The Mu2e Experiment at Fermilab

Yuri Oksuzian, DPF 2017
Quarks and neutrinos mix

- Do charged lepton flavors mix as well?

Mu2e will search for neutrino-less, coherent muon conversion into an electron

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

- Neutrino-less \( \mu \rightarrow e^- \) conversion is Charge Lepton Flavor Violation (CLFV)

\[ \mu \rightarrow e\gamma, \quad \mu \rightarrow 3e, \quad \tau \rightarrow e\gamma, \quad \tau \rightarrow \mu\gamma... \]

- In the SM, \( \mu \rightarrow e^- \) occurs at the rate of \(<10^{-50}\)

  - Signal observation at Mu2e is unambiguous sign of new physics

**Rate_{SM} < 10^{-50}**

**Rate_{BSM} \sim 10^{-15}**
Mu2e will measure the ratio of $\mu \rightarrow e^-$ conversions to the number of muon captures by Al nuclei:

$$R_{\mu e} = \frac{\Gamma(\mu^- + (A, Z) \rightarrow e^- + (A, Z))}{\Gamma(\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1))}$$
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$E_{e^-} = 104.96$ MeV
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Irreducible background \( \text{BR} = 39\% \)
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\[
R_{\mu e} = \frac{\Gamma(\mu^- + (A, Z) \rightarrow e^- + (A, Z))}{\Gamma(\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1))}
\]

- Mu2e single event sensitivity: $R_{\mu e} = 3 \times 10^{-17}$
  - Expect 7 events and 5$\sigma$ discovery sensitivity at $R_{\mu e} = 2 \times 10^{-16}$
- Expected limit: $R_{\mu e} = 8 \times 10^{-17}$ @ 90% CL
- Mu2e needs to stop $\sim 10^{18}$ muons
  - $3.6 \times 10^{20}$ protons on target (POT) over 3 years
- Need to keep background small and well understood
  - Total expected background 0.4 events
History of CLFV Searches

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

Limit vs. Year

- $\mu \rightarrow e\gamma$
- $\mu \rightarrow 3e$
- $\mu N \rightarrow eN$

Mu2e, COMET

10^{-4}
Mu2e Physics Reach

Effective CLFV Lagrangian

\[ L = \frac{m_\mu}{(\kappa+1)\Lambda^2} \bar{\mu} R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2} \bar{\mu} L \gamma_\mu e_L \sum_{q=u,d} \bar{q} L \gamma_\mu q_L \]

Magnetic moment type operator

Contact term operator

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<tr>
<th>State</th>
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Magnetic moment type operator

Supersymmetry
Heavy neutrinos
Two Higgs Doublets

Contact term operator

Compositeness
Leptoquarks
Heavy Z'

\[ \bar{\chi}_i^0 \]

\[ \bar{\chi}_i \]

\[ \tilde{\tau}_j e^- \]

\[ N \]

\[ W \]

\[ H \]

\[ t \]

\[ \mu^- \]

\[ \mu^- \]

\[ q \]

\[ q \]

\[ q \]

\[ q \]

\[ q \]

\[ q \]
Mu2e proton beam

- Mu2e will recycle the existing accelerator infrastructure
- **Booster** provides batches of 8 GeV protons to recycler
- **Recycler** divides proton batches into 8 smaller bunches
- **Delivery ring** gets 1 out of 8 bunches from recycler
- Mu2e gets the **proton beam** pulses from delivery ring every 1695 ns
Every 1695 ns, 8 GeV protons hit production target to produce $\pi^-$
- $\pi^-/\mu^-$ are reflected toward the transport solenoid

Transport Solenoid delivers $\pi^-/\mu^-$ to Detector Solenoid
- Selects particle’s momentum and charge
- Avoids direct line of sight

Muons stop on the Al Stopping Target
- 1,000 POT $\rightarrow$ 4(2) muons reach(stop on) the Al target
- Conversion electron momentum, energy and timing are measured in the tracker and calorimeter
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1. Transport Solenoid delivers $\pi^-/\mu^-$ to Detector Solenoid
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Prompt background: particles produced by proton pulse which interact almost immediately when they enter the detector

Muons travel with pions. Pions produce background when captured on target

\[ \pi^- N \rightarrow \gamma N^* \rightarrow e^+ e^- N^* \]

Other examples of prompt backgrounds: beam electrons, \( \mu/\pi \) decay in flight

Solution: Suppress prompt backgrounds by employing a delayed signal window

Delivery ring revolution period of 1695 ns is well matched for \( \tau^{\text{Al}} = 864 \) ns

- 50% of muons decay/captured in the signal window
• Out-of-time protons can give rise to prompt backgrounds in the signal window
• RF structure in Delivery ring and sweeping AC dipole in front of PS will suppress out-of-time protons by \(>10^{-10}\)
• Only 1 in 10 billion POT will be outside of the main pulse

Out-of-time protons: \(10^{-10}\)
Muon2e expects 1 signal-like event per day induced by cosmic rays
- Reminder: Total expected background is 0.4 events over 3 years

Cosmic ray muons produce background though material interactions, decays and muon faking an electron

To achieve experiment’s designed sensitivity, Cosmic Ray Veto detection efficiency is required to be $> 99.99\%$
Cosmic Ray Veto

- CRV consists of 4-layer scintillating 5x2 cm$^2$ counters, read-out through wavelength-shifting fibers by 2x2 mm$^2$ SiPMs
- Cosmic ray muon detection - hits coincidence in 3/4 layers localized in time and space
- Veto (offline) 125 ns from a signal window after a coincidence in the CRV

- Area: 327 m$^2$
- 86 modules of 6 lengths
- 5,504 counters
- 11,008 fibers
- 19,840 SiPMs
- 310 Front-end Boards
Muon decays in orbit (DIO) produce irreducible background

Central part of the tracker is not instrumented
- blind to 99% of DIO spectrum and beam flash

Signal electrons travel at higher radii through the tracker fiducial volume
Decay In Orbit

- DIO spectrum spreads to the signal region

![Graph showing DIO spectrum for 27Al](image)

- Michel Peak
- Recoil Tail

$\frac{1}{N} \frac{dN}{dE}$ (MeV$^{-1}$) vs $E$ (MeV)
- DIO spectrum spreads to the signal region.
- In addition, signal is smeared due to energy losses
- Need good momentum resolution
  - < 200 KeV/c momentum resolution is achievable

![Tracker Resolution](image)

- Mean: 10 KeV/c
- Core $\sigma$: 120 KeV/c
- High side tail $<< 1\%$
Low mass straw drift tubes
- 5 mm diameter straws
  - 12 µm Mylar walls
  - Filled with Ar+CO₂
- 25 µm tungsten wires

96 Straws = Panel; 6 Panels = Plane; 2 Planes = Station; 18 Station = Tracker. Total number of straws: 22,000
Calorimeter

- Two disks of CsI scintillating crystals
  - Radiation hard, good time (110 ps) and energy (5%) resolution
- Provides precise timing, seed for tracking, triggering and PID
- Muon rejection x200 with 96% electron efficiency
All the backgrounds can be controlled to the level of <1 event

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected event yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic rays</td>
<td>0.209 ± 0.022(stat) ± 0.055(syst)</td>
</tr>
<tr>
<td>DIO</td>
<td>0.144 ± 0.028(stat) ± 0.11(syst)</td>
</tr>
<tr>
<td>Antiprotons</td>
<td>0.040 ± 0.001(stat) ± 0.020(syst)</td>
</tr>
<tr>
<td>Pion capture</td>
<td>0.021 ± 0.001(stat) ± 0.002(syst)</td>
</tr>
<tr>
<td>Muon DIF</td>
<td>&lt; 0.003</td>
</tr>
<tr>
<td>Pion DIF</td>
<td>0.001 ± &lt; 0.001</td>
</tr>
<tr>
<td>Beam electrons</td>
<td>(2.1 ± 1.0) × 10^{-4}</td>
</tr>
<tr>
<td>RMC</td>
<td>0.0000^{+0.004}_{-0.000}</td>
</tr>
<tr>
<td>Total</td>
<td>0.41 ± 0.13(stat+syst)</td>
</tr>
</tbody>
</table>
Mu2e Status

- Detector hall construction is complete
- Detector construction starts next year
- Solenoid installation in 2019
- Beam commissioning begins in 2020
- Physics data taking in 2022
23 talks and posters on Mu2e at DPF:

- A Novel Readout System for a High Efficiency Cosmic Ray Veto for the Mu2e Experiment
- Beam Line Extinction in the Mu2e Experiment
- Front-End Electronics Scheme for the Mu2e Straw Tracker
- A High Efficiency Cosmic Ray Veto Detector for the Mu2e Experiment at Fermilab
- Performance of Scintillation Counters with Silicon Photomultiplier Readout
- Studies of Beam Induced Radiation Backgrounds at the Mu2e Experiment and Implications for the Cosmic Ray Veto Detector Operations
- Quality Assurance on Un-Doped CsI Crystals for the Mu2e Experiment
- Mu2e Solenoid Field Mapping System
- Preliminary Results from the AlCap Experiment
- Normalizing to the Number of Stopped Muons in the Mu2e Experiment
- Design and status of the Mu2e crystal calorimeter
- Studies of effect of aging and studies to optimize scintillation counter response for the Mu2e Cosmic Ray Veto System
- Cosmic Ray Backgrounds in the Mu2e Experiment at Fermilab
- Pre-production and quality assurance of the Mu2e Silicon Photomultipliers
- Studies of Radiation Damage to Silicon Photomultipliers
- A Panel Prototype for the Mu2e Straw Tube Tracker at Fermilab
- The Mu2e Solenoid Cold Mass Position Monitor System
- Muon Intensity Increase by Wedge Absorbers
- Mu2e Trigger & DAQ Design and Challenges
- The Mu2e Experiment at Fermilab
- 3D Magnetic Field Calibration
- Studies of scintillation counter response for the Mu2e Cosmic Ray Veto System
- Aging Studies for the Mu2e Cosmic Ray Veto System
Mu2e Collaboration

200 scientists, 37 institutions
Mu2e has a great discovery potential and can reveal new physics

- Improves over previous conversion experiments by 4 orders of magnitude and probes new physics mass scales of $10^4$ TeV/$c^2$
- Provides discovery capability over wide range of new physics models
- Complementary to LHC and other experiments

Experimental design is mature and on schedule to start commissioning in 2020

Technical Design Report

Experiment web site
- [http://mu2e.fnal.gov](http://mu2e.fnal.gov)
Backup
- $R_{\mu e}$ is $Z$-dependent and can distinguish among new physics operators.
- Measuring $R_{\mu e}$ for different targets provides discrimination power between new physics models.

![Graph showing $R_{\mu e}$ for different elements]

- $R_{\mu e}$ (norm to Al)
- Al, Ti, Pb
- Scalar, Dipole, $V_\gamma$, $V_Z$
# Proton Beam Requirement

<table>
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<tr>
<th>Parameter</th>
<th>Design Value</th>
<th>Requirement</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total protons on target</td>
<td>$4.7 \times 10^{20}$</td>
<td>$\geq 4.7 \times 10^{20}$</td>
<td>protons</td>
</tr>
<tr>
<td>Time between beam pulses</td>
<td>1695</td>
<td>$&gt; 864$</td>
<td>nsec</td>
</tr>
<tr>
<td>Maximum variation in pulse separation</td>
<td>$&lt; 1$</td>
<td>$10$</td>
<td>nsec</td>
</tr>
<tr>
<td>Spill duration</td>
<td>43.1</td>
<td>$&gt; 20$</td>
<td>msec</td>
</tr>
<tr>
<td>Beamline Transmission Window</td>
<td>230</td>
<td>$&lt; 250$</td>
<td>nsec</td>
</tr>
<tr>
<td>Transmission Window Jitter (rms)</td>
<td>$&lt; 5$</td>
<td>$&lt; 10$</td>
<td>nsec</td>
</tr>
<tr>
<td>Out-of-time extinction factor</td>
<td>$1.6 \times 10^{-12}$</td>
<td>$\leq 10^{-10}$</td>
<td></td>
</tr>
<tr>
<td>Average proton intensity per pulse</td>
<td>$3.9 \times 10^{7}$</td>
<td>$&lt; 5.0 \times 10^{7}$</td>
<td>protons/pulse</td>
</tr>
<tr>
<td>Maximum Pulse to Pulse intensity variation</td>
<td>50</td>
<td>50</td>
<td>%</td>
</tr>
<tr>
<td>Target rms spot size</td>
<td>1</td>
<td>0.5 – 1.5</td>
<td>mm</td>
</tr>
<tr>
<td>Target rms beam divergence</td>
<td>0.5</td>
<td>$&lt; 4.0$</td>
<td>mrad</td>
</tr>
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</table>
The proton beam on target consists of a train of \(~25,000\) narrow pulses separated by \(1.695 \mu\text{sec}\).

Extinction \(\equiv\) No. of out-of-time protons / No. of in-time protons
Performance

Nominal: 9.2% ± 5%

Nominal: 116 KeV
Calorimeter performance

- Test beam results with calorimeter prototype
- Data well described by Monte Carlo
- Energy resolution: ~6.5% at 100 MeV
- Time resolution: 110 ps
Test beam results with CRV prototype
  ▪ 2x5 scintillating counters, read out through 1.4 mm WLS fibers by 2x2 mm² SiPMs

Light yield: 50 PE/SiPM at 1 m

Timing resolution: 1.7 ns single channel resolution

![Graph showing light yield and timing resolution](image)