Mu2e Experiment*

Eric Prebys
For the Mu2e Collaboration

*A Letter of Intent to Search for Charged Lepton Flavor Violation in Nuclear Muon Capture
Goals of Experiment

• Initial Phase (MECO design, No Project X):
  - Exploit NOvA accelerator modifications and post-Run II availability of Accumulator and Debuncher rings to mount a $\mu \rightarrow e$ conversion experiment patterned after MECO
    - 4x10^{20} protons in ~2 years
    - Measure
      \[ R_{\mu e} \equiv \frac{\Gamma(\mu^-\text{Al} \rightarrow e^-\text{Al})}{\Gamma(\mu^-\text{Al} \rightarrow \text{capture})} \]
      - Single event sensitivity of $R_{\mu e} = 2 \times 10^{-17}$
      - 90% C.L. limit of $R_{\mu e} < 6 \times 10^{-17}$
      - ANY signal = Beyond Standard Model physics

• Ultimate goal
  - Exploit Project X and improved muon transport to achieve dramatically increased sensitivity
    - If no signal: set limit $R_{\mu e} < 1 \times 10^{-18}$
    - If signal: measure target dependence, etc
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11 Institutions

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E Prebys
Search for Charged Lepton Flavor Violation (CLFV)

• The discovery of neutrino oscillations naturally raises the question:
  ➢ What is the rate of charged lepton flavor violation in nature?
• CLFV is a powerful probe of multi-TeV scale dynamics: complementary to direct collider searches
• Among various possible CLFV modes, rare muon processes offer the best combination of new physics reach and experimental sensitivity

Muon-to-Electron Conversion: $\mu+N \rightarrow e+N$

• Standard Model rate via Dirac neutrino mixing is too small to be observed ($\sim 10^{-52}$)
• Very common feature of Beyond Standard Model physics at much larger rates
• Similar to $\mu \rightarrow e\gamma$, with important advantages:
  ➢ No combinatorial background
  ➢ Sensitive to other types of BSM physics
  ➢ Relative rate depends on details of physics
Broadly Sensitive to New High Energy Dynamics

\[ \frac{m_\mu}{(\kappa+1)\Lambda^2} \bar{\mu} R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L \left( \bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L \right). \]

- At \( R_{\mu e} \sim 10^{-16} \) (first phase, this LOI), the sensitivity is already very compelling, well above the reach of colliders.
- At \( 10^{-18} \) (potentially, with upgraded apparatus and higher muon flux), energy scales probed would be difficult to access by other means.
Specific Model Examples

SU(5) GUT Supersymmetry: $\kappa \ll 1$

- Leptoquarks
- Z-prime
- Compositeness
- Heavy neutrino

Littlest Higgs: $\kappa \approx 1$

Randall-Sundrum: $\kappa \approx 1$

- Examples with $\kappa \gg 1$ (no $\mu \to e\gamma$ signal):
  - Leptoquarks
  - Z-prime
  - Compositeness
  - Heavy neutrino
Previous muon decay/conversion limits (90% C.L.)

LFV $\mu$ Decay:

\[
\begin{align*}
\Gamma(\mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu) &< 1.2 \times 10^{-2} \\
\Gamma(\mu^- \rightarrow e^-\gamma) &< 1.2 \times 10^{-11} \\
\Gamma(\mu^- \rightarrow e^-e^+e^-) &< 1.0 \times 10^{-12} \\
\Gamma(\mu^- \rightarrow e^-2\gamma) &< 7.2 \times 10^{-11}
\end{align*}
\]

High energy tail of coherent Decay-in-orbit (DIO)

\[
R_{\mu e} \equiv \frac{\Gamma(\mu^- Ti \rightarrow e^- Ti)}{\Gamma(\mu^- Ti \rightarrow \text{capture})} < 4.3 \times 10^{-12}
\]

- Rate limited by need to veto prompt backgrounds!
**Mu2e (MECO) Philosophy**

- Eliminate prompt beam backgrounds by using a primary beam with short proton pulses with separation on the order of a muon life time.

  \[ \sim 100 \text{ ns} \quad \sim 1.5 \mu s \]

- Design a transport channel to optimize the transport of right-sign, low momentum muons from the production target to the muon capture target.

- Design a detector to strongly suppress electrons from ordinary muon decays.
Detector Layout

- Straw Tracker
- Muon Stopping Target
- Superconducting Transport Solenoid (2.5 T - 2.1 T)
- Superconducting Production Solenoid (5.0 T - 2.5 T)
- Collimators
- Superconducting Detector Solenoid (2.0 T - 1.0 T)
- Muon Beam Stop
- Crystal Calorimeter
- Proton Beam
- Pion Production Target
Beam Related Rates

- Cut ~700 ns after pulse to eliminate most serious prompt backgrounds.

**Rate [MHz]**
- Full time between proton pulses

**Rate [kHz]**
- Detection time interval

**Graphical Elements**
- beam electrons
- $\mu^-$ decay in flight
- $\mu$-capture protons

**Time with respect to proton pulse [ns]**
- 0, 400, 800, 1200, 700, 900, 1100, 1300
Sensitivity

- $R_{\mu e} = 10^{-16}$ gives 5 events for $4 \times 10^{20}$ protons on target

- 0.4 events background, half from out of time beam, assuming $10^{-9}$ extinction
  - Half from tail of coherent decay in orbit
  - Half from prompt

Coherent Decay-in-orbit, falls as $(E_e - E)^5$
Mu2e History

• 1997
  - MECO proposed for the AGS at Brookhaven
  - Approved, along with KOPIO, as part of RSVP program

• 1998-2005
  - Design refined
  - Frequent favorable reviews

• 2005
  - June: final reviews, very positive
    - Physics goals: HEPAP RSVP Subpanel
    - Cost and schedule: “Wojcicki Panel”
  - July: RSVP cancelled for financial reasons
    - MECO and KOPIO “charged” for entire cost of continued AGS operation.

• 2006
  - January: First informal meeting at BNL
  - September: First meeting at Fermilab

• 2007
  - June: Mu2e expression of interest submitted to Fermilab Directorate
  - August: First Mu2e collaboration meeting
  - October: Letter of Intent submitted to Directorate
Mu2e at Fermilab

• If the current suite of proton source upgrades is effective, there should be at least enough excess 8 GeV protons during the NOvA era to do an experiment with similar sensitivity to MECO in a reasonable amount of time.
  - The resonant operation of the 8 GeV Booster makes it impossible to directly generate the desired time structure.
  - There is a scheme to generate this time structure using the antiproton Accumulator and Debuncher rings, which will become available after the termination of the collider program.
  - This scheme requires only modest modifications beyond those planned for NOvA, with which it is fully compatible.
Preloading for NOvA

Recycler → MI transfer

Available for 8 GeV program

Roughly $6 \times (4 \times 10^{12} \text{ batch})/(1.33 \text{ s}) \times (2 \times 10^7 \text{ s/year}) = 3.6 \times 10^{20}$ protons per year available
Delivering Protons: “Boomerang” Scheme

- Deliver beam to Accumulator/Debuncher enclosure with minimal beam line modifications and *no civil construction*.
Present Operation of Debuncher/Accumulator

- Protons are accelerated to 120 GeV in Main Injector and extracted to pBar target
- pBars are collected and phase rotated in the “Debuncher”
- Transferred to the “Accumulator”, where they are cooled and stacked
- Not used for NOvA
Rebunching in Accumulator/Debuncher

- Momentum stack 6 Booster batches directly in Accumulator (i.e. reverse direction)
- Capture in 4 kV h=1 RF System. Transfer to Debuncher
- Phase Rotate with 40 kV h=1 RF in Debuncher
- Recapture with 200 kV h=4 RF system
  \[ \sigma_t \sim 40 \text{ ns} \]
Resonant Extraction

- Exploit 29/3 resonance
- Extraction septum and Lambertson similar to Main Injector
  - Septum: 80 kV/1cm × 3m
  - Lambertson+C magnet ~0.8T × 3m

<table>
<thead>
<tr>
<th>Resonant Extraction Parameters</th>
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<tbody>
<tr>
<td>Kinetic Energy (GeV)</td>
</tr>
<tr>
<td>Working tune (νₓ/νᵧ)</td>
</tr>
<tr>
<td>Resonance (νₓ)</td>
</tr>
<tr>
<td>Normalized acceptance (x/y πmm-mr)</td>
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<tr>
<td>Normalized beam emittance (πmm-mr)</td>
</tr>
<tr>
<td>β at electrostatic septum (m)</td>
</tr>
<tr>
<td>β at Lambertson (m)</td>
</tr>
<tr>
<td>β at harmonic quads (m)</td>
</tr>
<tr>
<td>Septum Position (mm/σ)</td>
</tr>
<tr>
<td>Septum gap/step size (mm)</td>
</tr>
<tr>
<td>Sextupole Drive Strength (T-m/m²)</td>
</tr>
<tr>
<td>Initial Tuneshift</td>
</tr>
<tr>
<td>Septum field (MV/m)</td>
</tr>
<tr>
<td>Septum length (m)</td>
</tr>
</tbody>
</table>
Beam Extinction

- Need $10^{-9}$
- Get at least $\sim 10^{-3}$ from beam bunching
- Remainder from AC Dipole in beam line

- Working with Osaka (FNAL+US-Japan funds) to develop AC dipole design, as well as explore measurement options
Proposed Location

- Requires new building.
- Minimal wetland issues.
- Can tie into facilities at MiniBooNE target hall.
Cost and Time Scale

- A detailed cost estimate of the MECO experiment had been done just before it was cancelled*
  - Solenoids and cryogenics: $58M
  - Remainder of experimental apparatus: $27M
- Additional Fermilab costs have not been worked out in detail, but are expected to be on the order of $10M.
- Hope to begin Accelerator work along with NOvA upgrades
  - ~2010 (or 2011 if Run II extended)
- Based on the original MECO proposal, we believe the experiment could be operational within five years from the start of significant funding
  - Driven by magnet construction.
  - ~2014
- With the proposed beam delivery system, the experiment could collect the nominal $4 \times 10^{20}$ protons on target in about one to two years, with no impact on NOvA
  - NOvA rate limited by Main Injector

*Costs in 2005 dollars, including contingency
Mu2e and Project X

• We have described the initial phase of mu2e, which is based on the proposed data sample of $4 \times 10^{20}$ protons.
  ➢ 90% C.L. limit of $R_{\mu e} < 6 \times 10^{-17}$ (improvement over existing limit of more than 4 orders of magnitude).

• The Project X linac would provide roughly a factor of ten increase in flux.

• Slow extraction directly from Recycler ruled out by Project X Working Group
  ➢ Will need to load beam from Recycler to Accumulator as we are planning to do for Phase I.

• A preliminary scheme to exploit this additional flux will be included in our proposal.
Mu2e and Muon Collider/Neutrino Factory

• There are a number of synergies between this project and muon cooling efforts
  - The Debuncher beam could be extracted in a single turn to produce the short, intense bunch needed by muon production experiments
  - Muon cooling studies have increased the understanding of solenoidal transport.
  - It is possible that a “helical cooling channel”, of the sort envisioned for muon cooling, could generate a significantly higher muon yield for this experiment.

• We will investigate these in more detail for the proposal.

A combination of increased flux from Project X and a more efficient muon transport line could potentially result in a sensitivity as low as $10^{-18}$
Experimental Challenges for Increased Flux

- Achieve sufficient extinction of proton beam.
  - Current extinction goal directly driven by total protons
- Upgrade target and capture solenoid to handle higher proton rate
- Improve momentum resolution for the ~100 MeV electrons to reject high energy tails from ordinary DIO electrons.
- Operate with higher background levels.
- Manage high trigger rates
  - All of these efforts will benefit immensely from the knowledge and experience gained during the initial phase of the experiment.
- If we see a signal at a lower flux, can use increased flux to study in detail
  - Precise measurement of $R_{\mu e}$
  - Target dependence
  - Comparison with $\mu \rightarrow e\gamma$ rate
Required Resources for Proposal

- \( \sim \$100K \) of FESS time
  - for a preliminary cost estimate of the experimental facility and beam line civil construction
- \( \sim 1/2 \) FTE beam line design expert
  - to produce a preliminary design of the primary proton line, including extinction channel
- \( \sim 1/2 \) FTE of ES&H radiation safety expert
  - to help us produce a plan to deal with the increased flux in the pBar enclosure (VERY important!)
- \( \sim 1/2 \) FTE of a TD magnet expert
  - to evaluate the MECO magnet design, and advise of possible improvements.
- A dedicated postdoc and guest scientist position
  - Focus on Monte Carlo work.
  - Could also be supplemented with PPD resources
Conclusions

• The mu2e experiment is an opportunity for Fermilab to make an important measurement
  ➢ In the initial phase (without project X) we would either
    • Reduce the limit for $R_{\mu e}$ by more than four orders of magnitude
      ($R_{\mu e} < 6 \times 10^{-17}$ @ 90% C.L.)
    OR
    • Discover unambiguous proof of Beyond Standard Model physics
  • This experiment benefits greatly from both the voluminous work done for the MECO proposal and by fortuitous configuration and availability of Fermilab accelerator components.
  • With a combination of Project X and/or improved muon transport, we could either
    ➢ Extend the limit by up to two orders of magnitude
      OR
    ➢ Study the details of new physics
Backup Slides
Momentum Stacking

- Inject a newly accelerated Booster batch every 67 ms onto the low momentum orbit of the Accumulator.
- The freshly injected batch is accelerated towards the core orbit where it is merged and debunched into the core orbit.
- Momentum stack 3-6 Booster batches.

Energy

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>T=0</td>
<td>1st batch is injected onto the injection orbit</td>
</tr>
<tr>
<td>T&lt;66ms</td>
<td>1st batch is accelerated to the core orbit</td>
</tr>
<tr>
<td>T=67ms</td>
<td>2nd Batch is injected</td>
</tr>
<tr>
<td>T&lt;133ms</td>
<td>2nd Batch is accelerated</td>
</tr>
<tr>
<td>T=134ms</td>
<td>3rd Batch is injected</td>
</tr>
</tbody>
</table>
Rebunching Scheme

• Accumulator
  - Momentum stack 1 to 6 booster batches
  - Adiabatically bunch at $h=1$ - 4kV
    - 500ns gap for kicker
    - Some beam/halo cleaning in Acc and transfer
    - Adiabatic easier at $\gamma_t=5.5$
  - Transfer to Debuncher

• Debuncher
  - $h=1$ 90-degree phase rotation at fixed voltage
    - 40kV - 0.007s
  - Capture and store at $h=4$
    - $\sim200$ to 250 kV $\sim0.02s$; $\sigma_\tau=42$ns
    - Beam halo cleaning also ....
Attractive Features of Debuncher

- Large Acceptance
- Low chromaticity
- Long, dispersion-free segments
- Lots of open straight sections after cooling hardware removed
- Problem: Getting protons there
Production Region

- Axially graded 5 T solenoid captures pions and muons, transporting them toward the stopping target.

- Cu and W heat and radiation shield protects superconducting coils from effects of 50kW primary proton beam.
Transport Solenoid

- Curved solenoid eliminates line-of-sight transport of photons and neutrons
- Curvature drift and collimators sign and momentum select beam
- dB/ds < 0 in the straight sections to avoid long transit time trajectories
Detector Region

- Axially-graded field near stopping target to increase acceptance and reduce cosmic ray background
- Uniform field in spectrometer region to simplify momentum analysis
- Electron detectors downstream of target to reduce rates from $\gamma$ and neutrons
Expected Sensitivity of the MECO Experiment

We expect ~ 5 signal events for $10^7$ s (2800 hours) running if $R_{\mu e} = 10^{-16}$

<table>
<thead>
<tr>
<th>Contributions to the Signal Rate</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running time (s)</td>
<td>$10^7$</td>
</tr>
<tr>
<td>Proton flux (Hz) (50% duty factor, 740 kHz micropulse)</td>
<td>$4 \times 10^{13}$</td>
</tr>
<tr>
<td>$\mu$ entering transport solenoid / incident proton</td>
<td>0.0043</td>
</tr>
<tr>
<td>$\mu$ stopping probability</td>
<td>0.58</td>
</tr>
<tr>
<td>$\mu$ capture probability</td>
<td>0.60</td>
</tr>
<tr>
<td>Fraction of $\mu$ capture in detection time window</td>
<td>0.49</td>
</tr>
<tr>
<td>Electron trigger efficiency</td>
<td>0.90</td>
</tr>
<tr>
<td>Fitting and selection criteria efficiency</td>
<td>0.19</td>
</tr>
<tr>
<td>Detected events for $R_{\mu e} = 10^{-16}$</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Expected Background in MECO Experiment

We expect ~ 0.45 background events for 10^7 s running with sensitivity of ~ 5 signal events for $R_{\mu e} = 10^{-16}$

<table>
<thead>
<tr>
<th>Source</th>
<th>Events</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$ decay in orbit</td>
<td>0.25</td>
<td>$S/N = 20$ for $R_{\mu e} = 10^{-16}$</td>
</tr>
<tr>
<td>Tracking errors</td>
<td>&lt; 0.006</td>
<td></td>
</tr>
<tr>
<td>Radiative $\mu$ decay</td>
<td>&lt; 0.005</td>
<td></td>
</tr>
<tr>
<td>Beam $e^-$</td>
<td>&lt; 0.04</td>
<td></td>
</tr>
<tr>
<td>$\mu$ decay in flight</td>
<td>&lt; 0.03</td>
<td>Without scattering in stopping target</td>
</tr>
<tr>
<td>$\mu$ decay in flight</td>
<td>0.04</td>
<td>With scattering in stopping target</td>
</tr>
<tr>
<td>$\pi$ decay in flight</td>
<td>&lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>Radiative $\pi$ capture</td>
<td>0.07</td>
<td>From out of time protons</td>
</tr>
<tr>
<td>Radiative $\pi$ capture</td>
<td>0.001</td>
<td>From late arriving pions</td>
</tr>
<tr>
<td>Anti-proton induced</td>
<td>0.007</td>
<td>Mostly from $\pi^-$</td>
</tr>
<tr>
<td>Cosmic ray induced</td>
<td>0.004</td>
<td>Assuming $10^{-4}$ CR veto inefficiency</td>
</tr>
<tr>
<td>Total Background</td>
<td>0.45</td>
<td>Assuming $10^{-9}$ inter-bunch extinction</td>
</tr>
</tbody>
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