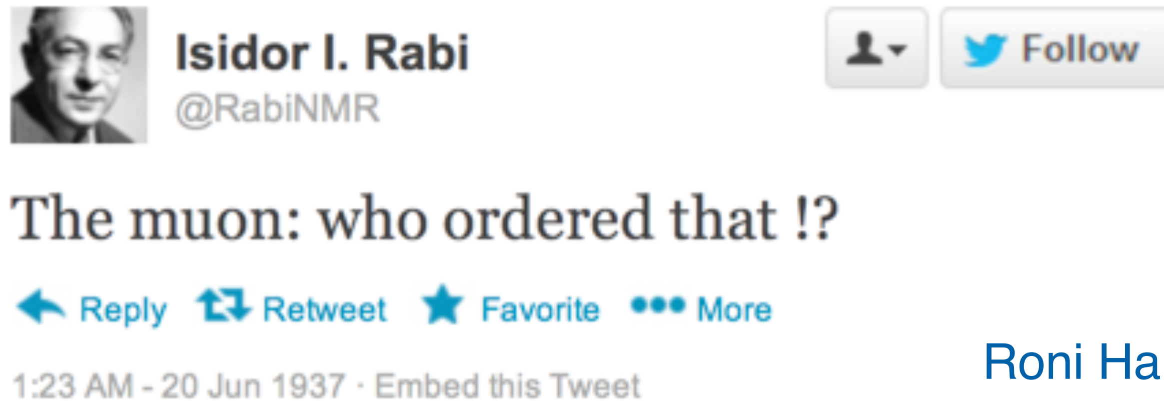
Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Experimental Issues for future muon CLFV experiments

Robert Bernstein
Muons in Minneapolis
Dec 2023

much of this talk is just stolen from Caltech workshop:
https://indico.fnal.gov/event/57834 and thanks to Echenard, Renga and others

Why is Muon CLFV Interesting?



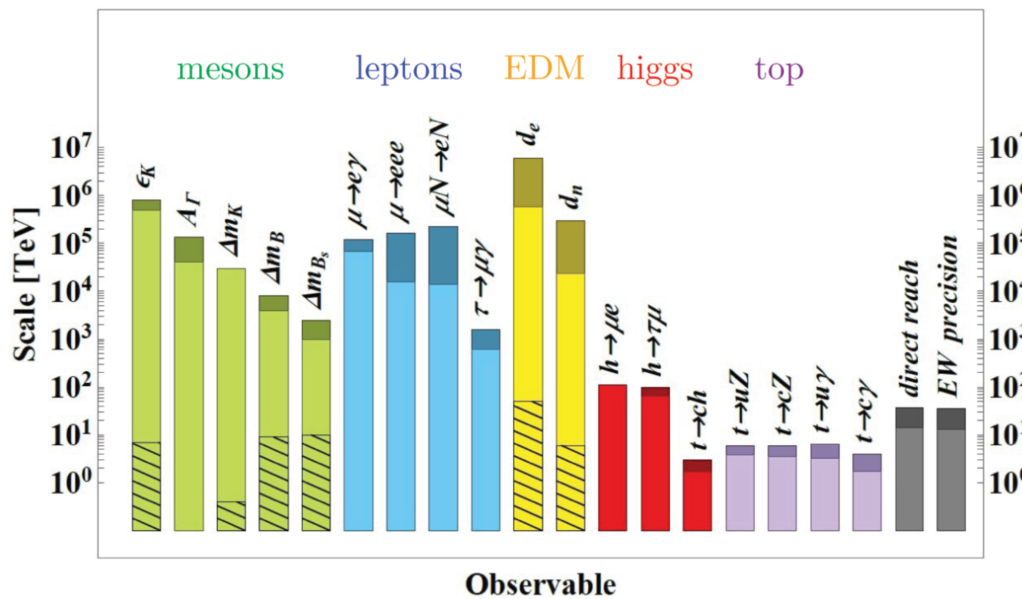
Roni Harnik

- Why are there lepton (or any) flavors?

- Muon Charged Lepton Flavor Violation (CLFV) probes mass scales $\geq 10^5$ TeV

- Can study $\Delta L = 2$ processes such as $\mu^- N \to e^+ N'$: related to Dirac/ Majorana neutrino mass

- Muonium-antimuonium oscillations



operator coefficients =1,
Physics Briefing Book, 1910.11775

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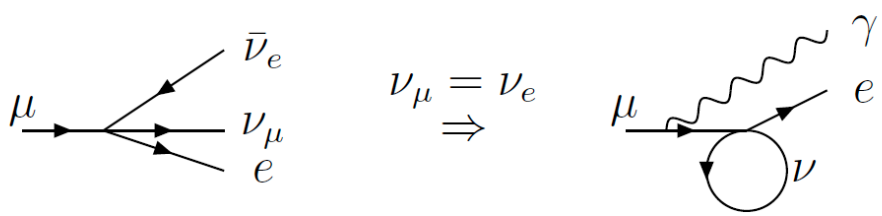
CLFV, Muons, and Neutrinos

- After the μ was discovered, it was logical to think the μ is just an excited electron:
  - expect BR($\mu \to e\gamma$) $\approx 10^{-4}$
  - Unless another ν, in Intermediate Vector Boson Loop, cancels (Feinberg, 1958)
    - ➡ same as GIM mechanism!



[1]Unless we are willing to give up the 2-component neutrino theory, we know that $\mu \to e + \nu + \bar{\nu}$.

CLFV Muon Processes

- $\mu^+ \to e^+\gamma$
  - most powerful limits, and the best experiments so far: MEG and MEG-II at PSI
  - exploit two-body kinematics to identify a signal
  - proceeds through loops
- $\mu^+ \to 3e$
  - Mu3e experiment at PSI
  - look for $3e$ at muon mass
- $\mu^- N \to e^- N$
  - Mu2e, Mu2e-II at FNAL, and COMET at J-PARC
  - signal is a mono-energetic electron at just under the muon mass

like many other indirect studies:
any of these would be an unambiguous signal of new physics; comparing channels pins down the source

Knapen, but other physics

μ^+ is preferred for the decay experiments, since you can stop the muons in material without nuclear capture

need to produce both $\mu^\pm$

Perrevoort

μ^- is required for the capture experiments

Heller, Kuno

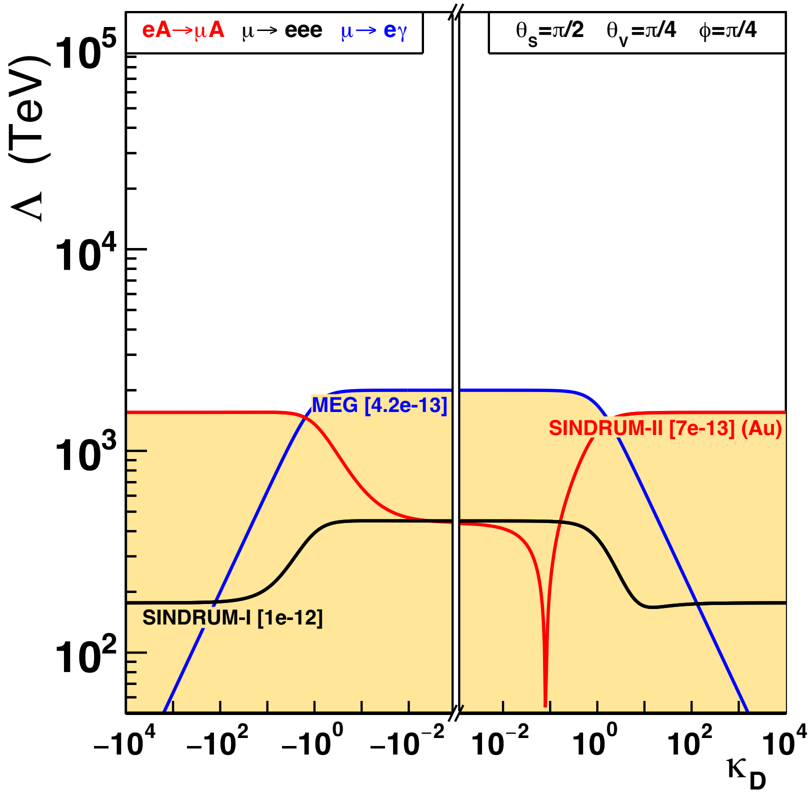
Upcoming Muon CLFV Experiments

- $\mu^+ \to e^+\gamma$ (PSI)
  - MEG II, finished first run
  - BR $(\mu^+ \to e^+\gamma) < 3.1 \times 10^{-13}$ @ 90% CL (*Afanaciev et al., 2310.12614*)
  - expect $\approx 4.2 \times 10^{-14}$ after a few years
- $\mu^+ \to 3e$ (PSI)
  - Mu3e experiment (*Hesketh et al., 2204.00001*)
  - SES of 2×10^{-15}
- $\mu^- N \to e^- N$ (FNAL, J-PARC)
  - Mu2e, COMET (*Edmonds, Tang CLFV Heidelberg*)
  - both $\approx (6-8) \times 10^{-17}$ @ 90% CL around end of decade

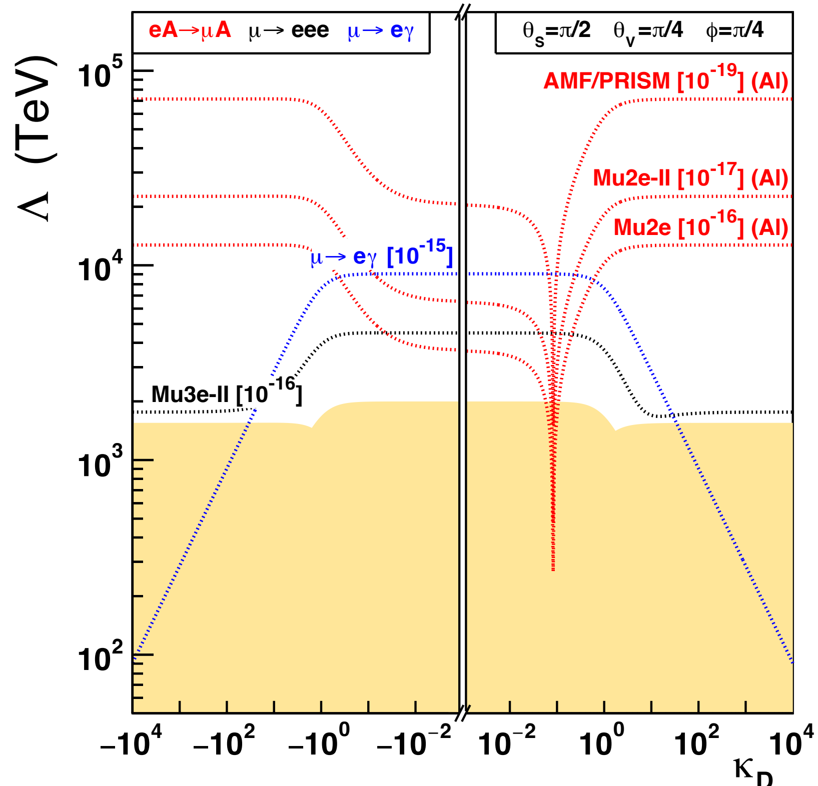
What are the Target Sensitivities for Next-Generation Studies?

S. Davidson and B. Echenard, 2010.00317 [hep-ph]

Today



Future



In an EFT Lagrangian we can define κ_D arising from “loop” vs. “contact” terms; Λ is the new physics mass scale

Goals:

- **improve discovery potential for muon-electron conversion by at least x10 over Mu2e/COMET (Mu2e/COMET are 10^4): mass scales at 10^5 TeV**
- **make corresponding improvements in $\mu \to e\gamma$ and $\mu \to 3e$**

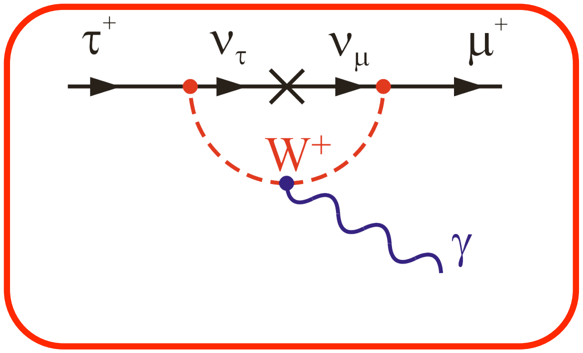
Echenard

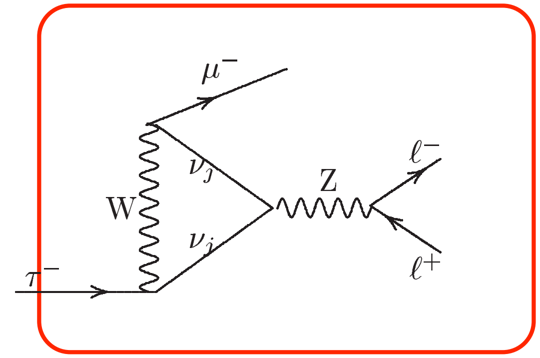
CLFV in τ Decays

- τ sector

τ processes also suppressed in Standard Model but less:

Lee, Shrock
Phys.Rev.D16:1444,1977





Pham, hep-ph/9810484

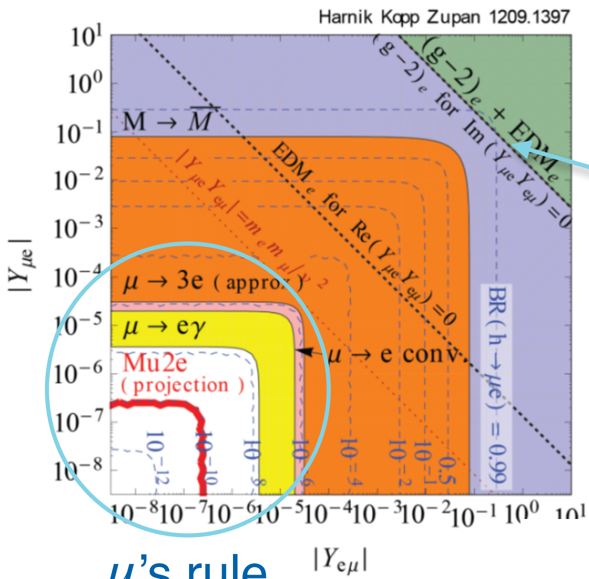
Good News:
Beyond SM rates can be orders of magnitude larger than in associated muon decays

Bad News:
τ's hard to produce: ~10^{10} τ/*yr* vs >10^{11} μ/*sec* in upcoming muon experiments

- Rough analogy to neutrinos: muon CLFV is "θ_{12}" ; anything involving the τ is in the θ_{13} or θ_{23} sector
- Colliders can also probe CLFV-violating Higgs decays

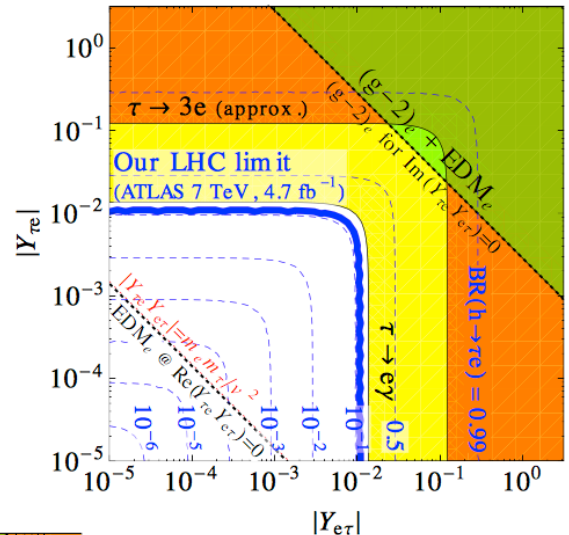
CLFV in Higgs Decays

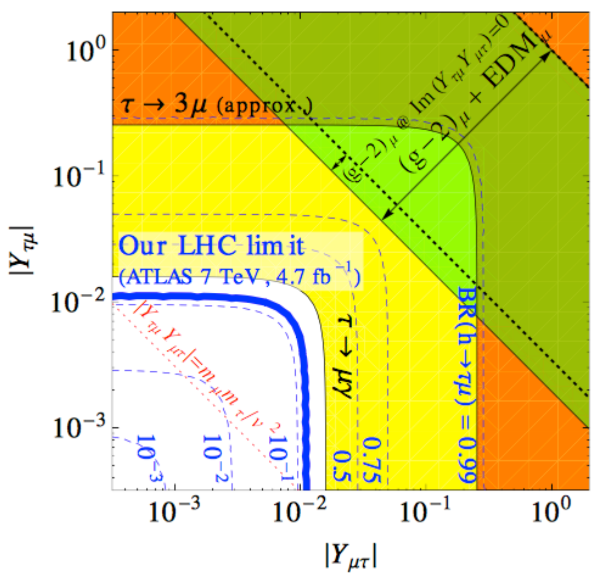
- Muon CLFV dominates in $e - \mu$ sector once again: 7-8 orders of magnitude



collider direct

μ's rule





we say nothing in τ processes

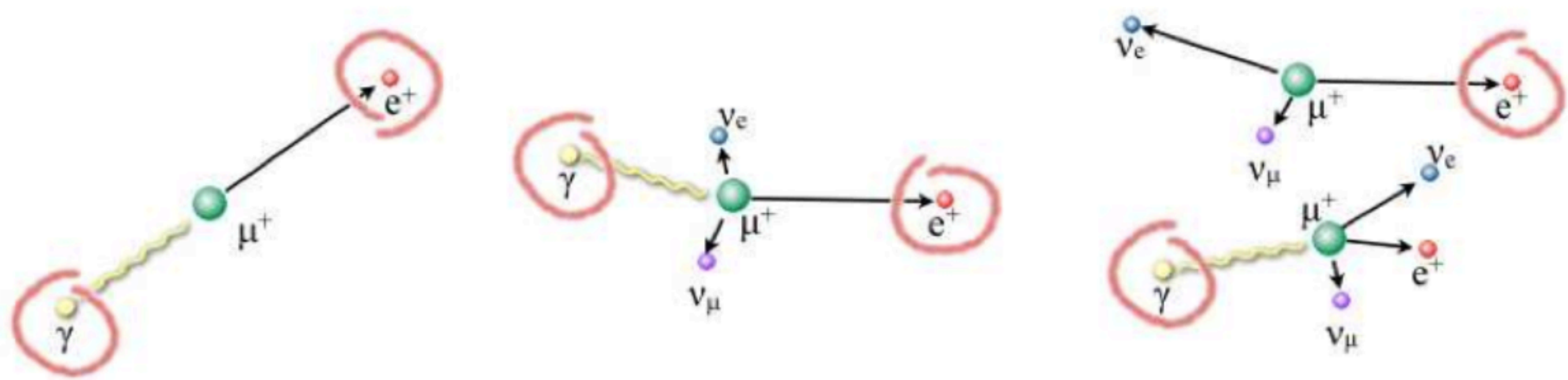
Upcoming Accelerator Improvements

- PSI:
  - HiMB: $\sim 10^{10}\mu$/sec, about x10 improvement *Papa, Muons4Future and here*
    - this will provide 3-10 x more beam for MEG and Mu3e
- FNAL
  - PIP-II can easily provide x10 for Mu2e @ 800 MeV–4 GeV (energy important later)
- J-PARC
  - 2nd target station, similar rate to HiMB (*Yamazaki, Muons4Future*) for surface muon beam
- And then AMF: *Echenard, this conf.*

What might be the next generation of experiments?

- Here we need to look at the experiments themselves: can they take advantage of the accelerator improvements?
- Can we use current designs with improvements in capability, or do we need a phase change?
- My opinion:
  - Mu3e is an evolution/completion of current design
  - Mu2e/COMET have an intermediate stage at PIP-II, but a phase change beyond that
  - MEG needs a phase change
- Let’s examine experiments

$\mu \to e\gamma$: MEG (MEG II, …)



Signal	Radiative Muon Decay	Accidentals
$E_\gamma = 52.8$ MeV	$E_\gamma < 52.8$ MeV[1]	$E_\gamma < 52.8$ MeV
$E_{e^+} = 52.8$ MeV	$E_{e^+} < 52.8$ MeV[1]	$E_{e^+} < 52.8$ MeV
$\Theta_{e\gamma} = 180°$	$\Theta_{e\gamma} < 180°$[1]	$\Theta_{e\gamma} < 180°$
$T_{e\gamma} = 0$ s	$T_{e\gamma} = 0$ s	$T_{e\gamma} \Rightarrow$ flat

Signal

Radiative Muon Decay
$\sim 0.1 \times B_{acc}$

Accidentals:
Dominant background:
RMD+Michel

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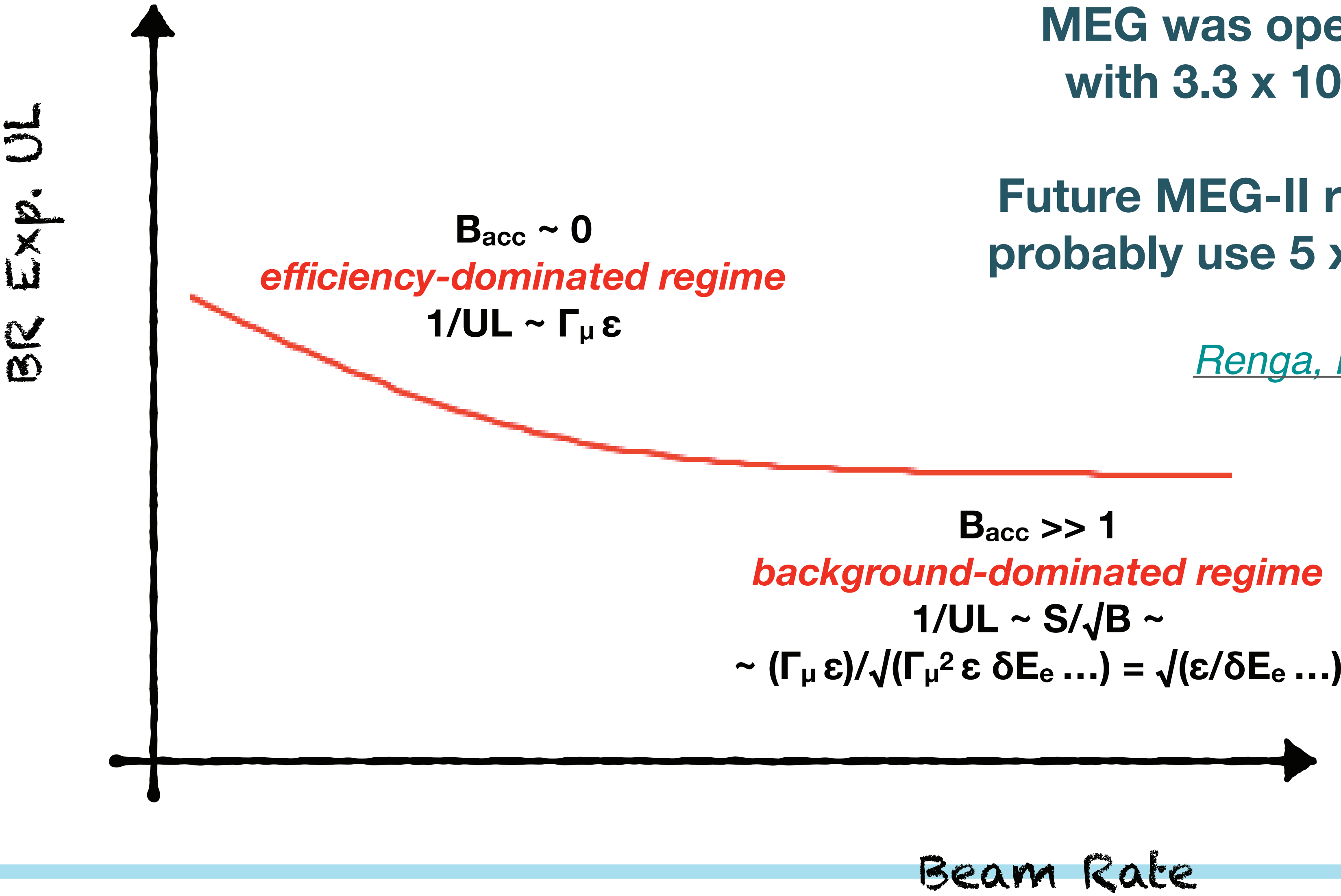
Dependences of MEG Background

$$\mathscr{B} \propto R_\mu^2 \times \Delta t_{e\gamma} \times \frac{\Delta E_e}{m_\mu/2} \times \left(\frac{\Delta E_\gamma}{15m_\mu/2}\right)^2 \times \left(\frac{\Delta\theta_{e\gamma}}{2}\right)^2$$

- The terms are the muon stop rate divided by the beam duty factor multiplied by the detector time resolution, the positron energy resolution, the photon energy resolution, and the angular resolution factors.
- The time difference between any two stops is essentially random, hence the $\Delta t_{e\gamma}$ term and the R_μ/D dependences.
- The Michel spectrum is $\Gamma(\epsilon)\,d\epsilon \propto (3-2\epsilon)\epsilon^2\,d\epsilon$, where $\epsilon = 2E_e/m_\mu$. Near $\epsilon = 1$ at the maximum the derivative is zero. Hence the $\Delta E_e/(m_\mu/2)$
- The radiative decay $\mu \to e\nu\nu\gamma$ near the zero-energy neutrino edge is a bremsstrahlung term that behaves as$(1-y)\,dy$ where $y = 2E_\gamma/m_\mu$. Hence the background under the $\mu \to e\gamma$ peak is proportional to the integral over the resolution window of width Δ, or $\int_{(1-\Delta)}^{1}(1-y)\,dy$ which is just proportional to Δ^2
- Since the direction of the photon is opposite to the direction of the electron, the area of the angular phase space is a small patch of area $\Delta\theta_{e\gamma}\Delta\phi_{e\gamma}$, yielding a quadratic dependence in angular resolution.

Why Do You Care About This?

- Current MEG-II would see background at HiMB intensities; and certainly at the even higher intensities of AMF
-



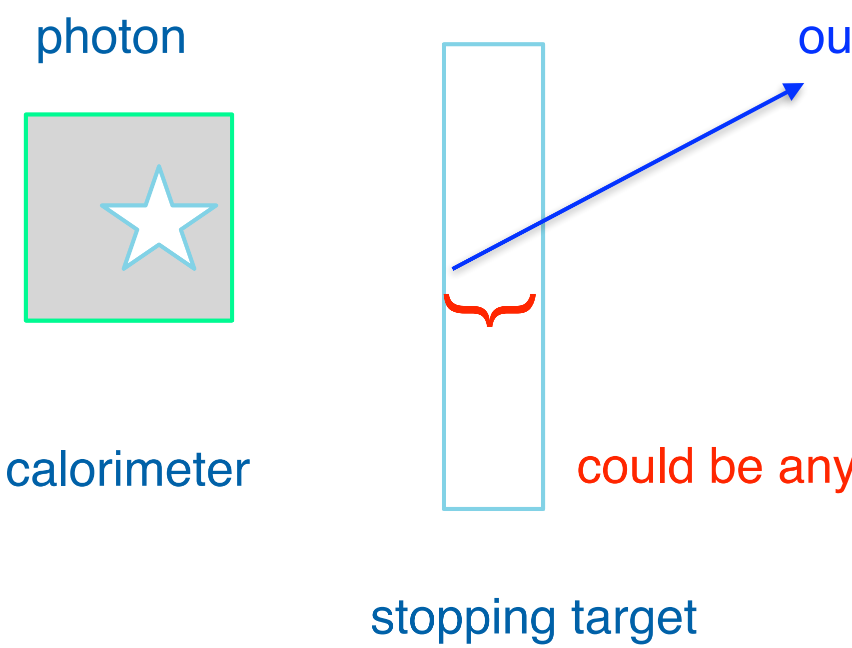
MEG was operated with 3.3 x 10^7 μ/s

Future MEG-II runs will probably use 5 x 10^7 μ/s

Renga, Muons4Future

$\mu \to e\gamma$: What Experimental Ideas Are There?

- $\mu \to e\gamma$ searches have gone back and forth between converting the photon
  - conversion has a big advantage: $\mu \to e\gamma \to e^+(e^-e^+)$ and three tracks make a vertex
  - as opposed to a back-to-back photon/electron pair



where's the vertex inside the stopping target?
can't calculate $\Delta\theta$ without it and
background is quadratically dependent

the photon is just a space point in the calorimeter;
where the μ^+ stopped is not known

$\mu \to e\gamma$: To Convert or Not to Convert

- Rate can make reconstruction of tracks difficult
  - this was the central problem of MEGA (LANL)

- MEG and MEG-II are much higher rate and did not convert

- But you lose ~x100 from converting

  - want a thin converter to minimize multiple scattering and energy loss
  - have to trade rate vs. resolution

- My uninformed opinion:
  - next generation of experiments should take advantage of PIP-II rates and convert the photon. Many of the players have thought about this but completely depends on the machine and rates and experimental details.

Systematic Study: Renga et al.

History: RHB and PS Cooper

one idea: Echenard et al.

$\mu \to e\gamma$: More Experimental Issues: Tracking

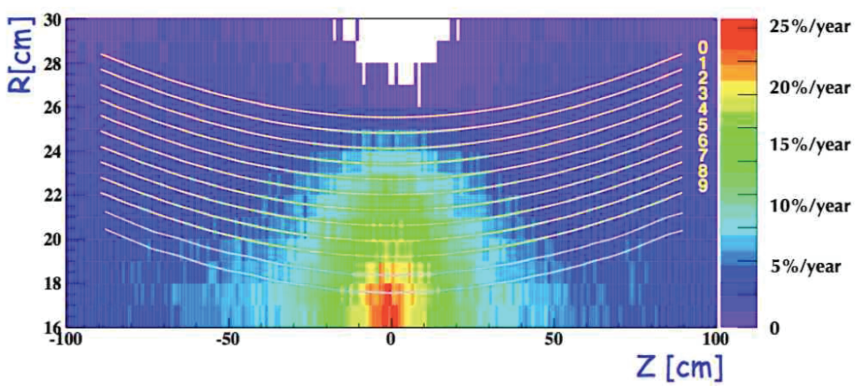
- Not the purpose of this meeting to discuss details, but just to tell you the issues

- Can't help showing you some of the ideas to demonstrate how interesting this is

- Tracking:
  - gaseous detectors?
    aging and pattern recognition at high rates
  - Silicon detectors? 25μm HV maps
  - Multiple scattering before the detector
    is a limiting factor (4 mead from target, gas, detector walls)

Expected aging (gain loss) in MEG II

A. Baldini et al., arXiv:1301:7225



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$\mu \to e\gamma$: More Experimental Issues: Photon

- Do we continue to use photon calorimetry?
  - MEG's LXe could not get a photon resolution much better than 1 MeV, and this is not understood (2310.11902)
  - Crystals like $LaBr_3(Ce)$ (Brilliance) might give 800 keV, but are very expensive
    - but 30 ps timing not out of the question

- Conversion: since momentum in a tracker is better measured than energy in a calorimeter
  - arrangement of converters? Several rings of converters vs. just one?
  - this idea has been around a while: 2021 Snowmass Echenard et al.
  - Do we make an *active converter?*

Ootani at Caltech Workshop

- MEG-II collaborators are discussing what to do at HiMB

$\mu^- N \rightarrow e^- N$: Mu2e, COMET, and beyond

- To anyone outside Mu2e and COMET they're the same
  - both based on Lobashev's idea

V. Lobashev, MELC 1992:

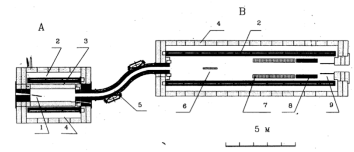


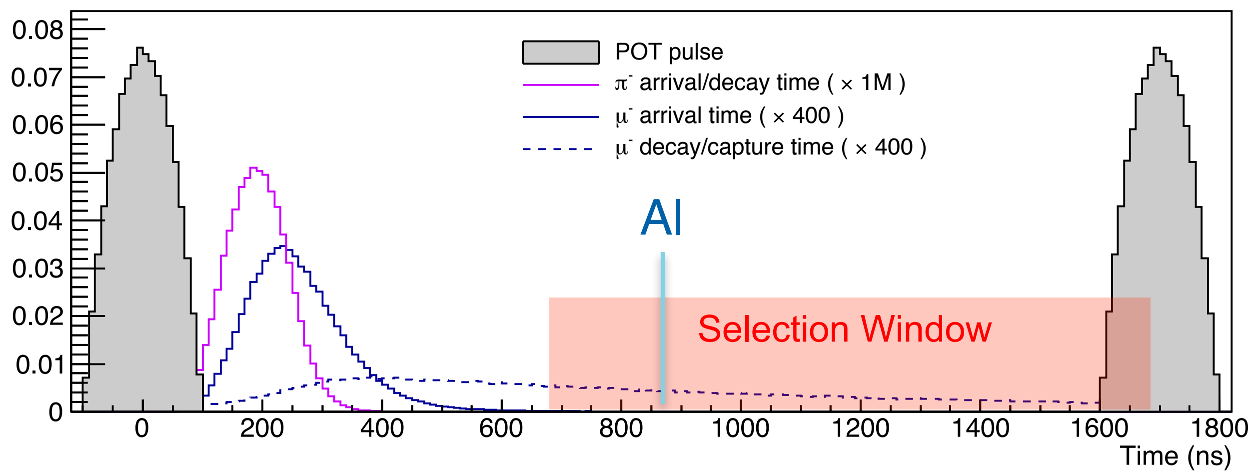
Fig. 1. Set-up MELC: A – meson-production part, B – detector part.
1 – tungsten target of the meson-production part (T_1),
2 – big superconducting solenoids, 3 – protection of the solenoid against radiation,
4 – steel magnetic circuit, 5 – solenoid-collimator,
6 – aluminium-target of the detector part (T_2),
7 – coordinate detector,
8 – total absorption scintillation spectrometer,
9 – protection of the detector against background.

- The beam design is driven by a simple problem:
  - the same $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$ that make our muons leave some un-decayed π^-
  - then radiative pion capture (RPC): $\pi^- N \rightarrow \gamma N^*, \gamma \rightarrow e^+ e^-$ (either internal or external conversion, external in the same material used to stop the muons) and sometimes that e^- is at the conversion energy.
  - *pulsed beam:* well-defined pulse, take advantage of π lifetime to let them decay before opening measurement window
    - make sure beam has no "leakage": extinction at 10^{-10}

$\mu^- N \to e^- N$: Time Structure

- Mu2e structure (COMET basically identical)

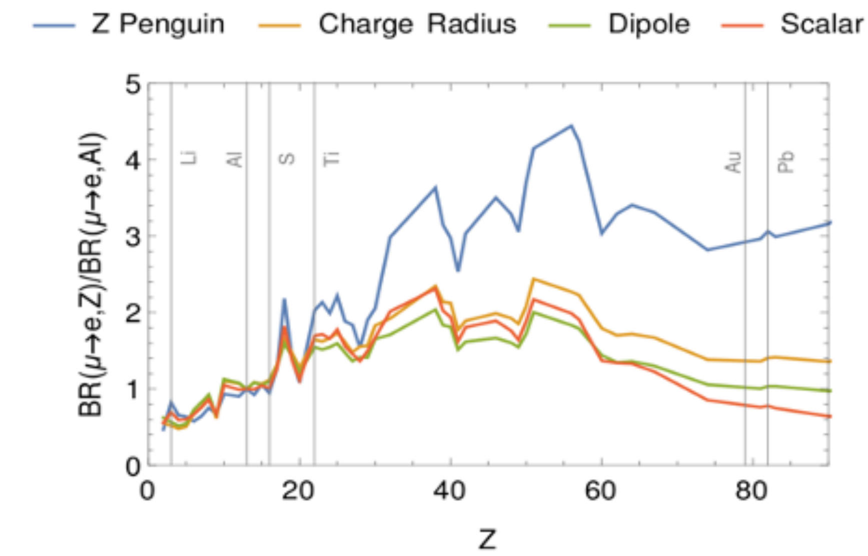
- Beam pulse: proton beam hits target of material *N:*
  - first, an enormous flash of e^- from $pN \to \pi^0$s, $\pi^0 \to \gamma\gamma \to e^-$'s over first few hundred ns that overwhelms detector
  - then wait ≈ 700 ns for π^-s to decay away (about 10^{-11})
  - nicely matched for Aluminum; $\tau^{\mu}_{\rm Al} = 864$ ns



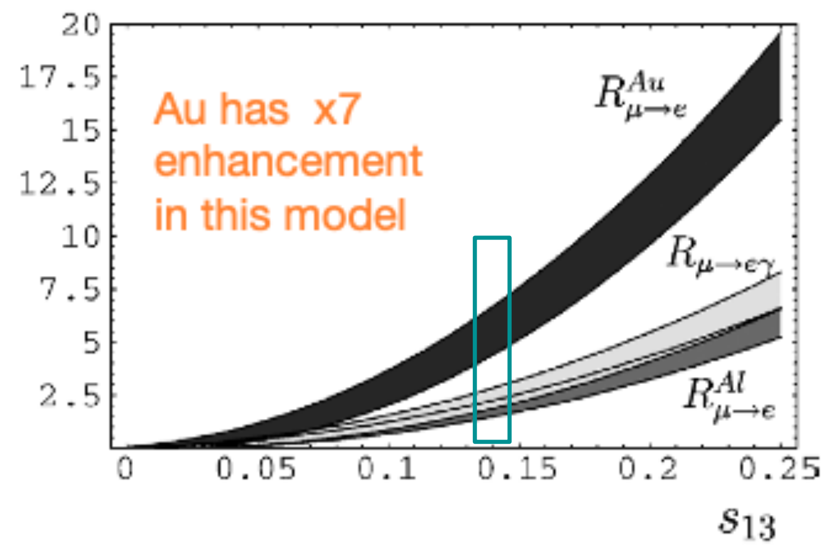
$\mu^- N \to e^- N$: limitation of Lobashev Technique

- Bertrand will tell you high Z is the next step

PDG



Kitano et al. 2002 hep-ph/0203110v4



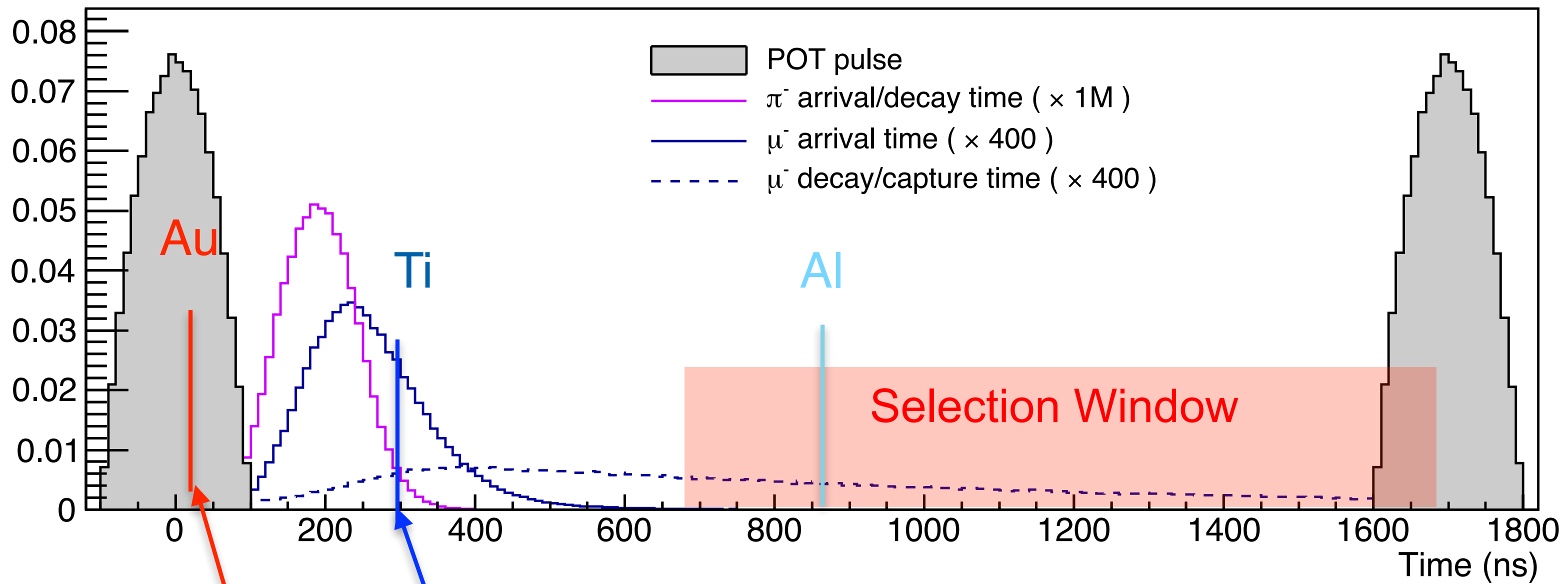
V. Cirigliano, B. Grinstein, G. Isidori, M. Wise **Nucl.Phys.B728:121-134,2005**

charged lepton flavor violation
and
neutral lepton flavor violation
(aka neutrino oscillations)
may well be linked
Teixera: 1612.06194

- we want to go to high Z;
  - Ti is about x1.7 Al, 5% measurement if we see a signal

$\mu^- N \rightarrow e^- N$: what's the problem with the Lobashev Technique?

- Can't go to very high Z



we can't look for a ~100 MeV electron in this beam flash

this should work; both Mu2e and COMET wanted experience with Al first; either Mu2e or Mu2e-II

$\mu^- N \to e^- N$: Next step, Mu2e-II at ~ 100 KW

- FNAL's PIP-II will provide something like 800 MeV protons
  - anywhere between 800 MeV - 4 GeV, precise value not important but best ~ 3 GeV
  - at easily x10 the intensity of Mu2e's 8 kW!! or if COMET can do 56 kW, then PIP-II can provide x10 COMET. PIP-II yields a firehose of muons…

- This eliminates an unpleasant background

  Sellner et al.

  - antiprotons evade extinction ($\tau_{\bar{p}} > 10.2$ sec 90% CL, or use CPT!)
  - $\bar{p}$ that make it to the Al stopping target annihilate and make lots of π^os which then make e^- in the signal region.
    - We can try to look for other signs of activity (2 GeV in annihilation makes lots of byproducts vs 105 MeV muon)
    - but it's better to eliminate the background altogether

- Eliminates by kinematics: suppose a $\bar{p}$ hits a nucleus:
  - $\bar{p}p \to (\bar{p}p) + p$ just kicking out the proton is the best you can do
  - E/p conservation threshold at 5.1 GeV, more like 4.1 GeV with Fermi motion
  - Mu2e at 8 GeV; PIP-II below threshold

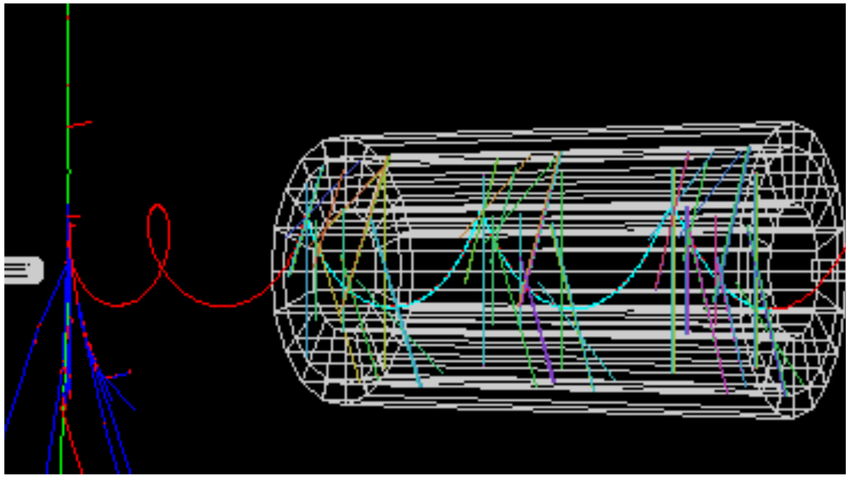
$\mu^- N \rightarrow e^- N$: What do we need for Mu2e-II?

- Mu2e's radiatively cooled target can't take x10 more beam

Rogers on High-brightness beams

- Existing Production Solenoid may not work
  - several issues:
    - shielding of superconductor needs to be greatly improved;
    - beam path at 800 MeV inside production solenoid is different; spent proton beam will exit in different place, different exit in solenoid, different dump,…

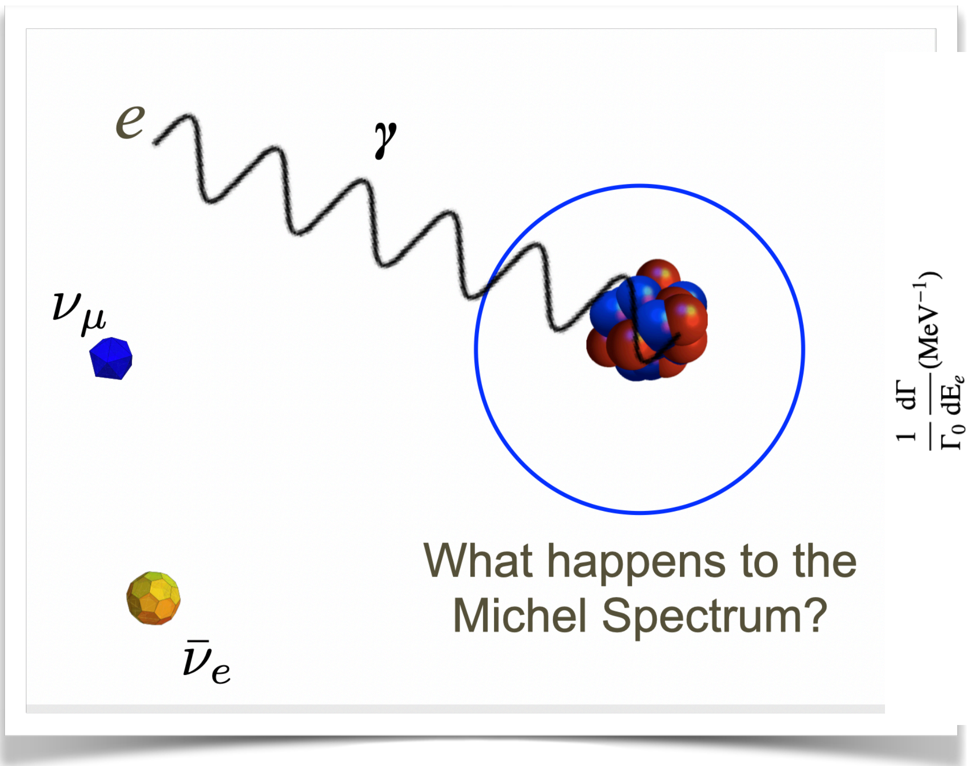
- Shielding of Cosmic Ray Veto (CRV):
  - protons on target basically make neutrons and pions
  - neutrons get to CRV and deaden it
  - Cosmics are a problem: ~1/day



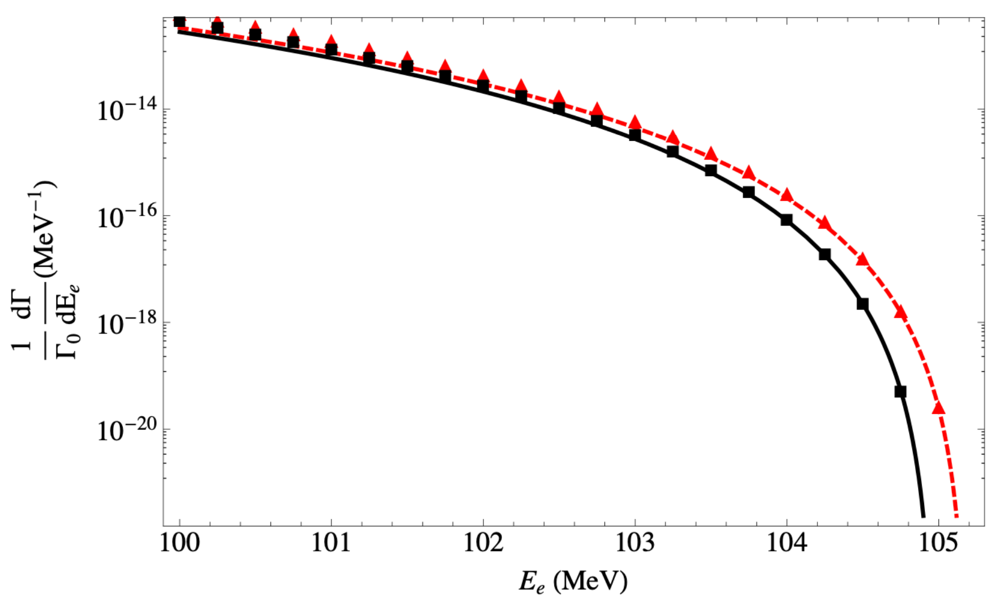
$\mu^- N \to e^- N$: Detector Issues

- And all our backgrounds just got x10 worse
- DIO: muons in atomic orbit that Michel decay in atomic orbit

- $\mu^- \to e^- \nu \bar{\nu}$; outgoing electron recoils
  - jump to neutrino rest frame and ignore neutrino mass: spectrum extends to conversion energy since you see outgoing electron, recoiling nucleus, and nothing else
  -



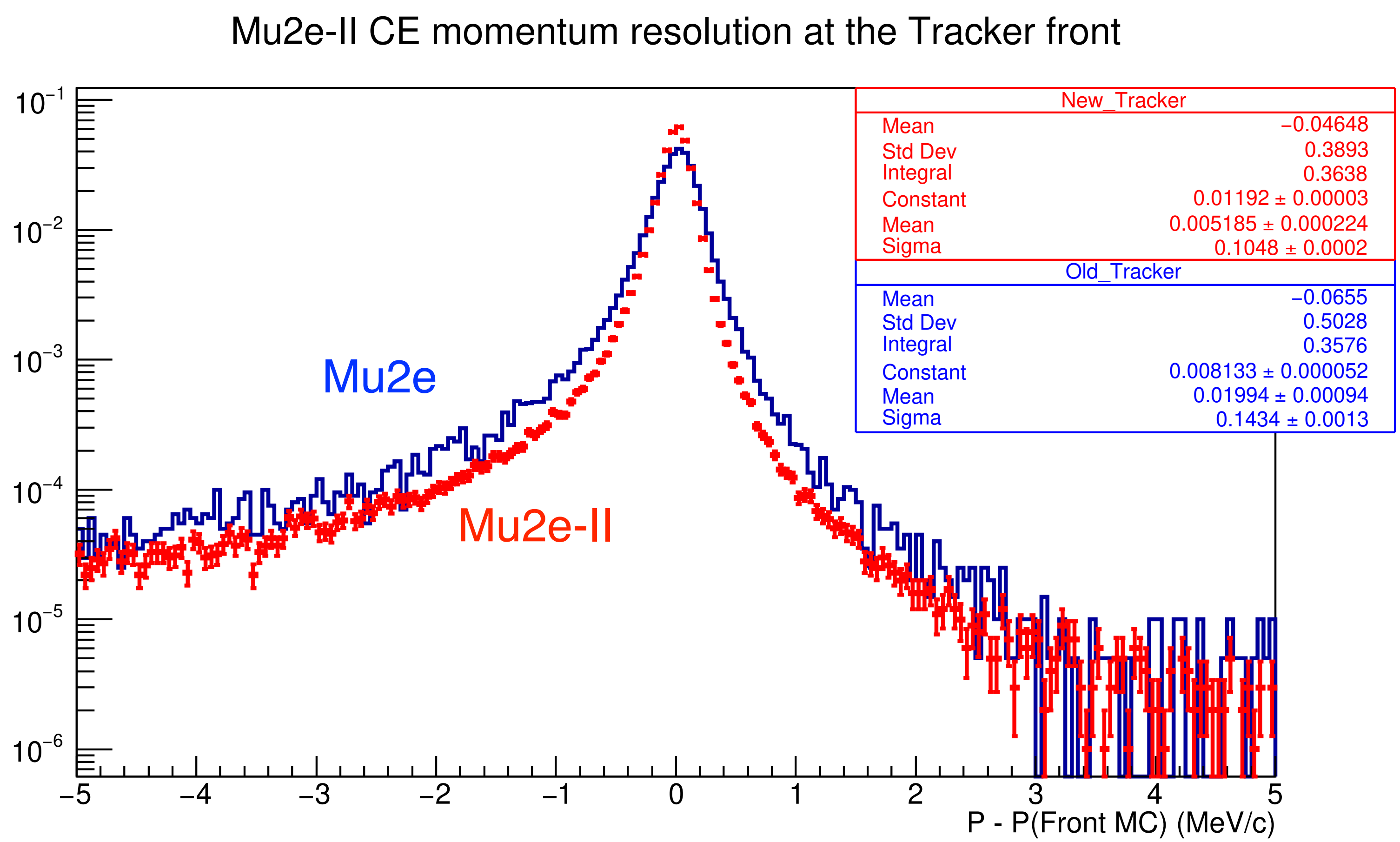
- with nuclear recoil, Czarnecki et al.



Mu2e-II: Detectors and Expectations

Byrum et al. 2203.07569

- Thinner straws (15 μ down to 8 μ).
  - this is already difficult. Minneapolis is world-expert on 15 μ straw construction!!
  - But this is not enough, many other improvements minimizing material



Mu2e-II Expectations

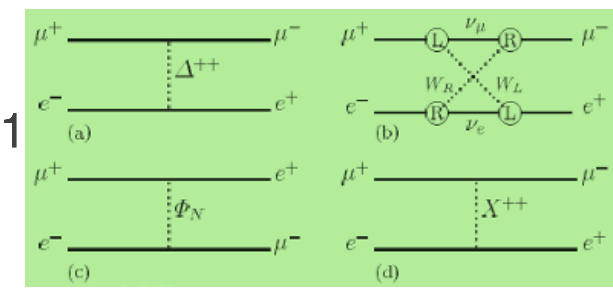
Results	Mu2e	Mu2e-II (5-year)
Backgrounds		
DIO	0.144	0.263
Cosmics	0.209	0.171
RPC (in-time)	0.009	0.033
RPC (out-of-time)	0.016	< 0.0057
RMC	< 0.004	< 0.02
Antiprotons	0.040	0.000
Decays in flight	< 0.004	< 0.011
Beam electrons	0.0002	< 0.006
Total	0.41	0.47
N(muon stops)	6.7×10^{18}	5.5×10^{19}
SES	3.01×10^{-17}	3.25×10^{-18}
$R_{\mu e}$(discovery)	1.89×10^{-16}	2.34×10^{-17}
$R_{\mu e}$(90% CL)	6.01×10^{-17}	6.39×10^{-18}

Three Things I didn't talk about

- Light neutral particles
  - $\mu^+, \pi^+ \to e^+ X$ *Hill et al., 2310.00043, Zupan this conf.*
    - come for free as calibration runs in Mu2e or COMET Stage I
    - under experimental study in Mu2e. Thesis by *Shihua Huang, Purdue*

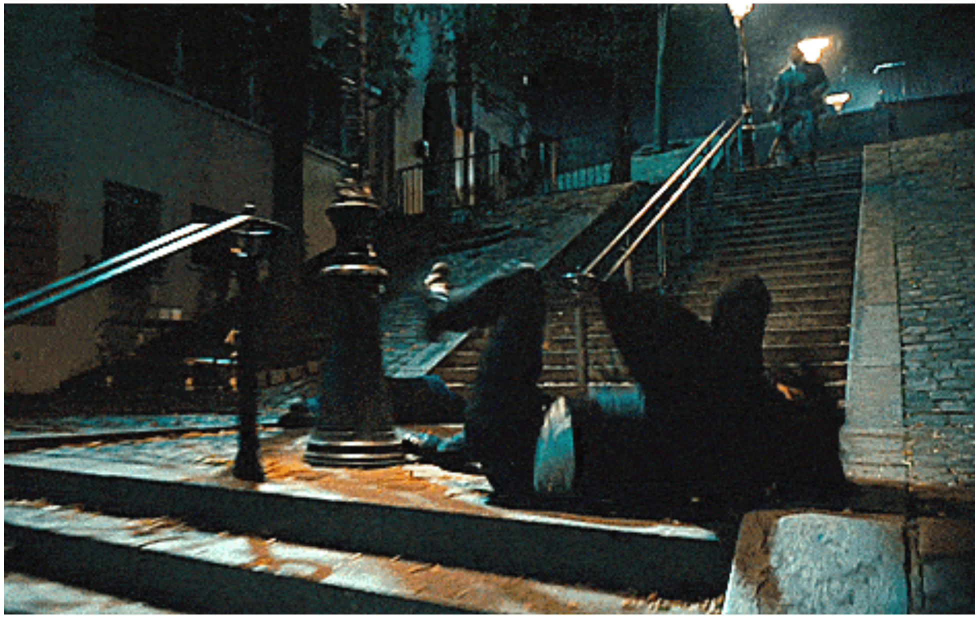
- $\Delta L = 2 \; \mu^- N \to e^+ N^*$
  - at Mu2e (simultaneous) or COMET Stage 1; special run at Stage II
  - by black-box *Schechter-Valle* theorem, implies Majorana neutrino mass
  - possibly about the same 10^4 improvement as muon-electron conversion
    - some tricky backgrounds and calculation of the radiative muon decay background spectrum $\mu^- N \to \gamma N^*, \gamma \to e^+ e^-$ needs improvement. It's hard, tedious, and not flashy.

- Muonium-Antimuonium doubly CLFV $\mu^- e^+ \to \mu^+ e^-$
  - MACE in China (*Bai et al. 2203.11406*)
  - also Japan https://journals.jps.jp/doi/10.7566/JPSCP.33.0111
  - can do this in muon complex at PIP-II
  - most experimenters think it's relatively straightforward to improve x100 with modern technology to $\sim 10^{-5} G/G_F$



Summary

- All these experiments are going to break new ground
- They complement each other
- We are all already thinking about the next generations
  - suspect qualitative changes will be needed to exploit accelerator improvements
  - if any of us see a signal we *have* to do all these channels!



experimenter vs DOE,
other funding agencies,
P5, etc.:
persistence is required!

Questions?

- Ask Jure…