$</td>
<td>$7.1 \cdot 10^{-15}$</td>
<td>$4.2 \cdot 10^{-14}$</td>
<td>$2.0 \cdot 10^{-14}$</td>
<td>$1.7 \cdot 10^{-15}$</td>
</tr>
<tr>
<td>$\text{BR}(\tau \rightarrow \mu\gamma)$</td>
<td>$5.0 \cdot 10^{-11}$</td>
<td>$1.1 \cdot 10^{-8}$</td>
<td>$7.3 \cdot 10^{-11}$</td>
<td>$1.3 \cdot 10^{-8}$</td>
<td>$2.9 \cdot 10^{-12}$</td>
</tr>
<tr>
<td>$\text{BR}(\tau \rightarrow \mu\mu\mu)$</td>
<td>$1.6 \cdot 10^{-13}$</td>
<td>$3.4 \cdot 10^{-11}$</td>
<td>$2.2 \cdot 10^{-13}$</td>
<td>$3.9 \cdot 10^{-11}$</td>
<td>$8.9 \cdot 10^{-15}$</td>
</tr>
</tbody>
</table>
Background for Mu2e

- **Intrinsic physics background:**
  - Muon Decay in Orbit (DIO) → end point @ signal energy
  - Radiative Muon Capture → πN → γN'; γ → e⁺e⁻
  - Neutron from muon nuclear capture
  - Proton from muon nuclear capture

- **Beam related backgrounds:**
  - Radiative Pion Capture (RPC)
  - Beam electron
  - Muon decay in flight
  - Neutron
  - Antiprotons producing pions when annihilating in the target

- **Cosmic rays**
DIO background

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

- The Michel spectrum is distorted by the presence of the nucleus and the electron can have an energy similar to the one of CE if neutrino are almost at rest

→ **To separate DIO endpoint from CE line Mu2e needs an high Resolution Spectrometer**
Minimizing prompt background

- Prompt backgrounds arise from the interaction occurring at the stopping target
  - Radiative Pion Capture (\( \tau_{\pi^{Al}} = 26 \) ns)
    \[ \pi^- N \rightarrow \gamma N^* \rightarrow e^+ e^- N^* \]
  - \( \pi/\mu \) decay in flight

- Muonic atomic life >> prompt background
- Narrow pulsed proton beam
- Delayed signal window starting 700 ns after the initial proton pulse
- Out-of-time proton suppressed by \( O(10^{10}) \)

E. Diociaiuti | The Mu2e experiment
A typical Mu2e event: calo track seeding

500 - 1695 ns windows

± 50 ns around conversion electron

- Search for tracking hits with time and azimuthal angle compatible with the calorimeter clusters ( |ΔT| < 50 ns ) \(\rightarrow\) **simpler pattern recognition**
What’s next

Signal?
- Yes
  - Precision measurement
  - Measure $R_{\mu e}$ for different targets
- No
  - Higher search sensitivity
  - Accelerator upgrade

Cirigliano, et al., PRD 80, 013002 (2009)

Vector $Z$-penguin
Vector $\gamma$-penguin
Dipole e.g. SUSY GUTS
Scalar e.g. SUSY SeeSaw