The Mu2e experiment
Finding a needle in a trillion haystack

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On behalf of the Mu2e Collaboration*

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* The full Mu2e Collaboration is listed at http://mu2e.fnal.gov/collaboration.shtml
The Mu2e collaboration

About 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 of Nuclear Research Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionale di Frascati, University of Houston, Helmholtz-Zentrum Dresden-Rossendorf, University of Illinois, INFN Genova, Lawrence Berkeley National Laboratory, INFN Lecce, University Marconi Rome, Kansas State University, Lewis University, University of Louisville, University of Minnesota, Muons Inc., Northwestern University, Institute for Nuclear Research Moscow, Northern Illinois University, INFN Pisa, Purdue University, Sun Yat-Sen University, Novosibirsk State University/Budker Institute of Nuclear Physics, Rice University, University of South Alabama, University of Virginia, University of Washington, Yale University
The Mu2e experiment at Fermilab will search for the neutrinoless conversion of a muon to an electron in the Coulomb field of a nucleus $\mu N \rightarrow eN$.

This reaction violates charged lepton flavor conservation (CLFV) and is extremely suppressed in the Standard Model because it occurs through neutrino mixing.

The conversion ratio $R_{\mu e} \sim 10^{-52}$ in the $\nu$SM, effectively zero! This is virtually a background free environment.

Many New Physics scenarios can enhance CLFV rates to observable values.

Mu2e aims to improve the current sensitivity by four orders of magnitude.

**Observation of CLFV is an unambiguous sign of New Physics**
Many people have searched for CLFV in muon decays

Muon an independent lepton, no $\mu \rightarrow e \gamma$

$\mu \rightarrow e \gamma \sim 10^{-4}/10^{-5}$ or two $\nu$

Feinberg (1958)

No $\mu \rightarrow e \gamma \Rightarrow$ Two neutrinos!
The Mu2e experiment will search for muon-to-electron conversion in the coulomb field of a nucleus $\mu N \rightarrow eN$ with a sensitivity 10000 better than the current world’s best limit.
## How rare is that?

<table>
<thead>
<tr>
<th>Probability of...</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>rolling a 7 with two dice</td>
<td>1.67E-01</td>
</tr>
<tr>
<td>rolling a 12 with two dice</td>
<td>2.78E-02</td>
</tr>
<tr>
<td>getting 10 heads in a row flipping a coin</td>
<td>9.77E-04</td>
</tr>
<tr>
<td>drawing a royal flush (no wild cards)</td>
<td>1.54E-06</td>
</tr>
<tr>
<td>getting struck by lightning in one year in the US</td>
<td>2.00E-06</td>
</tr>
<tr>
<td>winning Pick-5</td>
<td>5.41E-08</td>
</tr>
<tr>
<td>winning MEGA-millions lottery (5 numbers+megaball)</td>
<td>3.86E-09</td>
</tr>
<tr>
<td>your house getting hit by a meteorite this year</td>
<td>2.28E-10</td>
</tr>
<tr>
<td>drawing two royal flushes in a row (fresh decks)</td>
<td>2.37E-12</td>
</tr>
<tr>
<td>your house getting hit by a meteorite today</td>
<td>6.24E-13</td>
</tr>
<tr>
<td>getting 53 heads in a row flipping a coin</td>
<td>1.11E-16</td>
</tr>
<tr>
<td>your house getting hit by a meteorite AND you being struck by lightning both within the next six months</td>
<td>1.14E-16</td>
</tr>
<tr>
<td>your house getting hit by a meteorite AND you being struck by lightning both within the next three months</td>
<td>2.85E-17</td>
</tr>
</tbody>
</table>

~ Mu2e single event sensitivity

Courtesy of R. Hooper

Pretty rare!!! Please let us know if this happens to you...
Probing New Physics

New Physics can enhance rate to observable values, either through loops or exchange of heavy intermediates particles

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

Can probe mass scales way beyond direct reach of colliders

Complementary to other CLFV searches (e.g. $\mu \rightarrow e \gamma$) and direct searches at the LHC

See for example
A. de Gouvêa, P. Vogel, arXiv:1303.4097
**CLFV and SUSY**

Probe Supersymmetry (SUSY) through loops

If SUSY seen at LHC → rate $\sim 10^{-15}$

Implies dozens of signal events with negligible background in Mu2e for many SUSY models.

Complementarity between measurements

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Muon-to-electron conversion: experimental concept

Neutrinoless muon-to-electron conversion in the Coulomb field of a nucleus

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

\[ R_{\mu e} = \frac{\Gamma[\mu^- + A(Z, N) \rightarrow e^- + A(Z, N)]}{\Gamma[\mu^- + A(Z, N) \rightarrow \nu_\mu + A(Z - 1, N + 1)]} \]

Muon is captured by Al nucleus.
Neutrinoless muon-to-electron conversion in the Coulomb field of a nucleus

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

Muon quickly cascades to 1s orbit (~ps), emitting x-ray in the process.

Measure x-ray spectrum to estimate number of muon captures
Neutrinoless muon-to-electron conversion in the Coulomb field of a nucleus

$\mu^- N \rightarrow e^- N$

$$R_{\mu e} = \frac{\Gamma[\mu^- + A(Z, N) \rightarrow e^- + A(Z, N)]}{\Gamma[\mu^- + A(Z, N) \rightarrow \nu_\mu + A(Z - 1, N + 1)]}$$
Muon-to-electron conversion: experimental concept

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Experimental signature:

One single mono-energetic electron of 105 MeV for Al nucleus

Coherent process, the nucleus remains intact
We need both an accelerator complex that can produce a pulsed muon beam and an experiment that can detect the conversion signal with the required sensitivity.

Muon campus at Fermilab. Bonus: you’re not too far from the cafeteria...
**Production Target / Solenoid (PS)**

- Proton beam strikes target, producing mostly pions
- Graded magnetic field contains pions/muons and collimate them into transport solenoid → high muon intensity
Mu2e overview

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- Antiproton absorber
- The S shape eliminates photons and neutrons
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Target, Detector and Solenoid (DS)
- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- Graded field “reflects” downstream conversion electrons emitted upstream, improving efficiency
Pulsed beam with beam extinction between bunches and delayed search window reduces prompt backgrounds like $\pi N \rightarrow \gamma N^*$, $\gamma \rightarrow e^+e^-$ and $\pi N \rightarrow e^+e^- N^*$. 

Prompt background like radiative pion capture decreases rapidly ($\sim 10^{11}$ reduction after 700 ns)

Muonic Al has “long” lifetime $\tau = 864$ ns,

Mostly muon decay in orbit background

Pulsed beam and delayed search window

Proton beam hits target

Next bunch after 1700 ns

Particles hits the stopping target

Prompt flash
Expected sensitivity

3 years running period with $1.2 \times 10^{20}$ protons on target per year

Estimated background

<table>
<thead>
<tr>
<th>Category</th>
<th>Background process</th>
<th>Estimated yield (events)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic</td>
<td>Muon decay-in-orbit (DIO)</td>
<td>0.199 ± 0.092</td>
</tr>
<tr>
<td></td>
<td>Muon capture (RMC)</td>
<td>0.000 ± 0.000</td>
</tr>
<tr>
<td>Late Arriving</td>
<td>Pion capture (RPC)</td>
<td>0.023 ± 0.006</td>
</tr>
<tr>
<td></td>
<td>Muon decay-in-flight (μ-DIF)</td>
<td>&lt;0.003</td>
</tr>
<tr>
<td></td>
<td>Pion decay-in-flight (π-DIF)</td>
<td>0.001 ± &lt;0.001</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>Antiproton induced</td>
<td>0.047 ± 0.024</td>
</tr>
<tr>
<td></td>
<td>Cosmic ray induced</td>
<td>0.092 ± 0.020</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>0.37 ± 0.10</td>
</tr>
</tbody>
</table>

Reconstructed $e^-$ momentum

Bottom line:

Almost background free: background < 0.5 event
Single event sensitivity: $R_{\mu e} = 2.9 \times 10^{-17}$ (goal is $2.5 \times 10^{-17}$)
Typical SUSY Signal: ~50 events or more for rate $10^{-15}$
Our funding profile allows us to pursue a Technically limited schedule.
What is next?

A next generation Mu2e experiment makes sense in all scenarios

Study underlying New Physics if signal is seen or improve sensitivity

We will need more protons!
Upgrade accelerator (PIP II project at Fermilab)

Upgrade Mu2e experiment, see arXiv:1307.1168
Conclusion

Mu2e will search for muon-to-electron conversion

Discovery capabilities over a wide range of models

Improves sensitivity by factor $10^4$

Complementary to the LHC, flavor and neutrino physics

Operations should begin by the beginning of the next decade (that’s not that far), join us if you are interested …
Generic parametrization of CLFV process into two terms

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

Two parameters
- \( \kappa \): relative contribution of the contact term
- \( \Lambda \): effective mass scale of New Physics

Each New Physics model predicts a different value of \( \kappa \rightarrow \) model diagnosis

\( \kappa = 0 \)
- "Electromagnetic" (Loop)
- \( \kappa \) = 0
- \( \kappa \rightarrow \) model diagnosis
- Contributes to \( \mu \rightarrow e \gamma \)

\( \kappa = \infty \)
- "Contact"
- \( \kappa \rightarrow \infty \)
- No contribution to \( \mu \rightarrow e \gamma \)
A few more models...

**Higgs triplet model**

Dependence on neutrino mass hierarchy and CP-violating phase $\delta$

**Flavor violating Yukawa couplings**

![Graph showing dependence on neutrino mass hierarchy and CP-violating phase $\delta$.](image)

R. Harnik et al., JHEP 3, 26 (2013).

**Leptoquarks**

![Graph showing leptoquark interactions and conversion rates.](image)

SUSY model diagnosis

Measurement of CLFV in different channels has powerful discrimination power over the model parameters and is complementary to searches at the LHC.

SUSY GUT Models

L. Calibbi et al., JHEP 1211 (2012) 040

G. Isidori et al., PRD75(2007) 115019

$a_{\mu}^{(EXP)}$: PRD73(2006) 072
$a_{\mu}^{(SM)}$: Hagiwara et al., JPG38(2011)085003
Current best limits - SINDRUM II at PSI

SINDRUM II at PSI

Final results on Au:

$$R_{\mu e} < 7 \times 10^{-13} @ 90\% \text{ CL}$$

Timing cut shows the contribution of prompt background (0.3 ns muon pulse separated by 20 ns)

One candidate event past the end of the spectrum. Pion capture, cosmic ray?