Searching for Muon to electron conversion: The Mu2e experiment at Fermilab

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Charged Lepton Flavor Violation (CLFV) has never been observed

Standard Model of Elementary Particles

three generations of matter (fermions)			interactions / force carriers (bosons)	
			I	II
QUARKS	mass $\approx 2.2 \text{ MeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$	I u up	mass $\approx 1.28 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$	II c charm
	mass $\approx 173.1 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$	III t top	mass $\approx 124.97 \text{ GeV}/c^2$ charge 0 spin 0	H higgs
	mass $\approx 4.7 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$	d down	mass $\approx 96 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$	s strange
LEPTONS	mass $\approx 105.66 \text{ MeV}/c^2$ charge $-\frac{1}{2}$ spin $\frac{1}{2}$	μ muon	mass $\approx 1.7768 \text{ GeV}/c^2$ charge $-\frac{1}{2}$ spin $\frac{1}{2}$	τ tau
	mass $\approx 0.511 \text{ MeV}/c^2$ charge $-\frac{1}{2}$ spin $\frac{1}{2}$	e electron	mass $\approx 91.19 \text{ GeV}/c^2$ charge 0 spin 1	Z Z boson
	mass $\approx 80.39 \text{ GeV}/c^2$ charge ± 1 spin 1	W W boson	mass $< 2.2 \text{ eV}/c^2$ charge 0 spin $\frac{1}{2}$	ν_e electron neutrino
			mass $< 0.17 \text{ MeV}/c^2$ charge 0 spin $\frac{1}{2}$	ν_μ muon neutrino
			mass $< 18.2 \text{ MeV}/c^2$ charge 0 spin $\frac{1}{2}$	ν_τ tau neutrino
			mass $< 80.39 \text{ GeV}/c^2$ charge ± 1 spin 1	W W boson

- Standard model CLFV contribution is undetectably small ($< 10^{-50}$)
- Any detection of charged lepton flavor violation would be an unambiguous sign of new physics!

Muon searches reach the smallest branching ratio limits on CLFV processes

Process	Current Limit	Next Generation exp.
$\tau \rightarrow \mu\eta$	$\text{BR} < 6.5 \times 10^{-8}$	$10^{-9} - 10^{-10}$ (Belle II, LHCb)
$\tau \rightarrow \mu\gamma$	$\text{BR} < 6.8 \times 10^{-8}$	
$\tau \rightarrow \mu\mu\mu$	$\text{BR} < 3.2 \times 10^{-8}$	
$\tau \rightarrow eee$	$\text{BR} < 3.6 \times 10^{-8}$	
$K_L \rightarrow e\mu$	$\text{BR} < 4.7 \times 10^{-12}$	
$K^+ \rightarrow \pi^+ e^- \mu^+$	$\text{BR} < 1.3 \times 10^{-11}$	
$B^0 \rightarrow e\mu$	$\text{BR} < 7.8 \times 10^{-8}$	
$B^+ \rightarrow K^+ e\mu$	$\text{BR} < 9.1 \times 10^{-8}$	
$\mu^+ \rightarrow e^+ \gamma$	$\text{BR} < 4.2 \times 10^{-13}$	10^{-14} (MEG)
$\mu^+ \rightarrow e^+ e^+ e^-$	$\text{BR} < 1.0 \times 10^{-12}$	10^{-16} (Mu3e)
$\mu^- N \rightarrow e^- N$	$R_{\mu e} < 7.0 \times 10^{-13}$	10^{-17} (Mu2e, COMET)

Muon conversion can probe mass scales up to 10^4 TeV (assuming unit coupling)

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

- **loop:** $\kappa \ll 1$, $\mu N \rightarrow e N$ and $\mu \rightarrow e \gamma$
- **contact:** $\kappa \gg 1$, $\mu N \rightarrow e N$ only
- Mass scale reach makes these measurements complementary to LHC

Basics of a Muon conversion experiment

Measure the ratio of conversions to muon nuclear captures:

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

- Signal of CLFV conversion is single monoenergetic electron

Anything that can produce a ~ 105 MeV electron is a background to a μ to e conversion search

- Muon Decay in orbit: $\mu^- N \rightarrow e^- N \nu_\mu \bar{\nu}_e$
- Beam related: $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+ e^-$
- Cosmic rays: $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$

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Robert Szafron and Andrzej Czarnecki, Phys. Rev. D 94, 051301 (2016)

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- Cosmic rays: $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ (**Active veto**)

The Mu2e Experiment at Fermilab

- Aim is 10^4 improvement in sensitivity
 - Greatly increase muon production
 - Reduce backgrounds
 - High resolution detector that can survive event rate

Pulsed proton beam allows us to reject radiative pion capture events ($\pi^- + \text{Al} \rightarrow \text{Mg}^* + \gamma$)

- 8 GeV 8 kW proton beam from Fermilab booster
- Resonantly extracted to get pulses of 4×10^7 protons separated by $1.7 \mu\text{s}$
- 700 ns delay followed by $1 \mu\text{s}$ livegate
- Must have very few protons outside of pulse (ratio to in-pulse $< 10^{-10}$)

Mu2e experimental setup

- Consists of three superconducting solenoids:
 - Production Solenoid (PS)
 - Transport Solenoid (TS)
 - Detector Solenoid (DS)

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Production Target and Solenoid produce slow muon beam in the reverse direction of the proton beam

- Tungsten production target
- Magnetic mirror traps and redirects back to TS

Transport Solenoid sign selects charged particles

Detector solenoid directs electrons to detector elements

- Muons stopped on thin aluminum foils, again graded field for magnetic mirror
- Constant field in tracking volume
- High precision straw tracker in vacuum
- Electromagnetic calorimeter for PID

Straw Tracker designed to survive beam flash while providing resolution better than 200 keV/c

- 18 stations, each containing $12 \times 120^\circ$ panels for stereo measurement

Straw Tracker designed to survive beam flash while providing resolution better than 200 keV/c

- Blind to DIO electron momentum peak and beam flash

Straw Tracker designed to survive beam flash while providing resolution better than 200 keV/c

- $\sim 21,000$ low mass straw tubes in vacuum
- 5 mm diameter, 15 μm thick mylar walls
- 25 μm tungsten wire at 1425V
- 80:20 ArCO₂

8 straw tracker prototype used to tune simulation and verify expected resolution

Transverse Resolution

Longitudinal Resolution

Efficiency

Reconstruction using tuned simulation shows we expect tracker to meet momentum resolution requirements

1 μ s selection window after beam flash

Hits selected by track finder within ± 50 ns selection window

momentum resolution at start of tracker (simulation)

- Helix fit followed by iterative Kalman Filter track fit

Calorimeter provides particle ID for track rejection

- Two annular disks separated by half a “wavelength” (70cm) of electron’s helical path
 - Maximize probability to hit at least one disk
- Each disk contains 674 undoped CsI $34 \times 34 \times 200$ mm³ crystals read out by SiPMs
- 0.5 ns time, 5% energy, 1 cm position measurement independent of straw tracker
- Seed for tracking algorithm

Large calorimeter prototype tested in electron beam at BTF in Frascati

- Prototype has 51 crystals, 102 SiPMs, 102 FEE boards
- Demonstrates energy and time resolution

Cosmic rays can produce dangerous background events

- Cosmic muon track can look like 105 MeV/c electron (mitigated by Calorimeter PID)
- Or - cosmic muon can decay inside the detector volume or knock out electron from stopping target $\rightarrow$ indistinguishable from signal

- Expect 1 such event per day
- Need highly efficient cosmic ray veto

Reject with efficiency cosmic ray veto

- 4 overlapping layers of scintillator, read out on both ends with SiPMs
 - Veto on 3-fold coincidence
- Covers entire DS, half of TS, better than 10^{-4} inefficiency

CRV prototype counters tested with 120 GeV protons in Fer-milab test beam

Expected backgrounds for 3.6×10^{20} protons on target is 0.41 events

Process	Expected event yield
Cosmic ray muons	$0.21 \pm 0.02(\text{stat}) \pm 0.06(\text{syst})$
Muon decay in orbit	$0.14 \pm 0.03(\text{stat}) \pm 0.11(\text{syst})$
Antiprotons	$0.040 \pm 0.001(\text{stat}) \pm 0.020(\text{syst})$
Pion capture	$0.021 \pm 0.001(\text{stat}) \pm 0.002(\text{syst})$
Muon decay in flight	< 0.003
Pion decay in flight	$0.001 \pm < 0.001$
Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
Radiative muon capture	$0.000^{+0.004}_{-0.000}$
Total	$0.41 \pm 0.13(\text{stat+syst})$

Mu2e expects a $10^4\times$ increase in sensitivity

- Discovery reach (5σ): $R_{\mu e} \geq 2 \times 10^{-16}$
- Exclusion power (90% CL): $R_{\mu e} \geq 8 \times 10^{-17}$

Mu2e status: detector hall

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Mu2e status: beamline

- Most beamline elements installed or being fabricated
- Prototype AC dipole and collimators for extinction system fabricated
- Resonant extraction sextupoles being fabricated
- Prototype remote target handling system tested

Prototype Remote Target Handler

Res Extraction Sextupole

Extinction Collimator

Mu2e status: transport solenoid

- Solenoid production at ASG (Genova) and Fermilab
- All coils have been wound
- 4/14 modules delivered, 2 fully tested

TS Coils at ASG

TS Test Facility at Fermilab

Two units assembled on warm bore. Alignment ongoing

Mu2e status: production/detector solenoid

- Solenoid production at General Atomics (Tupelo)
- First demonstration coil with two layers of 70 turns each successfully completed
- Winding of PS began in April

Mu2e status: tracker

- All straws manufactured
- 10/12 pre-production panels built using final production tooling, full production (1 per day) starting soon

Panel assembly at UMN

Vacuum tests at FNAL

Mu2e status: Calorimeter

- All SiPMs delivered, and QA completed
- 1134/1450 crystals delivered (SICCAS and Saint Gobain) and tested, expected completion October 2019
- Electronics vertical slice test completed
 - Upgrading to Rad hard components

Caltech and INFN

Mu2e status: CRV

- 1229/2736 di-counters produced
- 5 pilot production modules complete and tested

Module being vacuum bagged at UVA

Mu2e is under construction, expect physics data in 2023

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

Mock data challenge: shows physics capability after $<1\%$ POT

- $R_{\mu e} = 8 \times 10^{-14}$, order of magnitude below current limit
- Created mixed samples with randomized/hidden parameters
 - will be used to test analysis tools

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Conclusion

- Mu2e will search for muon to electron conversion, a CLFV process, with a sensitivity of 8×10^{-17}
 - 10^4 improvement over current results
 - Sensitive to new physics, complementary to LHC and other CLFV measurements
- Prototypes and simulation demonstrating performance of detectors
- Construction underway: beamline, solenoids, detectors
- Currently undergoing mock data challenge
- Expect to start physics data taking in 2023

Backup

Mock data challenge sample creation

- Simulate signals and backgrounds with natural energy / time spectra
 - Signals only include conversion, DIO, RMC, RPC, cosmic rays
 - Events overlaid on top of beam backgrounds
- Randomly sample at expected normalizations into single mixed file
- Randomize R_{ue} , R_{up} , RMC kMax, effective proton beam intensity
- For closed ensembles, MC information is removed and hidden
- Assume nominal beam intensity ($3.9e7$ protons per pulse) on average

Mock data challenge - cuts used in figure

- Track $t_0 > 700$ ns and < 1695 ns
- Track quality MVA > 0.8
- Track PID MVA > 0.95
- Track geometry cuts:
 - $0.57735 < \tan \lambda < 1.0$
 - $-80 < d_0 < 105$
 - $450 < d_0 + \frac{2}{\Omega} < 680$
- No CRV trigger within -120 ns to +50 ns
- No upstream track reconstructed
- Triggered

Many models of new physics predict large additional contributions to CLFV

Supersymmetry

Leptoquark

Heavy Neutrinos

Second Higgs Doublet

Heavy Z' Anomal. Z Coupling

Kuno, Y. and Okada, Y. Rev. Mod. Phys. 73, 151 (2001)
 Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58 (2008)
 M. Raidal et al, Eur.Phys.J.C57:13-182, (2008)
 de Gouvea, A., and P. Vogel, Prog. Part. Nucl. Phys. 71, 75 (2013)

Search for CLFV started as soon as lepton flavors were discovered

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Previous experiment: SINDRUM II

- Beam backgrounds reduced by degrader
 - Pions have half the range in CH_2 compared to muons
- Limit: 7×10^{-13} (90% confidence) on Au

Previous experiment: SINDRUM II

Achieving required beam extinction

- Beam from delivery ring starts with 10^{-4} extinction
- 2 AC dipoles coupled with collimators expected to bring extinction to 10^{-12}

Extinction Monitor located downstream of production target

Extinction Monitor located downstream of production target

- Measure extinction at 10^{-10} to 10% in a few hours

Stopping Target Monitor measures capture rate for final normalization

- Muons cascade to 1s state emitting x-rays
- HPGe detector monitor these x-rays to measure capture rate
- Normalization of measurement $R_{\mu e} = \frac{\mu^- + A(Z, N) \rightarrow e^- + A(Z, N)}{\mu^- + A(Z, N) \rightarrow \nu_\mu + A(Z-1, N)}$

Mu2e Status: Conductor

- Conductor production (75 km of cables) complete

In the future, we can learn more by switching targets or by increasing muon yield with PIP-II

V. Cirigliano, R. Kitano, Y. Okada, P. Tuzon, Phys. Rev. **D80** 013002 (2009)

- Expression of interest for Mu2e-II, using PIP-II to increase sensitivity by factor of 10 ([arxiv.1802.02599](https://arxiv.org/abs/1802.02599))

- Joint project by Mu2e and COMET
- Measure particles emitted after muon capture on Al

Beam structure

RMC background

Phys. Rev. C 46 1094 (1992)

SO(10) SUSY GUT limits

Phys. Rev. D 74 116002 (2006)

- LHC accessible region: $m_0 < 5000$ GeV, $M_{1/2} < 1500$ GeV

SO(10) SUSY GUT limits

J. High Energ. Phys. 11 (2012) 040

- LHC accessible region: $m_0 < 5000$ GeV, $M_{1/2} < 1500$ GeV
- mSUGRA PMNS (red), NUHM PMNS (green), CKM (blue),
 $\tan\beta=10$ (left), $\tan\beta=40$ (right)

Leptoquark limits from CLFV

Flavor Violating Higgs Couplings