Mu2e: a search for charged lepton flavor violation
The Mu2e collaboration

~200 scientists from 35 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 for Nuclear Research, Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionali di Frascati, Helmholtz-Zentrum Dresden-Rossendorf, University of Houston, University of Illinois, INFN Genova, Kansas State University, Lawrence Berkeley National Laboratory, INFN Lecce and Università del Salento, Lewis University, University of Louisville, Laboratori Nazionali di Frascati and Università Marconi Roma, University of Minnesota, Muons Inc., Northern Illinois University, Northwestern University, Novosibirsk State University/Budker Institute of Nuclear Physics, Institute for Nuclear Research, Moscow, INFN Pisa, Purdue University, Rice University, University of South Alabama, Sun Yat Sen University, University of Virginia, University of Washington, Yale University

G. Pezzullo  (Yale University)
What is $\mu \rightarrow e$ conversion

- $\mu$ converts to an electron in the presence of a nucleus $\mu^- N \rightarrow e^- N$

$$E_e = m_\mu c^2 - B_\mu(Z) - C(A) = 104.973 \text{ MeV}$$

- for Aluminum:
  $B_\mu(Z)$ is the muon binding energy (0.48 MeV)
  $C(A)$ is the nuclear recoil energy (0.21 MeV)

- Signal normalization:

$$R_{\mu e} = \frac{\Gamma (\mu^- + N \rightarrow e^- + N)}{\Gamma (\mu^- + N \rightarrow \text{all captures})}$$
• **CLFV** process forbidden in the **SM**

• \( \mu \) conversion in the extend-SM is introduced by the **neutrino masses and mixing** at a negligible level \( \sim 10^{-52} \)

![Diagram showing CLFV process](image)

• Many **SM extensions enhance the rate** through mixing in the high energy sector of the theory (other particles in the loop…)

G. Pezzullo  (Yale University)
NP contributions to $\mu \rightarrow e$

- **SUSY**
- **Heavy neutrino**
- **Two Higgs doublet**
- **Compositeness**
- **Leptoquarks**
- **$Z'/\text{anomalous couplings}$**

- Any signal observation would be an unambiguous sign of **NP**
History of $\mu \rightarrow e$ search

History of $\mu \rightarrow e\gamma$, $\mu N \rightarrow eN$, and $\mu \rightarrow 3e$

Mu2e will improve the current limit by a factor $10^4$!
Model independent Lagrangian

\[ L_{CLFV} = \frac{m_\mu}{(\kappa + 1)} \Lambda^2 \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(\kappa + 1)} \Lambda^2 \bar{\mu}_L \gamma_{\mu} e_L (\bar{e}\gamma^\mu e) \]

“dipole term”

“contact term”

\( \Lambda \) (TeV)

All Limits are at 90\% CL

- \( R_{\mu e}(\mu N \rightarrow eN \text{ on Al}) < 6 \times 10^{-18} \)
- \( R_{\mu e}(\mu N \rightarrow eN \text{ on Au}) < 6 \times 10^{-18} \)
- \( B(\mu \rightarrow e\gamma) < 4.2 \times 10^{-14} \)\text{ MEG–II}
- \( B(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13} \)\text{ MEG}
- \( R_{\mu e}(\mu N \rightarrow eN \text{ on Al}) < 7 \times 10^{-13} \)
- \( R_{\mu e}(\mu N \rightarrow eN \text{ on Au}) < 7 \times 10^{-13} \)
- \( R_{\mu e}(\mu N \rightarrow eN \text{ on Al}) < 7 \times 10^{-13} \)

G. Pezzullo (Yale University)
Experimental setup

- **Production Solenoid:**
  ➡ Proton beam strikes target, producing mostly $\pi$
  ➡ Graded magnetic field contains backwards $\pi/\mu$ and reflects slow forward $\pi/\mu$

- **Detector Solenoid:**
  ➡ Capture muons on Al target
  ➡ Measure momentum in tracker and energy in calorimeter
  ➡ Graded field “focuses” $e^-$ in tracker fiducial

- **Transport Solenoid:**
  ➡ Select low momentum, negative muons
  ➡ Antiproton absorber in the mid-section
**Mu2e detector**

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

- **Tracker:**
  - ~20k straw tubes arranged in planes on stations, the tracker has 18 stations
  - Expected momentum resolution < 200 keV/c

- **Targets:**
  - 34 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (864 ns) that matches nicely the need of prompt separation in the Mu2e beam structure.

- **Calorimeter:**
  - 2 disks composed of undoped CsI crystals

- **Muon beam stop:**
  - made of several cylinders of different materials: stainless steel and polyethylene
Muonic atom

- Stopped $\mu^-$ is captured in atomic orbits
  - quickly (\(\sim\) fs) cascades into 1S state
- Bohr radius $\sim$20 fm (for Al)
  - significant overlap between the $\mu^-$ and nucleus wave-functions
- For a $\mu^-$ in orbit three processes may happen:

  - **decay** (39\%): $\mu^- N \rightarrow e^- \bar{\nu}_e \nu_\mu N$, **background**
  - **capture** (61\%): $\mu^- + N \rightarrow \nu_\mu + N'$, **normalization**
  - **conversion** (<10^{-13}): $\mu^- + N \rightarrow e^- + N$, **signal**
Mu2e detector

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

- **Tracker:**
  - ~20k straw tubes arranged in planes on stations, the tracker has 18 stations
  - Expected momentum resolution < 200 keV/c

- **Targets:**
  - 34 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (864 ns) that matches nicely the need of prompt separation in the Mu2e beam structure.

- **Calorimeter:**
  - 2 disks composed of undoped CsI crystals

- **Muon beam stop:**
  - made of several cylinders of different materials: stainless steel, lead and high density polyethylene
Physics background

• μ decay-in-orbit:
  ✓ low-mass tracker with high performance

• Cosmic-induced background:
  ✓ cosmic ray veto and PID

• Antiproton-induced background
  ✓ absorbers in the beam line to annihilate p-bar and PID

• Radiative π capture: \( \pi^- N_z \rightarrow N^{*}_{z-1} \gamma \), asymmetric \( \gamma \rightarrow e^- e^+ \)
  ✓ pulsed beam and extinction of out-of-time protons
\( \mu^ - N \rightarrow e^- \bar{\nu}_e \nu_\mu N \)

\[ \frac{R(DIO)}{R(\text{stopped-}\mu)} \sim 39\% \]

\( \sim 10^{18} \) \( \mu \) stopped in the Mu2e

@ the endpoint

conversion energy

\( (E_{\text{conversion}} - E)^5 \)

tail from recoil
Tracker design

- 18 stations equally spaced with straws transverse to the beam
- Straw technology employed:
  ✓ 5 mm diameter, 12 µm Mylar walls
  ✓ 25 µm Au-plated W sense wire
  ✓ 80/20 Ar/CO₂ with HV ~ 1500 V
- Inner 38 cm un-instrumented:
  ✓ blind to beam flash
  ✓ blind to low pT particles, almost all the DIO
Physics background

• \( \mu \) decay-in-orbit:
  ✓ low-mass tracker with high performance

• **Cosmic-induced background:**
  ✓ cosmic ray veto and PID

• Antiproton-induced background
  ✓ absorbers in the beam line to annihilate p-bar and PID

• Radiative \( \pi \) capture: \( \pi^- N_z \rightarrow N_{z-1}^* \gamma \), asymmetric \( \gamma \rightarrow e^- e^+ \)
  ✓ pulsed beam and extinction of out-of-time protons
Cosmic Ray Veto

- Veto system covers entire DS and half TS
- 4 layers of scintillator
  - each bar is $5 \times 2 \times \sim 450$ cm$^3$
  - 2 WLS fibers/bar
  - read out at both ends with SiPM
- required inefficiency $\sim 10^{-4}$
Calorimeter

- 2 disks; each disk contains 674 undoped CsI crystals 20 x 3.4 x 3.4 cm³
- Disk separation ~ 70 cm
- Inner/outer radii: 37.4/66 cm
- Readout system:
  - 2 large area SiPM-array/crystal
  - 12 bit, 250 MHz waveform-based digitizer boards
Physics background

- $\mu$ decay-in-orbit:
  - ✓ low-mass tracker with high performance

- Cosmic-induced background:
  - ✓ cosmic ray veto and PID

- **Antiproton-induced background**
  - ✓ absorbers in the beam line to annihilate p-bar and PID

- Radiative $\pi$ capture: $\pi^- N_z \rightarrow N^*_{z-1} \gamma$, asymmetric $\gamma \rightarrow e^- e^+$
  - ✓ pulsed beam and extinction of out-of-time protons
Physics background

- **µ decay-in-orbit:**
  - ✓ low-mass tracker with high performance

- **Cosmic-induced background:**
  - ✓ cosmic ray veto and PID

- **Antiproton-induced background**
  - ✓ absorbers in the beam line to annihilate p-bar and PID

- **Radiative π capture:** $\pi^+ N_z \rightarrow N^*_{z-1} \gamma$, asymmetric $\gamma \rightarrow e^- e^+$
  - ✓ pulsed beam and extinction of out-of-time protons
Pulsed beam

- Beam period: $1.7 \, \mu s \sim 2 \times \tau_{Al}^{A}$
- Beam intensity: $3.9 \times 10^7 \, \text{p/bunch}$
- Duty cycle: $\sim 30\%$
- Extinction: Out-of-time protons / in-time protons $< 10^{-10}$
Mu2e sensitivity

Mu2e simulation
3.6 \times 10^{20} \text{ POT}

- Conversion $R_{\mu e} = 2 \times 10^{-16}$
- Total background (stat+syst)
- DIO background
- Other backgrounds

Signal region
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
\[ R_{\mu e} \text{ rate vs } Z \]

- Can use ratio of rates to determine dominant operator contribution
- Life time of the $\mu$-atom plays also a role in the $Z$ choice:
  - $\tau_\mu(\text{Al}) = 864 \text{ ns}$
  - $\tau_\mu(\text{Ti}) = 338 \text{ ns}$
  - $\tau_\mu(\text{Au}) = 74 \text{ ns}$
Mu2e Upgrade

- Studies for x10 improvement with Ti look promising and will be continued; EOI written (1307.1168 and EOI at 1802.02599)

- Investigating $\mu^- N \rightarrow e^+ N$ related to Majorana neutrino physics

- We need detector and solenoid improvements
  - may need new production solenoid to handle lower energy beam and higher power.

- FNAL PIP-II natural for both pulsed and non-pulsed CLFV, could do $\mu^- N \rightarrow e^\pm N$, $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$, $\mu^- e^- \rightarrow e^- e^-$
Mu2e detector hall

Coils module @ ASC

Splice between solenoids @ GA

Primary beam line

North face
Summary

• Mu2e will improve the sensitivity by four orders of magnitude
• Provides discovery capabilities over a wide range of new Physics Models
• **R&D mature with data taking scheduled on 2022**
• More info: [http://mu2e.fnal.gov](http://mu2e.fnal.gov)
backup slides
Extinction of out-of-time protons

• The RF structure of the Recycler provides some “intrinsic” extinction:
  ✓ **Intrinsic extinction ~**10\(^{-5}\)

• A custom-made AC dipole placed just upstream of the production solenoid provides additional extinction:
  ✓ **AC dipole extinction ~ 10^{-6} - 10^{-7}\right]**

• Together they provide a total extinction:
  ✓ **Total extinction ~ 10^{-11} - 10^{-12}\right]**

• Extinction measured using a detector system: Si-pixel + sampling EMC
Muonic atom life times

![Graph showing muonic atom life times](image)

- Z=13 Al $\tau=864$ ns
- Z=22 Ti $\tau=329$ ns
- Z=79 Au $\tau=72$ ns
$R_{\mu e}$ rate vs $Z$

V. Cirigliano et al., phys. Rev. D80 013002 (2009)
# Mu2e sensitivity


<table>
<thead>
<tr>
<th>Effect</th>
<th>AC</th>
<th>RVV2</th>
<th>AKM</th>
<th>δLL</th>
<th>FBMSSM</th>
<th>LHT</th>
<th>RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 - \bar{D}^0$</td>
<td>★★★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★★</td>
<td>★</td>
</tr>
<tr>
<td>$\varepsilon_K$</td>
<td>★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★</td>
<td>★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$S_{\phi}$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★</td>
</tr>
<tr>
<td>$S_{\phi K^0}$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$A_{\phi}(B \to X_s \gamma)$</td>
<td>★</td>
<td>★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$A_{7,8}(B \to K^* \mu^+ \mu^-)$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$A_8(B \to K^* \mu^+ \mu^-)$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$B \to K^{(*)} \nu \bar{\nu}$</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>$B_s \to \mu^+ \mu^-$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$K^+ \to \pi^+ \nu \bar{\nu}$</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$K_L \to \pi^0 \nu \bar{\nu}$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$\mu \to e \gamma$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$\tau \to \mu \gamma$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$\mu + N \to e + N$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$d_n$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$d_e$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$(g-2)_\mu$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
</tbody>
</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.
## CLFV limits I

<table>
<thead>
<tr>
<th>Process</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+ \rightarrow e^+\gamma$</td>
<td>$&lt; 5.7 \times 10^{-13}$</td>
</tr>
<tr>
<td>$\mu^+ \rightarrow e^+e^-e^+$</td>
<td>$&lt; 1.0 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\mu^-\text{Ti} \rightarrow e^-\text{Ti}$</td>
<td>$&lt; 1.7 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\mu^-\text{Au} \rightarrow e^-\text{Au}$</td>
<td>$&lt; 7 \times 10^{-13}$</td>
</tr>
<tr>
<td>$\mu^+e^- \rightarrow \mu^-e^+$</td>
<td>$&lt; 3.0 \times 10^{-13}$</td>
</tr>
<tr>
<td>$\tau \rightarrow e\gamma$</td>
<td>$&lt; 3.3 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu\gamma$</td>
<td>$&lt; 4.4 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow e^-e^+e^-$</td>
<td>$&lt; 2.7 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^-\mu^+\mu^-$</td>
<td>$&lt; 2.1 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow e^-\mu^+\mu^-$</td>
<td>$&lt; 2.7 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^-e^+e^-$</td>
<td>$&lt; 1.8 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow e^+\mu^-\mu^-$</td>
<td>$&lt; 1.7 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^+e^-e^-$</td>
<td>$&lt; 1.5 \times 10^{-8}$</td>
</tr>
</tbody>
</table>
## CLFV limits 2

<table>
<thead>
<tr>
<th>Process</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0 \rightarrow \mu e$</td>
<td>$&lt; 8.6 \times 10^{-9}$</td>
</tr>
<tr>
<td>$K^0_L \rightarrow \mu e$</td>
<td>$&lt; 4.7 \times 10^{-12}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \mu^+ e^-$</td>
<td>$&lt; 2.1 \times 10^{-10}$</td>
</tr>
<tr>
<td>$K^0_L \rightarrow \pi^0 \mu^+ e^-$</td>
<td>$&lt; 4.4 \times 10^{-10}$</td>
</tr>
<tr>
<td>$Z^0 \rightarrow \mu e$</td>
<td>$&lt; 1.7 \times 10^{-6}$</td>
</tr>
<tr>
<td>$Z^0 \rightarrow \tau e$</td>
<td>$&lt; 9.8 \times 10^{-6}$</td>
</tr>
<tr>
<td>$Z^0 \rightarrow \tau \mu$</td>
<td>$&lt; 1.2 \times 10^{-6}$</td>
</tr>
</tbody>
</table>