The Advanced Muon Facility at Fermilab: Physics and Relationship to the Muon Collider

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ENIGMA Collaboration

IMCC Meeting
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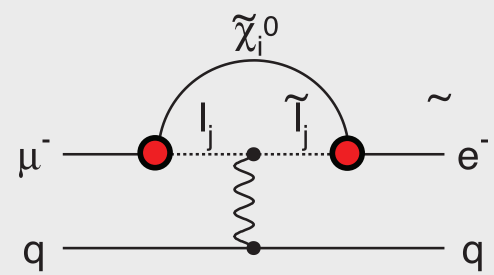
Charged Lepton Flavor Violation

- 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

Contributions to Muon CLFV

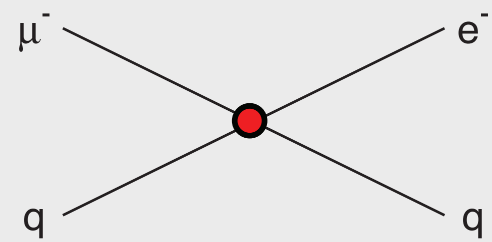
Supersymmetry

rate ~ 10^{-15}



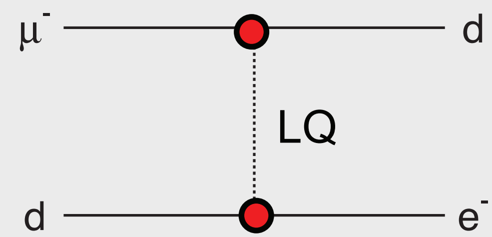
Compositeness

$\Lambda_c \sim 3000$ TeV



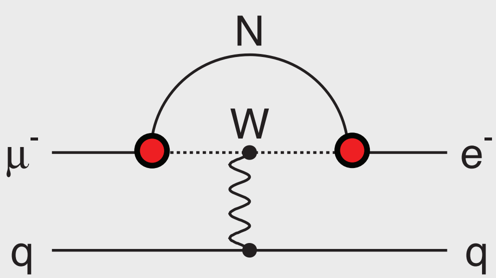
Leptoquark

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



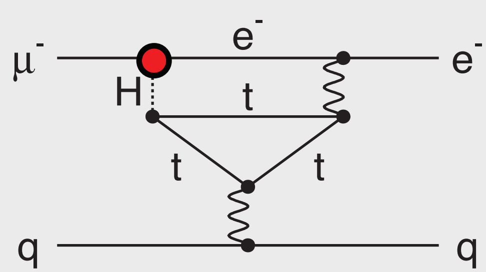
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2 \sim 8\times10^{-13}$



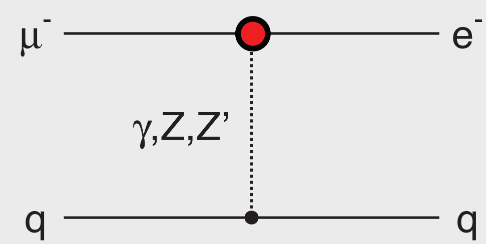
Second Higgs Doublet

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



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 ;

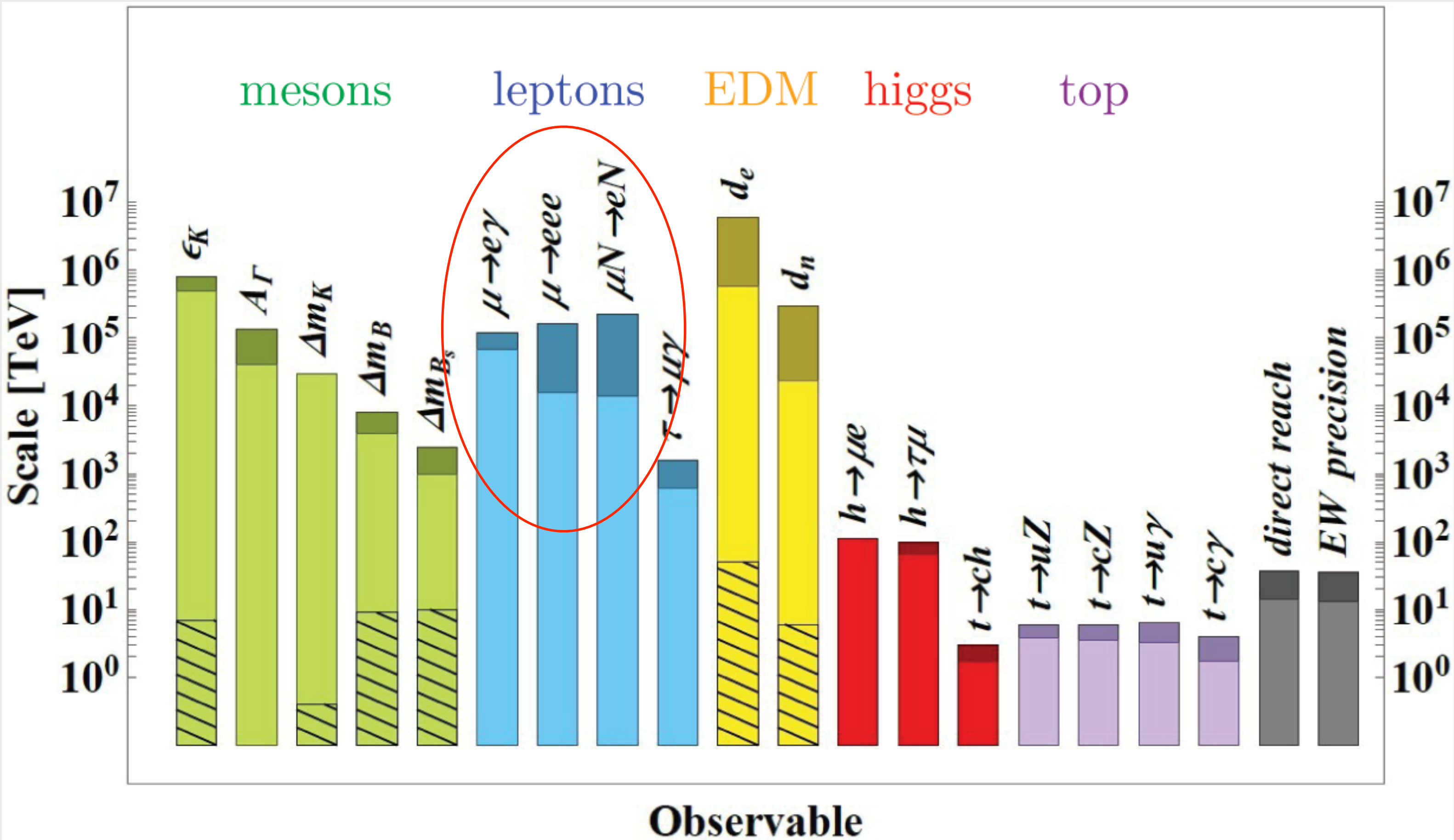
CLFV Muon Processes

- $\mu \rightarrow e\gamma$
  - oldest studied, most powerful limits, and the best experiment so far: MEG at PSI
- $\mu N \rightarrow eN$
  - muon to electron conversion: muon converts in field of nucleus, leaving nucleus unchanged

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

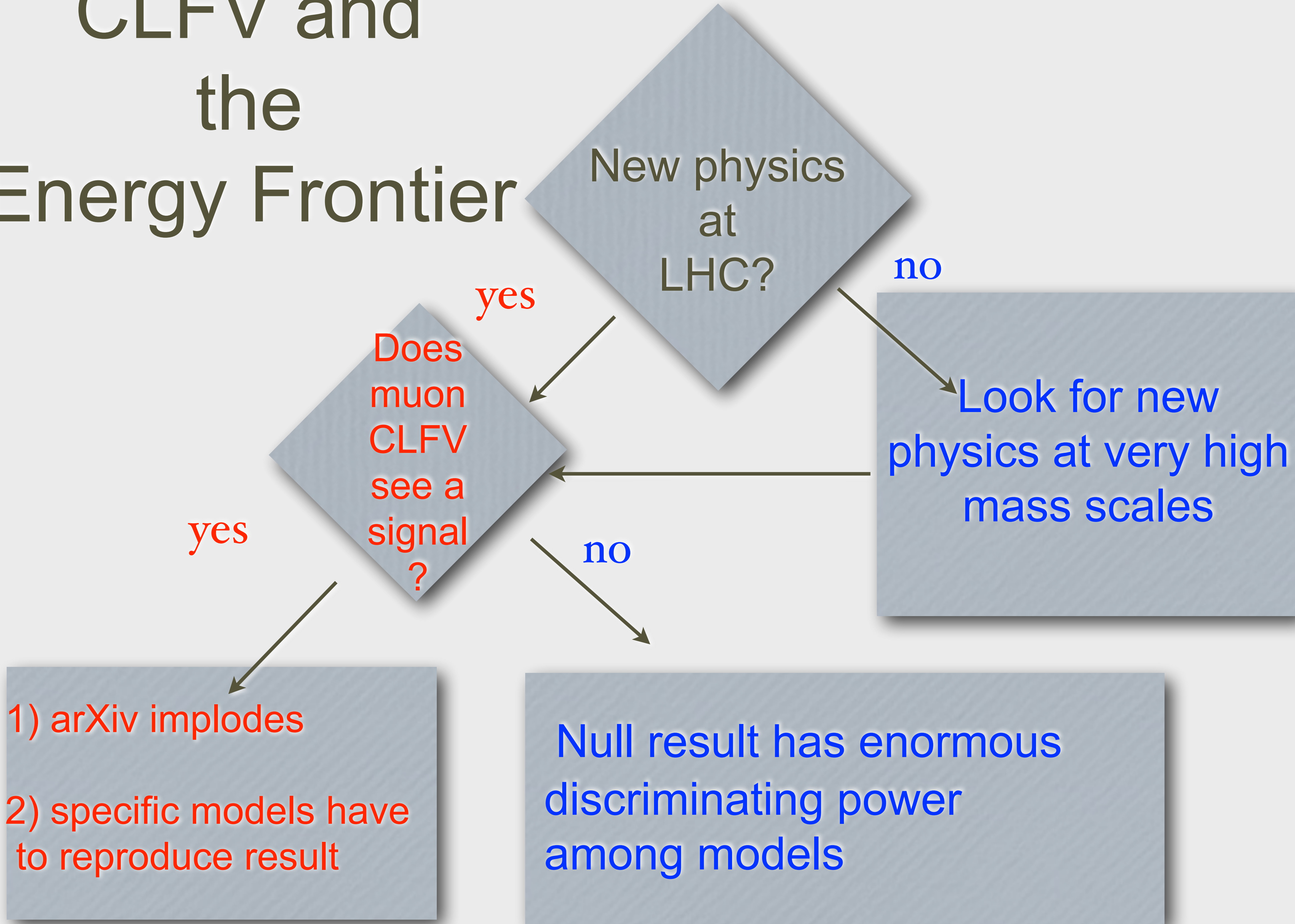
  - two experiments upcoming at FNAL and JPARC
- $\mu \rightarrow eee$
  - ambitious and unique, excellent partner to other two (at PSI)

Mass Scales of Muon CLFV Searches



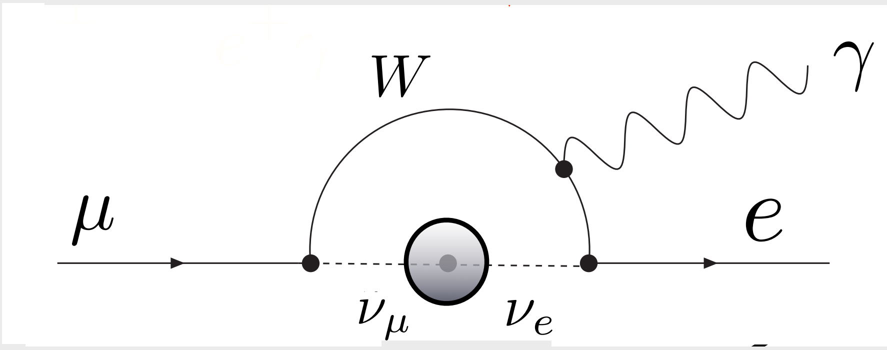
operator coefficients =1, from Physics Briefing Book, 1910.11775

CLFV and the Energy Frontier



Neutrino Oscillations and Muon CLFV

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

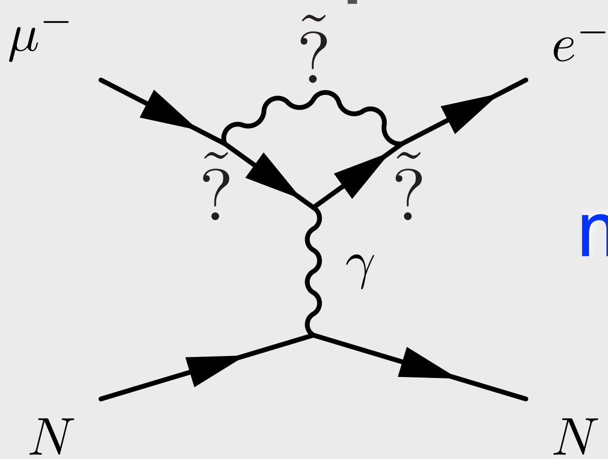


$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

Toy Lagrangian

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

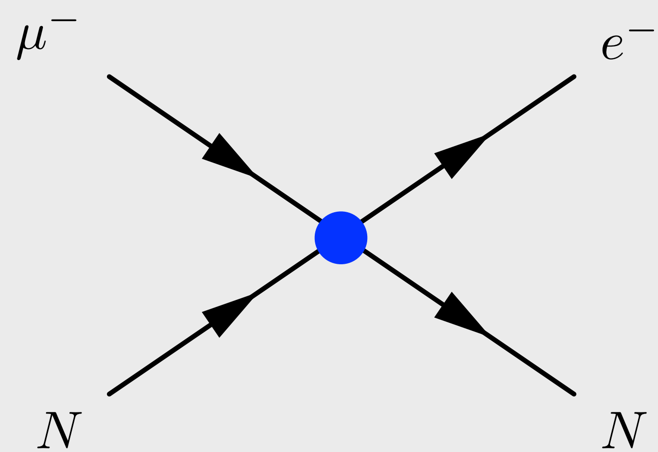
"Loops"



Supersymmetry and Heavy Neutrinos

mass scale Λ

"Contact Terms"



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

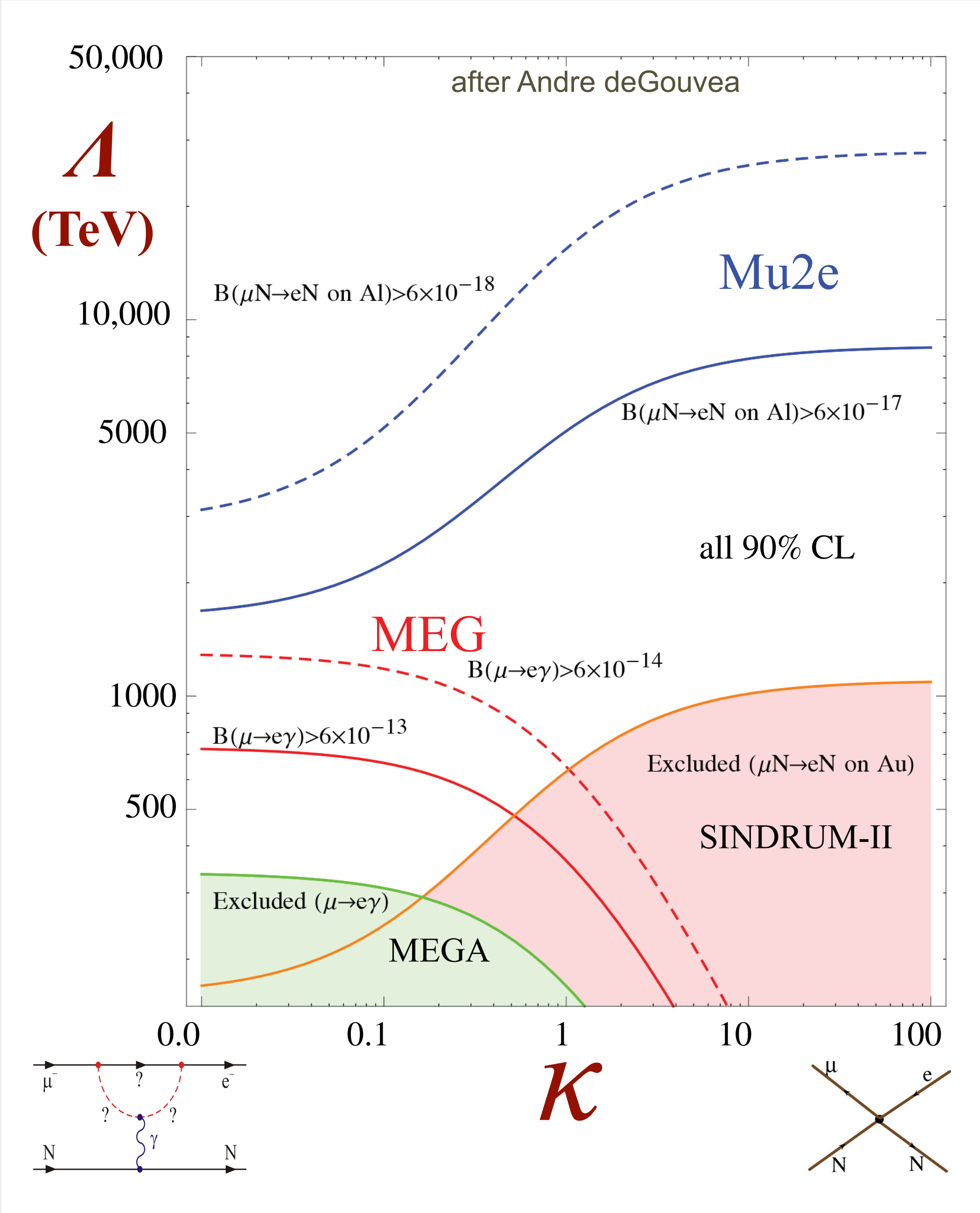
Contributes to $\mu \to e\gamma$
(just imagine the photon is real)

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

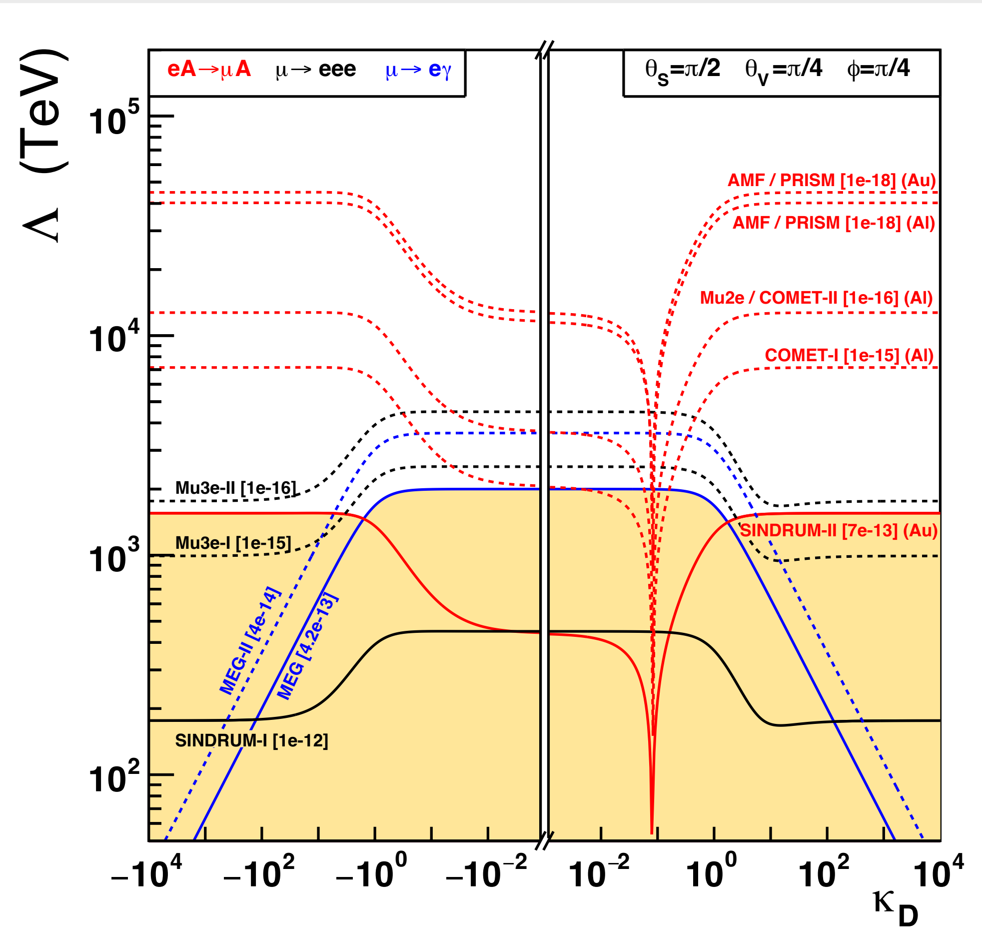
S. Davidson and B. Echenard, 2010.00317 [hep-ph]

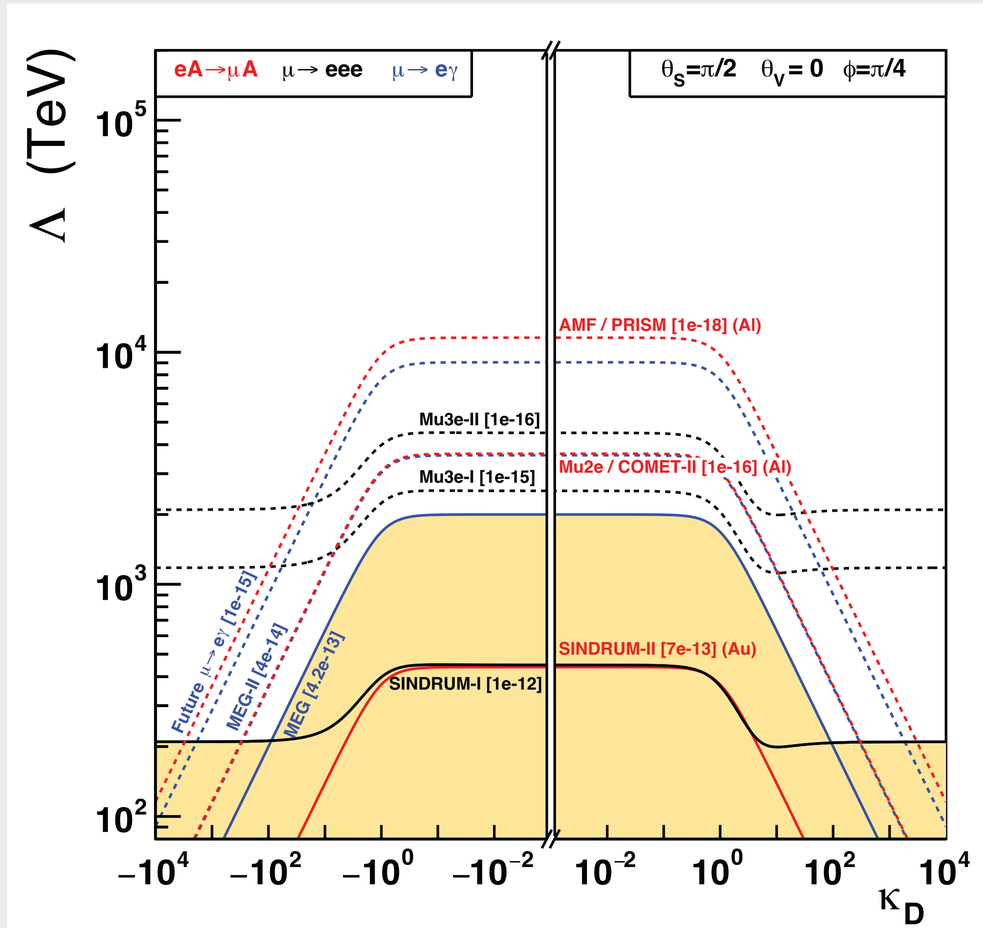
- Write EFT Lagrangian:
  - Dipole ($\mu \rightarrow e\gamma$) +
    Contact Scalar ($\mu \rightarrow 3e$)$_L$ +
    Contact Vector ($\mu \rightarrow 3e$)$_R$ +
    Contact $\mu N \rightarrow eN$ (light nuclei) +
    Contact $\mu N \rightarrow eN$ (heavy nuclei)
- Parameterize coefficient space with 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





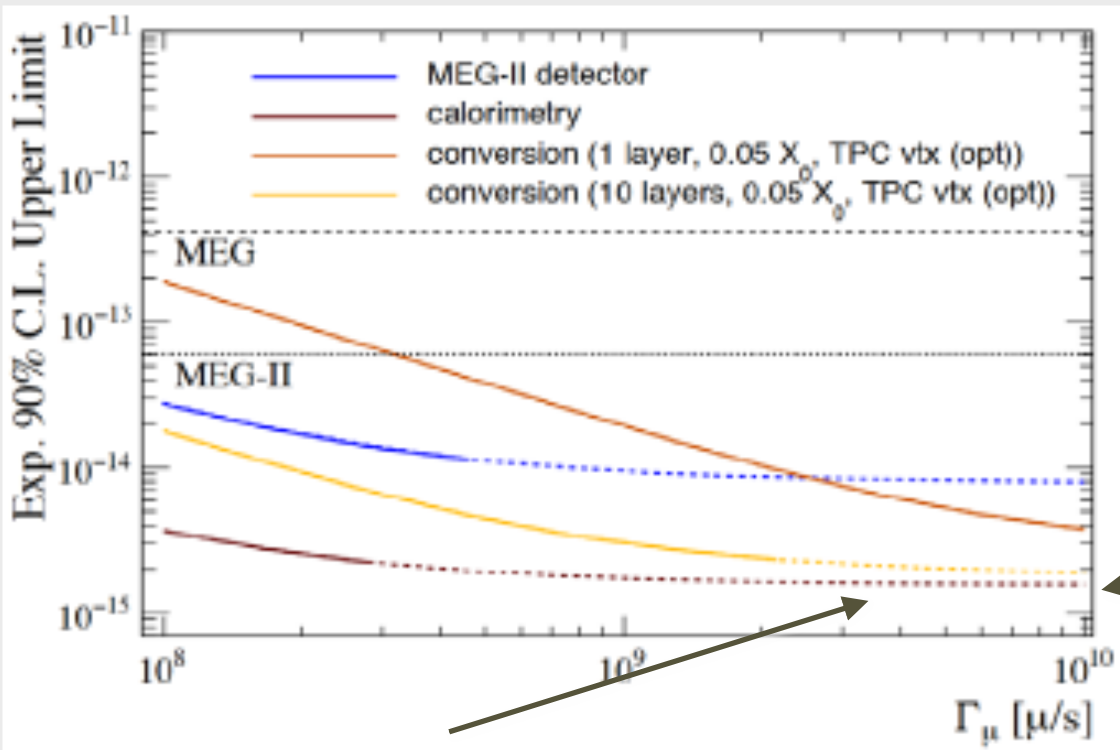
- $\mu \to e\gamma$ and $\mu \to 3e$ at $\mathcal{O}(10^{-15})$ are a next-gen target

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

$\mu \to e\gamma$ Limits

- $\mu^+ \to e^+\gamma$ 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 $\mu \to e\gamma$ and $\mu \to 3e$

New Ideas in Decay Experiments

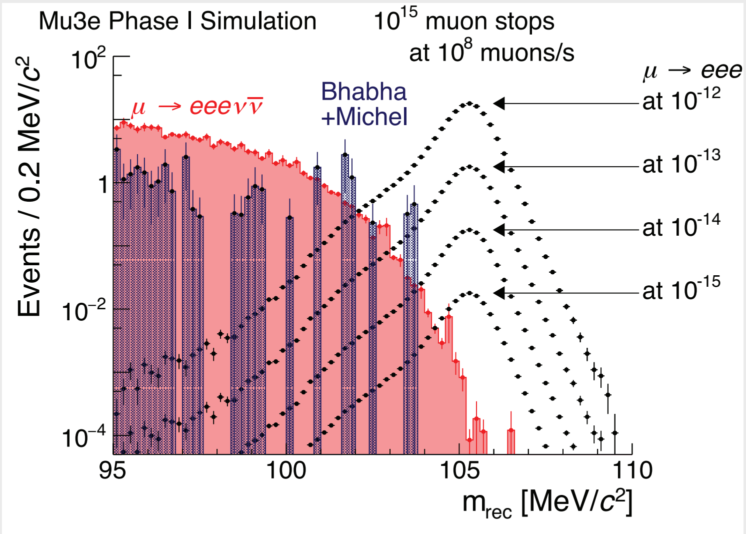
- $\mu \to e\gamma$: back-to-back electron and photon
  - $B \propto \Gamma_\mu^2 \cdot \delta E_e \cdot (\delta E_\gamma^2) \cdot \delta T_{e\gamma} \cdot (\delta\theta_{e\gamma}^2)$
  - converting $\gamma \to e^+e^-$ improves resolutions but there are limits: converters imply straggling in *dE/dx*,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

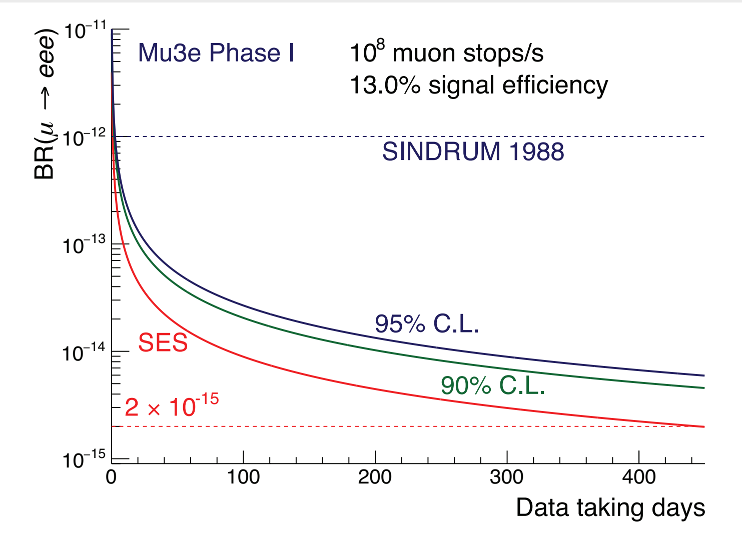
New Ideas in Decay Experiments

- $\mu \to 3e$:

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? new detector ideas?

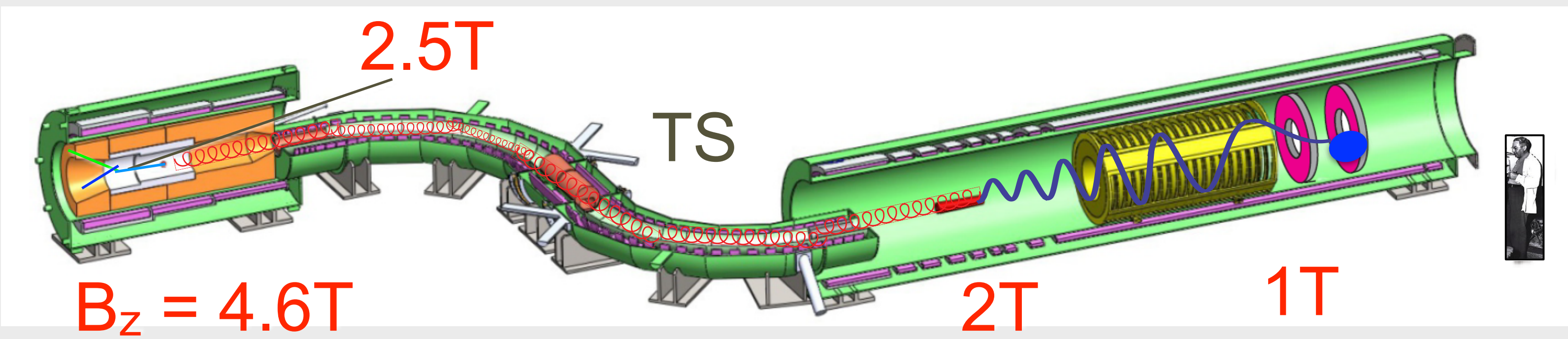
Capture Experiment

- $\mu^- N \to e^- N$ (N = $^{27}Al_{13}$ for Mu2e)
  - 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):
    - $\pi^- N \to \gamma N', \gamma \to e^+ e^-$ 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 Muon Beam: Three Solenoids and Gradient

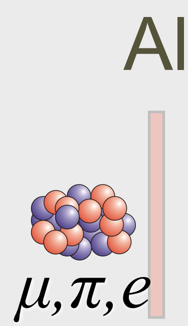
4.6T → B-field gradient → 1T

PS DS



8 kW

- Target protons at 8 GeV inside superconducting solenoid
- Capture muons and guide through S-shaped region to Al stopping target
- Gradient fields used to collect and transport muons

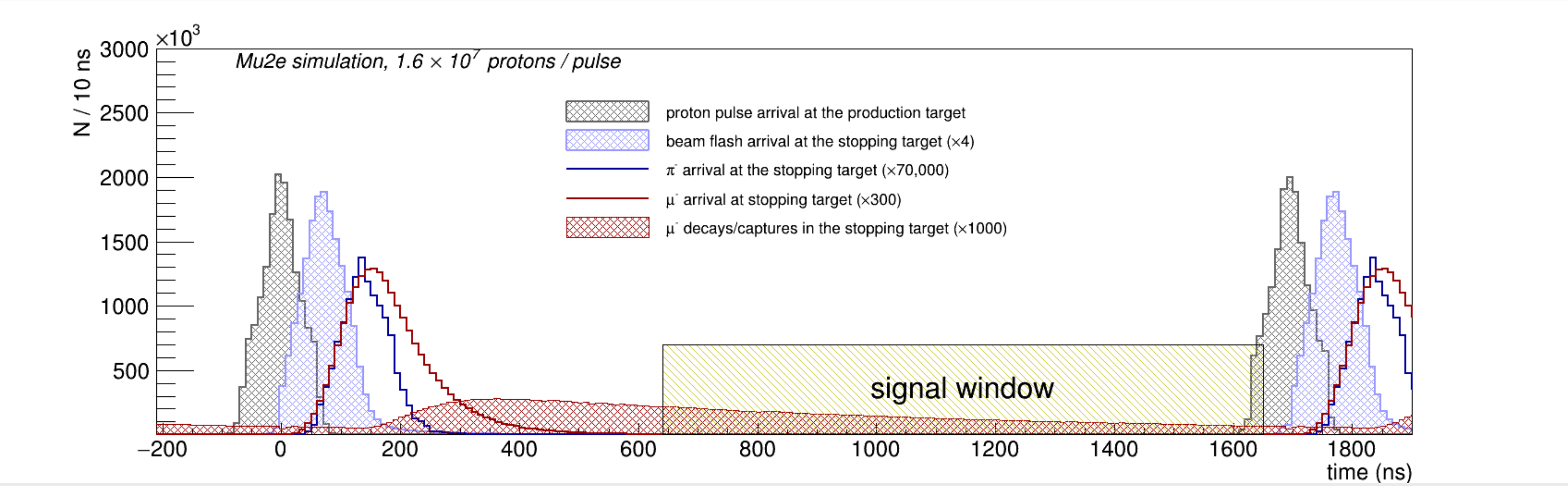


Muon K.E ~ 7 MeV muons range out by dE/dx in Aluminum

Mu2e/COMET timing scheme

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

Mu2e is $\mu^{-}\mathrm{Al} \rightarrow e^{-}\mathrm{Al}$

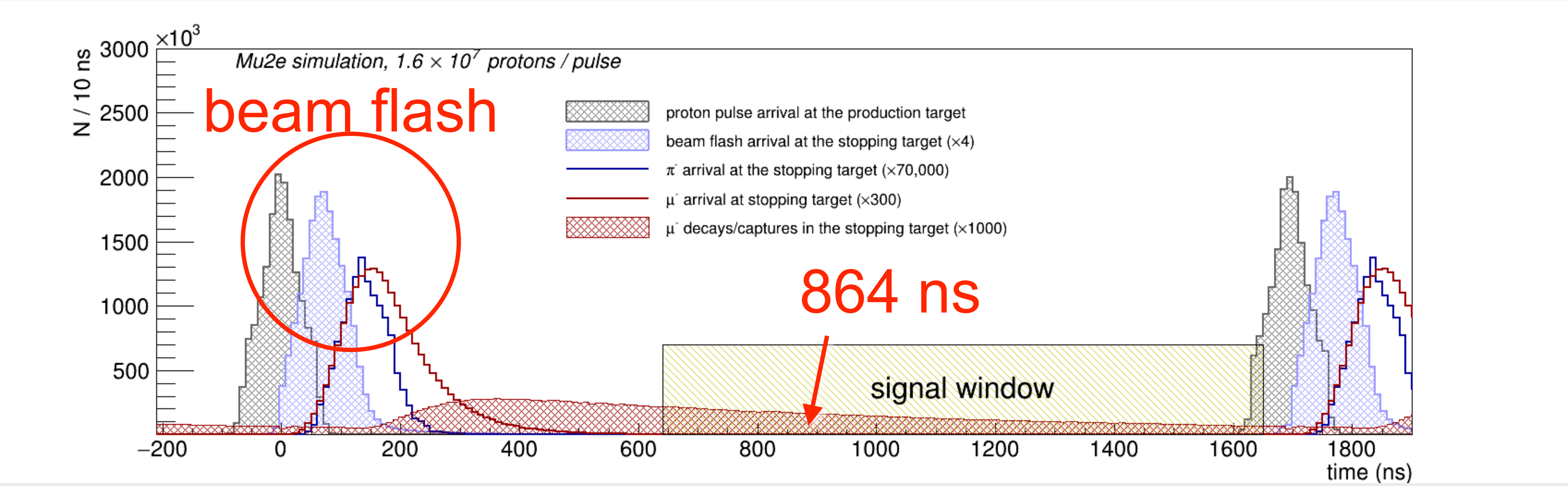


Mu2e/COMET timing scheme

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

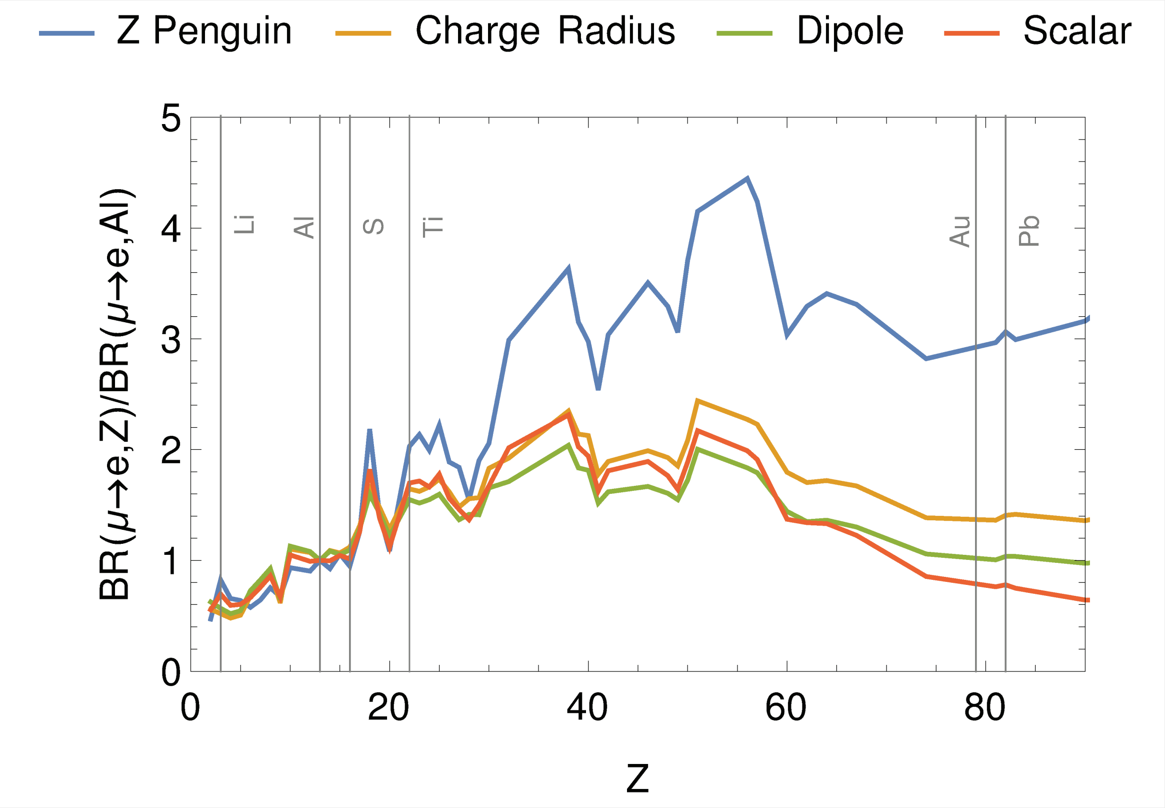
Mu2e is $\mu^- \mathrm{Al} \rightarrow e^- \mathrm{Al}$

864 ns μ^- Al atom lifetime well after beam flash



Conversion at Higher Atomic Number

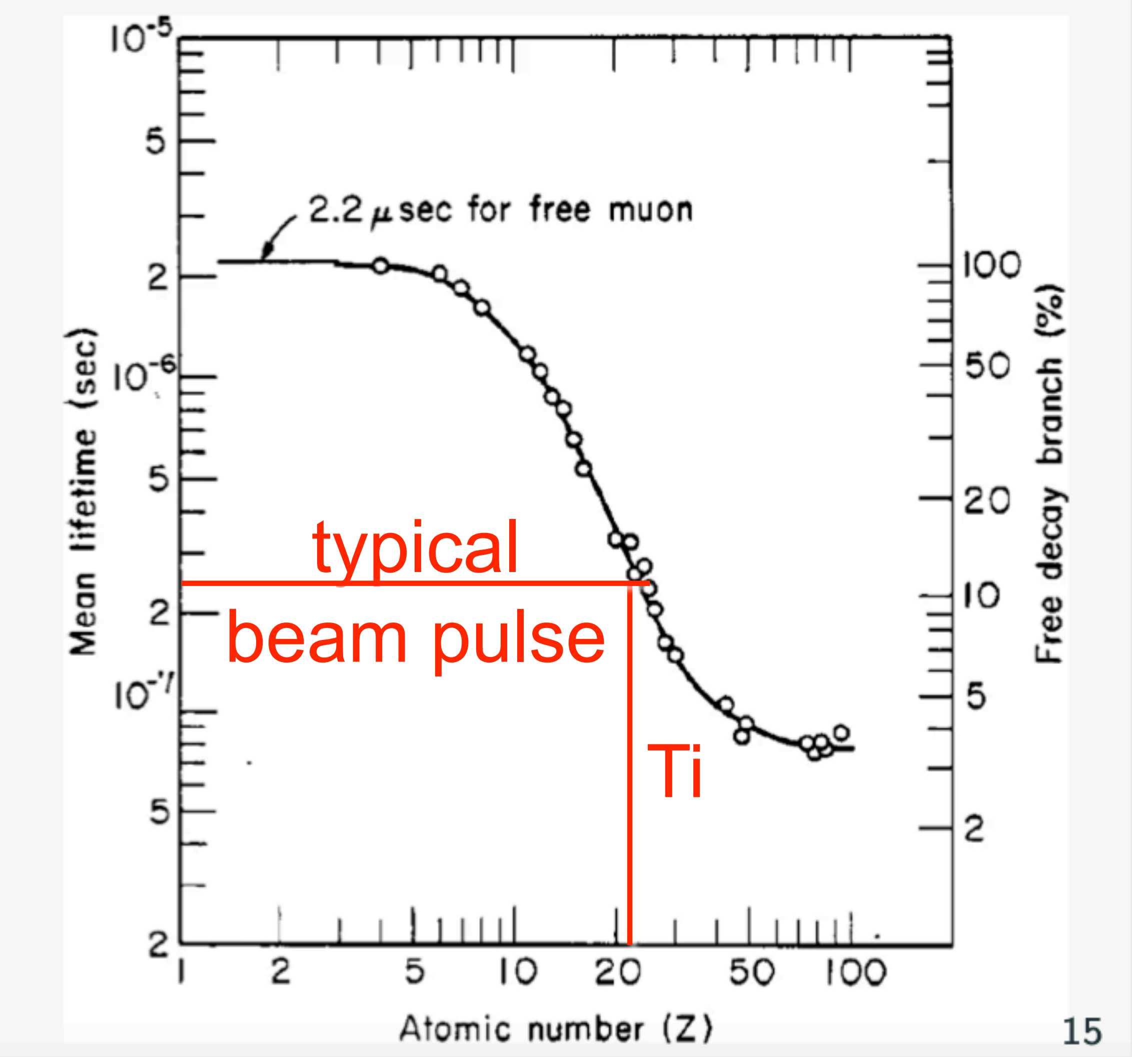
- Model Discrimination and Possibly Larger Signal at high Z
- if Mu2e sees a signal, this is the obvious next step
- if not, we should try for another x10-100 better constraints



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 Experiment

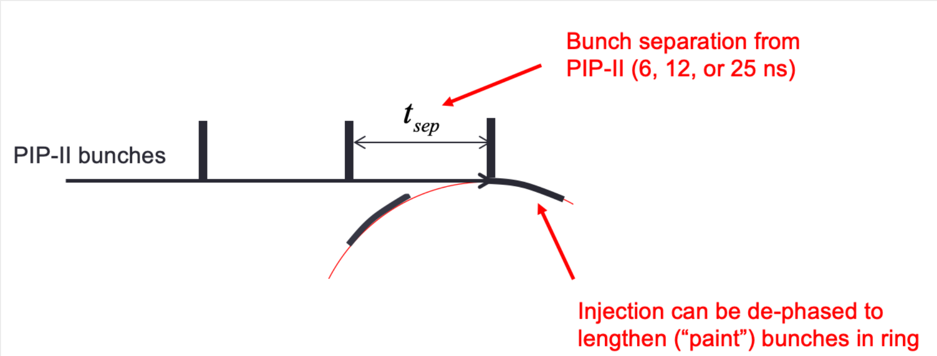
- Like Mu2e, target beam inside a solenoid, but at 100 kW - 1MW vs. Mu2e's 8 kW
  - Mu2e-II at 100 kW, but not high *Z*
- Rebunch PIP-II beam in a "compressor ring"
- next, bring to proton target

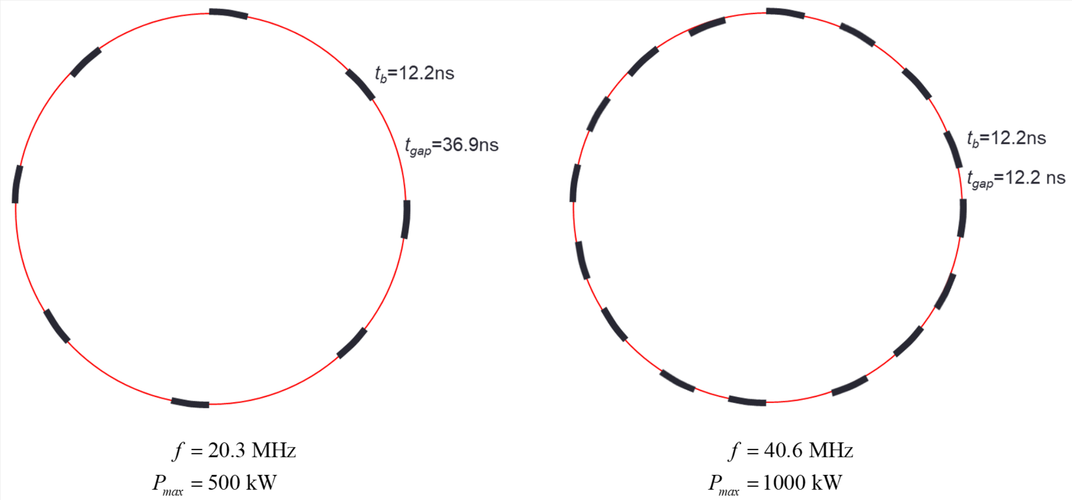
the FFA for conversion from Japan:
https://indico.fnal.gov/event/46669/contributions/203147/attachments/138314/173082/PRISM_CLFV_10122020_Pasternak.pdf

- Transfer to a fixed-field alternating (FFA) gradient ring
  - phase rotates to slow higher momentum muons, accelerate lower momentum muons.
  - pion contamination from RPC greatly reduced while muons are circulating in ring
  - Extract pure, cold muon beam to detector

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 (Japanese version) proposes 56 kW
- Mu2e-II 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: MuCol is working on this*

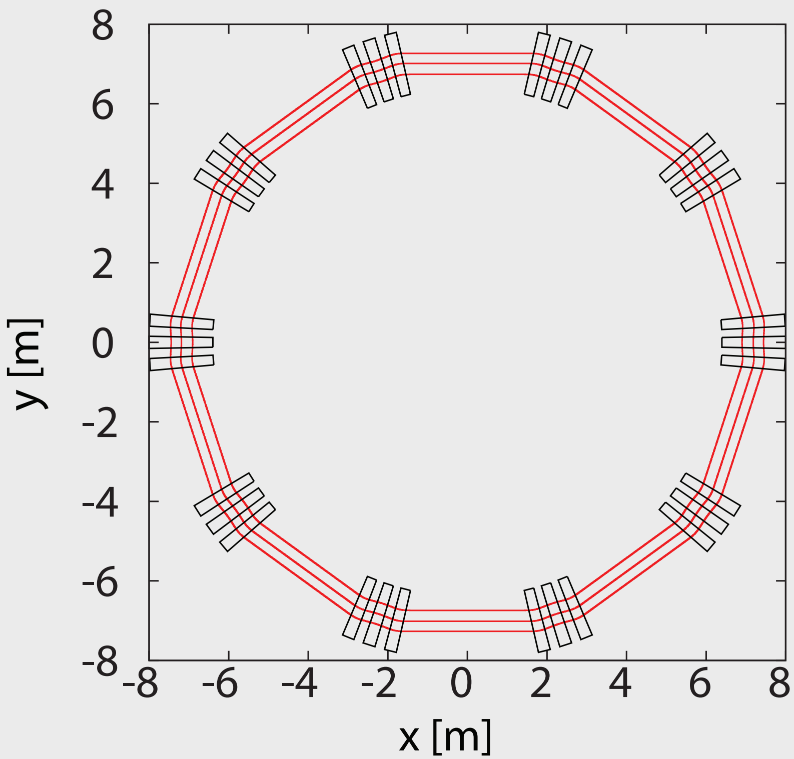
FFA

- PRISM (Phase Rotated Intense Source of Muons)

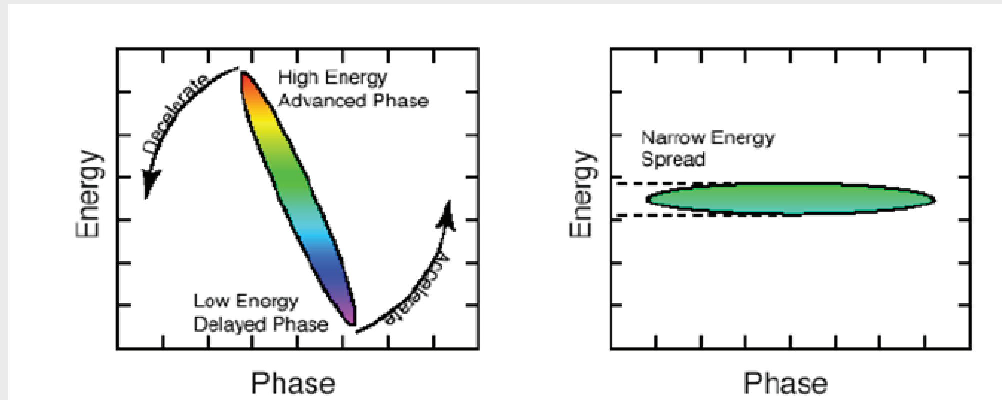
(arXiv:1310.0804 [physics.acc-ph])

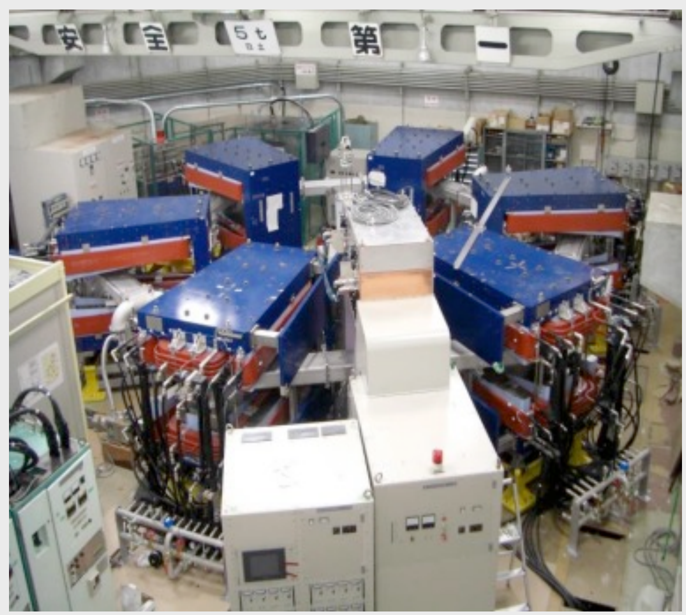
- EMMA, MuCol studies at higher momenta

https://indico.psi.ch/event/7313



~ 40 MeV/c central momentum; we actually want lower, ~15 MeV/c

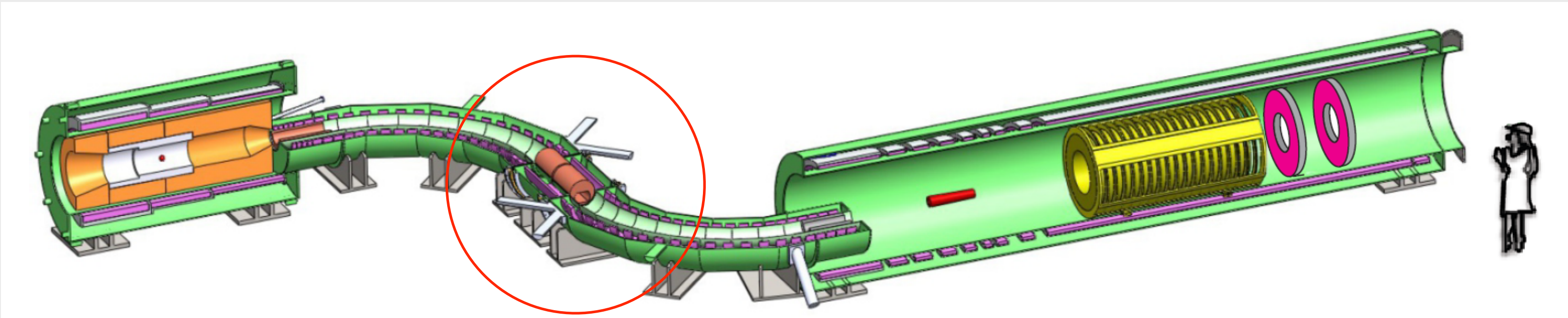




6 cell demonstrator at Osaka

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; rotate central collimator and get μ^- (charged particles traveling around a curved solenoidal field see effective centrifugal force)
  - will require detailed MCs to choose



Other ideas: Beam for Decay Experiments

- Reversing sign of solenoids not easy; initial proton beam doesn’t reverse charge and therefore follows a different trajectory inside solenoid, misses target, and then other “bad things”. But we could take beam out other end of solenoid…
- But is it possible to select muon momentum by “waiting?” Slowest, lowest energy muons are last and those are best.
  - enough beam to make this work, preliminary simulations indicate could work
- Active muon channel: *cooling ideas used in MuCol designs*
- Many ideas and will take a lot of work to sort through. Surface muons are conceptually simplest but we should be able to do better

Existing Attempts on Targeting

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

- Problem with a long history and a lot of thought:
  - liquid Hg in 1990's, moving away from that
  - MERIT experiment
- Tues AM session on Targeting:
  - Mori, Ximenes, Densham, Carrelli talks at this meeting

Calviani: https://indico.cern.ch/event/1016248/contributions/4282384/attachments/2215324/3752155/MCa__MUC_Targetry__25Mar2021_v1.pdf

Beam Technical Challenges

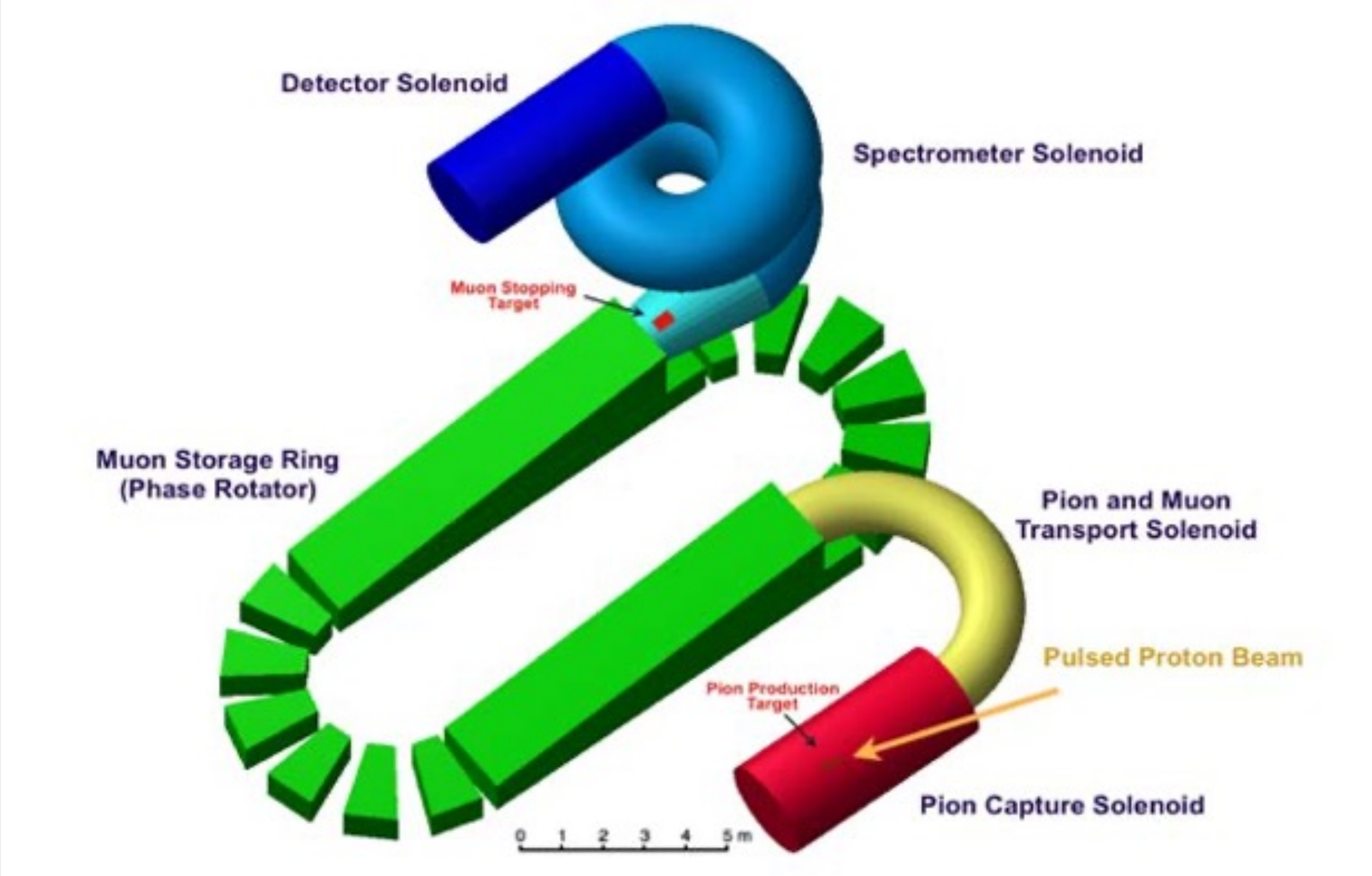
- Things that are very hard that we know how to do:
  - stopped muon beam at 1MW
  - compressor ring
  - FFA
- Things that are very hard that we don't know how to do
  - 1MW target inside a solenoid

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 $\mu^- N \rightarrow e^- N$

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



ENIGMA experiment

Overlaps

- Targeting inside a solenoid at up to 1MW
  - Does it make sense to use MuCol ideas about resistive/ superconducting solenoids for this program?
- Is an FFA the right answer, or are there cooling ideas to provide a better muon beam?
  - are there other ideas? PRISM is a large emittance beam in an FFA, is that the best option?
    - FFA solves a lot of problems: serves as a storage ring to let π's decay and we never see the beam flash
- Can this program either be a demonstrator for or a customer of a muon collider facility?

Summary

- Muon-based Charged Lepton Flavor Violation provides powerful searches and constraints for BSM physics
- A new facility at FNAL could provide all three muon channels, $\mu \to e\gamma, \mu \to 3e,$ and $\mu N \to eN$ with orders of magnitude more data and open new possibilities in $\mu N \to eN$ at high Z
    - plus a dark matter experiment and other muon measurements not discussed.
    - technical challenges directly related to muon collider R&D:
        - solenoid, targeting, and FFA are common
        - We hope for P5 to recommend design of the program with submission to next P5