A New Muon Program at Fermilab

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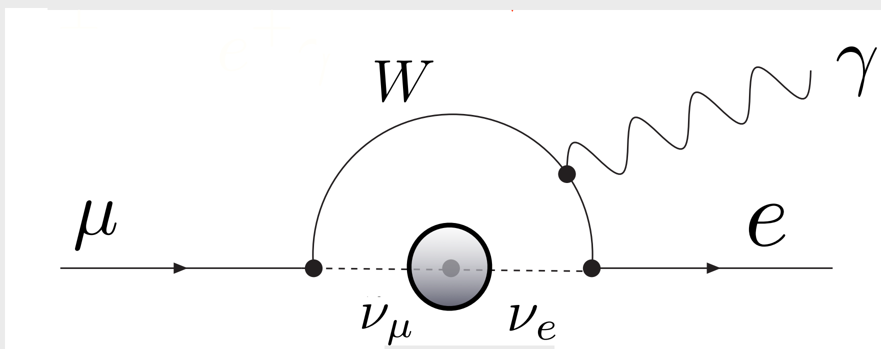
FNAL
Snowmass RPF5, 2021

Charged Lepton Flavor Violation

- Transitions among $\mu \leftrightarrow e \leftrightarrow \tau$ without neutrinos
  - cannot be weak interaction: non-SM process
- Directly linked to questions of flavor and generations
  - we observe mixing in quarks and neutral leptons: why not charged?
- Muon CLFV has been under study since the discovery of the muon; taus are also important

Neutrino Oscillations and Muon-Electron Conversion

- ν's have mass! *individual lepton numbers are not conserved*
- Therefore Lepton Flavor Violation occurs in Charged Leptons as well

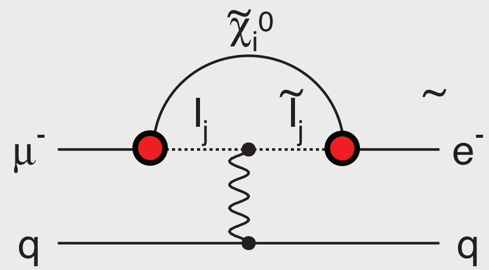


$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

Contributions to Muon CLFV

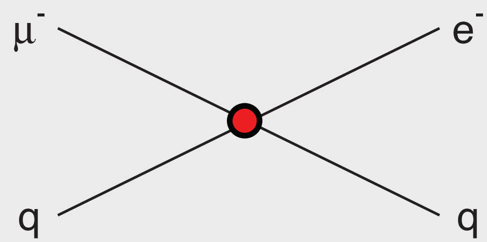
Supersymmetry

rate ~ 10^{-15}



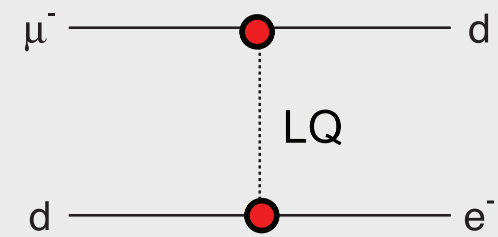
Compositeness

Λ_c ~ 3000 TeV



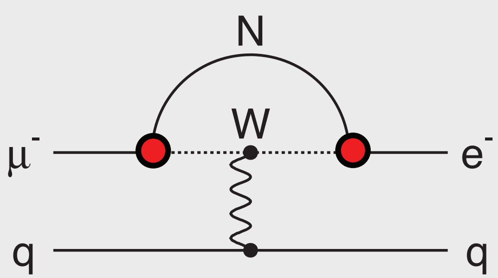
Leptoquark

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



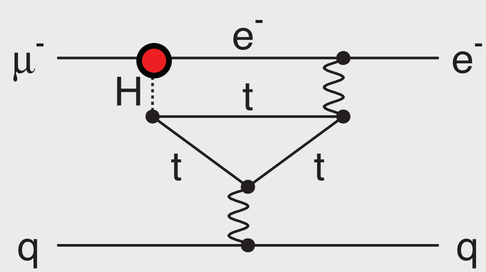
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



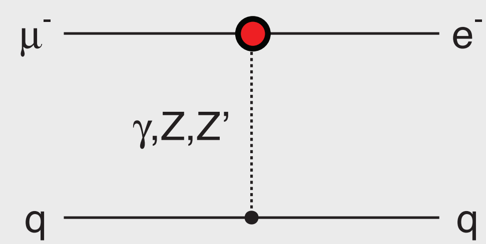
Second Higgs Doublet

$g(H_{\mu e})$ ~ $10^{-4} g(H_{\mu\mu})$



Heavy Z' Anomal. Z Coupling

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

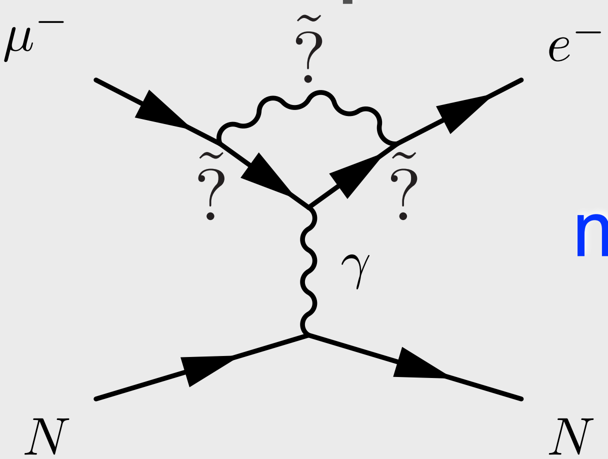


also see Flavour physics of leptons and dipole moments, arXiv:0801.1826 ;
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:10.1146/annurev.nucl.58.110707.171126 ;

Toy Lagrangian

$$\mathscr{L}_{\rm CLFV} = \frac{m_\mu}{\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} \quad + \quad \frac{1}{\Lambda^2}\bar{\mu}_L\gamma^\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

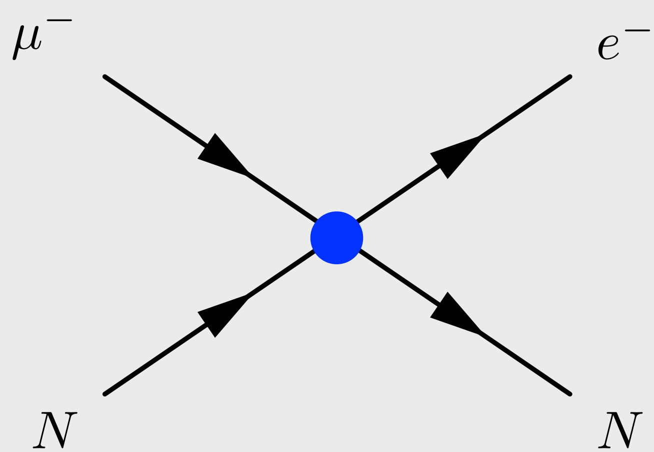
"Loops"



Supersymmetry and Heavy Neutrinos

mass scale Λ

"Contact Terms"



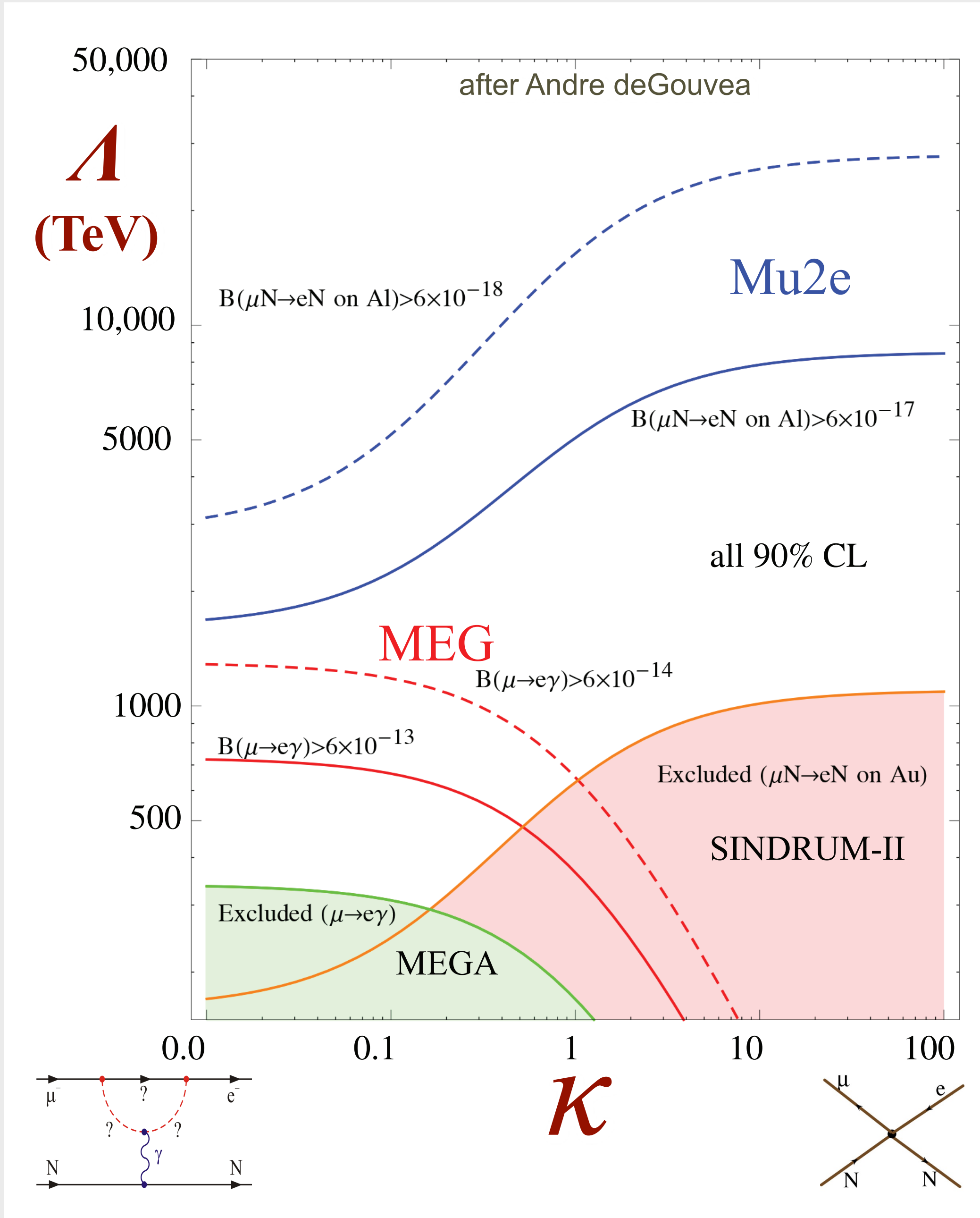
New Particles at High Mass Scale (leptoquarks, heavy Z,...)

Contributes to $\mu \to e\gamma$
(just imagine the photon is real)

Does not produce $\mu \to e\gamma$

A. DeGouvêa and P. Vogel, 1303.4097v2 [hep-ph]
for EFT treatment see S. Davidson and B. Echenard, 2010.00317 [hep-ph]

"DeGouvea Plot: 2013"



higher mass scale

de Gouvêa and Vogel, 1303.4097

EFT: Beyond Λ and κ

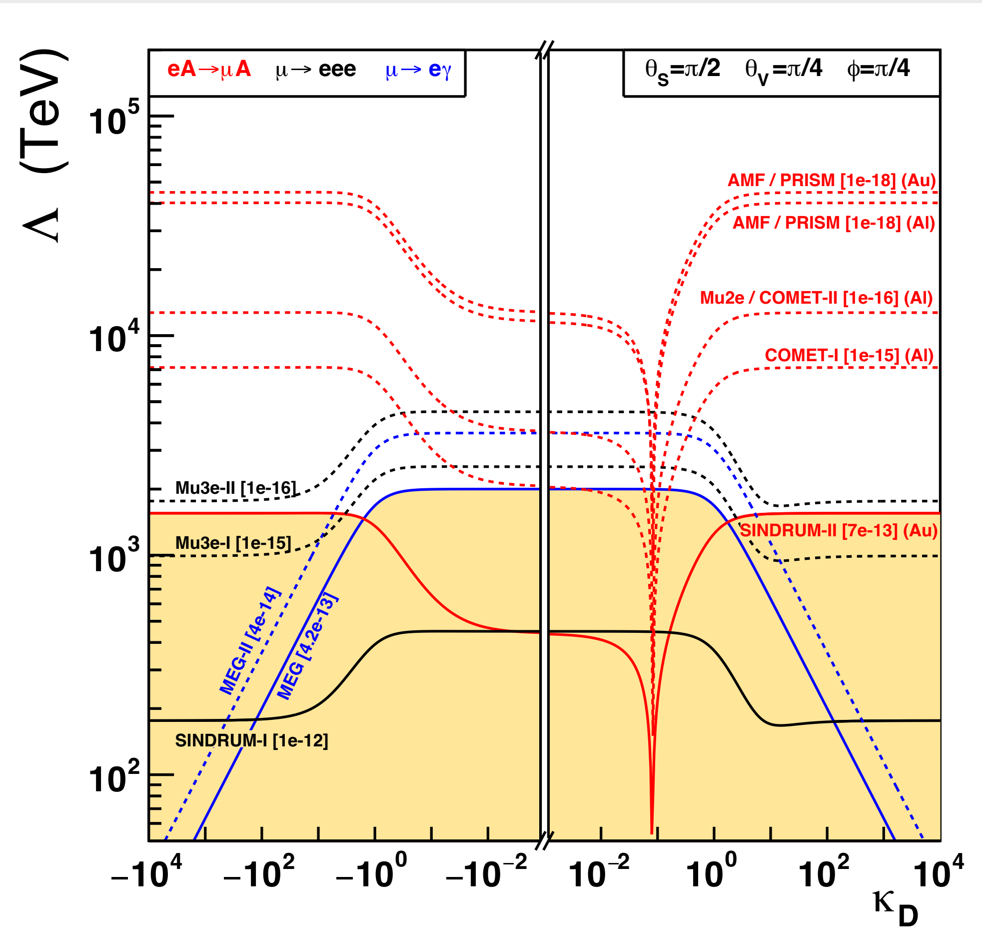
S. Davidson and B. Echenard, 2010.00317 [hep-ph]

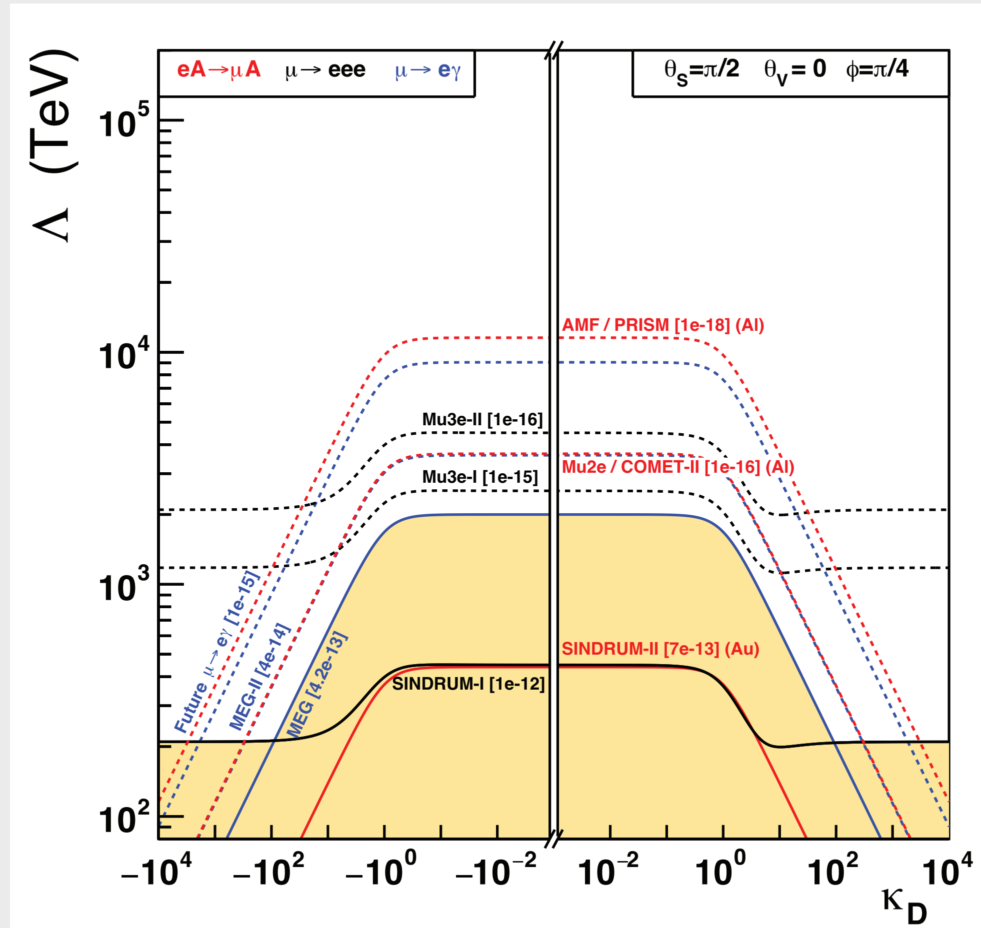
- Write EFT Lagrangian:
  - Dipole ($\mu \to e\gamma$) +
    Contact Scalar $(\mu \to 3e)_L$ +
    Contact Vector $(\mu \to 3e)_R$ +
    Contact $\mu N \to eN$ (light nuclei) +
    Contact $\mu N \to eN$ (heavy nuclei)
- Parameterize coefficient space with spherical coordinates: *lets you express constraints on all three processes simultaneously*
- Will show you "slices" in the multi-dimensional space

Complementarity

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

- All three channels have strengths; we need the combination





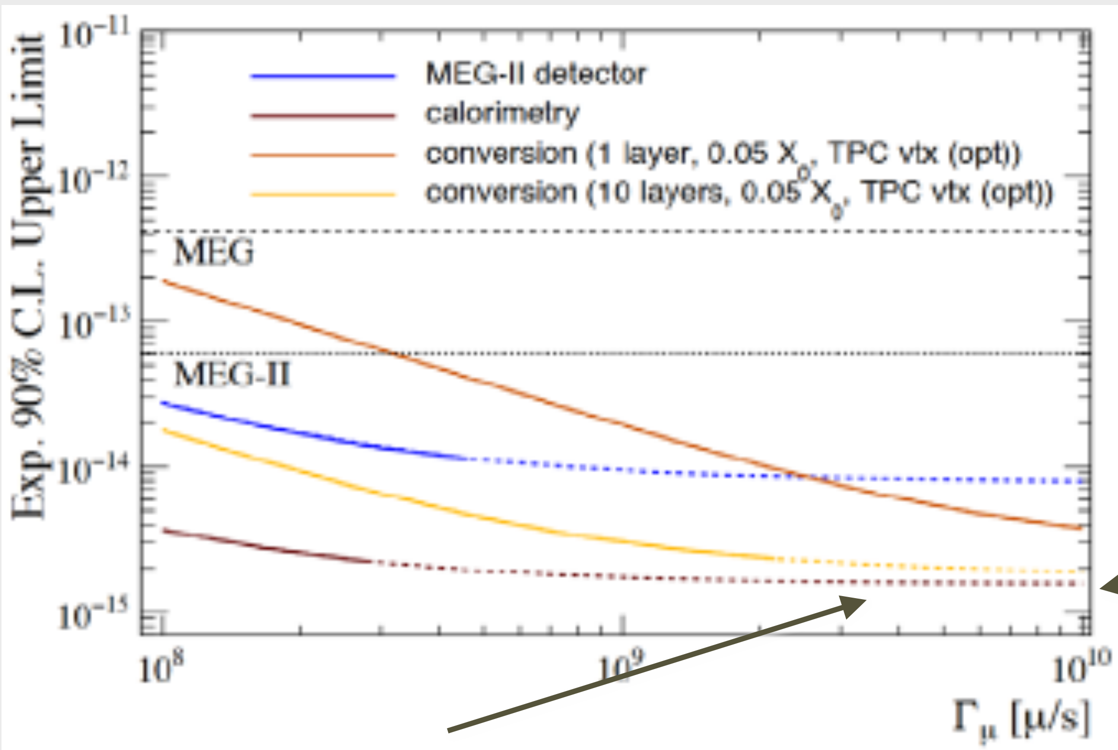
- $\mu \to e\gamma$ and $\mu \to 3e$ at $\mathcal{O}(10^{-15})$ are a next-gen target

Decay Experiments

- $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^+e^-$
  - these bring low energy (~ 30 MeV) μ^+ to rest in material and observe the decay (surface muon)
  - in $\mu^+ \to e^+\gamma$, accidentals scaling as I^2 are the limit; accidentals come from multiple muon decays and resolution limits
    - since accidentals drive the background, we want as continuous a beam as possible
  - in $\mu^+ \to e^+e^+e^-$, additional bkg from radiative muon decay, $\mu^+ \to e^+e^+e^-\nu_e\bar{\nu}_\mu$ with small E_ν

$\mu \rightarrow e\gamma$ Limits

- $\mu^+ \rightarrow e^+\gamma$ as in MEG, but convert the photon for improved resolution (have a vertex from tracks)
  - lowers statistics by ~x100 but improves background rejection



levels out at 10^{10} μ/sec, about HiMB PSI upgrade

Renga et al.,1811.12324[hep-ex]

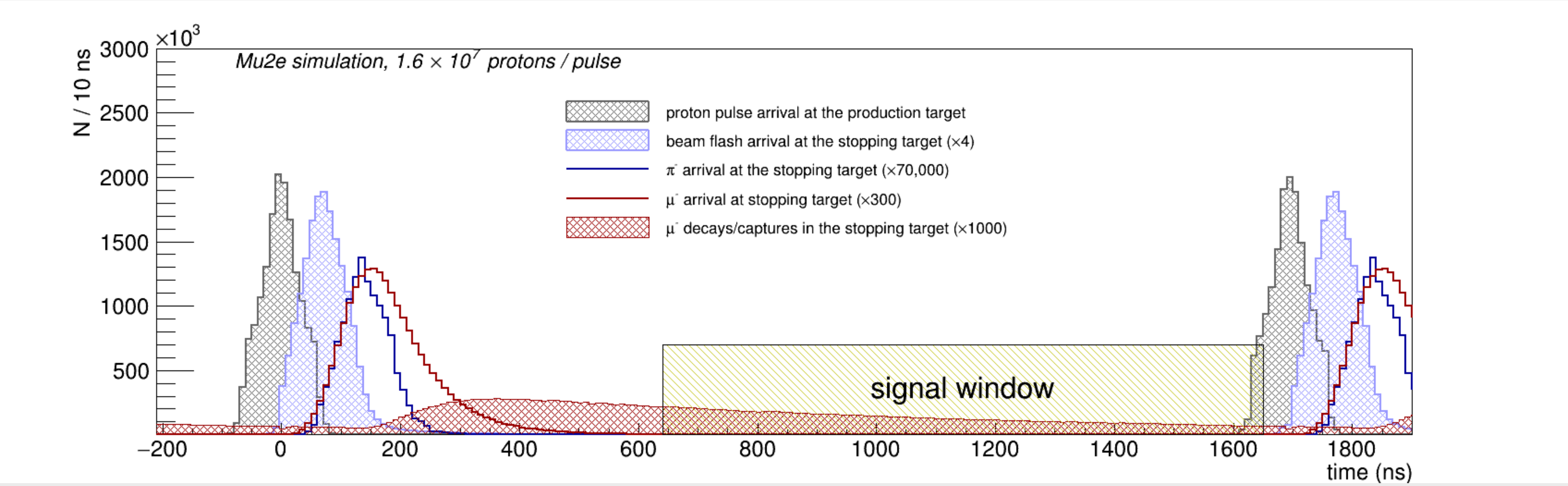
next-gen 10^{-15} goal for $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$

Capture Experiment

- $\mu^- N \rightarrow e^- N$
  - brings a muon near an atomic nucleus where it falls into a muonic 1s state: monoenergetic electron just below m_μ
  - for several generations of experiments, including Mu2e/COMET, the beam design was driven by radiative pion capture (RPC):
    - $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+ e^-$ at the signal energy
    - Mu2e/COMET use a *pulsed* beam and use the 26 ns pion lifetime vs 2.2 μs muon lifetime to “wait out” RPC

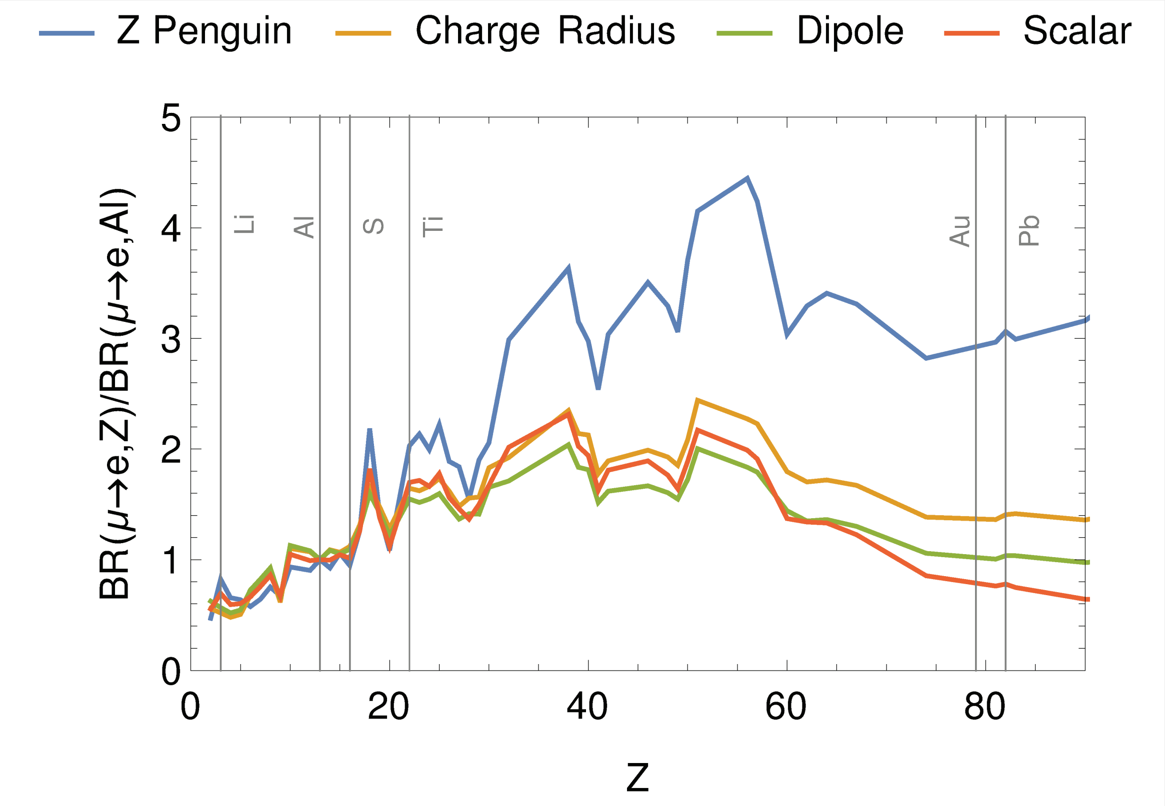
Mu2e/COMET timing scheme

- Complicated plot, but for both Mu2e/COMET
  - pulse at beginning
  - wait for pions to decay
  - open a signal window



Conversion at Higher Atomic Number

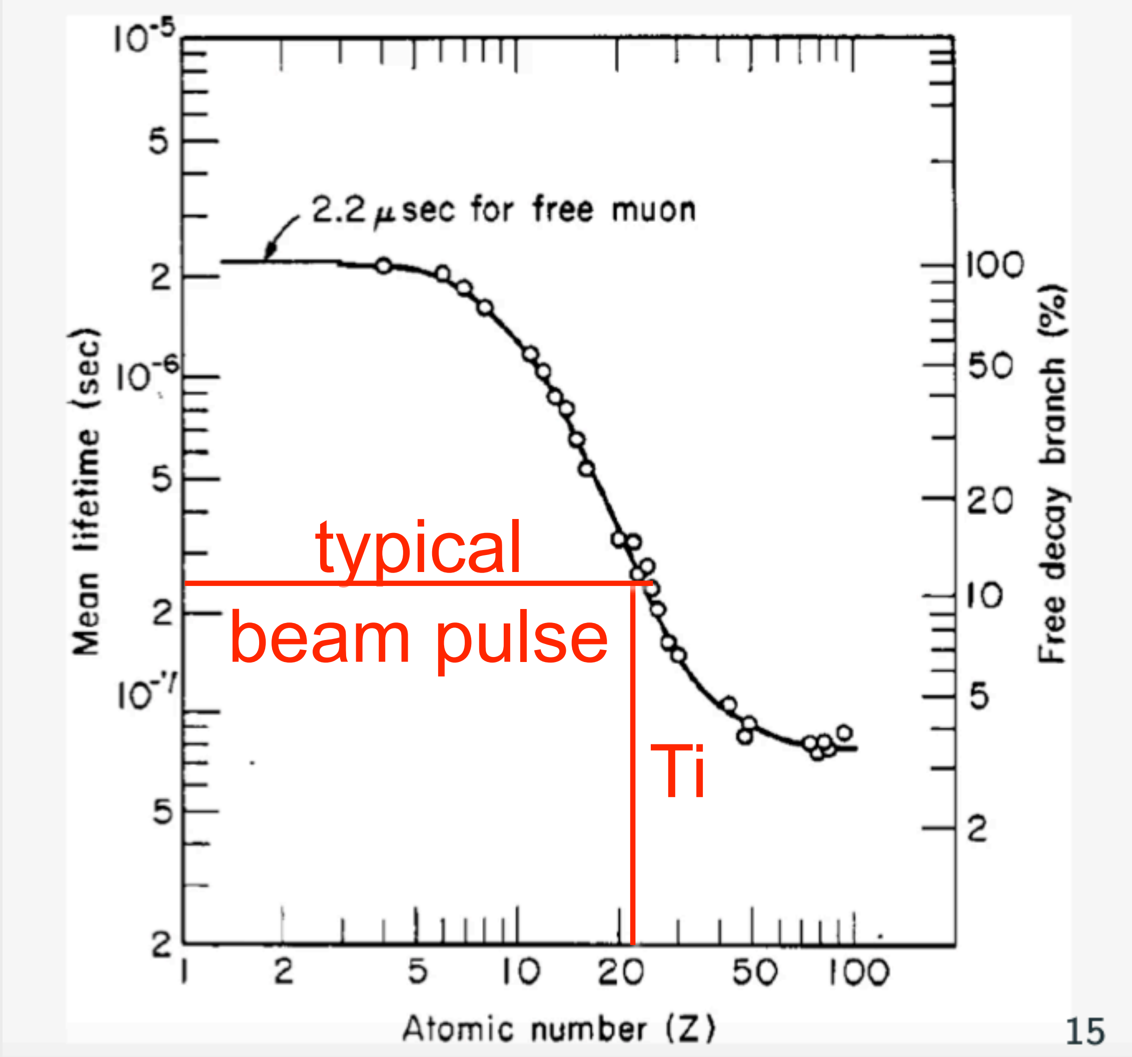
- Model Discrimination and Possibly Larger Signal at high Z
- if Mu2e sees a signal, this is the obvious next step
- if not, we should try for another x10-100 better constraints



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

Limitation of Mu2e Method

- A beam pulse is ~250 ns FWHM
- You can't do an experiment inside the debris from the beam pulse
- And therefore you can't go to high *Z:* Ti about limit



New Facility: AMF

hep-ex 2203.08278

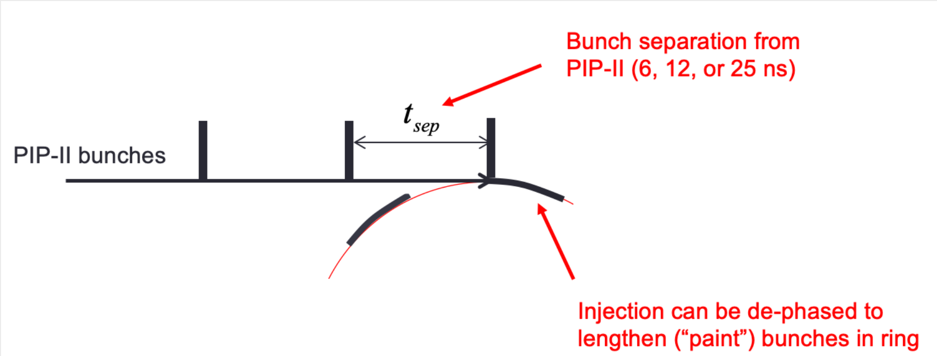
- The "Advanced Muon Facility" would use PIP-II to enable
  - ***CLFV in all three muon modes: world-leading facility***
    - two new small rings for $\mu N \rightarrow eN$ at high Z and additional x100 in rate
      - with a possible DM experiment
    - x100-1000 more beam for $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$ than are possible at PSI
  - Possible muonium-antimuonium and muon EDM

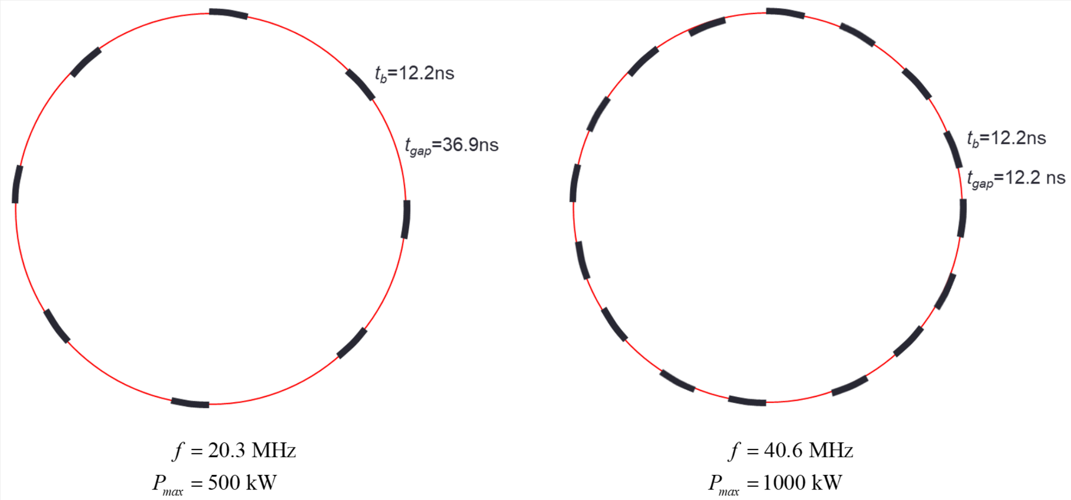
Conversion Physics

- Like Mu2e, target beam inside a solenoid, but at 100 kW - 1MW vs. Mu2e's 8 kW
  - Mu2e-II at 100 kW, but not high *Z*
- Rebunch PIP-II beam in a "compressor ring"
- bring to proton target
- Transfer to a fixed-field alternating (FFA) gradient ring
  - phase rotates to slow higher momentum muons, accelerate lower momentum muons
  - pion contamination greatly reduced while muons are circulating in ring (same notion of using π decay as Mu2e)

Beam for Conversion

- Compressor Ring:
  - 500 kW achievable;
    - 12 ns kickers are the limit for 1 MW





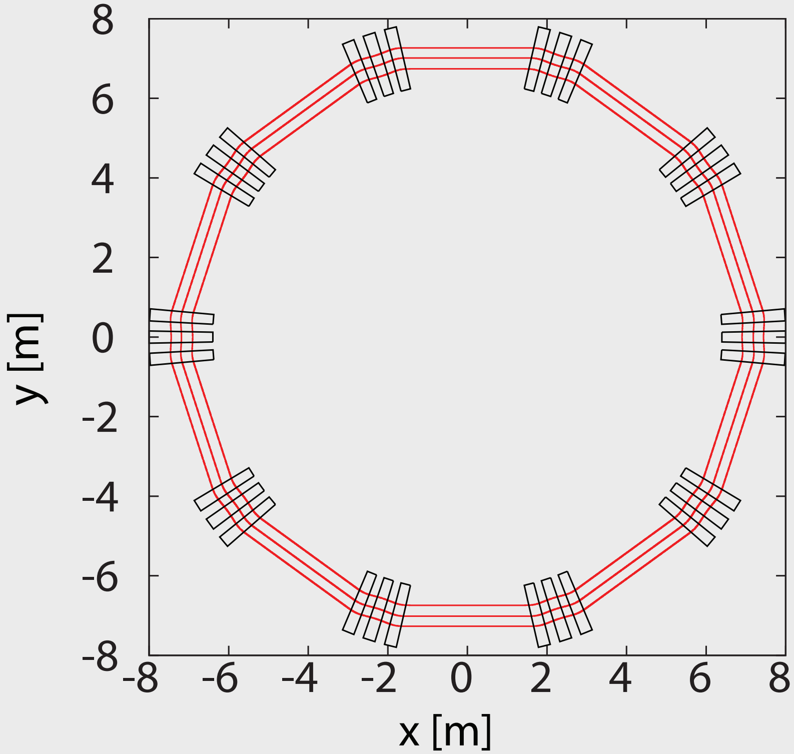
Description	Protons-Per-Pulse	Pulse Spacing (ns)	Repetition Rate (Hz)
AMF	7.8×10^{13}	24	100
Dark Matter	6.2×10^{14}	196	100

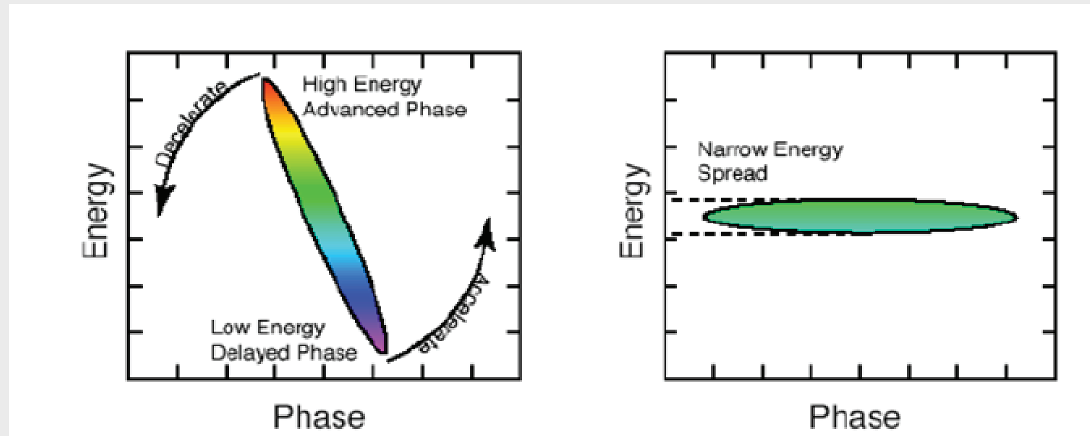
Production Solenoid

- Mu2e at 8 kW requires a complicated heat and radiation shield to keep superconductor from quenching; COMET proposes 56 kW
- Conceptual designs exist for 100 kW
  - “moving mass” target and thicker shield
- AMF would provide world-class physics at high-*Z* *;* 100 kW is just the first step
- Various ideas for 1MW have been promoted
  - ν targets for DUNE get to 1MW…why so hard?
  - *not inside a superconductor*

FFA

- PRISM (Phase Rotated Intense Source of Muons) (arXiv:1310.0804 [physics.acc-ph])





6 cell demonstrator at Osaka

Beam for Decay Experiments

- Two Options:
  - a conventional stopped muon beam at 1MW based on PSI but a new, dedicated facility for CLFV
  - use same production system as for capture experiments, but flip sign of selected muons
  - will require detailed MCs to choose

Existing Attempts

- MERIT experiment

  https://aip.scitation.org/doi/pdf/10.1063/1.3399332

  - Liquid mercury — this is an environmental problem (Minamata Convention)
  - Rep rates only about 70 Hz, limited by disruption of the jet. We need x10 faster
  - MERIT is not a proof as is sometimes claimed
- SNS moved to rotating tungsten
- Discussion of muon collider targetry: https://indico.cern.ch/event/1016248/contributions/4282384/attachments/2215324/3752155/

Beam Technical Challenges

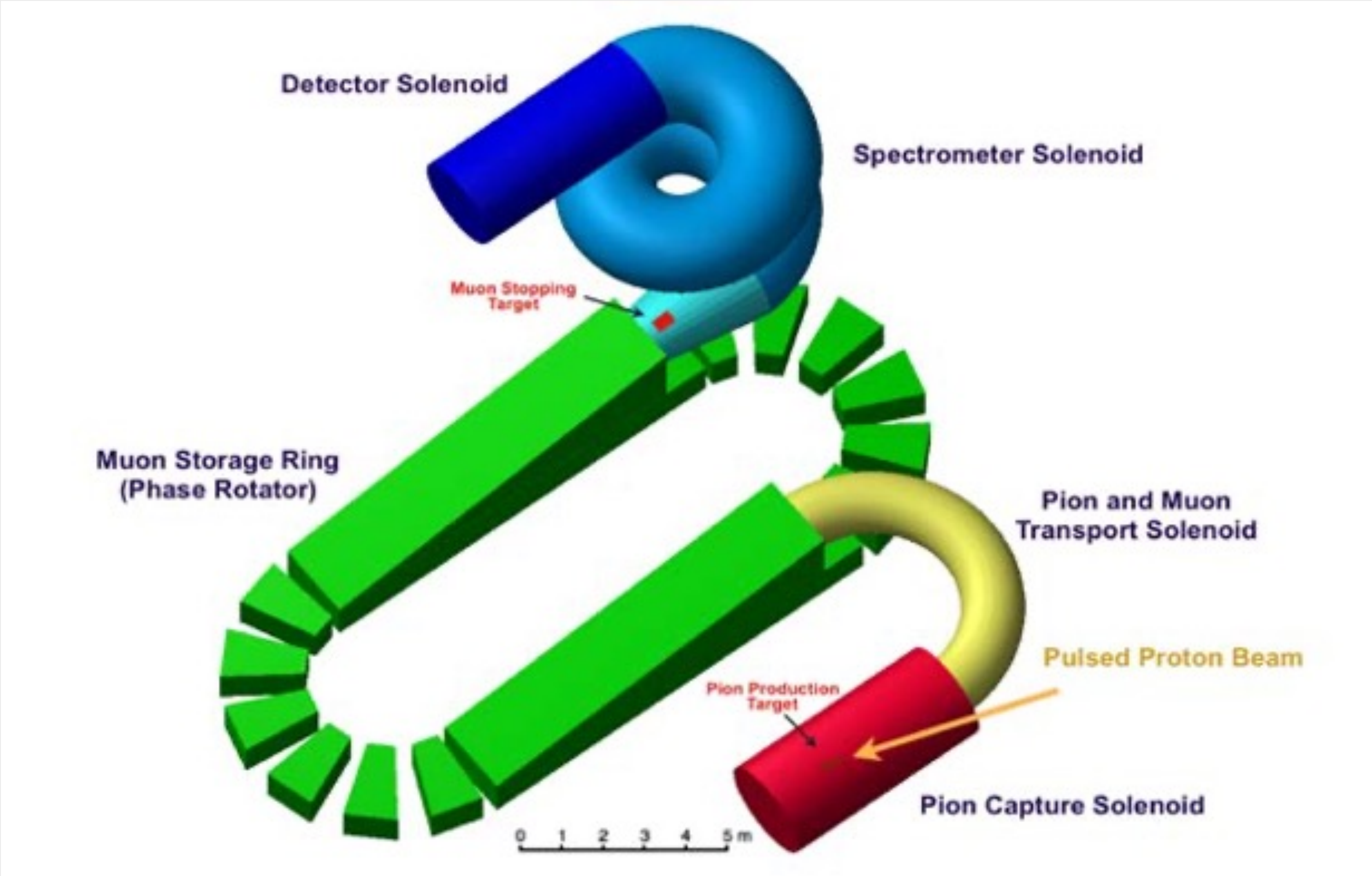
- Things that are very hard that we know how to do:
  - stopped muon beam at 1MW
  - compressor ring
  - FFA
- Things that are very hard that we don't know how to do
  - 1MW target inside a superconducting solenoid
  - R&D here closely related to muon collider!

Detector Technical Challenges

- $\mu^- N \rightarrow e^- N$
  - halving momentum resolution on signal e^-
    - not just making Mu2e straws thinner
    - rethink detector design
  - dominant background (we think) will be cosmic ray production of electrons in signal region
    - a CRV x100-x1000 better than Mu2e

One Concept for $\mu^- N \to e^- N$

- Spiral Detector Solenoid greatly reduces rate seen by detector, opens up new detector designs (from PRISM)



ENIGMA experiment

New Ideas in Decay Experiments

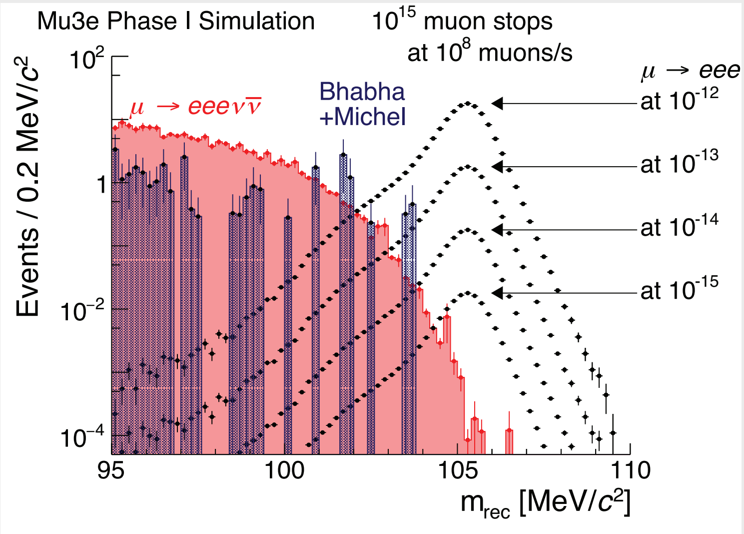
- $\mu \to e\gamma$: back-to-back electron and photon
  - $B \propto \Gamma_\mu^2 \cdot \delta E_e \cdot (\delta E_\gamma^2) \cdot \delta T_{e\gamma} \cdot (\delta\theta_{e\gamma}^2)$
  - converting $\gamma \to e^+e^-$ improves resolutions but there are limits: converters imply straggling in *dE/dx*, etc.
  - active target for vertex? fundamentally new approach?

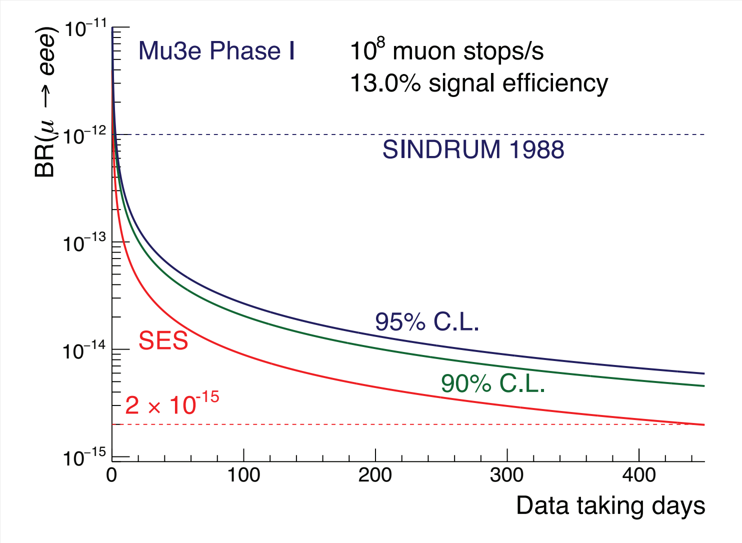
New Ideas in Decay Experiments

- $\mu \to 3e$:

2204.00001

- $\mu \to 3e\bar{\nu}_e\nu_\mu$ is main background





- target sensitivity of 10^{-16} at HiMB, 2e9 μ/s

- with more rate, harder cuts?

Summary

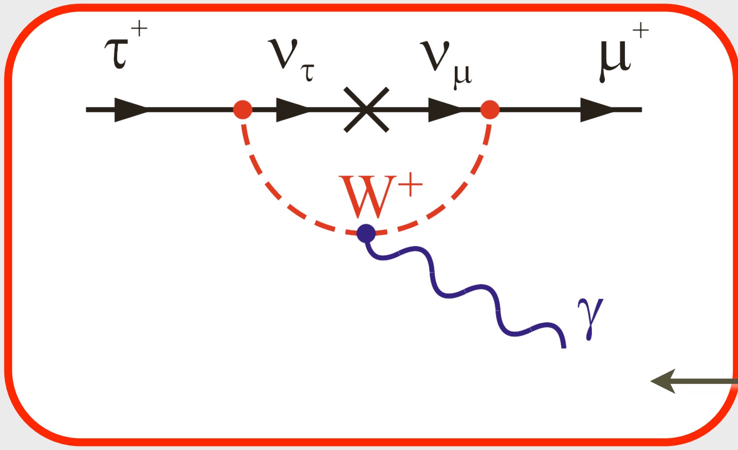
- Muon-based Charged Lepton Flavor Violation provides powerful searches and constraints for BSM physics
- A new facility at FNAL could provide all muon channels with orders of magnitude more data and open new possibilities in $\mu N \rightarrow eN$ at high Z
  - plus a dark matter experiment and other muon measurements not discussed.
  - technical challenges directly related to muon collider R&D
- We hope for P5 to recommend design of the program with submission to next P5

Backup

CLFV and Tau Decays

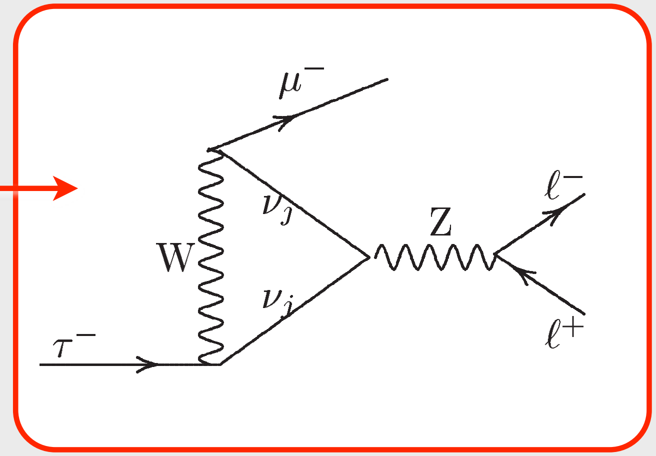
τ processes also suppressed in Standard Model but less:

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



$$\ln\left(\frac{m_3^2}{M_W^2}\right)^2$$

$$\left(\frac{\Delta m_{23}^2}{M_W^2}\right)^2$$



Pham, hep-ph/9810484

SM ~ 10^{-49}

SM ~ 10^{-14} ?

Good News:

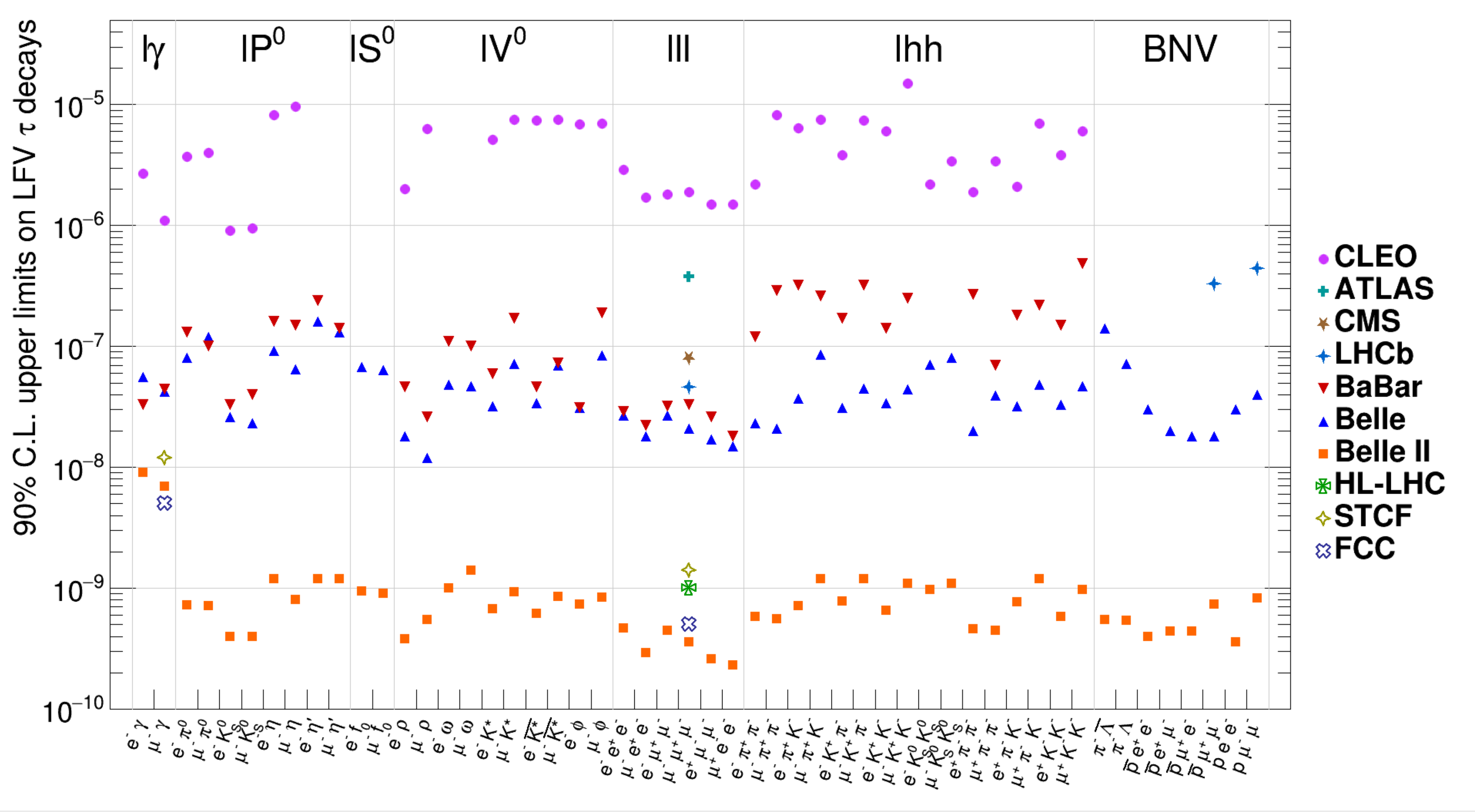
Beyond SM rates can be orders of magnitude larger than in associated muon decays

Bad News:

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

τ's help pin down models and sometimes biggest BR

τ Limits



90% C.L. upper limits on LFV τ decays
lγ
lP⁰
lS⁰
lV⁰
lll
lhh
BNV
CLEO
ATLAS
CMS
LHCb
BaBar
Belle
Belle II
HL-LHC
STCF
FCC