The Mu2e Experiment

Cole Kampa
Northwestern University
for the Mu2e Collaboration

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Conceptual Overview of Mu2e

- Muon converts to electron in the field of a nucleus
- Does not conserve muon number or electron number -- Charged Lepton Flavor Violation (CLFV)
- (Very) rare process
- An observation of the Mu2e signal process is unambiguous evidence of physics Beyond the Standard Model.
- Discovery experiment capable of improving current limit by factor 10,000
  - Pulsed proton beam
  - High intensity muon beam
  - Accurate momentum measurement

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

Mu2e goal

Current limit
The Mu2e Experiment at Fermilab

- An international collaboration of 237 members from 38 institutions
- Strong early-career presence
  - Young Mu2e group advocates for early-career members (≥30% of collaboration in Young Mu2e)

- US DOE flagship experiment at Fermilab
- Part of the cutting-edge muon campus
Charged Lepton Flavor Violation (CLFV)

- Flavor conservation is interesting
  - Quark mixing ✓
  - Uncharged leptons (neutrino oscillation) ✓
  - Charged leptons ?

- Do charged leptons conserve flavor?
- Many models beyond the Standard Model speculate CLFV within reach of current generation of experiments

"Who ordered that?" - I. I. Rabi
CLFV Landscape: Muons

- Parameterize with EFT terms added to the Lagrangian
  - Loop term
  - Contact term
- $\Lambda$ mass scale -- Mu2e will probe $\Lambda \sim 10^4$ TeV
- $\kappa$ tunes relative contribution from each term

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

[de Gouvêa and Vogel; arXiv:1303.4097]

[Bernstein and Cooper; arXiv:1307.5787]
CLFV Landscape: Muons

- Parameterize with dimension six EFT terms added to the SM Lagrangian ($\propto 1 / \Lambda^2$)
  - Loop term: e.g. SUSY, heavy $\nu$'s ...
  - Contact term: e.g. leptoquarks, heavy Z ...
- Mu2e sensitive to both types of terms
- $\Lambda$ mass scale -- Mu2e will probe $\Lambda \sim 10^4$ TeV

[Bernstein and Cooper; arXiv:1307.5787]

[see e.g. de Gouvêa and Vogel; arXiv:1303.4097]
Characterizing the Mu2e Signal

- Initial state is a muon in the Coulomb field of an Al nucleus
- The muon interacts coherently with the nucleus
- Final state is a mono-energetic electron with $p \approx m_\mu$
- Measure ratio of signal events to muon capture on the nucleus:

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

- Current limit (SINDRUM-II on Au): $R_{\mu e} < 7 \times 10^{-13}$ (90% CL)

(1) Conversion

(2) Muon Capture (61%)
Experimental Design

- Two superconducting solenoids create and manipulate the muon beam, while the third is designed to stop muons and direct electrons to detectors.
- Detectors measure the momentum and energy of outgoing electrons.
Transport Solenoid Critical Lift (August 2021)

https://twitter.com/Mu2eExperiment/status/1423045896305053703
Backgrounds Overview

1. Intrinsic backgrounds -- scale with the number of stopped muons
   a. Muons
      i. Decay-in-Orbit (DIO)
         ⇒ Motivates detector design
      ii. Radiative Muon Capture (RMC)

2. Beam-related backgrounds (formation of muon beam) / prompt backgrounds
   a. Pions
      i. Radiative Pion Capture (RPC)
         ⇒ Motivates beam design (pulsed)
   b. Antiprotons

3. Cosmic ray muons -- scale with detector live-time
Electron Momentum Spectrum

- Run 1 = ~10% of full dataset
- Analysis cuts optimized for mean 5σ discovery
Sensitivity Estimate for Run 1 (10% Data)

Single Event Sensitivity (signal):

\[ \text{SES} = 2.7 \times 10^{-16} \]

Median Discovery:

\[ R_{\mu e} = 1.1 \times 10^{-15} \]

\[ \geq 5 \text{ signal events for a discovery} \]

Upper Limit (90% CL):

\[ R_{\mu e} < 5.9 \times 10^{-16} \]

Run 2 will improve discovery potential by x10
Great progress in construction efforts
Lots of areas to contribute
Now is a great time to join Mu2e!
Summary and Outlook

- Mu2e is a flagship discovery experiment under construction at Fermilab.
- Run 1 in 2025-2026 and will improve current limit by x1,000
- Run 2 after LBNF/PIP-II shutdown will improve current limit by x10,000

It is an exciting time for Mu2e. Join us to help answer:

“Who ordered that?”

@Mu2eExperiment  @mu2eexperiment  https://mu2ewiki.fnal.gov
Backups
What happens next?

- **Mu2e Signal?**
  - **YES**
    - Precision Measurement if necessary
  - **NO**
    - Higher Sensitivity search
    - Measure conversion rate as a function of Z
    - Accelerator Upgrade

![Graphical representation of the decision process](image)
Mu2e II

- Next-generation of Mu2e -- goal of another x10 improvement in discovery potential
- Active in Snowmass 2021
- Expression of Interest: arxiv:1802.02599
Additional Mu2e Measurement: $\mu^- \to e^+$

- Violates lepton flavor and lepton number
- Primary background is RMC
  - Experimental data on RMC is sparse
- Mu2e will make a world-leading measurement in tandem with $\mu^- \to e^-$
Stopping Target

- Annular Al foils
- Optimized to maximize stopped muons and minimize energy loss of outgoing electrons
Tracker

- Metallized mylar straws (>20,000)
- 5 mm diameter
- 15 micron thick walls
- Tungsten sense wire as anode
- ArCO2 gas through straw tubes
Tracker Resolution

momentum resolution at start of tracker (simulation)

Core width = 159 keV/c
Calorimeter

- 1348 CsI crystals (fabrication complete)
- SiPMs for readout
- Aids in Particle ID (momentum + energy measurements)
- Track seeding
Cosmic Ray Muons

- Cosmic ray muons interact in detector material to produce signal-like $e^-$.
- Active vetoing detector encapsulates Detector Solenoid and half of Transport Solenoid.
- Software veto.
- Without Cosmic Ray Veto, we would see approx. 1 signal-like event per day.
Magnetic Field (TS)

- Charge and momentum selection yields low energy negative muons
- Collimator in middle of TS can be rotated 180° to pass positive muons for calibrations

\[
D[m] = -\frac{Q}{e} \frac{\pi}{0.6B[T]} \frac{P_L^2 + 0.5P_T^2}{P_L[GeV/c]}
\]
Magnetic Field (DS)

- Gradient region to direct electrons from Stopping Target to detectors
- Flat field in Tracker region for momentum measurement (1 T)
Field Mapping System

- DS field measured on discrete cylindrical grid of points
- Model function is fit to data
- $10^{-4}$ accuracy requirement
Time Window From RPC

- RPC drives live window start time
- End of time window set based on when the next proton pulse arrives