The Mu2e experiment

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on behalf of the Mu2e Collaboration
The Mu2e experiment

A search for Charged Lepton Flavor Violation (CLFV)

via the coherent conversion:

\[ \mu^- + \text{Al} \rightarrow e^- + \text{Al} \]

At the Fermilab Muon Campus

Will improve by a factor \(10^4\) the world’s best sensitivity (SINDRUM II*) on:

\[ R_{\mu e} = \frac{\Gamma (\mu^- + N \rightarrow e^- + N)}{\Gamma (\mu^- + N \rightarrow \text{all captures})} \]

down to a Single Event Sensitivity of \(3 \cdot 10^{-17}\)

SM prediction is \(O(10^{-54})\): any observation will be clear evidence for New Physics

CLFV searches

Muon sector currently provides the most stringent limits to CLFV

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.

“3 stars” discovery capability in many theoretical frameworks

Different sensibility to different processes makes the 3 experimental searches complementary

W. Altmanshofer at al. arxiv 0909.1333v2

See more in Angela Papa’s talk
The Mu2e Experiment at Fermilab: the beam line

Production Solenoid: \( p \) on \textit{tungsten}, graded field sweeps low momentum particles downstream

Transport Solenoid: transmit negative particles with the right momentum, antiproton absorber

Detector Solenoid: Al stopping target, proton absorber, graded field to direct to detectors
The Mu2e Experiment at Fermilab: the beam line

Production Solenoid

Transport Solenoid

Detector Solenoid

8 GeV pulsed proton beam

Pulsed Proton Beam Structure

Extinction Factor $<10^{-10}$
(fraction of protons out of bunch)

Time window to avoid prompt background from beam flash

Beam period: 1695 ns ~ $2\tau_{\mu}^{AI}$
Beam intensity: 39 MP/pulse ±50%
The Mu2e Experiment at Fermilab: detectors region

Acceptance improved by magnetic gradient
Minimum amount of material before momentum measurement
Constant field in the tracking volume
18 straw tube tracker stations, 2 CsI crystals calorimeter disks

The Detector Solenoid

Stopping target

13 m

Tracker

Calorimeter

2.0T

1.0T

The stopping target

37 foils of Al
100 μm thick
150 mm diameter
43 mm diameter central hole

μ
The Mu2e Experiment at Fermilab: Cosmic Rate Veto

**Cosmic Ray Veto:**
- 4 layers of scintillator counters covering the Detector Solenoid and Lower Transport Solenoid

About 1 cosmic event/day emulating a 105 MeV electron
The Mu2e Experiment at Fermilab: tracker

18 stations of 12 panels covering 120° each (stereo view)

Tracker not sensitive to particles with $p_T < 80$ MeV/c
(beam flash and most of DIOs)

~21000 straw tubes
5 mm diameter, 15 μm mylar
25 μm tungsten wire @1450V
80:20 ArCO$_2$ gas mixture
Each read by 2 ADCs & 2 TDCs
The Mu2e Experiment at Fermilab: tracker

Results of tests on prototypes

Transverse Resolution

FWHM = 283 μm

<table>
<thead>
<tr>
<th></th>
<th>Transverse Resolution</th>
<th>Longitudinal Resolution</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FWHM = 283 μm</td>
<td>σ = 43.4 mm</td>
<td>ε = 0.950</td>
</tr>
<tr>
<td></td>
<td>8-Straw Prototype</td>
<td>8-Straw Prototype Fit</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8-Straw Prototype Fit</td>
<td>G4 + Straw Simulation</td>
<td></td>
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</tbody>
</table>

Arbitrary Unit

Drift Radius Residual (mm)

Longitudinal Position Residual (mm)

Distance from wire (mm)
The Mu2e Experiment at Fermilab: tracker

momentum resolution at start of tracker (simulation)

Core width = 159 keV/c

Left tail due to energy loss in material
The Mu2e Experiment at Fermilab: calorimeter

**Geometry (acceptance optimized)**
2 disks spaced by 70 cm
inner radius: 37.4 cm
outer radius: 66 cm

**Active material:**
pure CsI crystals
674 crystals/disk
3.4x3.4x20 cm³

**Sensors:**
Arrays of 6 SiPMs
2 arrays/crystal
14x20 mm² each

**Readout electronics:**
Preamplifiers on sensors back
Voltage control and Waveform
Digitizers in crates around disks

**Calibration/monitoring system:**
Fluorinert liquid in front of each disk
Laser and electronic pulses
The Mu2e Experiment at Fermilab: calorimeter

Particle identification: 105 MeV/c Muon rejection factor ~400

Pattern recognition: use calorimeter cluster time to reduce combinatorial of tracker hits

Trigger: 90% efficiency on reconstructable CE, 97% if combined with straw hit information
The Mu2e Experiment at Fermilab: calorimeter

Test on a 51 crystal prototype with electrons and cosmic $\mu$ at Frascati Beam Test Facility

For 100 MeV electrons:

<table>
<thead>
<tr>
<th></th>
<th>0°</th>
<th>50° (CE peak)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy resolution</td>
<td>5.4%</td>
<td>7.3%</td>
</tr>
<tr>
<td>Time resolution*</td>
<td>160 ps</td>
<td>230 ps</td>
</tr>
</tbody>
</table>

*Obtained for 1 sensor from the time difference of 2 sensors

Mu2e requirements satisfied

Energy profile

Energy resolution

Time resolution
The Mu2e Experiment at Fermilab: cosmic veto

Light yield measured at Fermilab test beam

Efficiency compatible with Mu2e requirement: $1-\varepsilon \sim 10^{-4}$
## Current Background estimate

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected event yield</th>
<th>Mitigation strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic rays</td>
<td>0.209 ± 0.022 ± 0.055</td>
<td>Cosmic veto, PID</td>
</tr>
<tr>
<td>Decay in orbit</td>
<td>0.144 ± 0.028 ± 0.11</td>
<td>Momentum resolution</td>
</tr>
<tr>
<td>Antiprotons</td>
<td>0.040 ± 0.001 ± 0.020</td>
<td>Absorbers</td>
</tr>
<tr>
<td>Rad. Pion captures</td>
<td>0.021 ± 0.001 ± 0.002</td>
<td>Delayed Analysis Window</td>
</tr>
<tr>
<td>Muon decay in flight</td>
<td>&lt; 0.003</td>
<td></td>
</tr>
<tr>
<td>Pion decay in flight</td>
<td>0.001 ± &lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>Beam electrons</td>
<td>(2.1 ± 1.0) · 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>Rad. Muon captures</td>
<td>0.000^{+0.004}_{-0.000}</td>
<td>Kinematic end point</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>0.41 ± 0.13(stat+syst)</td>
<td></td>
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</tbody>
</table>
Current sensitivity estimate

**Discovery reach (5σ):**  
$R_{\mu e} \geq 2 \cdot 10^{-16}$

**Exclusion power (90% C.L.):**  
$R_{\mu e} \geq 8 \cdot 10^{-17}$
Mu2e status: detector hall
Mu2e status: detector hall
Mu2e status: beam line

M4 beamline completed up to the diagnostic absorber
First 8 GeV proton beam expected for April 2020

Final focus installation is in progress
Mu2e status: transport solenoid

All coils wound at AGS (Genova, Italy)

6/14 modules delivered to Fermilab

Under test at Fermilab Test Facility
Mu2e status: production/detector solenoid

In production at General Atomics (Tupelo, US)

First DS module completed! (244 turns 1 layer)

DS10 module

PS cryostat

DS cryostat
Mu2e status: tracker

All straws produced
15 pre-production panels built
using final procedure
1 panel/day production starting

Panel assembly at U. of Minnesota

Panel vacuum test at Fermilab
Mu2e status: calorimeter

All SiPM delivered, QA test completed
1134/1450 crystals delivered and tested
Radiation hard electronics tested, starting production
Mu2e status: cosmic ray veto

![CRV counter]

1229/2736 di-counters produced

5 pilot production modules completed and tested

![4 layer module at U. of Virginia]
Mu2e schedule

- Begin commissioning beam line: mid 2021
- Begin commissioning detector: early 2022
- First data taking: early-mid 2023
- Anticipate 4-5 years of run time for full data set (including calibration, ...)
Conclusion

• CLFV sensitivity in the muon sector is expected to be improved in the very next future by the experiments looking for $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$ or $\mu N \rightarrow eN$.

• If a violation will be observed in one of these processes, it will be very important to have the complementary information from the other two to investigate the origin of the violation.

• Mu2e will improve by 4 order of magnitudes the current world sensitivity on muon conversion to electron.

• Prototypes test and simulation are confirming the design detector performances.

• Construction of the beam line, solenoids and detectors is under way.

• Expect to start physics data taking in 2023.
Backup
The Mu2e Experiment at Fermilab: the beam line

Production Solenoid: \( p \) on *tungsten*, graded field sweeps low momentum particles downstream

Transport Solenoid: transmit negative particles with the right momentum, antiproton absorber

Detector Solenoid: Al stopping target, proton absorber, graded field to direct to detectors
Extinction monitor

Validates the assumption of an extinction factor $<10^{-10}$
Stopping target monitor

Ge and LaBr detectors to detect the monochromatic X and γ rays produced by muon captures in Al with a statistical error <10%
Calorimeter calibration

6 MeV liquid source in front of crystals (energy calibration)

Laser pulses (energy and time Calibration) FEE pulses

Cosmic muons (energy and time calibration)

E/\rho \text{ and } \Delta t \text{ from muon decays in orbit (DIO) and } \pi \rightarrow e\nu \text{ decays at reduced B field (energy and Tracker-ecal time)}

DIO spectrum
Mu2e track reconstruction

A typical Mu2e tracker event integrated over the 500-1695 ns daq window

Hits filtered according to their time, energy and position
Low momentum electrons hits rejected by dedicated algorithm
Candidate tracks searched by grouping hits in 50 ns time windows
COMET Phase I

Proton beam: 8 GeV, 0.4 mA, 3.2 kW

COMET Phase-I, 5 months data taking
- Directly measure the muon beam with prototypes of Phase-II detector.
- Very useful to guide Phase-II

See Manabu Moritsu’s poster!

Search for \( \mu - e \) conversion with cylindrical detector (CyDet) with S.E.S. = \( 3 \times 10^{-15} \) (2 orders of magnitude improvement).

From Wu Chen’s presentation at CLFV2019
COMET Phase II

Proton beam: 8 GeV, 7 mA, 56 kW

COMET Phase II, One year data taking

- Search for $\mu \rightarrow e$ conversion with S.E.S. = $2.6 \times 10^{-17}$ (4 orders of magnitude improvement)
- Further optimization on the way
  - Likely to improve sensitivity by factor of $10^{-10}$ ($O(10^{-18})$) with the same beam power.

See Weichao Yao's poster!

From Wu Chen's presentation at CLFV2019