The Mu2e Experiment

A Search for Charged Lepton Flavor Violation

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Charged Lepton Flavor Violation

Neutrino oscillations: Direct evidence of lepton flavor violation

Mixing between charged leptons: Never observed

Violation of charged lepton flavor “forbidden” in SM

Loophole: neutrino oscillations

- Some CLFV *must occur*
- But rate is vanishingly small, $<10^{-50}$

Any CLFV observation would be unambiguous sign of new physics

- Searches for CLFV are very powerful
- Well motivated, connections with:
 - Flavor in SM
 - Neutrino mass generation
 - B meson decays, lepton flavor universality
 - Muon $g-2$
 - ... and more

$\mu \rightarrow e$ conversion: The Mu2e search

Coherent conversion $\mu \rightarrow e$ in the field of a nucleus

Clean experimental signature

- monochromatic e^- – for Al:

$$E_e(\text{Al}) = M_\mu - E_b - E_{\text{recoil}}^{\text{Al}} \approx 104.97 \text{ MeV}$$

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

Conversion process

Ordinary muon capture

The Mu2e experiment will probe $R_{\mu e}$ at the level of $\sim 6 \times 10^{-17}$ (90% CL)

- Current limit: $R_{\mu e} < 7 \times 10^{-13}$ [SINDRUM II]
- 4 orders of magnitude improvement – a rare opportunity!
- Exploring unconstrained phase space favored by many BSM models

$\mu \rightarrow e$ conversion processes

Effective
Lagrangian:

$$\mathcal{L}_{\text{CLFV}} = \underbrace{\frac{m_\mu}{(1 + \kappa)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu}}_{\text{Loop}} + \underbrace{\frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)}_{\text{Contact}}$$

Λ : effective mass parameter
 κ : relative strength of loop-
and contact-dominated terms

Loop:

Contact:

Loop terms:

- Also mediate $\mu \rightarrow e\gamma$

Supersymmetry

Heavy neutrino

Two Higgs doublets

Compositeness

Leptoquarks

New heavy bosons

Contact terms:

- ~~$\mu \rightarrow e\gamma$~~

Model-independent Mu2e Physics reach: $\Lambda \sim 2,000 - 10,000 \text{ TeV}$ (effective)

The Fermilab Mu2e experiment

Mu2e will be performed in Fermilab, in the new Muon Campus.

The Mu2e Collaboration
>200 scientists, 37 institutions

Mu2e experimental apparatus

Entire system in vacuum

- **Production Solenoid**

- Pulsed **proton beam** hits target
- Magnetic field gradient captures pions

- **Transport Solenoid**

- Pions $\rightarrow$ muons
- S-shape eliminates line-of-sight
- Sign and momentum selection
 $\rightarrow$ only μ^- past collimator

- **Detector Solenoid**

- Muons stopped in Al target
- 10^{10} stopped μ/s
 - **world's most intense muon beam**
- Detector system must identify
105 MeV conversion electron

Background process: Decay in Orbit (DIO)

Michel spectrum of E_e after **free muon decay**, or **modified in field of nucleus**

Background process: Decay in Orbit (DIO)

Theory Predictions

Czarnecki et al., Phys.Rev.D84:013006,2011
Szafron and Czarnecki, 10.1103/PhysRevD.94.051301

After Reco Acceptance+ ΔE +Resolution

- Nuclear recoil pushes DIO spectrum near conversion electron energy
- Overlap after **energy loss in material and detector resolution**
- DIO electron only differs from signal through its momentum
→ **Need low mass detector with high resolution**

Straw tracker

Straw drift tubes

- 5mm diameter
- Wall: 12μm mylar + 3μm epoxy + 200Å Au + 500Å Al
- 25μm gold-plated tungsten wire at 1450V
- 80/20 Ar/CO₂ gas

Excellent fit to tracker requirements

- **Ultra low mass**, minimize multiple scattering
- Highly segmented, handle high rates
- Reliable operation in vacuum, must not leak

Resolution <180 keV @ 105 MeV, or <0.18%

120° panel of 2x48 straws,
two staggered layers

Tracker annular design

Panel unit is rotated and repeated

- Total 216 panels, ~21,000 straws
- 30° rotation for stereo reconstruction

Annular design, with hole in center

Tracker is **blind** to nearly all DIO background

Only electrons $>90\text{MeV}$ have **reconstructable tracks**

Vacuum, no detector material

Straws in active region,
 $380\text{mm} < r < 700\text{mm}$

Two disks separated by half wavelength,
→ ~90% acceptance

~1400 scintillating CsI crystals, readout by 2 SiPMs/crystal
 $\sigma_E/E < 5\%$ at 105 MeV, $\sigma_t < 5$ ns

- Measurement of E, timing, and position
- Protection from pattern recognition errors in tracker
- Particle ID, additional rejection of cosmics background

Cosmic Ray Veto (CRV) system

Cosmic μ

- Cosmic muon can decay or knock out electron from material
→ **indistinguishable from conversion e^-**
 - Expectation of 1 per day
- **Cosmic Ray Veto** covers half of transport solenoid and detector solenoid
 - 4 stacked layers of scintillation counters
 - **99.99% efficiency requirement**

Prompt backgrounds and delayed signal window

- Proton pulse period: 1695 ns (FNAL Delivery Ring)
- Delayed signal window: 700 $\rightarrow$ 1600 ns
 - Detector is live here
- **Pion lifetime**: 26 ns
 - prompt backgrounds decay before signal window
- **Muonic A1 lifetime**: 864 ns

Must also eliminate late-arriving protons

Require beam extinction (fraction of beam between pulses) $< 10^{-10}$

Backgrounds summary

3 years at 1.2×10^{20} protons/year (8 kW beam power)

Category	Background	Expected events
Intrinsic	Muon decay in orbit	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late arriving	Pion capture	0.023 ± 0.006
	Muon decay in flight	< 0.003
	Pion decay in flight	$0.001 \pm < 0.001$
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic rays	0.082 ± 0.018
Total		0.36 ± 0.10

Any observation will be strong evidence of CLFV

5σ discovery capability at $R_{\mu e} \sim 2 \times 10^{-16}$

Signal and DIO background

For $R_{\mu e} \approx 10^{-16}$ we expect:
~4 conversion events, no background contamination

The Mu2e experiment

- A search for the coherent conversion of a muon to an electron in the field of an Al nucleus, $\text{SES} < 3 \times 10^{-17}$
 - Sensitivity improvement of **4 orders of magnitude**
- Significant progress, construction underway
 - Mu2e building complete
 - All conductor procured
 - All straws manufactured
- **Commissioning expected in 2021**, followed by 3 years of data

Backup

Broad global interest in CLFV searches:

Process	Current limit	Planned Next Gen Experiment
$Z \rightarrow e\mu$	$\text{BR} < 7.5 \cdot 10^{-7}$	
$\tau \rightarrow eee$	$\text{BR} < 2.7 \cdot 10^{-8}$	10^{-9} , BELLE-II
$\tau \rightarrow \mu\mu\mu$	$\text{BR} < 2.1 \cdot 10^{-8}$	
$\tau \rightarrow \mu ee$	$\text{BR} < 1.5 \cdot 10^{-8}$	
$\tau \rightarrow \mu\eta$	$\text{BR} < 6.5 \cdot 10^{-8}$	
$\tau \rightarrow e\gamma$	$\text{BR} < 3.3 \cdot 10^{-8}$	
$\tau \rightarrow \mu\gamma$	$\text{BR} < 4.4 \cdot 10^{-8}$	
$K_L \rightarrow e\mu$	$\text{BR} < 4.7 \cdot 10^{-12}$	
$K^+ \rightarrow \pi^+ e\mu$	$\text{BR} < 1.3 \cdot 10^{-11}$	
$B^0 \rightarrow e\mu$	$\text{BR} < 7.8 \cdot 10^{-8}$	
$B^+ \rightarrow K^+ e\mu$	$\text{BR} < 9.1 \cdot 10^{-8}$	
$\mu^+ \rightarrow e^+ \gamma$	$\text{BR} < 4.2 \cdot 10^{-13}$	10^{-14} (MEG)
$\mu^+ \rightarrow e^+ e^- e^+$	$\text{BR} < 1.0 \cdot 10^{-12}$	10^{-16} (Mu3e)
$\mu^- A \rightarrow e^- A$	$R_{\mu e}^{\text{Au}} < 7.0 \cdot 10^{-13}$	10^{-17} (Mu2e, COMET)

- Most stringent limits come from the muon sector
- **The $\mu A \rightarrow e A$ process offers greatest potential sensitivity**
 - Best control of backgrounds

History of CLFV searches

- Dramatic improvement in next generation experiments, especially $\mu N \rightarrow eN$
- Exploring unconstrained phase space favored by many New Physics models

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

Λ : effective mass parameter

κ : relative strength of loop- and contact-dominated terms

Mu2e improves sensitivity in all New Physics scenarios

Effective mass scale reach up to 10^4 TeV, well beyond the direct reach of current or future colliders

We obtain model discriminating power on underlying physics mechanism by comparing CLFV rates on different stopping targets

Mu2e-II expression of interest:
<https://arxiv.org/abs/1802.02599>

Stopping Target

17 Al disks,
200 μm thick

Muons stopped in thin Al target foils.
Quickly cascade to 1s ground state (~ 1 fs),
emitting X-rays at characteristic energies

Fermi radius ~ 20 fm
Muonic Al lifetime: 864 ns

Muonic atom at rest

High-purity Ge detector monitors de-excitation X-rays from stopping target

Prompt event: occurs shortly after particle reaches stopping target

Example: **Radiative pion capture**

Non-decayed pion reaches stopping target, is radiatively captured, then photon converts.

Photon momentum endpoint at m_π .

The electron can have momentum in signal window, and **mimic conversion event**.

Pion lifetime: only ~26 ns, much shorter than muonic Al (864 ns)

Prompt backgrounds: decay quickly after proton pulse

Concept to suppress prompt backgrounds:

Simply wait until their rates are lowered
before initiating live window to look for signal.

From individual straw hits in tracker we need to:

- Remove background hits
- Identify hits from single particle (**pattern recognition**)
- Reconstruct particle's trajectory (**helix fitting**)

Signal electron + all hits over 500-1695 ns window

Detailed G4 model: straws, electronics, supports, B-fields

Helix fit, least squares fit, followed by iterative Kalman Filter track fit

Tracker momentum resolution requirement:
 $\sigma_p / p < 0.2\%$ for a 105 MeV electron, or $\sigma_p < 180 \text{ keV/c}$

Signal momentum spectrum

Smearing dominated by interactions at the target and at neutron/proton absorbers upstream of the tracker

Left: Tracker panel prototype on Duke x-ray machine for measuring wire positions inside straws. All straws manufactured, panel production ramping up using final production tooling.

Mu2e Schedule