New Muon Facility at FNAL

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(for the organizers)
Jan 2022

Over-overview

- Rare and Precision and Accelerator Frontiers have organized a series of “agora”
- We start with four RPF-oriented sessions (physics case):
  - Two on a CLFV muon program; today is the first
  - One on other muon ideas, g-2, muonium-antimuonium, storage ring EDMs
  - One on Accelerator-based DM
- Accelerator Frontier-oriented session
  - discussing the accelerator technology, new machines, etc.

CLFV Muon Program Overview

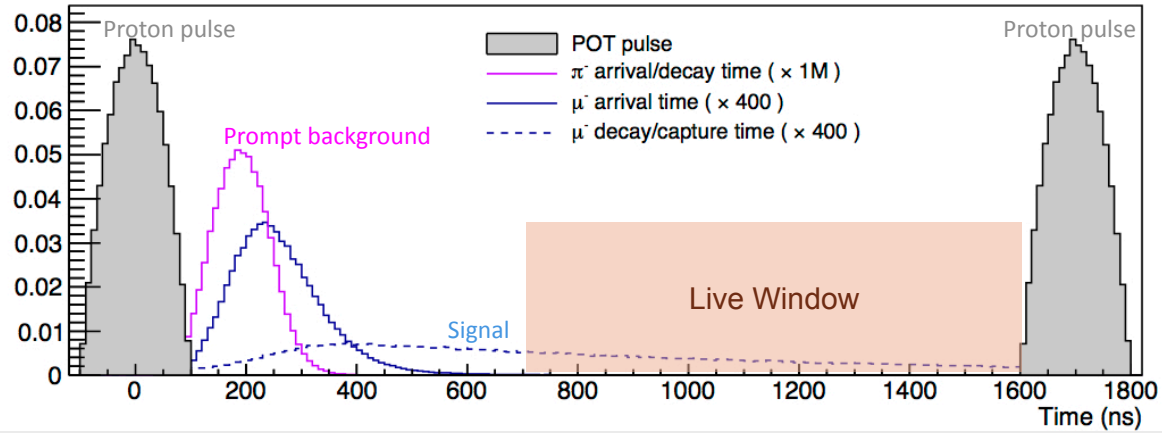
- A single facility that does the major CLFV muon channels
  - $\mu^- N \rightarrow e^- N, \mu^+ \rightarrow e\gamma, \mu^+ \rightarrow 3e$
  - μ^-required for conversion, μ^+ for decay
- Exploits PIP-II and grows with Booster Upgrade
  - Adopt next-generation ideas to reach $\mathcal{O}(10^{-19})$ on Au for muon-to-electron conversion
    - *Z*-dependence is a discriminator among physics models
  - x100 improvement for $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$
- All experiments reaching similar mass range with different physics sensitivities; can pin down new models with multiple measurements

Existing Work on these Ideas

- A lot of thought has already been done:
  - HiMB: https://arxiv.org/pdf/2111.05788.pdf
  - Limiting $\mu \rightarrow e\gamma$: https://www.mdpi.com/2218-1997/5/1/27
  - PRISM/PRIME: https://indico.fnal.gov/event/46669/contributions/203149/attachments/138299/173056/201210_PRISM_sato.pdf
  - Snowmass 2013 on Muon-Electron Conversion: https://arxiv.org/pdf/1307.1168.pdf
  - Potential Muon Campus & Storage Ring Experiments, May 2021, https://indico.fnal.gov/event/48469

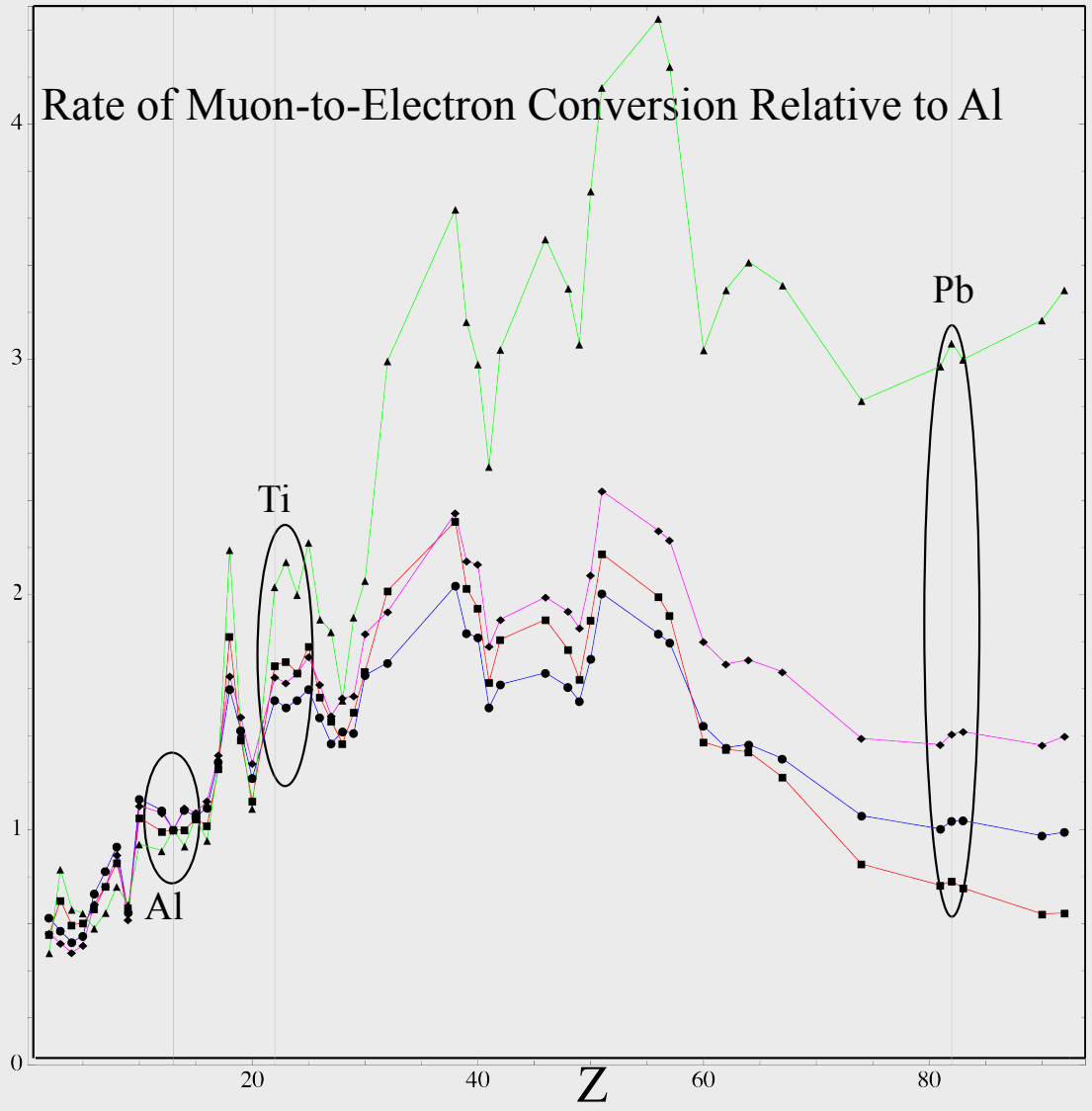
Muon-to-Electron Limitations

- Limit of previous best experiment (SINDRUM-II) was radiative pion capture, $\pi^- N \rightarrow \gamma N^*, \gamma \rightarrow e^+ e^-$
  - PSI beam is almost continuous (20 ns)
  - these π^- also make our μ^- and can't time-separate them in a continuous beam, and therefore can't improve much past SINDRUM-II
  - *pulsed* beam to take advantage of short π^- lifetime



Muon-To-Electron Opportunities

- There is an advantage to using high-Z materials!
- But these have short lifetimes, within the activity from the beam pulse (< 200 ns)
- Can't do an experiment!



Decay Experiments

- MEG-II and Mu3e ($\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$)
  - want as continuous a beam as possible
  - backgrounds from accidentals go as Intensity^2
- Experiments hit limits at $\mathcal{O}(10^{10})\mu^+$/sec (Renga)
  - can obtain few 10^9 at PSI with HiMB (Kiselev)
  - can get $> 10^{10}$/sec at PIP-II

Best of Both Worlds: Muon Storage Ring

- Conversion Experiments:
  - If we could make a pure muon beam with a storage ring, and hold them until pions decay, then we could
    - eliminate radiative pion capture
    - eliminate beam pulse activity
    - allowing us to look at much higher intensities at high *Z*
- Decay Experiments: use same rings and choose time structure
- *Single community of > 400 physicists for FNAL Muon Campus*

Three Ingredients

- We need a compressor ring to rebunch PIP-II beam to give us the right time structure (Prebys)
- Mu2e solenoid is at 8 kW; Mu2e-II at 100 kW. We need to go up and target primary beam in a solenoid at higher beam power (Lynch)
- We need a small muon storage ring (FFA, Pasternak) to
  - hold muons and let pions decay
  - make a pure, cold muon beam to look at high *Z*

1 MW target in a Solenoid

- We know how to build 1 MW targets (neutrino program)
  - We have thought about horn beams (NuSTORM)
- But 1MW in a superconducting solenoid presents unique challenges
  - *needed for muon collider*
    - this program could be a test bed/existence proof

Intermediate Plans

- FFA will produce pure cold muon beams of either sign for either conversion or decay experiments
  - Current design will alternate μ^+ and μ^- experiments
    - is it possible to use FFA for μ^+ and μ^- at once? then could run decay experiments and conversion experiments in same calendar period.
    - 10^{10} useful muons/sec can be obtained; MEG technique limited there by accidentals in any known method
- Initial design at 1MW limited by power deposition into superconducting solenoids (requires R&D!)
  - FFA at 100 kW (x10 Mu2e) still groundbreaking since we can use high-*Z* targets

Experiment Issues

- Decay Experiments: (Renga)
  - in $\mu \rightarrow e\gamma$ the next step may be to convert the photon for forming a vertex and tracking, vs. calorimetric γ measurement in MEG/MEG-II
    - lose rate since you need a thin converter
    - but PIP-II/Booster upgrades can provide more than 10^{10} useful muons/sec and that makes up for the loss
    - will learn about PSI HiMB program
  - in $\mu \rightarrow 3e$ we may be able to combine with $\mu \rightarrow e\gamma$ if we are tracking three e^+/e^-

Experiment Issues

- Conversion Experiments (Echenard)
  - with an FFA, remove beam backgrounds and radiative pion backgrounds that inspired Mu2e technique
  - decay-in-orbit backgrounds require better detector resolution
  - dominant background will be cosmic-ray induced events, which can be controlled with veto and overburden (and much better than in Mu2e)

CLFV Muon Plan

- We have written a Snowmass LOI
  - https://www.dropbox.com/s/36b3gzfnkukcqgg/clfvLOI.pdf?dl=0
- Will turn this into a white paper
- Goal is to have P5 say that this facility should be part of the US program and R&D for design should be funded

Summary

- CLFV is one part of an extensive, world-class muon program
- These are kickoff talks to stimulate discussion and explore options
- CLFV and other muon experiments along with DM fit together in a coherent program
- And Accelerator Frontier will have a summary session on the machine issues