The Mu2e experiment

Zhengyun You, University of California, Irvine
On behalf of the Mu2e Collaboration

48th Fermilab Users Meeting
June 11, 2015
Flavor Violation

• Does Charged Lepton Flavor Violation (CLFV) exist?

Quarks Flavor Violation
Observed (CKM matrix)

Neutrino Flavor Violation
Observed (PMNS matrix)

Charged Lepton Flavor Violation
NOT observed!
• In the Standard Model, CLFV $<10^{-50}$ unmeasurable

CLFV Searches History

$BR(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{ii}^2}{M_W^2} \right|^2 < 10^{-54}$

• Observation of CLFV means new physics

• Current best limit
  MEG $<5.7 \times 10^{-13}$ (90% C.L.)

• Mu2e goal $<6 \times 10^{-17}$ (90% C.L.)

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

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

One of the most effective channels

- ★★★★ Large effects
- ★★★ Visible, but small
- ★ No sizable effect

<table>
<thead>
<tr>
<th></th>
<th>AC</th>
<th>RVV2</th>
<th>AKM</th>
<th>5LL</th>
<th>FBMSSM</th>
<th>LHT</th>
<th>RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D^0 - D^0 )</td>
<td>★★★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>?</td>
</tr>
<tr>
<td>( \epsilon_K )</td>
<td>★</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
</tr>
<tr>
<td>( S_{\nu\phi} )</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>★★★</td>
</tr>
<tr>
<td>( S_{\delta K_S} )</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>( A_{CP}(B \rightarrow X_d\gamma) )</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>( A_{\tau,K}(B \rightarrow K^+\mu^+\mu^-) )</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>( A_0(B \rightarrow K^+\mu^+\mu^-) )</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>?</td>
</tr>
<tr>
<td>( B \rightarrow K^{(*)}\nu\bar{\nu} )</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>( B_\mu \rightarrow \mu^+\mu^- )</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
</tr>
<tr>
<td>( K^+ \rightarrow \pi^+\nu\bar{\nu} )</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>★★★</td>
</tr>
<tr>
<td>( K_L \rightarrow \pi^0\nu\bar{\nu} )</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>★★★</td>
</tr>
<tr>
<td>( \mu \rightarrow e\gamma )</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
</tr>
<tr>
<td>( \tau \rightarrow \mu\gamma )</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
</tr>
<tr>
<td>( \mu + N \rightarrow e + N )</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
</tr>
<tr>
<td>( d_{\mu} )</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
</tr>
<tr>
<td>( d_e )</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
</tr>
<tr>
<td>((g-2)_\mu )</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
<td>★★★★★★★★★★★</td>
</tr>
</tbody>
</table>

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.

Altmannshofer et al., NPB 830, 17 (2010)
Probing new physics with CLFV

Effective Lagrangian

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

- Contact $\kappa$, mass scale $\Lambda$
- ‘Loops’, electromagnetic operator, $\kappa \ll 1$, can be probed by $\mu \to e\gamma$ and $\mu N \to eN$
- ‘Contact terms’, direct coupling between quarks and leptons, $\kappa \gg 1$, accessible by $\mu N \to eN$
- Mu2e will probe mass scale $\Lambda$ 2,000 ~10,000 TeV
What to measure

- The ratio of muon to electron conversions to the number of muon captures by nuclei

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

- Signal: Neutrinoless conversion of a muon to electron in the field of a nucleus

- Experimental signature
  - Mono-energetic electron
  - \(E_e = m_\mu - E_{\text{bind}} - E_{\text{recoil}}\)
  - For Al, \(E_e = 104.97\) MeV
Current Best Limit in $\mu N \rightarrow eN$

- Current best limit
  - by SINDRUM II at PSI
  - $R_{\mu e} (Au) < 7 \times 10^{-13}$ (90% C.L.)

- Au target: different electron energy endpoint than Al

---


**Fig. 11.** Momentum distributions of electrons and positrons for the two event classes. Measured distributions are compared with the results of simulations of muon decay in orbit and $\mu - e$ conversion.
The Mu2e Experiment

- Search for the conversion of $\mu N \rightarrow eN$ in the field of Aluminum nucleus
- Single event sensitivity (TDR)
  - $R_{\mu e} = 2.9 \times 10^{-17}$ (7 x $10^{-17}$ @ 90% C.L.)
- Statistics
  - Requires $\sim 10^{18}$ stopped muons
  - Requires $\sim 3.6 \times 10^{20}$ protons on target (POT)
  - 3 years data taking
- Requires background events negligible (<1 events)
- Discovery sensitivity: $R_{\mu e} > \text{few } 10^{-16}$
The Mu2e Collaboration

~160 People, 32 Institutions, 4 Countries
Proton Delivery & Muon Campus

- 8 GeV protons beam
- $3 \times 10^7$ protons per bunch
- Bunch spacing 1.7 $\mu$s
- Run simultaneously with NOvA
Overview of Mu2e Design

- **Production Solenoid**
  - Protons + target → π + X; π decay into muons
  - Solenoid reflect slow forward μ/π and contains backward μ/π

- **Transport Solenoid**
  - Filter low momentum μ⁻

- **Stopping Target, Detector Solenoid and Detectors**
  - Stop μ⁻ on Al foils and wait for them to decay
  - Tracks reconstructed by tracker and calorimeter, optimized for 105MeV
Pulsed Beam

- $\mu^-$ captured on stopping target to form muonic atoms ($\tau=864$ns)
- Wait for prompt backgrounds to decay
- Select tracks in search window, when $\pi^-$ disappear
- Beam extinction $< 10^{-10}$ required to remove backgrounds between pulses
Tracker

- 5 mm diameter straw drift tubes
- 15 µm Mylar walls, filled with Ar/CO₂
- 18 stations, 2 planes/station, 6 panels/plane
- Blind to beam flash and >97% DIO
- Expect 100 µm hit resolution
Calorimeter

- Two disks composed of square BaF$_2$ crystals
- Provides independent energy (up to 5%), time (0.5ns) and position (1cm) measurements
- Particle ID, Cosmic Ray rejection, tracking seed
- Independent trigger
Background(1): Intrinsic

- Muon Decay-in-orbit (DIO)
  - $\mu \rightarrow e \nu_\mu \bar{\nu}_e$
  - Dominant background
  - 39% of stopped muons
  - DIO Rate $\sim (E_{\text{MAX}} - E_e)^5$, $E_{\text{MAX}} \sim 105$ MeV
  - Requires good energy resolution

- Radiative Muon Capture (RMC)
  - $\mu N \rightarrow \gamma \nu_\mu N'$
  - 61% of stopped muons
  - 3 MeV under DIO end point
  - Small contribution
Background(2): Prompt Backgrounds

- Radiative Pion Capture (RPC)
  - $\pi^- N \rightarrow \gamma N'$, $\gamma \rightarrow e^+ e^-$
  - $\pi^- N \rightarrow e^+ e^- N'$
  - 2% of captured $\pi^-$
  - Mitigate by waiting

- Beam and free decays
  - Beam Electrons
  - Muon Decay In Flight
  - Pion Decay In Flight

Delayed search time window help to mitigate prompt backgrounds
Background(3): Anti-protons

- 8GeV proton above anti-proton production threshold
  - $pp \to \bar{pppp}$,
  - Anti-proton annihilate, produce $\pi^0 \to e^+e^-$,
  - $\pi^-$ contribute to RPC backgrounds
  - Anti-protons travel 10x more slowly
  - Do not decay, time rejection does not help

Add absorbers at some locations in the muon beamline to absorb anti-protons
Background(4): Cosmic Rays

- Cosmic ray background ~1 event / day
- Requires <10^{-4} inefficiency → 0.1 event in 3 years
- Cosmic Ray Veto (CRV) made of 4 layers of overlapping scintillators
- Surrounding DS & part of TS area
## All Backgrounds

<table>
<thead>
<tr>
<th>Category</th>
<th>Background process</th>
<th>Estimated yield (events)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic</td>
<td>Muon decay-in-orbit (DIO)</td>
<td>0.199 ± 0.092</td>
</tr>
<tr>
<td></td>
<td>Muon capture (RMC)</td>
<td>0.000 ±0.004</td>
</tr>
<tr>
<td>Late Arriving</td>
<td>Pion capture (RPC)</td>
<td>0.023 ± 0.006</td>
</tr>
<tr>
<td></td>
<td>Muon decay-in-flight (μ-DIF)</td>
<td>&lt;0.003</td>
</tr>
<tr>
<td></td>
<td>Pion decay-in-flight (π-DIF)</td>
<td>0.001 ± &lt;0.001</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>Beam electrons</td>
<td>0.003 ± 0.001</td>
</tr>
<tr>
<td></td>
<td>Antiproton induced</td>
<td>0.047 ± 0.024</td>
</tr>
<tr>
<td></td>
<td>Cosmic ray induced</td>
<td>0.092 ± 0.020</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>0.37 ± 0.10</strong></td>
</tr>
</tbody>
</table>

Numbers normalized to 3 years run, \(3.6 \times 10^{20}\) POT events
Signal and Backgrounds

With $3.6 \times 10^{20}$ POT, assuming $R_{\mu e} = 1 \times 10^{-16}$, expect 3.5 events in signal window

DIO yield = 0.20 events
Others $\sim$ 0.17 events

Full Geant4 simulation and reconstruction
Background overlaid with signal
Mu2e Prototypes

Tests of a prototype tungsten production target at RAL.

Panel prototype (96 straws) for vacuum tests.

Prototype counter for cosmic veto.

TS Coll Module prototype at Fermilab.

Mu2e, Fermilab.
Mu2e Status

- TDR published in 2014
- DOE CD2/3b received in 2015
- Ground breaking in 2015
Mu2e Schedule

- CD-1: Superconductor R&D
- CD-3a: Solenoid Design
- CD-2/3b: Fabricate and QA Superconductor
- CD-3c: Detector Hall Construction
- Project Complete
  - KPPs satisfied
  - Solenoid Installation and Commissioning
  - Detector Construction
  - Cosmic Tests
  - Accelerator and Beamline

Timeline:
- FY14
- FY15
- FY16
- FY17
- FY18
- FY19
- FY20
- FY21

Now
Summary

- CLFV has great potentials to probe new physics
- Mu2e will search for CLFV with $\mu N \rightarrow eN$
  - $R_{\mu e} = 2.9 \times 10^{-17}$
  - 4 orders of magnitude improvement
  - Mass scale up to $10^4$ TeV
- Project is going well
  - Technical design mature
  - DOE CD-2/3b received
  - Start running in 2021
- Thanks for all the supports to Mu2e
Thank you!
Backup Slides
Target and Heat Radiation Shield

• Production Target
  • Protons + target → π + X; π decay into muons
  • High A and high density material Tungsten to maximize muons production
  • High melting temp, radiative cooling (~1600°C), with 8kW beam (700w in target)

• Heat Radiation Shield
  • To protect superconductor of PS and upstream TS
  • To limit heat load and radiation damage
  • ~25 tons of Bronze

Zhengyun You / UCI
Mu2e, Fermilab Users Meeting 2015
Transport Solenoid

- Gradient magnetic field from 2.5 T to 2.0 T
- S-shaped magnetic channel to transmit low-momentum negatively charged particles in helical trajectories
- Collimators to remove positively charged and high-momentum particles
Detector Solenoid

- Stopping target to stop muons
- Graded magnetic field from 2 T to 1 T, captures conversion electrons with bigger acceptance, shifts the pitch of beam particles to reduce background
- Tracker and Calorimeter in a uniform field to reconstruct and identify electrons