Fermilab is a global leader in Muon Physics

The Fermilab Muon Campus

2 of the most powerful and promising tests of the SM
The Fermilab Muon g-2 experiment
Anomalous Magnetic Moment

Muon magnetic moment: \[ \mu = g_\mu \frac{e}{2m} \vec{s} \]

The anomalous magnetic moment:

\[ a_\mu \equiv \frac{g_\mu - 2}{2} \]

Dirac theory predicts \( g=2 \)

Quantum fluctuations give rise to \( a_\mu \)

Entire theory encoded into \( g-2 \)

A powerful precision test of SM validity
The $\alpha_\mu$ discrepancy

BNL E821 measured $\alpha_\mu$ to 540 ppb
- Discrepancy with SM

$\alpha_\mu^{\text{exp}} - \alpha_\mu^{\text{SM}} = (27.9 \pm 7.6) \times 10^{-10}$

Muon $g$-2 Theory Initiative
https://muon-gm2-theory.illinois.edu

Full re-evaluation of SM value
The discrepancy stands at $3.7\sigma$

Fermilab E989 aims to improve precision on $\alpha_\mu^{\text{exp}}$ by x4
The g-2 experiment at Fermilab

Muon g-2 storage ring, moved from BNL
The $g$-2 experiment at Fermilab

3.1 GeV/c muons injected in storage ring
Highly longitudinally polarized
Muon spin precesses in 1.45 T field
**Spin precession**

Muon spin precession inside the magnetic storage ring

Anomalous precession due to $g \neq 2$

**Anomalous precession frequency:**
(idealized expression: perfect motion, field, “magic momentum”)

$$\vec{\omega}_c = -\frac{e \vec{B}}{m \gamma}$$

$$\vec{\omega}_s = -\frac{geB}{2m} - (1 - \gamma) \frac{eB}{m \gamma}$$

$$\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = a_\mu \frac{e \vec{B}}{m}$$

Need measurement of $\omega_a, B$
Precession signal

Self-analyzing decay: highest-E $e^+$ emitted preferentially along $\mu^+$ spin

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$\omega_a$ extracted from fit to calorimeter signal:

$$N(t) = N_0 e^{-t/\tau} [1 + A \cos(\omega_a t + \varphi)]$$

(Muon decay) $\times$ (Oscillation due to precession)
**Magnetic field**

Monitored with proton NMR probes

- Probes pulled in trolley for measurement in muon region (~3 days)
- Fixed probes for interpolation

Field maps from multipole decomposition:

\[ B(r, \theta) = B_0 + \sum_{n=0}^{4} \left( \frac{r}{r_0} \right)^n \left[ a_n \cos(n\theta) + b_n \sin(n\theta) \right] \]

Field map to be **convoluted** with muon distribution

Azimuthally averaged, 250 ppb contours
Muon distribution from trackers

Straw trackers reconstruct muon distribution, determine complex beam dynamics

Station 12 - 3.50 us

Entries: 61187
Mean: -4.912
Std Dev: 24.46
Underflow: 0
Overflow: 0
Integral: 8.11e+04
Run1 $\omega_\alpha$ analysis

Simplistic 5-parameter fit:

$$N(t) = N_0 e^{-t/\tau} [1 + A \cos(\omega_\alpha t + \varphi)]$$

Realistic, with beam dynamics:

$$N(t) = N_0 e^{-t/\tau_p} [1 + A_{cbo}(t) \cos(\omega_{cbo} t + \phi_{cbo}(t))] \times N_{2cbo}(t)$$
$$\times [1 + A_{cbo} \cdot e^{-t/\tau_{cbo}} \cdot \cos(\omega_{cbo} t + \phi_0)]$$
$$\times [1 + A_{vw} \cdot e^{-t/\tau_{vw}} \cdot \cos(\omega_{vw} t + \phi_{vw})]$$
$$\times [1 - K_{loss} \int_{t_0}^{t} e^{t/\tau} L(t) dt]$$

$$A_{cbo}(t) = A(1 + A_{cbo-A} e^{-t/\tau_{cbo}} \cos(\omega_{cbo} t + \phi_{cbo-A}))$$
$$\phi_{cbo}(t) = \phi_0 + A_{cbo-\phi} e^{-t/\tau_{cbo}} \cos(\omega_{cbo} t + \phi_{cbo-\phi})$$
$$N_{2cbo}(t) = (1 + A_{2cbo-N} e^{-2t/\tau_{cbo}} \cos(2\omega_{cbo} t + \phi_{2cbo-N}))$$

D. Sweigart URA Thesis Award
**Current status**

Up to 8x BNL raw statistics collected so far

Run3 cut short due to pandemic, planning to resume in fall 2020

First results from Run1 expected in few months

\[ \approx \text{BNL statistics} \]
Run1 $\omega_\alpha$ analysis

- 6 independent analysis teams
  - Different algorithms, sensitivities, reconstructions

Agreement fully within statistically allowed variance

- Similarly great agreement between independent analysis teams for field measurement
Run1 result expected soon!

- Tremendous work done on systematic cross-checks
- Run1 result, highly anticipated by global community, is expected in few months!
- First cross-check to BNL discrepancy after nearly 2 decades
- Hugely important for future prospects of the field
The Mu2e Experiment

- Scheduled to start after Muon g-2
- Currently in construction phase
Any observation of Charged-Lepton Flavor Violation (CLFV) would be unambiguous evidence of New Physics

The charged-lepton analog to neutrino oscillations

- Neutrino oscillations
- Lepton flavor violated!

- Mixing between charged leptons: never observed
  - Powerful probe of flavor models
  - Especially well motivated given $\nu$-oscillations, LFU-violation
The Mu2e search

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

$$\mu^- + A(Z,N) \to e^- + A(Z,N)$$

Clean experimental signature

- mono-energetic $e^-$ – for Al:

$$E_{\mu e}(\text{Al}) = m_\mu - E_b - E_{\text{rec}} = 104.97 \text{ MeV}$$

Current limit (SINDRUM-II, 90% CL):

$$R_{\mu e} = \frac{\mu^- + N \to e^- + N}{\mu^- + N \to \text{nuclear capture}} < 7 \times 10^{-13}$$

Mu2e aims to improve on $R_{\mu e}$ by 4 orders of magnitude

A vast increase in sensitivity covering unconstrained phase space
Physics reach

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

\( \Gamma \): effective mass parameter

\( \kappa \): relative strength of loop- and contact-dominated terms

Mu2e improves sensitivity in all NP scenarios

Effective mass scale reach up to \( 10^4 \) TeV
**Mu2e solenoids**

System of 3 functional solenoid units

8 GeV pulsed proton beam, ~7e12 protons/s on W production target

Efficient collection and transport: $10^{10}$ stopped muons/s on Al stopping target → World’s most intense muon beam
Mu2e solenoids: Detector

Detector system:
Straw tracker and calorimeter
Identify 105 MeV conversion electron
Reject backgrounds from conventional processes

Background:
Standard muon decay-in-orbit (DIO)
**Straw tracker**

Hole-in-center annular design:
Detector blind to nearly all backgrounds and remnant beam

Resolution <180 keV @ 105 MeV

Performance validated with prototypes
EM Calorimeter

1348 CsI crystals, SiPM readout
Redundant E, position, timing information
Prototype in Frascati demonstrated
\[ \sigma_E \sim 7\%, \ \sigma_t \sim 150 \text{ ns}, \ \text{well within spec} \]

Atanov et al, arXiv:1801.02237
Cosmic backgrounds

Cosmic events may produce 105 MeV e

Cosmic Ray Veto system encases DS and downstream TS

4 layers of extruded polystyrene Under construction in UVA
Background budget

Expected total number of background events from each source, over entire Mu2e:

3 years at $1.2 \times 10^{20}$ p/yr
(8 kW beam power)

<table>
<thead>
<tr>
<th>Background process</th>
<th>Expected events</th>
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<tbody>
<tr>
<td>Cosmic ray muons</td>
<td>$0.21 \pm 0.02 \pm 0.055$</td>
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<tr>
<td>Intrinsic</td>
<td></td>
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<tr>
<td>DIO</td>
<td>$0.14 \pm 0.03 \pm 0.11$</td>
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<tr>
<td>RMC</td>
<td>$0.000^{+0.004}_{-0.000}$</td>
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<tr>
<td>Prompt, late-arriving</td>
<td></td>
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<tr>
<td>RPC</td>
<td>$0.021 \pm 0.001 \pm 0.002$</td>
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<tr>
<td>Muon DIF</td>
<td>$&lt; 0.003$</td>
</tr>
<tr>
<td>Pion DIF</td>
<td>$0.001 \pm &lt; 0.001$</td>
</tr>
<tr>
<td>Beam electrons</td>
<td>$(2.1 \pm 1.0) \times 10^{-4}$</td>
</tr>
<tr>
<td>Antiproton-induced</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$0.04 \pm 0.001 \pm 0.02$</td>
</tr>
</tbody>
</table>

Total                                     $0.41 \pm 0.03$ (stat+syst)

Expect $<0.5$ background event in 3 years
Any observation will be strong evidence for CLFV

08/11/2020
Sensitivity

$\text{5}\sigma$ discovery sensitivity at $R_{\mu e} = 2 \times 10^{-16}$

*orders of magnitude beyond currently constrained*

Single-event sensitivity at $R_{\mu e} = 3 \times 10^{-17}$

**Real discovery potential**
Solenoids - progress

- Production Solenoid (PS)
- Detector Solenoid (DS)
- Transport Solenoid (TSu, TSD)

Fully tested and assembled @ HAB

Coil layer compaction

Post VPI

DS

DS10 shell
**Mu2e outlook**

- Begin installation in 2021
- Physics data beginning 2024
- Aim for $10^3$ improvement on $R_{\mu e}$ by 2025
- LBNF/PIP-II accelerator shutdown
- By end of decade: complete data taking, improve $10^4$ on $R_{\mu e}$

Intense effort over next years as project nears completion

Global program may well produce first observations of CLFV this decade
Defining the Next Decade

Mu2e-II, evolution to Mu2e with PIP-II

- Improving sensitivity by another order of magnitude
- Powerful in any scenario

Many more proposals for physics at the Muon Campus in the PIP-II era, integrated into the Snowmass process

$R_{\mu e}$ Z-dependence to study structure of new physics
Summary

Fermilab is a global leader in Muon Physics

Muon g-2
Highly anticipated Run1 result out soon, full result in few years

Mu2e
Large increase in sensitivity, well motivated physics, real discovery potential

Results will be decade-defining for Fermilab and entire field
Lattice HVP: BMW 2020

![Graph showing lattice HVP results for different collaborations and years, with a note indicating 'No New Physics'.]
Lepton moments

\[
\alpha_\ell(\text{Exp}) - \alpha_\ell(\text{SM})
\]

Sensitivity to heavy new physics:

\[
a_\ell^{\text{NP}} \sim \frac{m_\ell^2}{\Lambda^2}
\]

\[
(m_\mu/m_e)^2 \sim 4 \times 10^4
\]

plot by Shaun Lahert

BNL E821

Harvard'08
Beam to Muon Campus
• transform from μ-rest frame to lab frame yields higher energy positrons when emitted along μ-direction (i.e. spin along momentum)

• transform from μ rest frame to lab frame yields lower energy positrons when emitted opposite μ-direction (i.e. spin opposite momentum)
CLFV

Ordinary muon decay conserves lepton flavor:

$$\mu^- \rightarrow e^- \bar{v}_e \nu_\mu$$

\[
\begin{array}{cccc}
\text{L}_\mu & 1 & 0 & 0 & 1 \\
\text{L}_e & 0 & 1 & -1 & 0 \\
\end{array}
\]

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 evidence that rate is enhanced by new physics
- A search for rare forbidden processes at the Intensity Frontier
- Complementarity and synergy with LHC

- The charged-lepton analog to neutrino oscillations!
## Complementarity between searches

<table>
<thead>
<tr>
<th></th>
<th>AC</th>
<th>RVV2</th>
<th>AKM</th>
<th>$\delta$LL</th>
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<td>$B \to K^{(*)} \nu \bar{\nu}$</td>
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<tr>
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<td>$(g - 2)_\mu$</td>
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<td>★★★</td>
<td>★</td>
<td>?</td>
</tr>
</tbody>
</table>

*W. Altmanshofer et al. 0909.1333v2*
Several prompt background sources could give 105 MeV $e$

Characteristic: pion lifetime 26 ns

**Concept**: Simply wait for prompt bkgds to decay

- Delayed signal window by 700 ns
- Muonic Al lifetime 864 ns
- Proton pulse period 1695 ns, from Fermilab Delivery Ring

**Time structure eliminates prompt backgrounds**

Example: Radiative pion capture

$$\pi^- N \rightarrow \gamma N$$

$$\gamma \rightarrow e^- e^+$$
The COMET detector has an extra curved magnet acting as an electron spectrometer.
CLFV and g-2

Loop terms:

\[ \mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(1 + \kappa) \Lambda^2} \bar{\mu} R \sigma_{\mu\nu} e_L F^{\mu\nu} \]

\[ \mathcal{L}_{g-2} \supset \frac{m_\mu}{\Lambda^2} \bar{\mu} R \sigma_{\mu\nu} \mu_L F^{\mu\nu} + h.c. . \]


Loop operator relates to Muon g-2

- The CLF-violating part of any NP that modifies g-2 would give Mu2e events
- MEG already constrains \( \Lambda > 1000 \) TeV, or NP not very CLF-violating
- For the given \( \Delta a_\mu \):

\[ B(\mu^+ \rightarrow e^+ \gamma) \simeq 6 \times 10^{-3} |\epsilon_{e\mu}|^2 \]

William J. Marciano, Toshinori Mori, and J. Michael Roney
https://doi.org/10.1146/annurev.nucl.58.110707.171126

Flavor violating suppression factor