A New Charged Lepton Flavor Violation Program at Fermilab

RPF Town Hall
2 October 2020

ENIGMA: nExt geNeration experIments with hiGh intensity Muon beAms
more references in backup;
Johnstone/Pasternak/Prebys talks in this session; also Papa, Tassielli talks
and Middleton, Mackenzie, Borrel, Chislett on Mu2e/Mu2e-II
https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0-AF5_AF0_Robert_Bernstein-027.pdf
Overview

• Charged Lepton Flavor Violation, or transitions from $\tau \to \mu \to e$ without neutrinos have never been observed.

• We’ve seen quark mixing and neutral lepton mixing (oscillations). Why not charged leptons?
  • Fundamental puzzle dating to the discovery of the muon.
  • Really about the generation/flavor puzzles.
  • CLFV is forbidden in the Standard Model but it is extremely common in extensions, particularly SUSY.

• Observation and study of CLFV could drive the choice of the next high-energy collider.
Muons And CLFV

• Three main modes (note there are no neutrinos, hence charged lepton flavor violation!)
  • $\mu^+ \rightarrow e\gamma$ at PSI (MEG)
  • $\mu^+ \rightarrow 3e$ at PSI (Mu3e)
  • $\mu^- N \rightarrow e^- N$ at FNAL (Mu2e) and J-PARC (COMET)

• Muons have a unique advantage since you can make beams, effective luminosity $10^{48}/\text{cm}^2/\text{sec}$ in Mu2e or COMET

• Note: two decay experiments with $\mu^+$ and a capture experiment with $\mu^-$
Advantage of Multiple Experiments

- Each of these experiments probes new physics in different ways
  - complementary, not competing
- $Z$-dependence of $\mu^- N \rightarrow e^- N$ can reveal nature of new physics
  - need to go to high atomic number like Au ($Z=79$)
  - Mu2e and COMET are for Al ($Z=13$) or Ti ($Z=22$)
Goals of this Effort

• A facility for

  • one muon beam for the decay experiments 
    \( \mu \rightarrow e\gamma \) and \( \mu \rightarrow 3e \)

  • this is similar to existing beams at PSI

  • a second muon beam for the \( \mu^-N \rightarrow e^-N \)
    experiment that can go to high \( Z \)

    • this is a new beam, and probing high \( Z \) not possible with Mu2e/COMET beams

• Reaching orders of magnitude beyond current experiments to mass scales \( \mathcal{O}(10^5) \) TeV
Comparisons

• For a sense of scale: how many stopped muons for the decay experiments could we make (under reasonable assumptions)?

• approximate, but ratios are the take-away

• PIP-II is transformative

<table>
<thead>
<tr>
<th>Facility</th>
<th>Stopped Muon Rate/ sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current PSI</td>
<td>$2 \times 10^8$</td>
</tr>
<tr>
<td>HiMB at PSI</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>Mu2e Design (+ mode)</td>
<td>$10^{11}$</td>
</tr>
<tr>
<td>PIP-II</td>
<td>$&gt;10^{12}$</td>
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</tbody>
</table>
Beam I: decay experiments

• Decay Experiments: stop $\mu^+$ and let them decay

• these muon beams are old technology. A 1.4 MW-target is already the source for the PSI muon program, but PSI muon program only receives small fraction; we do not have similar competition

• the statistics are so high that one can convert the $\gamma$ so $\mu \rightarrow e\gamma, \gamma \rightarrow e^+e^-$ which greatly improves momentum resolution and reduces background

• $x100$ better than MEG-II, probing $\mathcal{O} (10^4)$ TeV in SUSY-like models
Beam II: capture experiments

- Protons hit target in a solenoid, making $\pi \rightarrow \mu$ (capture solenoid)

- PRISM concept:
  - and place $\mu^-$ in a fixed-field, alternating gradient ring (FFA)
  - phase rotate muons to have a narrow momentum spread
    - slow down leading edge, speed up trailing edge of bunches

- Extract muons to detector system

- PIP-II time structure requires a compressor ring to rebunch the beam, since phase rotation takes time and PIP-II is too fast
Challenges:

- Target 1MW of beam inside a superconducting solenoid to capture pions and create muon beam.
  - A lot of study has gone into this for muon colliders! *Many overlaps and synergies with muon colliders and neutrino factories throughout*
- FFA built at small scale at Osaka (MUSIC)
- Injection/Extraction to FFA
- Kickers to transfer beam around 1 kHz
Forming Collaboration

• This LOI has people from the different programs and Labs: J-PARC, PSI, FNAL experiments

• $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$, and $\mu^-N \rightarrow e^-N$

• Beam and Detector Groups for decay and conversion experiments being formed

• Discussions with Proponents for Low-Energy Muon Facility about overall Muon Program (see C. Johnstone talk)

  • muonium-antimuonium (Tang & Petcov)
Preliminary Groups

• Decay Experiments:
  • Beam: use CDR for HiMB at PSI for starting point; HiMB planned for funding 2025-2028, this would follow that generation
  • Detectors: it possible to build one detector for both $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$? Multiple stopping targets?
    • tracking? aging? calorimetry? timing? $\gamma$ converter design?
Preliminary Groups

- Capture Experiment
  - Beam: compressor ring preliminary design underway; adapt FFA design from PRISM group; kickers, injection/extraction, and targeting
    - need to form connection to muon collider work ([https://indico.cern.ch/event/930508/](https://indico.cern.ch/event/930508/))
  - Detector: is a Mu2e/COMET-style detector best? Can crystal calorimetry handle the rates without excessive pile-up? Tracker lifetime?
Muons are a Community Priority

• Just from this session, we see:
  
  • two muonium-antimuonium talks (Tang/Petcov)
  
  • rare muon decays and light physics (Redigolo)
  
  • \( \mu \rightarrow e\gamma \) (Papa, Tassielli)
  
  • \( \mu^- N \rightarrow e^- N \) Mu2e and Mu2e-II (Middleton, Chislett, Prebys)
  
  • \( \mu^- N \rightarrow e^+ N \) (\( \Delta L = 2 \) process!) at Mu2e and Mu2e-II (MacKenzie)
  
  • General Low Energy Muon Facility (Johnstone)
  
• A large community committed to muon physics over Snowmass period and beyond
What We Want from Snowmass/P5

**Snowmass:**

- Set “requirements”. Collaboration will work on a coherent early-stage design of both beams and detectors
- We would like the Snowmass report to discuss the physics case for a large-scale new muon program at PIP-II and to include this opportunity in the report

**P5:**

- We would like P5 to endorse the physics concept and resources for design studies
Backup
Some Relevant Papers

- Experimental Limiting Factors for the Search of $\mu \rightarrow e\gamma$ at Future Facilities, Renga et al., 1811.12324

- Towards a High Intensity Muon Beam (HiMB) at PSI

- A Phase Rotated Source of Muons (PRISM) for a $\mu \rightarrow e$ Conversion Experiment
  - [https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0-AF5_AF0_J_Pasternak-096.pdf](https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0-AF5_AF0_J_Pasternak-096.pdf)

- Bunch Compressor for the PIP-II Linac
  - [https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF5_AF0-RF5_RF0_Prebys2-203.pdf](https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF5_AF0-RF5_RF0_Prebys2-203.pdf)
Some Relevant Papers (2)

- An Upgraded Low-Energy Muon Facility at Fermilab

- The MEG-II Experiment and its Future Developments
  - [https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0_MEGII-062.pdf](https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0_MEGII-062.pdf)

- Mu2e-II

- A New Experiment for the $\mu \to e\gamma$ Search
  - [https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0_Tassielli-067.pdf](https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0_Tassielli-067.pdf)
Contributions to $\mu e$ Conversion

Supersymmetry

rate $\sim 10^{-15}$

Compositeness

$\Lambda_c \sim 3000$ TeV

Leptoquark

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

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

also see Flavour physics of leptons and dipole moments, arXiv:0801.1826;
R. Bernstein, FNAL

new CLFV Program: RPF Town Hall
Effective Lagrangian

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

“Loops”

Supersymmetry and Heavy Neutrinos

Contributes to \( \mu \to e\gamma \)

(just imagine the photon is real)

“Contact Terms”

New Particles at High Mass Scale (leptoquarks, heavy Z, ...)

Does not produce \( \mu \to e\gamma \)

from André deGouvêa
Simplistic Comparison

\[ \Lambda (\text{TeV}) \]

RPF (muN->eN on Al)<6x10^{-18}

B(\mu->\gamma)<4.2x10^{-14}

MEG-II

B(\mu->\gamma)<4.2x10^{-13}

MEG

Excluded (\mu->\gamma)

SINDRUM-II

Excluded (\muN->eN on Au)<7x10^{-13}

\[ K \]

\[ \text{higher mass scale} \]

All Limits are at 90% CL

after Andre deGouvea

MEG Upgrade

B(\mu->e\gamma)=10^{-12}

B(\mu->e\gamma)=10^{-13}

B(\mu->e\gamma)=10^{-14}

EXCLUDED (90% CL)

RBN, FNAL

new CLFV Program: RPF Town Hall
Mu2e Upgrades and Z-Dependence

- Different Operators have different Z-dependence
- Combine depending on the particular model

5% measurement on Al/Ti needed to see split

Lepton flavor violating mu - e conversion rate for various nuclei
DOI: 10.1088/0954-3899/29/8/401

R. Bernstein, FNAL
Example of Physics Reach

- just one example

\[ R_{\mu \rightarrow e} \]

\[ R_{\mu \rightarrow e\gamma} \]

\[ R_{Au} \]

\[ R_{Al} \]

\[ \sim 1\sigma \text{ band on } \theta_{13} \]

\sim x5 \text{ from Au to Al}

- V. Cirigliano, B. Grinstein, G. Isidori, M. Wise
  
  Nucl.Phys.B728:121-134,2005