Summary and Status of the Mu2e Experiment at Fermilab

2011 DPF Meeting

Craig Group
(University of Virginia and Fermilab)
...on behalf of the Mu2e collaboration.
The Frontiers of Particle Physics

The Energy Frontier
- Origin of Mass
- Dark Matter
- Origin of Universe
- Unification of Forces
- New Physics
- Beyond the Standard Model

The Intensity Frontier
- Neutrino Physics
- Proton Decay

The Cosmic Frontier
- Cosmic Particles
- Dark Energy

Mu2e
One can probe the properties of the universe by looking for extremely rare processes.

Complementary alternative to using higher energies.

The medium-term future of accelerator-based particle physics on US soil is the intensity frontier:
- Neutrino experiments (NOvA, LBNE, MINOS, MINERvA, and others...)
- Precision measurements (g-2)
- Rare decays (Mu2e, MEG, COMET, and others)
Charged Lepton Flavor Violation (CLFV)

• Neutrinos have mass!

→ individual lepton numbers are not conserved!

• Therefore, Lepton Flavor Violation occurs in Charged Leptons!

\[ BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54} \]
Can look for muon decaying into an electron plus a photon:

\[ \mu \rightarrow e \gamma \]

Experiments: MEGA, MEG, and others...
In the presence of a nucleus (N):

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

The electron is mono-energetic in CM frame!

Experiments: Mu2e, SINDRUM II, TRIUMF, COMET, and others...
Mu2e

Experiment with preliminary approval that is proposed to begin data taking in 2018 at Fermilab.

• Goal: Search for

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

– Measure ratio:

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

– With sensitivity to R at 90% C.L. of \( 6 \times 10^{-17} \)

\[ \rightarrow 4 \text{ orders of magnitude better than current limits} \]

\[ \rightarrow \text{Need more than } 10^{17} \text{ stopped muons!} \]

-- \( 3.6 \times 10^{20} \) protons on target (2 year run – 2x10^7 s)

\[ \rightarrow \text{Need to keep background small and well understood} \]
Experimental Signature

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

- A single monoenergetic electron
- If \( N = \text{Al} \), \( E_e = 105. \text{MeV} \)
  (Electron E depends on Z)
- Nucleus coherently recoils off outgoing electron, no breakup
Background Processes

- Signal is a single 105 MeV e-.
- Many possible sources of background events:
  - Muon decay in Coulomb orbit (DIO)
  - Radiative muon/pion capture
    - Photon produced that can convert asymmetrically
  - Beam electrons can scatter in target
  - Muon/pion decay in flight
  - Antiprotons and other late arriving particles
  - Cosmic-ray induced electrons

  These can all be controlled and none produce a sharp peak at 105 MeV!
History of CLFV Searches

![Graph showing the history of CLFV searches with data points from various experiments such as MARKII, CLEO, ARGUS, DELPHI, BaBar, Belle, SINDRUM, SINDRUM II, MEGA, MEG, and Mu2e. The graph plots branching fraction upper limits against year, with data points marked by different symbols and colors representing different decay modes.]
History of CLFV Searches

New MEG result: $2.4 \times 10^{-12}$

arXiv:1107.5547
July 2011

Mu2e Project X reach
In Mu2e, a signal of Terascale physics at LHC implies:

40 signal events

~

0.2 background events
Other “new physics” also provide Mu2e signal

Supersymmetry

rate $\sim 10^{-15}$

Compositeness

$\Lambda_c \sim 3000$ TeV

Leptoquark

$M_{LQ} = 3000 \left( \lambda_{\mu d} \lambda_{\mu d} \right)^{1/2} \text{TeV/c}^2$

Heavy Neutrinos

$|U_{\mu N} U_{e N}|^2 \sim 8 \times 10^{-13}$

Second Higgs Doublet

$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu \mu})$

Heavy Z’

Anom. Z Coupling

$M_{Z'} = 3000$ TeV/c$^2$

CLFV in $\mu^+ \to e^+ \gamma$ and $\mu^- N \to e^- N$

$L = \frac{m_\mu}{(\kappa+1)^2} \mu R \sigma_{\mu \nu} e_\nu F_{\mu \nu} + \frac{\kappa}{(\kappa+1)^2} \mu L \gamma_\mu e_L$

Mass scales probed
~10,000 times that probed directly by LHC

Loops

$\kappa \ll 1$

magnetic moment type operator

$\mu \to e\gamma$ rate $\sim 300X$
$\mu N \to eN$ rate

Contact Interactions

$\kappa \gg 1$

four-fermion interaction

$\mu N \to eN \gg \mu \to e\gamma$ rate

Model independent effective CLFV Lagrangian

8/2011

C. Group - Mu2e Summary - 2011 DPF Meeting

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Constraints on new physics


Neutrino-Matrix Like (PMNS)  Minimal Flavor Violation (CKM)

Can distinguish between PMNS and MFV

$\tan \beta = 10$

Current limits

BR($\mu \to e$) $\times 10^{12}$

Complementarity between Lepton Flavor Violation (LFV) and LHC experiments
Constraints on new physics

Littlest Higgs (Blanke et al.) vs MEG Goal

$R_{\mu e}$ in $10^{-11}$ vs $\text{Br}(\mu \rightarrow e\gamma)$

Goal
Mu2e Beyond the LHC

Provides information about flavor structure of new physics even if it is not easily accessible at the LHC.

A null result at the proposed sensitivity will severely constrain new physics models.

CLFV is predicted at observable rates for Mu2e in many models of new physics.

Mu2e can probe mass scales up to $10^4$ TeV, far beyond the direct reach of the LHC.
1) Proton beam hits production target in Production Solenoid.
   - Pions captured and accelerated towards Transport Solenoid by graded field.
   - Pions decay to muons.
The Mu2e Experiment

- Proton beam hits production target in Production Solenoid.
- Pions captured and accelerated towards Transport Solenoid by graded field.
- Pions decay to muons.

(for sense of scale)

Courtesy of Symmetry Magazine
• Transport solenoid performs sign and momentum selection.
• Eliminates high energy negative particles, positive particles and line-of-sight neutrals.
3) 

- Muons stop in target and decay.
- Conversion electron trajectory measured in tracker, validated in calorimeter.
- Cosmic Ray Veto surrounds Detector Solenoid.
Sensitivity Goal

Current limits: \[ R_{\mu e} = \frac{\mu^- \text{Au} \rightarrow e^- \text{Au}}{\mu^- \text{Au} \rightarrow \text{capture}} < 7 \times 10^{-13} \text{ (SINDRUM II)} \]

Mu2e goal: \[ R_{\mu e} = \frac{\mu^- \text{Al} \rightarrow e^- \text{Al}}{\mu^- \text{Al} \rightarrow \text{capture}} < 6 \times 10^{-17} \text{ (90\% c.l.)} \]

X10000 improvement over current best limit!

How:

- Improved efficiency for producing and stopping muons
  - Production target in gradient field*
  - Mu2e will stop 50 billion muons per second!
  - Expect to stop 21 muons per 10,000 proton on target.
- Reduced backgrounds and detector occupancy due to pulsed beam
  - Single event sensitivity! <0.2 bkg events expected in 2-year run

* Djilkibaev, Lobashev et. al.
4 Orders-of-Magnitude?

- We have the best accelerator setup in the world for this measurement! Ideal pulse spacing...

Extinction level of $10^{-10}$ between bunches is crucial! (Removes ‘prompt’ backgrounds!)
4 Orders-of-Magnitude?

→ Straw tracker designed such that no acceptance for lower-energy electrons from muon decay in orbit.
4 Orders-of-Magnitude?

Signal and DIO Background

Long tail due to nuclear recoil

\[ R_{\mu e} = 10^{-15} \]

Conversion momentum shifted due to material interactions
Mu2e Schedule

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<th>FY11</th>
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- **Design Phase**
  - CD-1
  - CD-2/3a
  - CD-3b

- **Solenoid Design**
- **Solenoid Fabrication**
- **Detector Hall Construction**
  - Cosmic Ray Tests
  - Install Detector

- **Hardware R&D effort to finalize design**
- **Detector Construction**
  - Solenoid Installation

- **Accelerator R&D**
The Mu2e Collaboration

- Boston University
- Brookhaven National Laboratory
- Cal Tech
- University of California, Berkeley
- University of California, Irvine
- City University of New York
- Duke University
- Fermilab
- University of Houston
- University of Illinois, Urbana-Champaign
- Institute for Nuclear Research, Moscow
- JINR, Dubna, Russia
- Lawrence Berkeley National Laboratory
- Los Alamos National Laboratory
- Northwestern University
- INFN Frascati
- INFN Pisa, Università di Pisa, Pisa, Italy
- University of Massachusetts

~120 collaborators
• The intensity frontier and flavor physics may well reveal a sign of exotic physics!

• Mu2e will improve sensitivity by 4 orders-of-magnitude relative to past CLFV searches.

• Mu2e will provide complementary information relative to the LHC and is sensitive to mass scales many orders of magnitude higher than can be directly probed at colliders.
Conceptual Design Report
March 2011

DRAFT
The Mu2e Project

Fermilab
Mu2e Review Status

• **Mu2e received mission-need approval from DOE in November 2009.**
• From our Mission Need Statement:
  – “A muon-to-electron conversion experiment at Fermilab could provide an advance in experimental sensitivity of four orders of magnitude.”
• We have a complete set of requirements designed to meet this goal:
  → Describes what each major system component must achieve
• We have a conceptual design that we believe satisfies these requirements.
• **Mu2e had a successful Independent Design Review on May 3rd and 4th**
• Two more reviews later this Summer...

**Goal:** Approved conceptual design by end of 2011
Possible Scenarios

• We see something the first year!
  – Change target to better constrain the new physics rule out some backgrounds.

• See something with two years of data:
  – Plan for intensity upgrade
  – New targets...

• Don’t see anything:
  – Intensity upgrade to Project X for sensitivity improvement of two additional orders-of-magnitude.
CLFV and Tau Decays

τ processes also suppressed in Standard Model but less:

Good News:
Beyond SM rates are several orders of magnitude larger than in associated muon decays

Bad News:
\( \tau \)'s hard to produce:
\( \sim 10^{10} \text{ \( \tau \)/yr} \) vs \( \sim 10^{11} \text{ \( \mu \)/sec} \) in fixed-target experiments (Mu2e/COMET)

also e\( \rightarrow \)τ at electron-ion collider?

M. Gonderinger, M. Ramsey-Musolf, arXiv:1006.5063v1
Supersymmetry in Tau LFV


Neutrino-Matrix Like (PMNS)  Minimal Flavor Violation (CKM)

Neutrino mass via the see-saw mechanism, analysis is performed in an SO(10) framework

\[ \tan \beta = 10 \]