Searches for Lepton Flavor Violation

David Hitlin
Caltech
DISCRETE 2021
December 2, 2021
Charged lepton flavor violation (CLFV)

- CLFV denotes a transition involving $\mu$, $e$ and $\tau$ lepton states that doesn’t conserve lepton family number, i.e., there are no neutrinos involved
  - A CLF conserving transition: $\mu^- \rightarrow e^- \nu_e \overline{\nu}_\mu$
  - A CLFV transition: $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$, $\mu N \rightarrow e N (\mu \rightarrow e$ conversion)

- Family number is not a symmetry of the Standard Model Lagrangian
  - Quark family number is violated in weak decays (c.f. the CKM matrix)
  - Neutrino oscillations are proof of the violation of neutral lepton flavor conservation as well as evidence for BSM physics (e.g., see-saw)

- A natural question: “Is there also observable charged lepton flavor violation?”
  - In the Standard Model (+ heavy neutrinos), CLFV is very small:

\[
\mathcal{B}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m^2_{1i}}{M_W^2} \right|^2 < 10^{-54}
\]

- Thus CLFV searches are a clean probe of NP in the charged lepton sector
Searching for CLFV

- Many NP models predict CLFV processes to occur in an observable regime
- The sensitivity to CLFV in loop processes can exceed that in direct production
  - There are many distinct experimental probes and a rich phenomenology, leading to a robust experimental scene
    - $\mu \rightarrow e\gamma$: most powerful limits: MEG-II at PSI
    - $\mu N \rightarrow e N$ muon to electron conversion: three experiments upcoming: Mu2e at FNAL and DeeMe and COMET at JPARC
    - $\mu \rightarrow 3e$: Mu3e at PSI
    - $\mu^- N \rightarrow e^+ N (\text{Z-2})$ (Mu2e–II, COMET Phase 2?)
    - $\mu^+ e^- \rightarrow \mu^- e^+$
    - $\tau \rightarrow (e, \mu)\gamma$ and many other $\tau$ decays (Belle II)
    - $H^0 \rightarrow \mu, e, \tau + X$ (LHC)
    - $K_L \rightarrow \mu e, B \rightarrow \mu e, K \rightarrow \mu e, \ldots$ (LHCh, expts at J-PARC, CERN)
- The form of the CLFV Yukawa coupling matrix is model-dependent, e.g., it could be PMNS-like or CKM-like
- Different theories predict distinct correlations between CLFV processes

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{all muon captures})}$$
CLFV Processes

- Low energy probes: rare $\mu, \tau$ and $H^0$ decays, $\mu \rightarrow e$ conversion, CLFV in meson decay

$\mu^+ \rightarrow e^+\gamma$

$\tau \rightarrow \mu\gamma, e\gamma$

$(g-2)_\mu$

$Higgs$ decay: $H^0 \rightarrow \tau \mu$ (also $\tau e, \mu e$)

$B \rightarrow \ell\ell'$

$B \rightarrow X_s\ell\ell'$
New Physics contributions to $\mu \rightarrow e$ conversion

$\mu N \rightarrow e N$ is sensitive to a wide variety of New Physics models, e.g., SUSY, 2HDM, Extra Dimensions, Leptoquarks, GUTs, LHT,…

**Supersymmetry**
rate $\sim 10^{-15}$

$\mu^e \rightarrow e^e$ is sensitive to a wide variety of New Physics models, e.g., SUSY, 2HDM, Extra Dimensions, Leptoquarks, GUTs, LHT,…

**Compositeness**
$\Lambda_c \sim 3000$ TeV

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

**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’**
Anomalous Z’Coupling
$M_{Z'} = 3000 \text{TeV/c}^2$
Model-independent effective Lagrangian

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

Dipole interaction (SUSY, ……)

\[ \mu \rightarrow e \gamma \]

Contact interaction (\(Z',\) leptoquarks, …)

\[ \mu \rightarrow e \text{ conversion} \]

CLFV processes have unique sensitivity to New Physics at high mass scales

Also \( \mu \rightarrow eee \)

Derived from A. de Gouvêa & P. Vogel, Prog.Part.Nucl. Phys 71, 75 (2013)
Purely leptonic case: $\mu \rightarrow e\gamma, \mu \rightarrow 3e \ (\tau \rightarrow)$

\[
\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2} \bar{e}_\mu \sigma_{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{e}_L \gamma_\mu e_L) + h.c.
\]
• $\mu \rightarrow e$ expts probe multi-loop effects in NP theories with a greater $\Lambda_{NP}$ reach than LHC
• CLFV BSM contact interactions can be parametrized by a set of 2, 3 and 4 point functions that respect QED and QCD:

$$\sum_\zeta \sum_O \left( \begin{array}{c}
\nu \rightarrow \nu \\
\mu \rightarrow e \\
\mu \rightarrow 3e \\
\mu N \rightarrow e N \\
\end{array} \right)$$

• These can be evaluated as loops in EFT in a model-independent manner
  • Loops rescale the couplings and can mix interactions
• For $\mu \rightarrow e \gamma$, $\mu \rightarrow 3e$, $\mu N \rightarrow e N$ there are a total of 82 operators
• A combination of limits or observations of the three processes can help to isolate those operators involved in particular models
• In particular, the Z dependence of $\mu N \rightarrow e N$ can be an important tool
  • In $\mu \rightarrow e$ conversion, different nuclei with different spins pick out particular linear combinations of new physics operators

Crivellin, Davidson, Pruna, Signer, JHEP 05, 117, 2017
Davidson, Kuno, Yamanaka, Phys.Lett. B 790, 380, 2019
Davidson, JHEP 02, 172, 2021
## Current and future CLFV limits (90%CL)

<table>
<thead>
<tr>
<th>Process</th>
<th>Current Limit</th>
<th>Next Generation exp</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu \eta$</td>
<td>BR $&lt; 6.5 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \gamma$</td>
<td>BR $&lt; 6.8 \times 10^{-8}$</td>
<td>$10^{-9} - 10^{-10}$ (Belle II)</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \mu \mu$</td>
<td>BR $&lt; 3.2 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$\tau \rightarrow eee$</td>
<td>BR $&lt; 3.6 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$K_L \rightarrow e\mu$</td>
<td>BR $&lt; 4.7 \times 10^{-12}$</td>
<td></td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ e^- \mu^+$</td>
<td>BR $&lt; 1.3 \times 10^{-11}$</td>
<td></td>
</tr>
<tr>
<td>$B^0 \rightarrow e\mu$</td>
<td>BR $&lt; 7.8 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+ e\mu$</td>
<td>BR $&lt; 9.1 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$\mu^+ \rightarrow e^+ \gamma$</td>
<td>BR $&lt; 6.1 \times 10^{-13}$</td>
<td>$10^{-14}$ (MEG-II)</td>
</tr>
<tr>
<td>$\mu^+ \rightarrow e^+ e^+ e^-$</td>
<td>BR $&lt; 1.0 \times 10^{-12}$</td>
<td>$10^{-16}$ (Mu3e)</td>
</tr>
<tr>
<td>$\mu N \rightarrow eN$</td>
<td>$R_{\mu e} &lt; 7.0 \times 10^{-13}$</td>
<td>$10^{-17}$ (Mu2e, COMET, DeeMe)</td>
</tr>
</tbody>
</table>

Calibbi and Signorelli  
Bounds on Higgs exchange models

- Bounds on CLFV couplings to the Higgs can be derived from LHC limits as well as conventional leptonic processes.

**CLFV Higgs decay**

\[ \mathcal{L}_Y \supset - Y_{e\mu} \bar{e}_L \mu_R h - Y_{e\tau} \bar{e}_L \tau_R h - Y_{e\tau} \bar{\tau}_L e_R h - Y_{\mu\tau} \bar{\mu}_L \tau_R h - Y_{\tau\mu} \bar{\tau}_L \mu_R h + h.c. \]

\[ \Gamma(h \to \ell^\alpha \ell^\beta) = \frac{m_h}{8\pi} (|Y_{\ell^\beta \ell^\alpha}|^2 + |Y_{\ell^\alpha \ell^\beta}|^2) \]

- \( \mu \to e\gamma \) (\( \tau \to \mu\gamma \))
- \( \mu \to 3e \) (\( \tau \to \ell'\ell\ell \))
- \( \mu N \to eN \)
- \( g-2 \)
Higgs CLFV

CLFV Higgs couplings to $\tau$ ($\tau e$, $\tau \mu$) can likely be best measured at the LHC

$\mu e$ couplings are best measured in dedicated muon experiments
Model discrimination through correlations

Calibbi et al.  

Littlest Higgs (Blanke et al.)  
MEG

A. Vicente & C.E. Yaguna – Scotogenic model, N₁-N₁ annihilation region  
Model discrimination through correlations

<table>
<thead>
<tr>
<th>ratio</th>
<th>LHT</th>
<th>MSSM (dipole)</th>
<th>MSSM (Higgs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{Br(\tau \to e e e)}{Br(\mu \to e e e)}$</td>
<td>0.02 . . 1</td>
<td>$\sim 6 \cdot 10^{-3}$</td>
<td>$\sim 6 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$\frac{Br(\tau \to e e e)}{Br(\tau \to e \gamma)}$</td>
<td>0.04 . . 0.4</td>
<td>$\sim 1 \cdot 10^{-2}$</td>
<td>$\sim 1 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$\frac{Br(\tau \to e e e)}{Br(\tau \to \mu \mu)}$</td>
<td>0.04 . . 0.4</td>
<td>$\sim 2 \cdot 10^{-3}$</td>
<td>0.06 . . 0.1</td>
</tr>
<tr>
<td>$\frac{Br(\tau \to e e e)}{Br(\tau \to \mu \gamma)}$</td>
<td>0.04 . . 0.3</td>
<td>$\sim 2 \cdot 10^{-3}$</td>
<td>0.02 . . 0.04</td>
</tr>
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<td>$\frac{Br(\tau \to e e e)}{Br(\tau \to \mu \mu)}$</td>
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<td>$\sim 1 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$\frac{Br(\tau \to e e e)}{Br(\tau \to e \gamma)}$</td>
<td>0.8 . . 2.0</td>
<td>$\sim 5$</td>
<td>0.3 . . 0.5</td>
</tr>
<tr>
<td>$\frac{Br(\tau \to e e e)}{Br(\tau \to \mu \mu)}$</td>
<td>0.7 . . 1.6</td>
<td>$\sim 0.2$</td>
<td>5 . . 10</td>
</tr>
<tr>
<td>$\frac{Br(\mu \to e Ti)}{Br(\mu \to e \gamma)}$</td>
<td>$10^{-3} \ldots 10^2$</td>
<td>$\sim 5 \cdot 10^{-3}$</td>
<td>0.08 . . 0.15</td>
</tr>
</tbody>
</table>

Correlations in the $\tau \to \mu \gamma$ and $\ell \ell \ell$ branching fractions

$B(\tau \to \mu \gamma)$ vs. $B(\mu \to e e e)$ and $CR(\mu \to e$ on Ti) in an SO(10) Type II SUSY model
Calibbi, et al., JHEP 0912 057 (2009)

Blanke, Buras, Duling, Recksiegel & Tarantino,
Excellent sensitivity to many BSM models

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.
Chronology of $\mu$ and $\tau$ CLFV searches

$\mu$ beam
$\muN \rightarrow eN$

$\pi$ beam
$\tau \rightarrow 3\mu$
$\tau \rightarrow \mu\gamma$
$e^+e^- \rightarrow \tau^+\tau^-$

Limit (90% CL)

$\mu \rightarrow e\gamma$
$\mu \rightarrow 3e$

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David Hitlin
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Limits on CLFV $\tau$ decays

90% CL upper limits on $\tau$ LFV decays

- ATLAS
- BABAR
- Belle
- CLEO
- LHCb

Belle II
“naive extrapolation”
The target integrated luminosity of 50 ab\(^{-1}\) (~5x10\(^{10}\) \(\tau\bar{\tau}\)) will be reached in ~2025-2031.

The improvement in sensitivity to CLFV \(\tau\) decays depends on whether or not a particular mode has backgrounds.

- e.g., limits on \(B(\tau\rightarrow\ell\ell\ell)\) improve as \(1/\int\mathcal{L}dt\) if there is no background, but more slowly, as \(\sim 1/\int\mathcal{L}dt^{1/2}\), if there is background.
Belle II $\tau$ CLFV limits

- The target integrated luminosity of 50 ab$^{-1}$ ($\sim 5 \times 10^{10}$ $\tau\tau$) will be reached in ~2025-2031.
- The improvement in sensitivity to CLFV $\tau$ decays depends on whether or not a particular mode has backgrounds.
  - e.g., limits on $\mathcal{B}(\tau \rightarrow \ell\ell\ell)$ improve as $1/\mathcal{L}dt$ if there is no background, but more slowly, as $\sim 1/\mathcal{L}dt^{1/2}$, if there is background.
Backgrounds: the name of the game

• At the sensitivities required to advance the state of the art in both $\tau$ decays and muon experiments, the primary issue is control of backgrounds in a high rate environment
  • Irreducible backgrounds
  • Accidental backgrounds

• Problematic backgrounds are specific to the type of experiment

• Handles on background control are
  • Charged particle energy resolution
  • Neutral energy resolution
  • Time resolution
  • Particle identification
  • Prompt beam particle rejection
  • Cosmic ray rejection

New muon experiments
• MEG II
• Mu3e
• DeeMe, Mu2e, COMET

New $\tau$ decay experiments
• Belle II
• LHC$b$

Higgs decay experiments
• ATLAS
• CMS
Muon experiments: CW vs pulsed beams

- **Muon decay** experiments \(\mu \rightarrow e\gamma, \mu \rightarrow eee\) use a continuous \(\mu^+\) beam, such as the PSI synchrocyclotron surface muon beam.
- The dominant backgrounds come from accidental coincidences of two decays:
  - background \(\propto (rate)^2\)
  - signal \(\propto rate\)

- **\(\mu \rightarrow e\) conversion** experiments use a pulsed \(\mu^-\) beam, such as FNAL or J-PARC.
  - There are many prompt pion-induced backgrounds immediately after the proton pulse.
  - Use the muon/pion lifetime difference to reduce background.

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**Diagrams:**

- **CW operation optimizes the S/N**
- **Pulsed operation optimizes the S/N**
Muon experiments: CW vs pulsed beams

- **Muon decay** experiments $\mu \rightarrow e\gamma, \mu \rightarrow eee$ use a continuous $\mu^+$ beam, such as the PSI synchrocyclotron surface muon beam
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- There are many prompt pion-induced backgrounds immediately after the proton pulse

**Live Window**

**CW operation optimizes the S/N**

**Pulsed operation optimizes the S/N**
\[ \mu^+ \rightarrow e^+ \gamma \]

CLFV signal \( \propto R_\mu \)

Radiative muon decay correlated \( \propto R_\mu \)

Accidental background uncorrelated \( \propto R_\mu \)

Events are described by five variables: \( E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma} \)

MEG at PSI
MEG backgrounds

- Backgrounds are dominated by accidental coincidences from 
  \[ \mu \rightarrow e \nu \nu \gamma \sim (1 - 2E_\gamma / m_\mu) \]
  \[ \Gamma_{acc} \propto \Gamma_\mu^2 \cdot \varepsilon_e \cdot \varepsilon_\gamma \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot (\delta \theta_{e \gamma})^2 \cdot \delta t_{e \gamma} \]
- These considerations dictated the original MEG design and the improvements incorporated in the upgrade

- MEG employed a DC surface muon beam: \(|p_\mu| 28\, \text{MeV/c}, 3 \times 10^7 \mu\, \text{stops/s}\)
- With a total of \(7.5 \times 10^{14}\) stopped muons, gathered in runs from 2009 - 2013
  MEG set a 90% CL limit of \(< 4.2 \times 10^{-13}\) (Baldini et al., Eur.Phys.J. C76434, 2016)
MEG II – 2x resolution improvement

- Improved uniformity with VUV-sensitive 12x12mm SiPMs
- Intensity $7 \times 10^7 \mu/s$
- He:iC4H10 gas
- Small stereo cells
- Reduced mass $\sim 1.6 \times 10^{-3} \chi_0$
- 35ps time resolution with multiple hits
- Reduction of radiative background

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MEG upgrade – 2x resolution improvement

Improved uniformity with VUV-sensitive 12x12mm SiPMs

Intensity $7 \times 10^7$ $\mu$A/s

He:iC4H10 gas

Small stereo cells

30ps time resolution with multiple hits

Reduction of radiative background
MEG II status

• The MEG II Upgrade improves the detector (2x improvements in resolution and efficiency) to achieve a 90% CL limit of $6 \times 10^{-14}$ in a three year run

• Schedule
  • Commissioning runs in 2017-2020
  • Engineering run in Aug 2021
    • Install full DAQ, electronics
    • Full LXe electronics
    • Degradation of MPPC PDE ($\Rightarrow$ limit on $\mu$ stops/run),
    • Drift chamber conditioning to reduce corona discharge
    • New chamber to be built by March 2023
  • Physics runs start presently
$\mu^+ \rightarrow e^+ e^+ e^- \Rightarrow \text{Mu3e at PSI}$

**Signal**

$E = m_\mu$

$\sum p_i = 0$

Vertex

**Background**

Accidentals

Radiative decay with internal conversion

- **Current limit**: $1.0 \times 10^{-12}$ (SINDRUM at PSI, 1988)
- Mu3e at will provide substantial improvement
  - Uses a surface muon beam - $\pi E5$ beamline
  - Phase I
    - 2018 - $10^8 \mu^+ / s$
    - Sensitivity $10^{-15}$
  - Phase II HIMB $10^9 \mu^+ / s$
    - Sensitivity $10^{-16}$
Mu3e detail

- Muons: stopping rate up to $10^8 \mu/s$
- Tracking: double layers, HV-MAPS (high voltage monolithic active pixel sensor), $\lesssim 50 \mu m$ minimize multiple scattering
- Timing: scintillating, $-250 \mu m$ fibres (few 100 ps), $-1 \text{ cm}^3$ tiles (100 ps), Silicon Photomultipliers
- Requirement: very good vertex/time resolution, low material budget to get best possible momentum resolution

Combinatorial background (bg) and $\mu \rightarrow eee\nu\nu$ background (bg: $\mu \rightarrow eee\nu\nu$)
\( \mu^+ \rightarrow e^+ e^+ e^- \Rightarrow \text{Mu3e at PSI} \)

**Signal**
\[
E = m_\mu \\
\Sigma p_i = 0 \\
\text{Vertex}
\]

**Background**

- **Accidentals**
- **Radiative decay** with internal conversion

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    - 2018 - \( 10^8 \mu^+/s \)
    - Sensitivity \( 10^{-15} \)
  - **Phase II** HIMB \( 10^9 \mu^+/s \)
    - Sensitivity \( 10^{-16} \)
- **Mu3e** had an integration run in the \( \pi E5 \) beamline from May to July 2021 with a reduced detector: 2 pixel layers + fiber detector inserted into the magnet

\[ E = m_\mu \]

\[ \Sigma p_i = 0 \]

\[ \text{Vertex} \]
Mu3e sensitivity

Mu3e Phase I

Events per 0.2 MeV/c^2

- $10^{15}$ muon stops at $10^8$ muons/s
- $\mu \to eee$ at $10^{-12}$
- $\mu \to eee$ at $10^{-13}$
- $\mu \to eee$ at $10^{-14}$
- $\mu \to eee$ at $10^{-15}$

m_{rec} [MeV/c^2]
Mu3e sensitivity

**Mu3e Phase I**

- $10^{15}$ muon stops at $10^8$ muons/s
- $\mu \rightarrow eee$ at $10^{-12}$
- $\mu \rightarrow eee$ at $10^{-13}$

**BR(\(\mu \rightarrow eee\))**

- $10^8$ muon stops/s
- 18.4% signal efficiency

- SINDRUM 1988
- SES
- 90% C.L.
- 95% C.L.

- $2 \times 10^{15}$

- Data taking days
μ to e conversion experiments

- The signal is a single mono-energetic electron
- If $N = \text{Al}$, $E_e \sim 105 \text{ MeV}$
  - electron energy depends on $Z$, due to atomic binding energy
- Coherent nuclear recoil
- There are three experiments in various stages of preparation
  - DeeMe
  - COMET Phase I and Phase II
  - Mu2e
  - Origins trace to MELC and MECO proposals
- All face similar challenges, addressed in specific ways
  - High rates to achieve required sensitivity
  - Prompt and delayed beam-related backgrounds
  - Cosmic ray backgrounds
- PRISM/Prime is a muon storage ring based accelerator/detector concept

\[
R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{all muon captures})}
\]

$e^- = 104.96 \text{ MeV}$

$\text{BR} = 61\%$
Decay-in-Orbit Shape

\[ \frac{1}{E_{\text{max}}} \frac{dN}{dE} \]

\[ E_e (\text{max}) = 52.8 \text{ MeV} \]
Decay-in-Orbit Shape

With $\mu$-Al\textsuperscript{27} binding energy and radiative corrections
Decay-in-Orbit Shape

With $\mu$-Al$^{27}$ binding energy and radiative corrections

\[
\frac{1}{E_{\text{max}}} \frac{dN}{dE}
\]
DeeMe at JPARC

μN → eN

Novel Idea: μ-e conversion in the primary production target

Signal is a delayed single mono-energetic electron identified by measuring its momentum in spectrometer using Pac-Man magnet from TRIUMF

Beamline shared with other experiments (g-2)
DeeMe at JPARC

$\mu N \rightarrow eN$

Novel Idea: $\mu$-e conversion in the primary production target

Signal is a delayed single mono-energetic electron identified by measuring its momentum in spectrometer using Pac-Man magnet from TRIUMF

Beamline shared with other experiments ($g$-2)

Start with carbon target
- Lifetime of muonic atom $\sim 2\mu s$
- Energy of electron from $\mu \rightarrow e$ conversion = 105 MeV
- Single event sensitivity (1 year = $2 \times 10^7$ sec)
  - $1 \times 10^{-13}$
  - $2 \times 10^{-14}$ (4 years)

Upgrade to SiC
- $3 \times 10^{-14}$
- $5 \times 10^{-15}$ (4 years)
DeeMe status

- H1 beamline expected to be completed in Jan 2022
- Pac-Man magnet installed
- Tracking + electronics exists
  - Measured DIO spectrum
- Data-taking to start in 2022
The Mu2e sensitivity goal $2.6 \times 10^{-17}$ demands a total of ~ $6 \times 10^{17}$ stopped muons in a 3 year run of ~ $6 \times 10^7$ seconds total.

This requires a muon stopping rate of $10^{10}$/sec

Experimental design
- Pulsed proton beam produce pions, which are captured in the backward direction
- Transport muons from pion decay, with momentum and sign selection
- Since electron backgrounds are at lower momentum than the sought conversion electrons, confine lower momentum particles to smaller helical radii in a solenoid and a provide hole in tracker and calorimeter for them to pass through
- Reject cosmic ray events
Cosmic ray veto (four layers)

Covers as much of the transport and detector solenoids as possible. Nonetheless, timing properties of the calorimeter are required to achieve required cosmic ray rejection.
What happens during a microbunch?

Use of pulsed proton beam and a delayed live gate allows suppression of prompt backgrounds by many orders of magnitude.

Proton pulses must be narrow.

Out-of-time protons must be suppressed by $O(10^{10})$.

Simulations encompass a full ~1μs, including all the background overlays from the beam flash, μ capture products, neutrons, etc. and properly account for contributions from previous bunches.
What happens during a microbunch?

- Simulations encompass a full ~1 µs, including all the background overlays from the beam flash, μ capture products, neutrons, etc. and properly account for contributions from previous bunches.

Use of pulsed proton beam and a delayed live gate allows suppression of prompt backgrounds by many orders of magnitude.

Proton pulses must be narrow.

Out-of-time protons must be suppressed by $O(10^{10})$.

(particles with hits within +/-40 ns of signal electron $t_{\text{mean}}$)

- Simulations encompass a full ~1 µs, including all the background overlays from the beam flash, μ capture products, neutrons, etc. and properly account for contributions from previous bunches.
Mu2e components

Inserted DS10 Coil
Calorimeter Disk 1
Tracker planes
CRV Slice Test
Mu2e schedule/sensitivity

- Beam on target late 2024
- Run 1: 2025-2026 half beam intensity
  - x1000 improvement over SINDRUM-II
- Shutdown for PIP-II/LBNF at end of 2026
- Data-taking resumes early 2029 at full beam intensity
  - x10000 improvement over SINDRUM-II 90% CL limit

Total background
(Cosmics+DIO+RPC+\bar{p})
= 0.11\pm0.03 \text{ events}

5\sigma \text{ discovery reach}

\[ R_{\mu e} = 1.1 \cdot 10^{-15} \]

If no events are observed:
90\% CL limit:

\[ R_{\mu e} = 5.9 \cdot 10^{-16} \]
COMET Phase I

SES 3 x 10^{-15}

or < 6 x 10^{-15} @ 90% CL

for 150 days at 3.2 kW
COMET Phase-II

SES (1.0 – 2.6) x 10^{-17} for 2 x 10^7 s at 56kW
COMET Phase-I: CyDET(CDC+CTH)

Cylindrical Drift Chamber, constructed in 2016

**CDC** All stereo-wire drift chamber
- 20 layers, ~5000 sense wires
- He:iC₄H₁₀ = 9:1
- HV=1850V
- Momentum resolution <200keV/c @ 105 MeV/c,
- Spatial resolution 170 µm
- Cosmic test underway in KEK

**CTH** 64-segmented two-layered scintillators, providing trigger
- ~0.8 ns timing resolution

Stopping Target Al
CTH Trigger Hodoscope
Cylindrical Drift Chamber
Shielding Cryostat
COMET Phase-II

SES (1.0 – 2.6) x 10^{-17} for 2 \times 10^7 \text{ s at 56kW}

ECAL, Straw Tracker

(# of straw stations is not determined) in vacuum under 1T magnetic field
# COMET Phase-I & Phase-II

<table>
<thead>
<tr>
<th></th>
<th>COMET-Phase-I</th>
<th>COMET-Phase-II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment starts (*)</strong></td>
<td>in ~2023</td>
<td>Ready in 3 years after completion of</td>
</tr>
<tr>
<td>* including engineering run</td>
<td></td>
<td>Phase-I</td>
</tr>
<tr>
<td><strong>Beam power</strong></td>
<td>3.2kW (8GeV, 400nA)</td>
<td>56kW (8GeV, 7μA)</td>
</tr>
<tr>
<td><strong>Running time</strong></td>
<td>150 days</td>
<td>2.0 x 10^7 (sec)</td>
</tr>
<tr>
<td><strong># of protons</strong></td>
<td>3.0 x 10^{19}</td>
<td>8.5 x 10^{20}</td>
</tr>
<tr>
<td><strong># of muon stops</strong></td>
<td>1.5 x 10^{16}</td>
<td>2.0 x 10^{18}</td>
</tr>
<tr>
<td><strong>Muon rate</strong></td>
<td>5.8 x 10^{9}</td>
<td>1.0 x 10^{11}</td>
</tr>
<tr>
<td><strong># of μ stops / p</strong></td>
<td>0.00052</td>
<td>0.00052</td>
</tr>
<tr>
<td><strong>Background events</strong></td>
<td>0.02</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>S.E.S.</strong></td>
<td>3.1 x 10^{-15}</td>
<td>2.6 x 10^{-17}</td>
</tr>
<tr>
<td><strong>U.L. (90%CL.)</strong></td>
<td>7.0 x 10^{-15}</td>
<td>6.0 x 10^{-17}</td>
</tr>
</tbody>
</table>
Z dependence of $\mu$ to $e$ conversion

- If $\mu \rightarrow e$ conversion is observed with $^{27}\text{Al}$, comparison of the conversion rates on different nuclei can provide information on the Lorentz structure of the New Physics.

Choice of target

- The choice of a follow-on high Z target involves several considerations
  - Shorter muon lifetime limits the sensitive window
The choice of a follow-on high Z target involves several considerations:
- Shorter muon lifetime limits the sensitive window.
- Can target be a single isotope or natural abundance?
- Nuclear spin of target matters.
  - As with DM, there are spin-dependent and spin-independent couplings.
  - In EFT, each nucleus probes a particular combination of operators, e.g. $\tilde{C}^V_{epp}, \tilde{C}^S_{epp}, \tilde{C}^V_{enn}, \tilde{C}^S_{enn}$.

<table>
<thead>
<tr>
<th>Target</th>
<th>Isotopes [abundance]</th>
<th>J</th>
<th>$S_p^A, S_n^A$</th>
<th>$S_I(m_{\mu})/S_I(0)$</th>
<th>$B_Z$</th>
<th>BR (90% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>$Z = 13, A = 27$ [100%]</td>
<td>5/2</td>
<td>0.34, 0.030</td>
<td>[21,22]</td>
<td>0.29 [21,22]</td>
<td>132</td>
</tr>
<tr>
<td>Sulfur</td>
<td>$Z = 16, A = 32$ [95%]</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$&lt; 7 \times 10^{-11}$ [23]</td>
</tr>
<tr>
<td>Titanium</td>
<td>$Z = 22, A = 48$ [74%]</td>
<td>0</td>
<td>0.0, 0.21</td>
<td>[24]</td>
<td>~0.12</td>
<td>234</td>
</tr>
<tr>
<td>Titanium</td>
<td>$Z = 22, A = 47$ [7.5%]</td>
<td>5/2</td>
<td>0.0, 0.21</td>
<td>[24]</td>
<td>~0.12</td>
<td>-</td>
</tr>
<tr>
<td>Titanium</td>
<td>$Z = 22, A = 49$ [5.4%]</td>
<td>7/2</td>
<td>0.0, 0.29</td>
<td>[24]</td>
<td>~0.12</td>
<td>-</td>
</tr>
<tr>
<td>Vanadium</td>
<td>$Z = 23, A = 50$ [0.25%]</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Vanadium</td>
<td>$Z = 23, A = 51$ [99.75%]</td>
<td>7/2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Copper</td>
<td>$Z = 29, A = 63$ [70%]</td>
<td>3/2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Copper</td>
<td>$Z = 29, A = 65$ [31%]</td>
<td>3/2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gold</td>
<td>$Z = 79, A = 197$ [100%]</td>
<td>5/2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>285</td>
</tr>
<tr>
<td>Lead</td>
<td>$Z = 82, A = 206$ [24%]</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lead</td>
<td>$Z = 82, A = 207$ [22%]</td>
<td>1/2</td>
<td>0.0, -0.15</td>
<td>[24]</td>
<td>0.55 [28]</td>
<td>0.026</td>
</tr>
<tr>
<td>Lead</td>
<td>$Z = 82, A = 208$ [52%]</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Next steps: PIP2/Mu2e II and HIMB

- PIP2 is a new 800 MeV, 120 kW superconducting linac for LBNF and the muon campus
- There is an active Snowmass study of an upgrade of Mu2e to Mu2e-II
  - An order of magnitude increase in $\mu^-$ stops and therefore SES, with only a x3-5 increase in instantaneous rate
  - Detector systems must be upgraded accordingly

- A surface beam intensity ($\mu^+$) upgrade (HIMB) is being considered at PSI

- “When you come to a fork in the road, take it” – Yogi Berra
  - If $\mu \rightarrow e$ conversion has been found, use heavier targets to ascertain the $(A, Z)$ - dependence of conversion rate
  - If $\mu \rightarrow e$ conversion is not seen, improve sensitivity of the search
Going further at JPARC and/or Fermilab

**Phase Rotated Intense Slow Muon source**

**PRISM Muon Electron conversion**

- A muon storage ring, feeding a COMET-like channel and detector
- High muon intensity: \((10^{11}-10^{12}) \mu^-/s\)
- Large 6D acceptance (FFAG)
- Pulsed beam >100 Hz,
- Low momentum, quasi-mono-energetic muons
- Pion contamination <10^{-18}
- Requires a high intensity proton driver
- Aims for SES - \(3\times10^{-19}\)
- Time scale well beyond 2030

- A similar concept with protons from PIP2 is now taking shape at Fermilab as part of the Snowmass exercise
  - Aims at \(\mu^+\) and \(\mu^-\) beams to cover a full spectrum of CLFV experiments
Outlook

- Current limits on charged lepton flavor violation provide useful constraints on many New Physics models.
- Over the next decade, improved $\mu$ decay, leptonic and semileptonic meson decay, $\mu \rightarrow e$ conversion and $\tau$ decay experiments will have the sensitivity to probe the regime predicted by many New Physics models.
  - Sensitivities reach well beyond what is possible in direct production of new particles at the LHC.
  - Should evidence for CLFV be found, comparison of branching ratios and conversion rates will be diagnostic of specific models.