The Mu2e: The Muon to Electron Conversion Experiment

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What are we looking for?

Experimental Method Employed by Mu2e.

Hardware and Infrastructure.

Current Status of Hardware.

Looking Further ahead.

Questions?
Mu2e is an experimental search for the coherent, neutrinoless conversion of a muon to an electron in the presence of an Aluminium nucleus.

\[
R_{\mu e} = \frac{\Gamma(\mu^- + A(Z, N) \rightarrow e^- + A(Z, N))}{\Gamma(\mu^- + A(Z, N) \rightarrow \nu_{\mu} + A(Z - 1, N))} < 7 \times 10^{-13} (90\% CL)
\]


Mu2e will use the Fermilab accelerator complex to improve the sensitivity by $10^4$ on current limit.

Mu2e aims to achieve a limit of $R_{\mu e} < 8 \times 10^{-17} (90\% CL)$.

Measure a signal with Single Event Sensitivity of $\approx 3 \times 10^{-17}$, discovery at $2 \times 10^{-16} (5\sigma)$. 
The Quarks commit Flavor Violation
- Mixing strengths are parameterized by CKM matrix.

ν oscillations → Lepton Flavour Violation (LFV)
- Mixing strengths parameterised by the PMNS matrix.

What about Charged Leptons?
- LFV - Rate constrained by mixing parameters & neutrino masses
- Neutrino Oscillations give rise to CLFV!
- Other sources of CLFV are model-dependent:
  → Can vary over many orders of magnitude.
  → Relative rates of different CLFV processes is important.
→ CLFV depends on mechanism behind neutrino masses and lepton mixing.

*CLFV=Charged Lepton Flavor Violation
Multitude of possible new physics contributions to $\mu N \rightarrow eN$ which predict $R_{\mu e} \sim O(10^{-15})$ or higher:

**New Physics (NP) Scenarios**

- **SUSY**
- **Heavy Neutrinos**
- **2 Higgs Doublets**
- **Compositeness**
- **Leptoquarks**
- **Anomalous Couplings**

**Figures:**

1. SUSY Loop (Photonic)
2. Heavy Neutrinos
3. 2 Higgs Doublets
4. Compositeness
5. Leptoquarks
6. Anomalous Couplings

**Theory Reviews:**
- Y. Kuno, Y. Okada, 2001
- M. Raidal et al., 2008
- A. de Gouvêa, P. Vogel, 2013
To elucidate the mechanism responsible for NP—must look at relative rates of CLFV for many processes.

Intense muon beams put muon sector at forefront.

3 muon CLFV channels with complementary sensitivity to NP effects:

- $\mu^{\pm} \rightarrow e^{\pm} \gamma$
  - Current Limit: $5.7 \times 10^{-13}$ [1]
  - Future Limit: $4 \times 10^{-14}$
  - Experiment/s: MEG II [4]

- $\mu^- N \rightarrow e^- N$
  - Current Limit: $7 \times 10^{-13}$ [2]
  - Future Limit: $10^{-15} / 10^{-17}$
  - Experiment/s: COMET [5]/ Phase 1/ Mu2e [6]

- $\mu^+ \rightarrow e^+ e^+ e^-$
  - Current Limit: $\sim 10^{-12}$ [3]
  - Future Limit: $10^{-15} \sim 10^{-16}$
  - Experiment/s: Mu3e [7]

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Estimate sensitivity CLFV process in model independent manner by adding 2 different LFV effective operators to the SM Lagrangian:

\[ \mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(1 + \kappa)} \Lambda^2 \bar{\mu}_R \gamma_{\mu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)} \Lambda^2 \bar{\mu}_L \gamma_{\mu} e_L (\sum_{q = u, d} \bar{q}_L \gamma_{\mu} q_L) \]

"Photonic"
\[ \mu^\pm \rightarrow e^\pm \gamma , \mu \rightarrow eee \]
\[ \mu^- N \rightarrow e^- N \]

"Contact"
Only \( \mu^+ \rightarrow e^+ e^+ e^- \)
And \( \mu^- N \rightarrow e^- N \)

\( \Lambda \) = the effective mass scale of NP,
\( \kappa \) = controls the relative contribution of the two terms
\( \text{e.g. SUSY } \kappa = 0 \)


Mu2e can probe very high mass scales \( O(1000 \text{ – } 10,000 \text{ TeV}) \)

*From Bob Bernstein*
The SINDRUM-II results was limited by 2 main factors:

- Backgrounds from prompt pions,
- The muon stopping rate (~$10^7 \mu$-s -with a ~1 MW beam).

Mu2e must address these issues to improve limit on $R_{\mu e}$.

Following the proposal by V. Lobashev & R. Djilkibaev (Sov. J. Nucl. Phys. 49(2), 384 (1989)) , Mu2e will:

- Utilize a pulsed proton beam & delayed “gate window” – Eliminates pion induced backgrounds.
- Use intense muon source – $10^{10}$ muons/s -3 year run equates to $10^{18}$ stopped muons.
- Use superconducting solenoids – For efficient muon collection and transport to stopping target.
1. Low momentum (-) muons are captured in the Al target’s atomic orbit and quickly (~fs) cascades to 1s state.

2. The Signal:
   - $t_{\mu_{Al}} = 864$ ns – important for discriminating backgrounds.
   - Monoenergetic electron consistent with $E_e = m_\mu - E_{recoil} - E_{1S\ B.E}$, For Al: $E_e=104.97$ MeV.
   - Nucleus coherently recoils off outgoing electron; it does not break-up!
Design choices ensure Mu2e is to almost background free

- **Intrinsic**: Scale with number of stopped muons.
- **Late arriving**: Scale with number of late protons/extinction performance

<table>
<thead>
<tr>
<th>Type</th>
<th>Source</th>
<th>Mitigation</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic</td>
<td>Decay in Orbit (DIO)</td>
<td>Tracker Resolution</td>
<td>$0.144 \pm 0.028$ (stat) $\pm 0.11$ (sys)</td>
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<tr>
<td>Late Arriving</td>
<td>Pion Capture</td>
<td>Beam Structure</td>
<td>$0.021$ (stat) $\pm 0.001 \pm 0.002$ (sys)</td>
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<td></td>
<td>Pion Decay in Flight</td>
<td>-</td>
<td>$0.001$ (stat) $\pm &lt;0.001$ (sys)</td>
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<tr>
<td>Other</td>
<td>Anti-proton</td>
<td>Thin windows</td>
<td>$0.04 \pm 0.022$ (stat) $\pm 0.020$ (sys)</td>
</tr>
<tr>
<td></td>
<td>Cosmic Rays</td>
<td>Veto System</td>
<td>$0.209 \pm 0.0022$ (stat) $\pm 0.055$ (sys)</td>
</tr>
</tbody>
</table>
Mu2e uses a pulsed beam with a long interval between pulses.

- Search window begins 700ns in—this suppresses prompt backgrounds e.g. pion background reduced by $>10^{-11}$.
- Must eliminate protons that arrive late. These can give rise to additional pion backgrounds in delayed live window.
- AC Dipole in beamline helps ensure $<10^{-10}$. Extinction monitor measures.
✧ In 39% of stopped muons will decay in orbit (DIO).

✧ This is a 3 body decay. In free decay maximum electron energy is far below our signal energy (104.97 MeV).

✧ The free decay spectrum is distorted by the presence of the nucleus.
Mu2e requires excellent tracker resolution of <200 keV/c to suppress DIO background.

With $\mu$-Al$^{27}$ binding energy and radiative corrections

$$E_e(\text{max}) = \frac{m_\mu^2 + m_e^2}{2m_\mu} \approx 52.8 \text{ MeV}$$

(no detector effects – just math functions)
In order to reach design sensitivity Mu2e will use:

- Low mass straw tracker provides excellent momentum resolution $<200$ keV/c on electrons.
- Pulsed proton beam with:
  - Narrow proton pulses ($< +/-125$ ns).
  - Very few out-of-time protons ($< 10^{-10}$).
- Anti-proton backgrounds reduced by thin anti-proton windows in beamline.
- Passive and active shielding means high cosmic ray veto efficiency ($>99.99$%).
Graded fields important to suppress backgrounds, to increase muon yield, and to improve geometric acceptance for signal electrons.
A low mass, annular, highly segmented detector is used to:

1. Minimizes scattering and energy loss:
   - Entire Detector Solenoid held under vacuum (~10^{-4} torr).
   - Ultra low mass tracker.

2. Minimizes Background Tracker - excludes low momentum electrons via hollow centre:
   - Inner 38 cm instrumented.
   - Reduces need to reject ~ 10^{18} to ~10^5.
   - Blind to >99% of DIO spectrum.

3. Handle high rates and provide high-precision momentum measurements:
   - Highly segmented design.
Tracker is constructed from self-supporting panels of low mass straws tubes detectors
- 18 stations, 2 planes per station, 6 panels per plane, 96 straws per panel.
- Straw drift tubes aligned transverse to the axis of the Detector Solenoid.
  - 1m, 5 mm diameter straw
  - Walls: 12 mm Mylar + 3 mm epoxy
  - 25 mm Au-plated W sense wire
  - 33 – 117 cm in length
  - 80:20 Ar:CO₂ with HV < 1500 V

The Tracker: Design

Panels Plane Station

The Straws:
- ~ 3m, 1 T field
The calorimeter is vital for providing:

- Particle identification,
- Fast online trigger filter,
- Accurate timing information for background rejection
- Seed for track reconstruction.

The calorimeter must:

- Have a large acceptance.
- Provide time resolution < 0.5 ns,
- Energy resolution < 10%;
- Position resolution of 1 cm.
- Function in region with radiation exposure up to 20Gy/crystal/year and with neutron flux $10^{11} /\text{cm}^2$.
Mu2e calorimeter uses 2 annular, disks with radius 37-66 cm.
- 674 undoped CsI(34 x 34 x 200) mm³ square crystals in each disk.
- Separated by 70 cm - distance chosen so if signal electron goes down through centre it hits the next disk.
- Redundant readout - Each crystal 2 UV-extended SiPMs.
- 1 FEE/SiPM - SiPM holders with front end electronics (FEE) are inserted into the backplane.
Cosmic Ray Veto will prevent cosmic muons faking a signal:

- 4 layers of extruded polystyrene scintillator counter.
- Surrounds the top and sides of DS and the downstream end of the Transport Solenoid.
- Suppresses the spurious detection of conversion-like particles initiated by cosmic-ray muons.
- 99.99% efficiency requirement!

Each day, ~1 conversion-like electron is produced by cosmic rays

Each panel is composed of 5 x 2 x 450 cm³ scintillator bars:
✧ Production & Detector Solenoids built at General Atomics (GA):
✧ Completed winding the first of the three PS coils.
✧ Now winding first of the 11 DS coils as the PS coil goes through its finishing operations (potting, machining, insertion into its housing shell).
✧ Transport solenoid built at ASG & Shipped to Fermilab
✧ ASG, has delivered 25% of the 27 TS coil modules.
✧ Prototype panels complete, ramping-up production line.
✧ Full-sized pre-production panels assembled and tested.
✧ Multiple panels have been assembled into a prototype station.
✧ Final straw production is currently underway.
✧ FEE Readout QA taking place at LBNL/Berkeley, this summer.
The Tracker

8 channel prototype

Measured gain, crosstalk, resolution...

- Use Cosmic Rays.
- Use information gained to update MC.
- Measured performance and resolutions.
- Performance met requirements!
R&D and Prototyping successfully completed.
Crystal and SiPM fabrication has begun.
67% of crystals, 100% SiPMs.

Test beam with e\(^-\) with E = 60-120 MeV.
Good agreement between MC/Data!
Meets energy and timing performance requirements!
Di-counter production started June 2018.
1/3 of production is now done.
Modules will be built at University of Virginia at a rate of 1-2 per week and shipped to FNAL -begins this summer (2019).

Modules built @ University of Virginia

6 crates scintillator (4.7m) arriving:
Various operator coefficients add coherently in the amplitude.

Weighted by nucleus-dependent functions.

Requires measurements of R in other target materials!

If we do see a signal at Mu2e in Al:

- Various operator coefficients add coherently in the amplitude.
- Weighted by nucleus-dependent functions.

5% measurement on Al/Ti needed to see split


If we do see a signal at Mu2e in Al:
✧ Use ~100 kW of PIP-II protons at 800 MeV to achieve an x10 improvement in sensitivity.

✧ If there is no signal at Mu2e:
  ✧ We could extend our sensitivity to find a signal or set new limits.

✧ If Mu2e does see something:
  ✧ Mu2e-II would improve statistical significance, different target materials to narrow down the NP processes.

✧ Mu2e-II could begin taking data around 2030.
The Mu2e Experiment is a search for CLFV based at Fermilab looking for signal of coherent, neutrinoless conversion of muon to electron in nucleus. Aims:

- To improve sensitivity on relative rate to reach $R_{\mu e} < 8 \times 10^{-17}$
- With SES $\sim 3 \times 10^{-17}$
- And $5\sigma$ discovery at $2 \times 10^{-16}$.

- Will constrain New Physics models up to a scale of $10^4$ TeV.
- Lots of activity currently underway at both FNAL and at our many collaborating institutions.
- Commissioning will begin in the next year with physics data taking expected by 2022.
Thank You For Listening!
In Minimal Extension to SM possible in loop diagrams due to neutrino oscillations:

\[ BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \sum_{i=2,3} |U_{\mu i}^{*} U_{ei}|^{2} \frac{\Delta m_{1i}^{2}}{M_{W}^{2}} < 10^{-54} \]

=> An observation is unambiguous evidence of New Physics!

- Broad array of New Physics models predict rates observable at next generation CLFV experiments - New Physics models predict rates in $10^{-14} - 10^{-16}$ region.
- Mu2e sees 40 conversions at $10^{-15}$. 
Mu2e has discovery sensitivity across the board.
Relative Rates however will be model dependent.

<table>
<thead>
<tr>
<th></th>
<th>AC</th>
<th>RVV2</th>
<th>AKM</th>
<th>δLL</th>
<th>FBMSSM</th>
<th>LHT</th>
<th>RS</th>
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<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>?</td>
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<tr>
<td>$\epsilon_K$</td>
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<tr>
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<tr>
<td>$S_{\phi_KS}$</td>
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<td>?</td>
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<tr>
<td>$A_{\text{CP}}(B \to X_s\gamma)$</td>
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<td>★</td>
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<td>$A_{\tau,8}(B \to K^{*}\mu^+\mu^-)$</td>
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<td>★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$B \to K^{(*)}\nu\bar{\nu}$</td>
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<td>★</td>
<td>★</td>
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<td>★</td>
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<tr>
<td>$B_s \to \mu^+\mu^-$</td>
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<tr>
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<tr>
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<tr>
<td>$\tau \to \mu\gamma$</td>
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<td>★★★</td>
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<td>★★★</td>
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<tr>
<td>$\mu + N \to e + N$</td>
<td>★★★</td>
<td>★★★</td>
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</tbody>
</table>

*arXiv:0909.1333[hep-ph]
Figure 1: Planned data taking schedules for current experiments that search for charged-lepton flavor violating $\mu \to e$ transitions. Also shown are possible schedules for future proposed upgrades to these experiments. The current best limits for each process are shown on the left in parentheses, while expected future sensitivities are indicated by order of magnitude along the bottom of each row.

*Y. Kuno
Why Aluminium?

- Must be chemically stable and available in the required size, shape, and thickness.
- Conversion energy such that only tiny fraction of photons produced by muon radiative capture.
- Muon lifetime long compared to transit time of prompt backgrounds.
- Conversion rate increases with atomic number, reaching maximum at Se and Sb, then drops. Lifetime of muonic atoms decreases with increasing atomic number.

Al (or Ti) best choices

The lifetime of a muon in a muonic atom decreases with increasing atomic number.
Where do the muons come from?

- Mu2e uses 8kW of 8 GeV protons from the Booster.
- 2 batches of 4 x 10^{12} protons, transported from Booster via MI-8 beamline to the Recycler Ring.
- Circulate and re-bunched by a 2.5 MHz RF system.
- Reformatted bunches are kicked into the P1 line and transported to the Delivery Ring.
- They are slow extracted to the Mu2e detector through a new external beamline.
Where will our muons come from?
✧ Must have out-of-time : in-time proton ratio < $10^{-10}$

✧ 2 steps:

1. The technique for generating the required bunch structure in the Recycler Ring leads to a high level of extinction. Fast “kicker” which transfers the proton beam from the Recycler to the Delivery Ring preserves extinction. Extinction of $10^{-5}$ is expected as the proton beam is extracted and delivered.

2. The beam line from the Delivery Ring to the production target has a set of AC oscillating dipoles that sweep out-of-time protons into a system of collimators. This should achieve an additional extinction of $10^{-7}$ or better.
✧ Tungsten rod in frame
✧ Fabrication in progress
Built at ASG & Shipped to Fermilab

- Successful R&D and prototype campaign completed.
- Vendor, ASG, has delivered 25% of the 27 TS coil modules.
- 100% of the 52 TS coils wound at cold mass vendor.
- Good progress made with the fabrication of the coils’ housing shells
- FNAL solenoid test facility operational.
- The first of the coil modules has been installed around the magnet bore at assembly site.
- Fabrication of the outer TS cryostat is underway.
The Transport Solenoid
Recent Solenoid Progress at FNAL

Completed transfer lines

Power Supply

Cryogenic Distribution Box

Warm bore and thermal shield procurement completed

Field Mapper
Design still being finalized
- Target must be massive to stop significant number of muons
- Target must not distort momentum measurement
- Use Combination of lower energy muons and a thin foil Al target help alleviate corruption
The Stopping Target Monitor (STM)

- Need an accurate measure of total number of stopped muons in the target (within 10%).
- Placed far downstream of DS (~34 m from target).
- STM uses HPGe and LaBr₃ detectors to measure X/gamma-rays produced by stopped muons in Al target:
  - Prompt X-ray emitted from muonic atoms at 347keV;
  - Semi-prompt gamma ray at 1.809MeV;
  - Delayed gamma ray at 844keV.
The DAQ system must provide readout and control for all detector subsystems.

- Trigger processing is handled entirely in software.
- This allows use of commercial computing hardware.
- Filtering can be designed in offline environment and can then be run in online trigger environment.
Lots of progress over the last year:
- Test stand set up at the Feynman Computing Centre at FNAL
- Need to synchronize all the sub-detectors
- A joint platform (OTSDAQ) has been set up to allow compatibility between trackers, calorimeter and STM interfaces.
Comparing other channels?

- Relative rates important in determining new physics:

<table>
<thead>
<tr>
<th>Model</th>
<th>$\mu \rightarrow eee$</th>
<th>$\mu N \rightarrow eN$</th>
<th>$\frac{BR(\mu \rightarrow eee)}{BR(\mu \rightarrow e\gamma)}$</th>
<th>$\frac{CR(\mu N \rightarrow eN)}{BR(\mu \rightarrow e\gamma)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSSM</td>
<td>Loop</td>
<td>Loop</td>
<td>$\approx 6 \times 10^{-3}$</td>
<td>$10^{-3} - 10^{-2}$</td>
</tr>
<tr>
<td>Type-I seesaw</td>
<td>Loop*</td>
<td>Loop*</td>
<td>$3 \times 10^{-3} - 0.3$</td>
<td>$0.1 - 10$</td>
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<tr>
<td>Type-II seesaw</td>
<td>Tree</td>
<td>Loop</td>
<td>$(0.1 - 3) \times 10^3$</td>
<td>$\mathcal{O}(10^{-2})$</td>
</tr>
<tr>
<td>Type-III seesaw</td>
<td>Tree</td>
<td>Tree</td>
<td>$\approx 10^3$</td>
<td>$\mathcal{O}(10^3)$</td>
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<tr>
<td>LFV Higgs</td>
<td>Loop†</td>
<td>Loop†</td>
<td>$\approx 10^{-2}$</td>
<td>$\mathcal{O}(0.1)$</td>
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<td>Composite Higgs</td>
<td>Loop*</td>
<td>Loop*</td>
<td>$0.05 - 0.5$</td>
<td>$2 - 20$</td>
</tr>
</tbody>
</table>

Interesting Overviews:


Constraining NP with CLFV

SUSY


Scalar Leptoquarks

Figure shows the reach in the new coupling $\lambda$ for a range of scalar leptoquark masses for the $\mu \rightarrow e$ conversion rate for two values of the $\text{Br}(\mu \rightarrow e \text{ conversion in Al})$ relevant for the Mu2e experiment.