A Compelling Program
in Physics Beyond the Standard Model
Using Intense Muon Beams at Fermilab

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• Search for charged lepton flavor violation
  – New, sensitive search for muon to electron conversion in the field of a nucleus, mu2e LOI
  – Based on the MECO experimental approach that was developed to a high level of technical and cost understanding

• Measurement of anomalous magnetic moment of the muon, $g-2$
  – Improved measurement based on extrapolation of techniques used for the very successful E821 experiment at BNL
  – Improve precision by factor of 5 (to 0.1 ppm) for a measurement that is currently $>3\sigma$ discrepant with Standard Model prediction
Charged Lepton Flavor Violation

• Search for CLFV using $\mu^{-}N\rightarrow e^{-}N$ is a unique opportunity
  - Experimental signature is an electron with $E_{e}=m_{\mu}$ coming from a target in which muons stop
  - Unaffected by backgrounds from overlapping decays, allowing much higher data rates
  - Contrast with $\mu\rightarrow e\gamma$: sensitivity limited to $10^{-13} - 10^{-14}$ by accidental backgrounds at high rates
  - With modern detectors, experiments can handle much higher instantaneous rates
  - Backgrounds measured and removed with appropriate muon beam and electron detectors

• Beam and experiment design motivated by lessons learned from the best previous experiment – SINDRUM2 at Paul Scherrer Institute:

\[ R_{\mu e} \equiv \frac{\Gamma(\mu^{-}N\rightarrow e^{-}N)}{\Gamma(\mu^{-}N\rightarrow \tau N')} < 7 \times 10^{-13} \]
Features of a New $\mu\rightarrow e$ N–N Experiment

• >1000 fold increase in muon intensity
  – High Z target for improved pion production
  – Graded solenoidal field to maximize pion capture

• Pulsed beam to eliminate prompt backgrounds
  – Beam pulse duration $\ll \tau_\mu$
  – Pulse separation $\approx \tau_\mu$
  – Large duty cycle $\rightarrow 100%$
  – Extinction between pulses $< 10^{-9}$

• Improved detector resolution and rate capability
  – Detector in graded solenoid field: improves acceptance, rate handling, background rejection
  – Electron spectrometer with very high resolution

Some variant of these ideas used in all new proposals
\[\mu^+N \rightarrow e^-N\] at Fermilab: \textit{mu2e Letter of Intent}

- Ultimate sensitivity would be provided by Project X linac as proton source
  - Deliver up to 200 kW average beam current: \(\sim 1.5 \times 10^{14}\) protons/s at 8 GeV
  - Option to use Booster in first phase with 16-20 kW: \(\sim 1.5 \times 10^{13}\) protons/s

- Storage ring(s) to provide appropriate time structure
  - accumulator/debuncher is a possible example, maybe new ring
  - high duty factor
  - Pulse spacing of \(\sim 1.6 \, \mu\text{sec}\): nearly ideal for conversion experiment
  - Beam extinction provided by combination of RF time structure in ring and external devices

- Muon beam based on that of MECO, designed for 100(50) kW instantaneous(average) proton beam power, with upgrades to handle increased power
  - Requires improved cooling of small, water cooled gold target
  - Requires increased shielding of superconducting production solenoid
  - Trade reduced muon flux per proton for smaller muon momentum spread and beam size
MECO/mu2e Detector

• Designed for muon stop rate of $\sim 10^{11}$ Hz (100 kW instantaneous beam power)
  - Intensity limited by high detector rates that have the potential to cause tails in momentum resolution
  - Rates dominated by $\mu$ capture processes emitting p, n, $\gamma$
  - Ideas for reducing detector rates under study
    • New proton absorber with design that exploits opposite helicity of $e^-$ and $p^+$ to preferentially absorb protons:
    • Increase length of production solenoid to reduce solid angle of detectors for neutrals
    • Consider curved detector solenoid
MECO/mu2e Background Rejection Performance

- MECO designed to detect 1 detected event if $R_{\mu e} = 2 \times 10^{-17}$ for $4 \times 10^{20}$ protons on target with background/signal of 0.25
  - 20 kW beam power would provide that sensitivity in less than a year of mu2e running
  - 200 kW beam power would allow a precise study of A dependence and comparison with $\mu \rightarrow e\gamma$ branching fraction if $R_{\mu e}$ exceeds $10^{-15}$ – background at $10^{-17}$ would not be important
  - a search sensitivity approaching $10^{-18}$ would be possible if no signal is seen – backgrounds would need to be reduced wrt that of the MECO design
- Expected background in the MECO/mu2e design is dominated by muon decay in orbit, reduced only with improved resolution, with other sources that can be reduced by improved beam extinction.

<table>
<thead>
<tr>
<th>Background Source</th>
<th>Events</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$ decay in orbit</td>
<td>0.25</td>
<td>N/S = 0.25 for $R_{\mu e} = 2 \times 10^{-17}$</td>
</tr>
<tr>
<td>Tracking errors</td>
<td>&lt; 0.006</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>No scattering in target</td>
</tr>
<tr>
<td>$\mu$ decay in flight</td>
<td>0.04</td>
<td>Scattering in target</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>$10^{-4}$ CR veto inefficiency</td>
</tr>
<tr>
<td>Total Background</td>
<td>0.45</td>
<td>With $10^{-9}$ inter-bunch extinction</td>
</tr>
</tbody>
</table>
What is the Competition?

• MEG experiment (running) at Paul Scherrer Institute: $\mu \rightarrow e\gamma$ to $\sim 10^{-13}$
  - Difficult to improve beyond that (perhaps to $10^{-14}$) due to accidental backgrounds

• Reprise of MECO/mu2e at BNL
  - Fermilab has better time structure, duty cycle, running time per year, higher intensity

• COMET at JPARC
  - Muon beam flux, time structure similar to MECO design
  - Sensitivity below $10^{-16}$
  - Detectors displaced from stopping target to reduce rates

• PRISM/PRIME at JPARC
  - Very different muon beam: FFAG storage ring for phase rotation, very intense pulses at low frequency (<1kHz)
  - Very small, narrow momentum spread beam, thin target, detector arrangement similar to COMET
  - Would require new building, technical advances

• Prime disadvantage of both COMET and PRISM/PRIME is conflict with running neutrino beam
Muon Anomalous Magnetic Moment: $g-2$

\[ \omega_a = \frac{q}{m} a_\mu B \]

Momentum  \hspace{1cm} Spin

\[ a_\mu (\text{expt.}) = 11659208. \times 10^{-10} \ (0.54 \text{ ppm}) \]
\[ a_\mu (\text{theor.}) = 11658180. \times 10^{-10} \ (0.48 \text{ ppm}) \]
\[ \Delta a_\mu (\text{expt-thy}) = (295 \pm 88) \times 10^{-11} \ (3.4 \sigma) \]

Bennett et al, PRD 73, 072003 (2006)

Goal of a new experiment is precision of 0.1 ppm
Muon $g-2$ Determined by Ratio of $\omega_a$ and $B$

**E821 Systematic Uncertainty on $\omega_\mu$**

<table>
<thead>
<tr>
<th>Contribution</th>
<th>$\sigma$[ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile-up</td>
<td>0.08</td>
</tr>
<tr>
<td>AGS Background</td>
<td>0.015*</td>
</tr>
<tr>
<td>Lost Muons</td>
<td>0.09</td>
</tr>
<tr>
<td>Timing Shifts</td>
<td>0.02</td>
</tr>
<tr>
<td>E-Field, Pitch</td>
<td>0.06*</td>
</tr>
<tr>
<td>Fitting/Binning</td>
<td>0.06*</td>
</tr>
<tr>
<td>CBO</td>
<td>0.07</td>
</tr>
<tr>
<td>Beam Debunching</td>
<td>0.04*</td>
</tr>
<tr>
<td>Gain Change</td>
<td>0.13</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>0.21</strong></td>
</tr>
</tbody>
</table>

**E821 Systematic Uncertainty on $B$**

<table>
<thead>
<tr>
<th>Contribution</th>
<th>$\sigma$[ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute Calibration</td>
<td>0.05</td>
</tr>
<tr>
<td>Trolley Calibration</td>
<td>0.009</td>
</tr>
<tr>
<td>Trolley Measurements of B0</td>
<td>0.05</td>
</tr>
<tr>
<td>Interpolation with Fixed Probes</td>
<td>0.07</td>
</tr>
<tr>
<td>Inflector Fringe Field</td>
<td></td>
</tr>
<tr>
<td>Muon Distribution</td>
<td>0.03</td>
</tr>
<tr>
<td>CBO</td>
<td>0.10</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>0.17</strong></td>
</tr>
</tbody>
</table>
Calculation of SM Value of $g-2$ Relies on Theory and Exp. Input

Contributions to theory uncertainty

<table>
<thead>
<tr>
<th>Uncertainty contribution</th>
<th>$\sigma$[ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic lowest order</td>
<td>(+69)</td>
</tr>
<tr>
<td>Experimental</td>
<td>0.42</td>
</tr>
<tr>
<td>radiative</td>
<td>0.19</td>
</tr>
<tr>
<td>QCD</td>
<td>0.07</td>
</tr>
<tr>
<td>Hadronic higher order</td>
<td>(-1.0)</td>
</tr>
<tr>
<td>Hadronic light-by-light</td>
<td>(+1.1)</td>
</tr>
</tbody>
</table>

hep-ph 0705.4617 (slightly dated)
Possible Improvements to $g$-2 Experiment

- Increase muon flux with better beam optics
- Improve efficiency of injection into ring
- Improve detectors for higher rates
- Select truly forward decays (BNL/J-PARC, Fermilab) or backward decays (J-PARC)
- Reduce $\pi$ contamination at injection by storing in pre-accumulator for many $\tau_\pi$ (BNL) or use a long transport channel (Fermilab) or use a backward decay beam (J-PARC)
- Increase number of muon stores per second from ~4 (E821) to ~13 (BNL) 15 or higher (J-PARC), ~60 (Fermilab) – all require R&D

MuPAR can get up 15 times more flux (simulation)
Possible g-2 Implementation at Fermilab

• Decrease $\pi$ contamination with long transport in existing tunnel
• Increase $\mu$ store frequency by bunching proton beam, for example in accumulator/debuncher, and developing fast kicker to eject ~40 pulses per accumulator/debuncher cycle (~60 Hz, c.f. 4-13 Hz at BNL)
• Staged running with ultimate goal of 0.1 ppm statistical precision
• Siting of experiment being studied in context of integrated approach to a broad program of precision experiments
Even Higher Experimental Precision with New Technique

- Integrate charge in detectors rather than counting electrons from decays – integrates over decay asymmetry, weighted towards high energy electrons.

Geant simulation using new detector schemes

**Event Method**

- $\chi^2 / \text{ndf}$: 2280 / 1999
- Norm: $1246 \pm 2.5$
- Tau: $6.404 \times 10^4 \pm 99$
- Asym: $0.3947 \pm 0.0018$
- Omega: $1.438 \times 10^6 \pm 85$
- Phi: $-40.4 \pm 0.0$

**Energy Method**

- $\chi^2 / \text{ndf}$: 2334 / 1999
- Norm: $2340 \pm 2.6$
- Tau: $6.431 \times 10^4 \pm 55$
- Asym: $0.2016 \pm 0.0010$
- Omega: $1.438 \times 10^6 \pm 93$
- Phi: $-40.4 \pm 0.0$
Possible Implementation Strategy

- Both mu2e and g-2 could start construction relatively soon, based on modifications to existing designs.

- Both mu2e and g-2 would benefit from phased approach, with early running at lower power: doesn’t provide ultimate sensitivity, but still provide world’s best experiment potential for discovering new physics in the time leading to Project X.

- These two experiments could be a big part of a world leading physics program at a Fermilab intense proton source.