Charged Lepton Flavor Violation Experiments with Muons:

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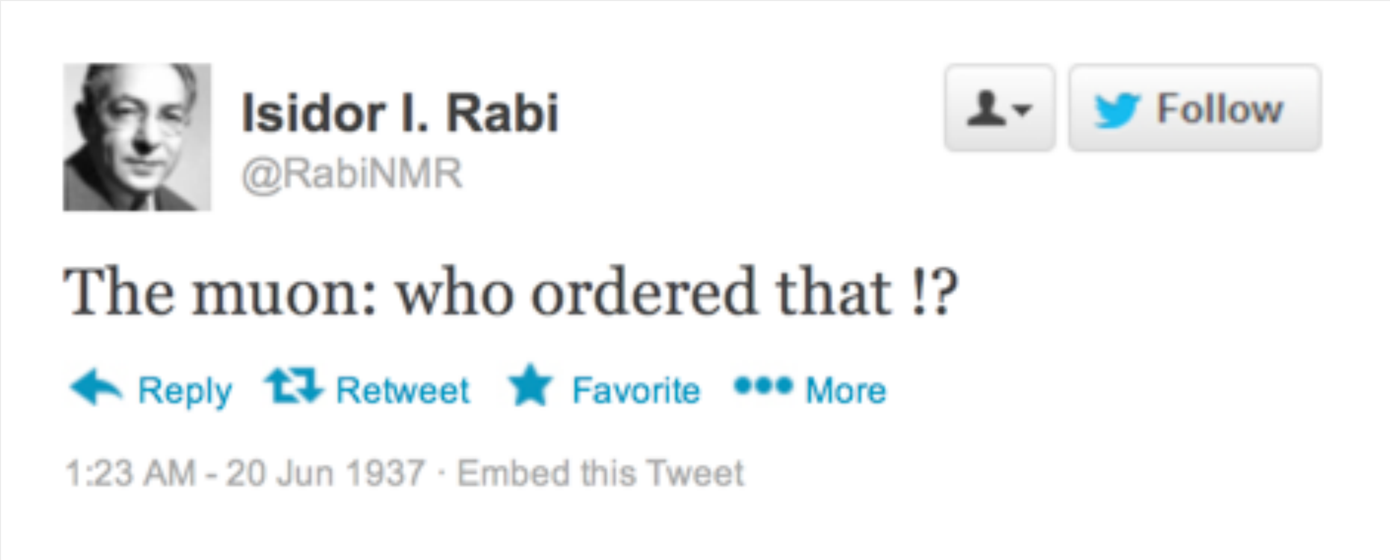
Topics

- What is Charged Lepton Flavor Violation (CLFV) and how does it relate to flavor physics in general?
- Why do CLFV experiments with muons?
- What are the experiments that will be done in muon beams, and what are their contributions?
- A few words about collider CLFV and 3rd generation

Problem of Generations



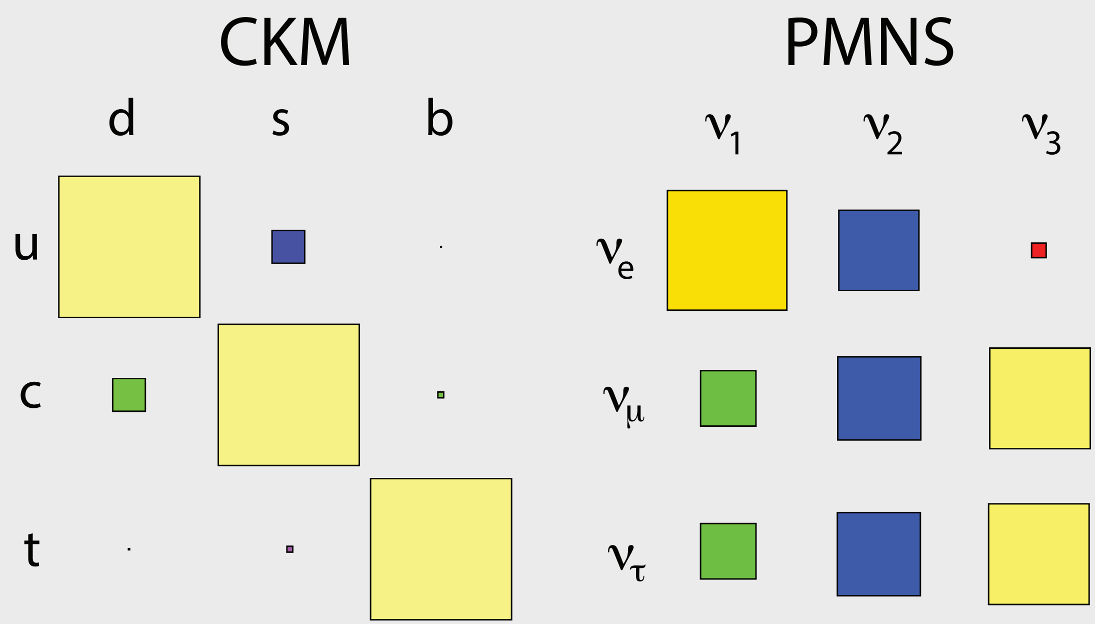
- Why are there generations at all?
- three generations of quarks; three of leptons, three of neutrinos
- why more than one? why three?

Flavor Physics

- Flavor is the name we give to the physics that distinguishes the generations
  - are quark flavors related to lepton flavors?
  - is there flavor universality?
    - from $B \to Kll$ ratios to $\pi \to l\nu$
  - *what is flavor? why are there generations? we don't know.*
- One of our Snowmass conclusions was that flavor should have its own P5 "driver"

Flavor Physics and Mixing

- Quarks and neutrinos (*aka* neutral leptons) change flavor
- PMNS and CKM matrices are very different

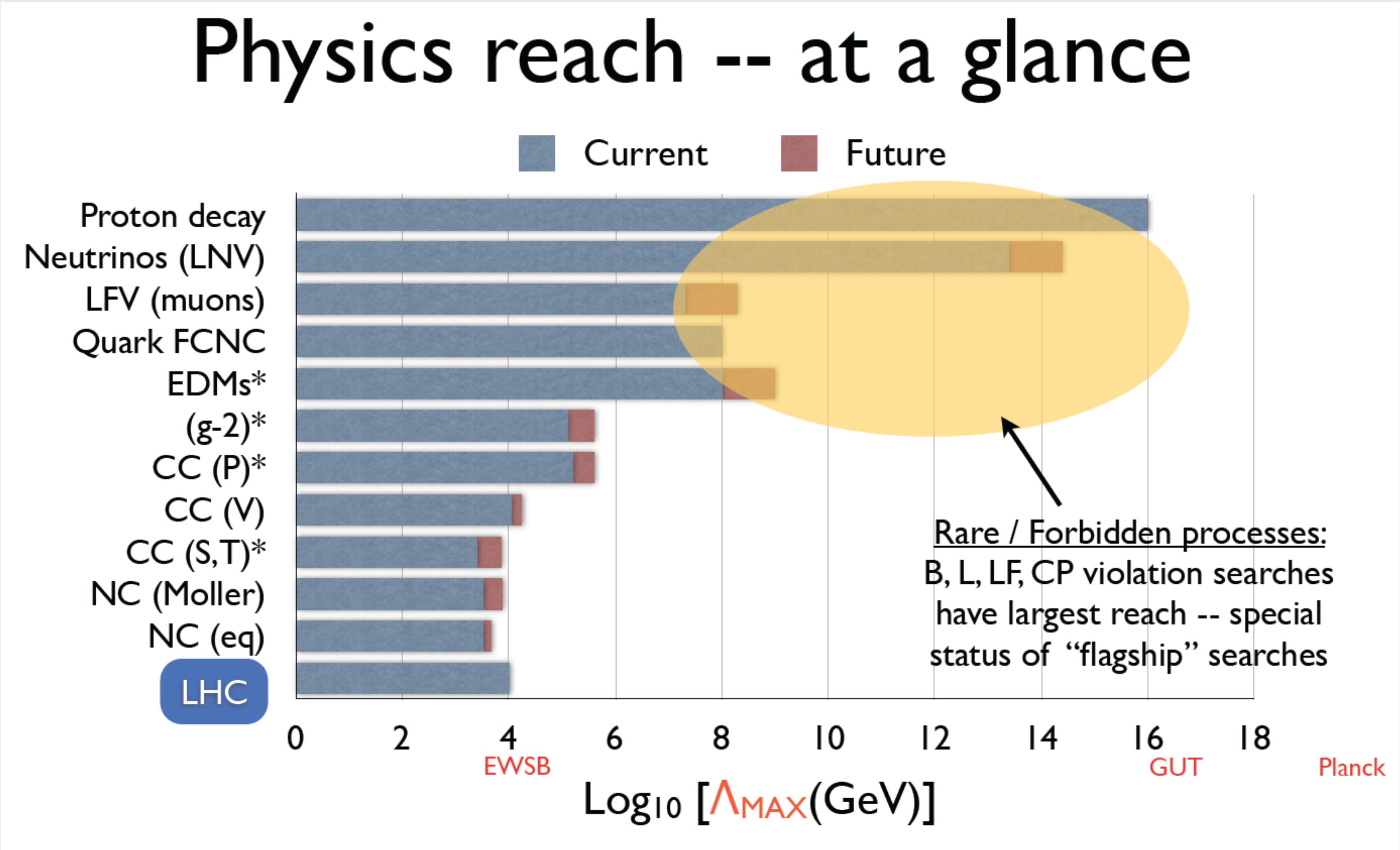


box $\propto V_{ij}^2$

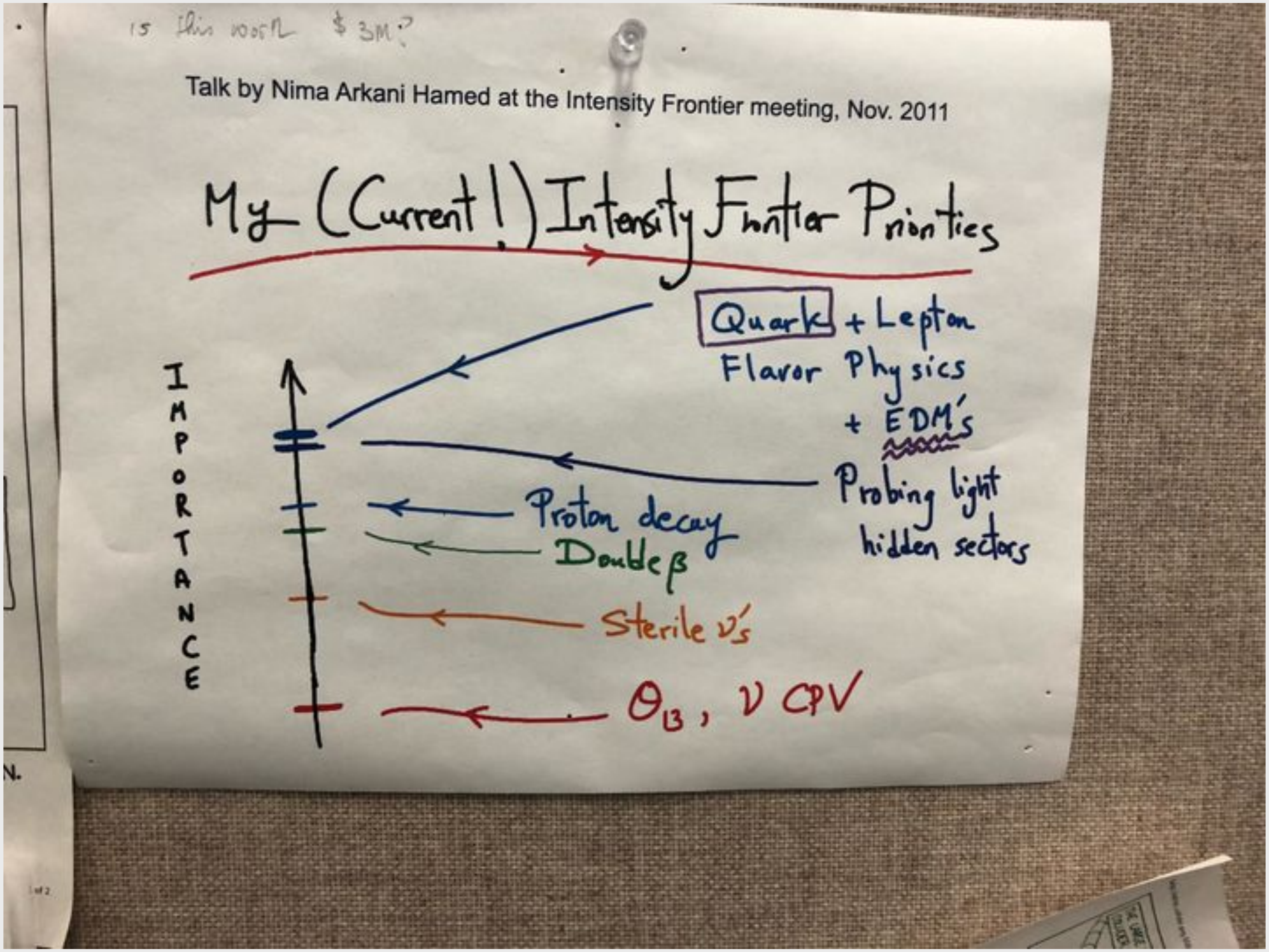
- why don't charged leptons change flavor?

Rare Processes and Precision Measurements

adapted from V. Cirigliano and M.J. Ramsey-Musolf, 1304.0017

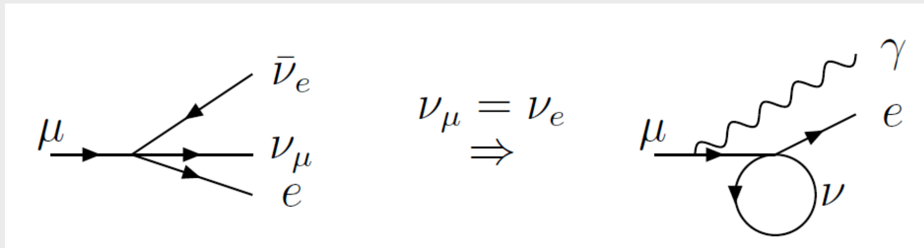


So Flavor Physics is Interesting



CLFV and Neutrinos

Feinberg, 1958

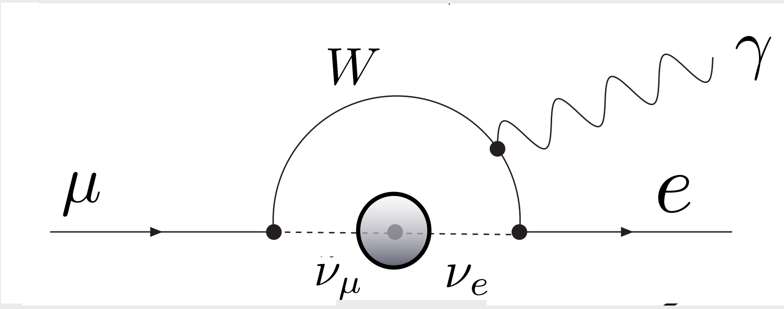


[1]Unless we are willing to give up the 2-component neutrino theory, we know that $\mu \to e + \nu + \bar{\nu}$.

- $\mu \to e\gamma$ "should" be around 10^{-4}
- observed suppression implied
  - the muon is not just an excited electron
  - at least two neutrinos

Neutrino Background

- Neutrino Oscillations are the only Standard Model background, except neutrino oscillations are not in the Standard Model



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

- nobody understood why $\mu \to e\gamma$ wasn't 10^{-4} until we hypothesized two neutrinos ($\nu_\mu \neq \nu_e$)!

CLFV Muon Processes

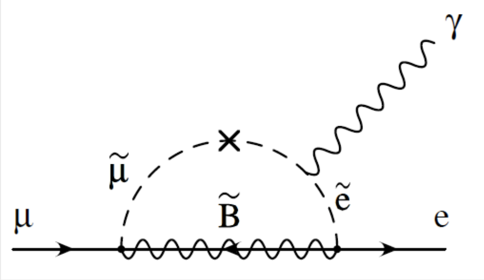
- ***$\mu \rightarrow e\gamma$***
  - oldest studied, most powerful limits, and the best experiment so far: MEG at PSI
- ***$\mu N \rightarrow eN$***
  - muon to electron conversion: muon converts in field of nucleus, leaving nucleus unchanged

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

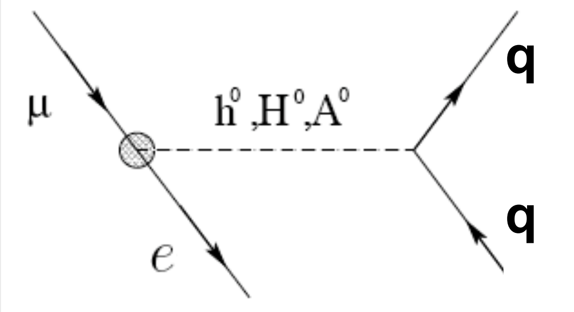
  - two experiments upcoming at FNAL and JPARC
- ***$\mu \rightarrow eee$***
  - ambitious and unique, excellent partner to other two (at PSI)

What New Physics Can Muons See?

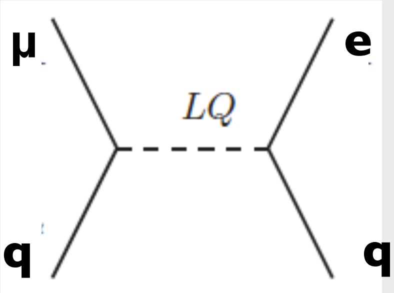
- Each of these diagrams has a different sensitivity in $\mu \rightarrow e\gamma$, and $\mu \rightarrow 3e$, and $\mu^{-}N \rightarrow e^{-}N$
- All three in order to pin down a signal or increase constraints



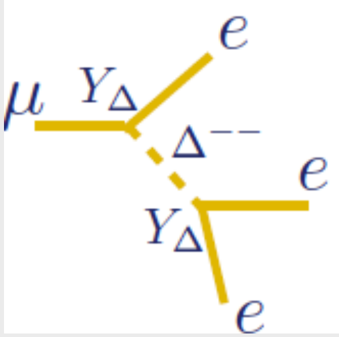
Dipole: SUSY-GUT and SUSY see-saw scenarios, …



Scalar: RPV SUSY and RPC SUSY for large tan(β) and low m_A, leptoquarks, …



Vector Type III seesaw, LRSM, leptoquarks, …



$+\ldots$

V. Cirigliano

4-lepton: Type II seesaw, RPV SUSY, LRSM, …

Effective Lagrangian

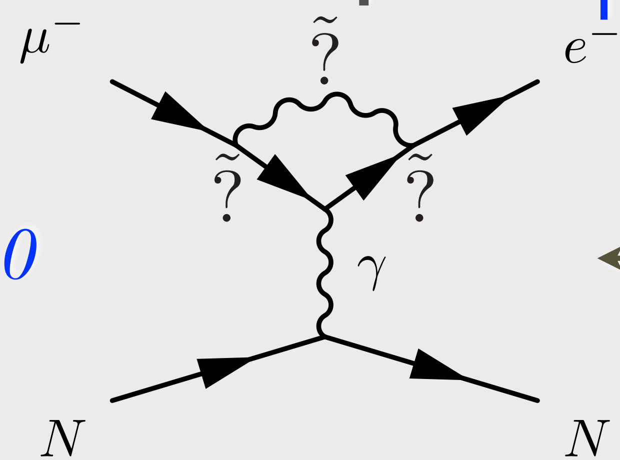
$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

"Loops"

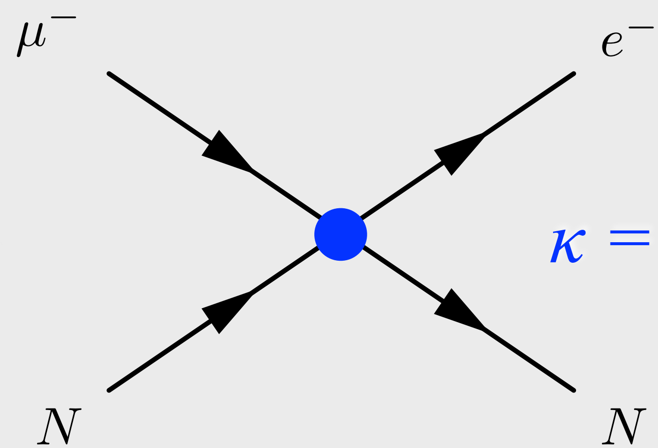
mass scale Λ

"Contact Terms"

$\kappa = 0$



κ ⟷



$\kappa = \infty$

Supersymmetry and Heavy Neutrinos

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

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

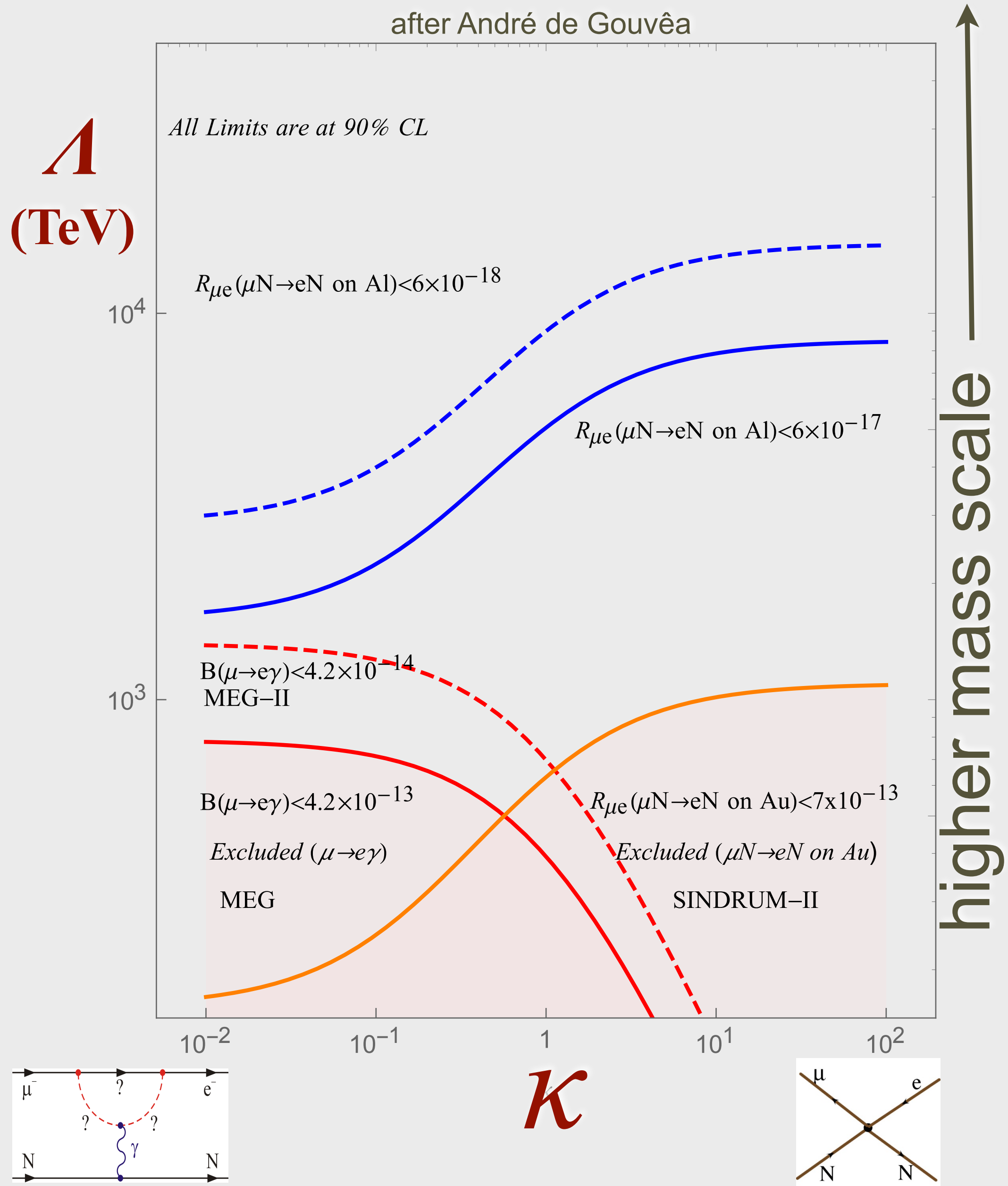
Does not produce $\mu \to e\gamma$

μe Conversion and $\mu \to e\gamma$

1) *Mass Reach to ~10⁴ TeV for unit coupling, x10000 existing experiments*

2) *Mu2e/MEG upgrade complementary in loop-dominated physics.*

3) *These are discovery experiments*

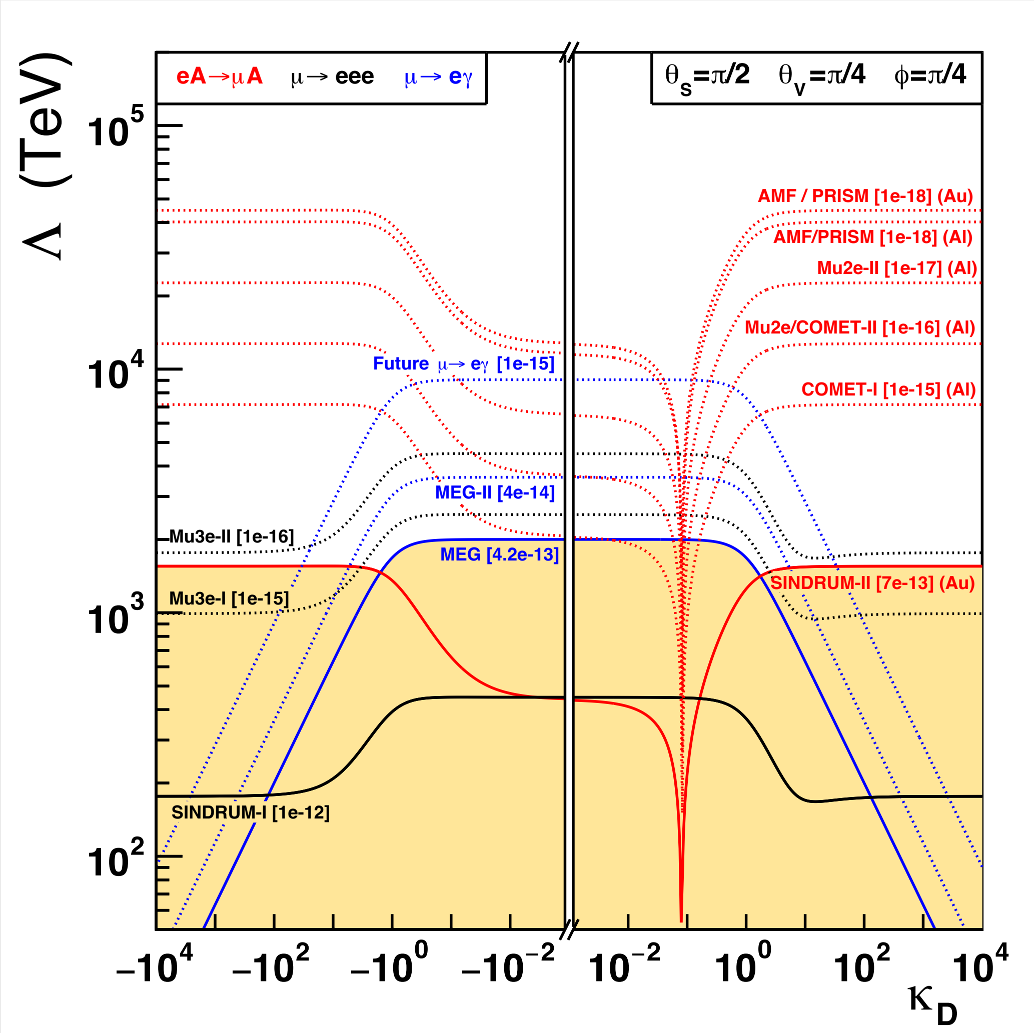


EFT: beyond κ and Λ

- 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

Mass Reach

Davidson-Echenard 2204.00564

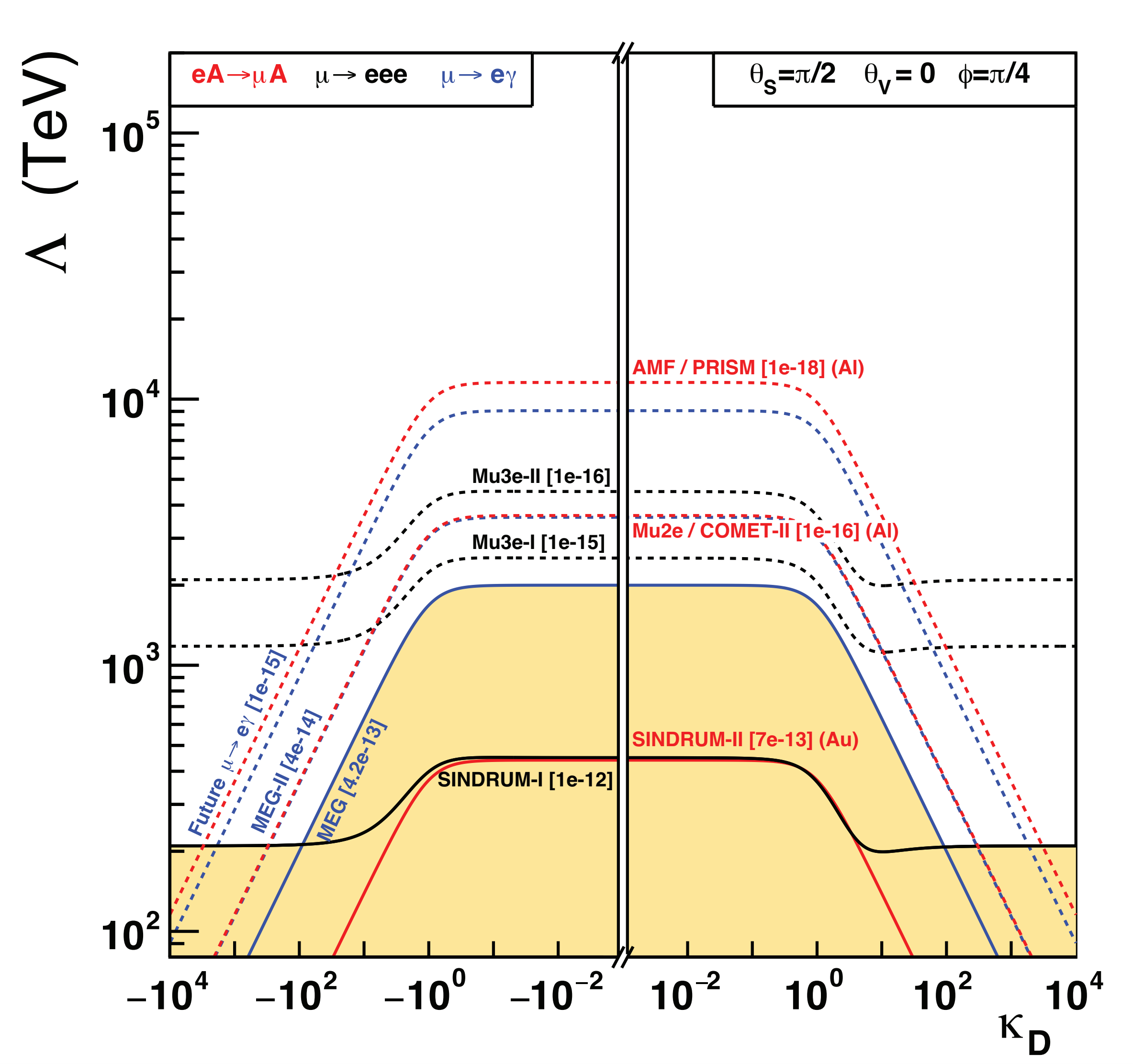


- Mass scales of $10^3 - 10^5$ TeV
- "Best Probe" doesn't exist; depends on model

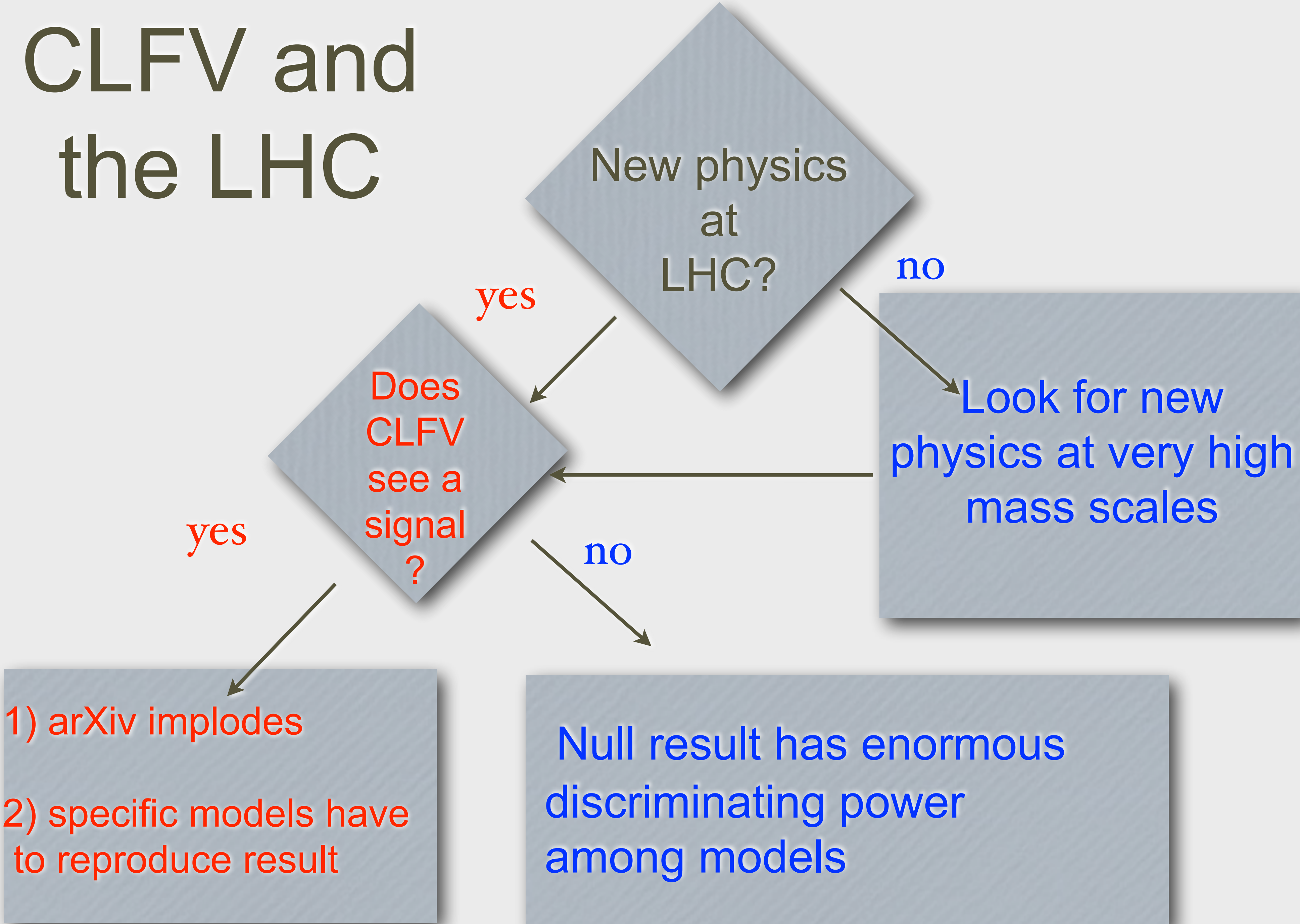
like κ; $|\kappa_D| << 1$ dipole dominant; $|\kappa_D| >> 1$ four-fermion dominant

All Three Muon Experiments

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



CLFV and the LHC



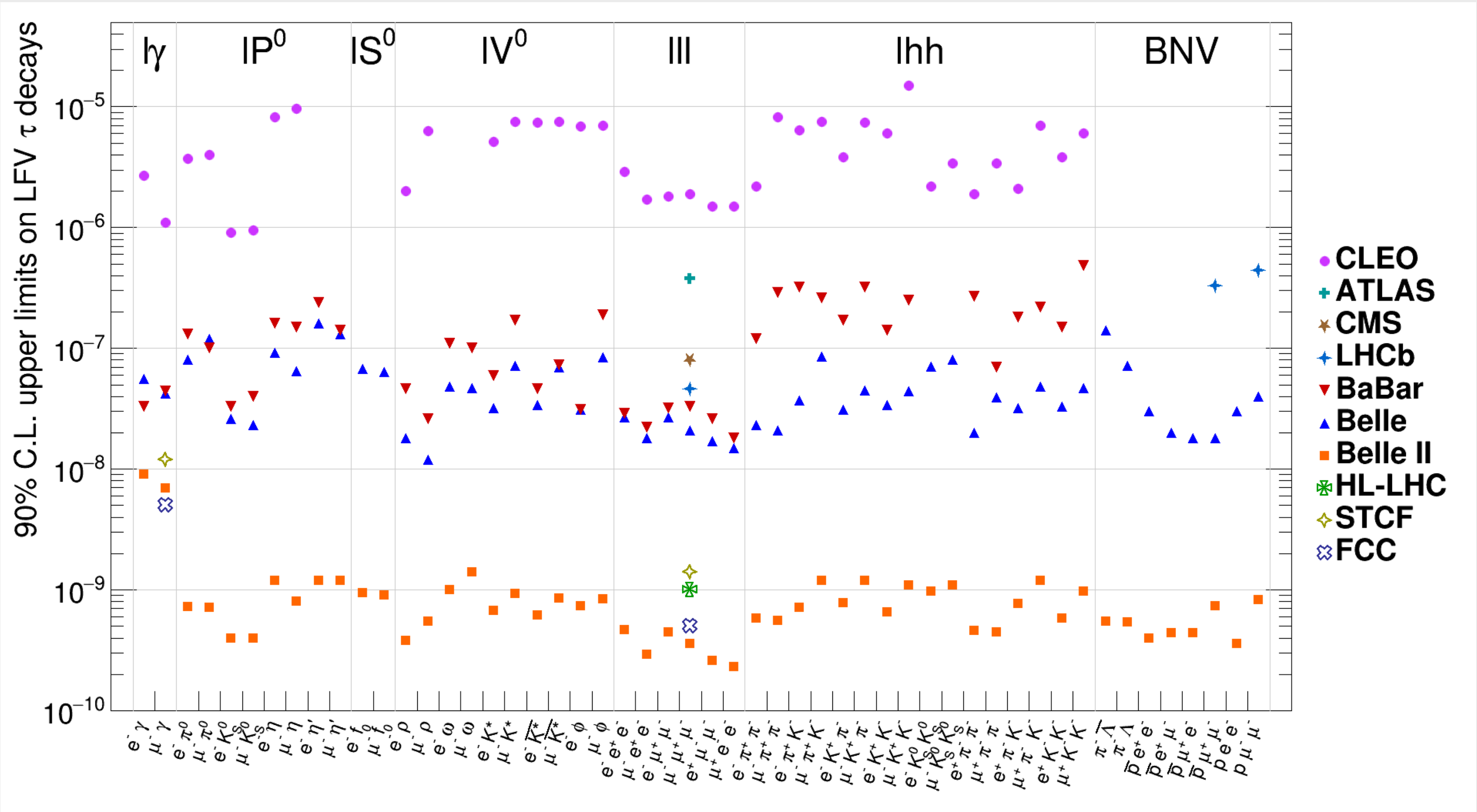
Why Muons

Facility		Experiment	stopped μ/sec
PSI	μ^+	MEG, Mu3e	few $\times 10^8$
PSI/HiMB	μ^+	MEG, Mu3e	$\mathcal{O}(10^{10})$
J-PARC	μ^-	COMET Phase I	3×10^{10}
		COMET Phase-II	7×10^{10}
FNAL	μ^-	Mu2e	3×10^{10}
FNAL/PIP-II	μ^-	Mu2e-II	3×10^{11}
FNAL-AMF	$\mu^\pm$	ENIGMA	$\mathcal{O}(10^{13})$

BR's 10^{-13} to 10^{-20} depending on mode

Compare to τ's

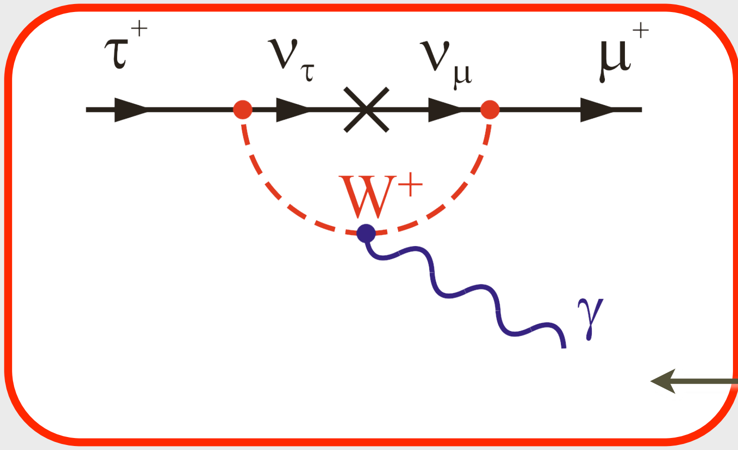
- Smaller samples



CLFV and τ Decays

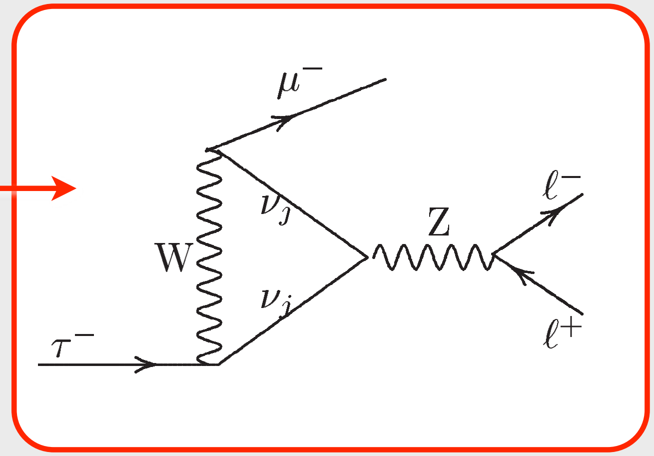
τ processes also suppressed in Standard Model but less:

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

Swagato Banerjee, this conf.

Stopped vs. Capture

- Decay experiments: $\mu^+ \to e^+\gamma,\ \mu^+ \to 3e$
  - bring positive muons to rest in material and let them decay
  - best in the world with "stopped muon beam" at PSI
  - want a "DC" beam to minimize accidental coincidences from two events. PSI perfect.
- Capture experiments: $\mu^- N \to e^- N$
  - bring negative muons to rest; fall into 1s state; interact with nucleus.
  - want a "pulsed" beam of order muon lifetime to eliminate π-induced background

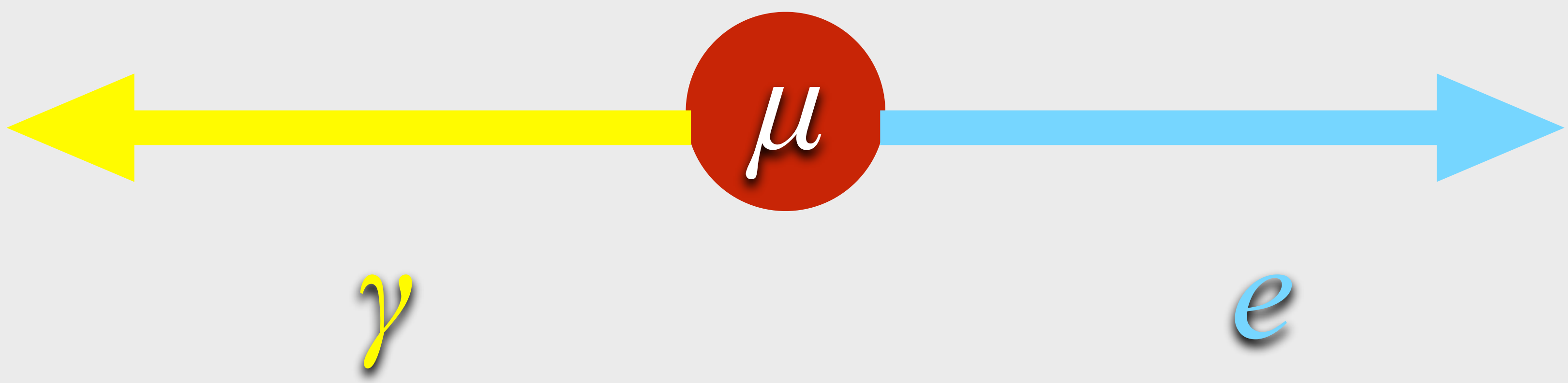
MEG and $\mu \to e\gamma$

- Kinematics simple:
  - back-to-back and γ and e in-time

$$\theta_{e\gamma} = 180^\circ$$

$$E_e = E_\gamma = 52.8 \text{ MeV}$$

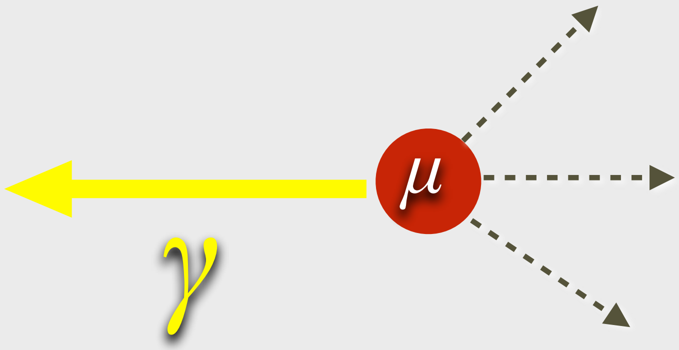
$$T_e = T_\gamma$$



Backgrounds

- Accidental: Dominant

scales as I^2



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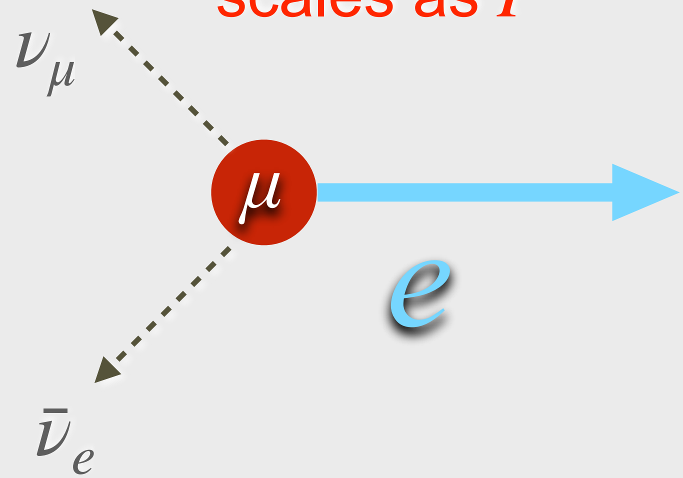
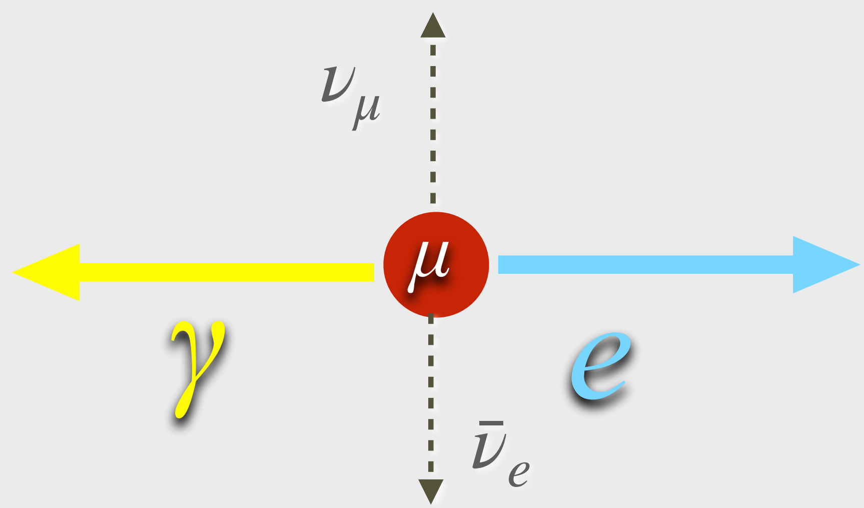
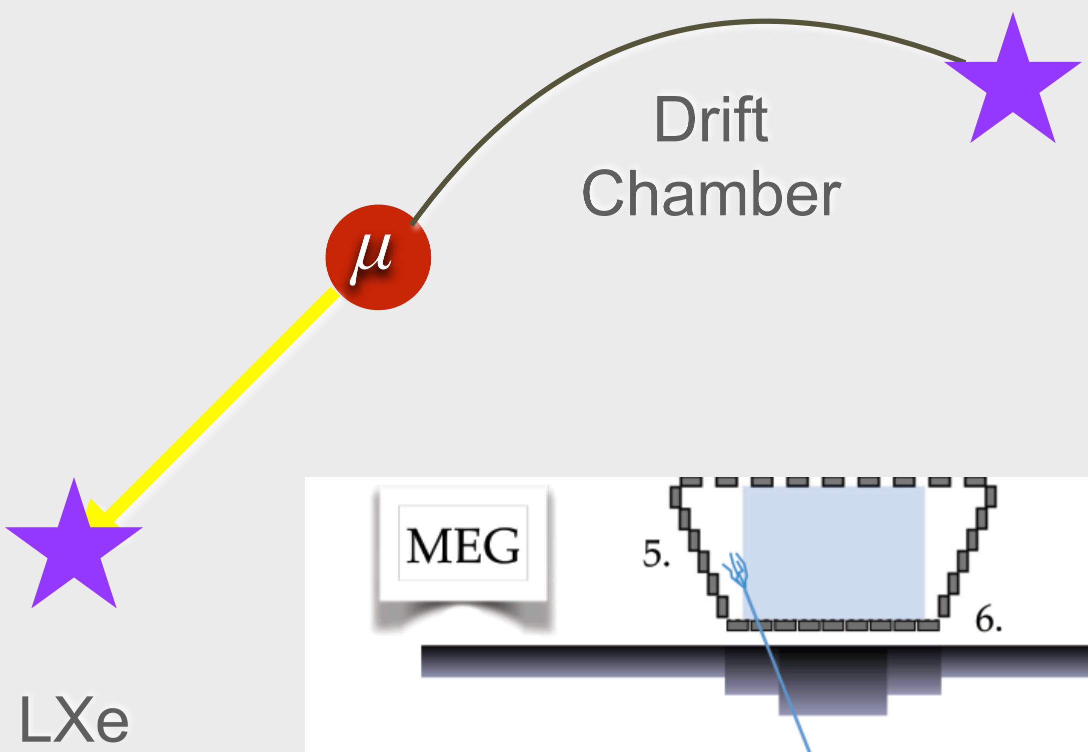


photon produced in muon stop + Standard Model weak decay

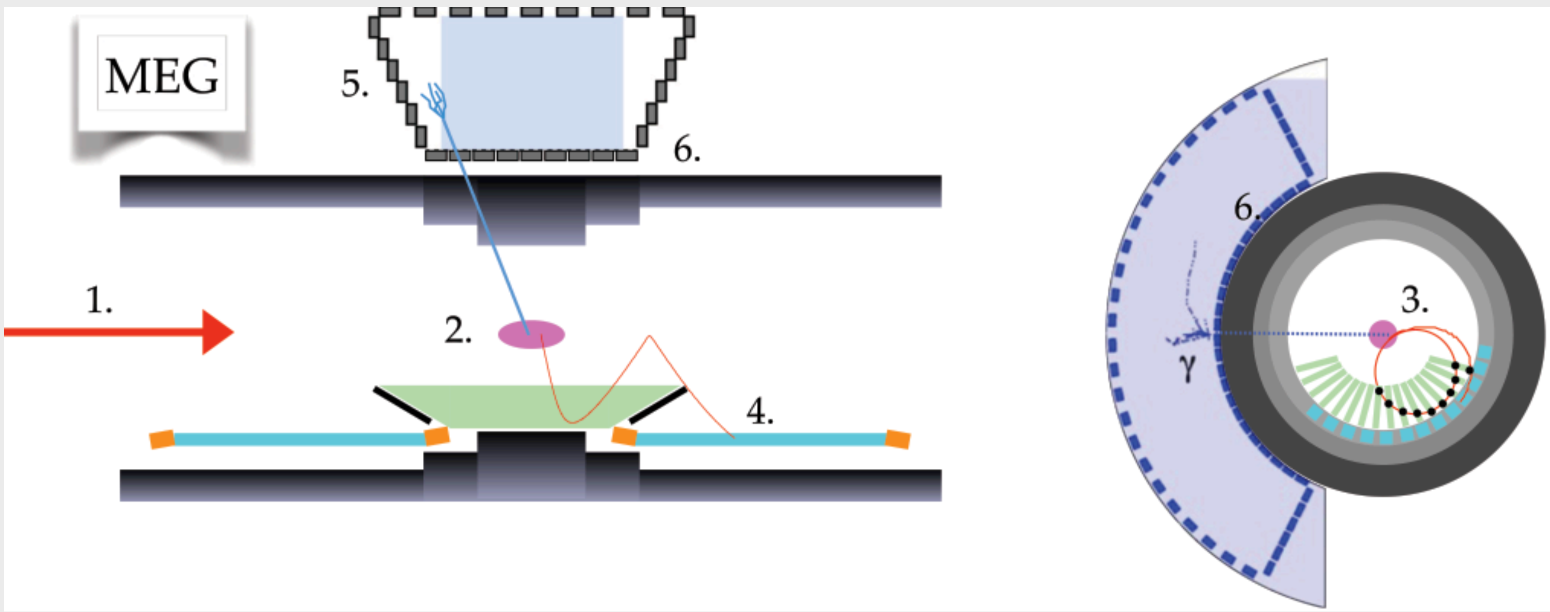
- Radiative Muon Decay
  - neutrinos have small energy/momentum



MEG Experiment



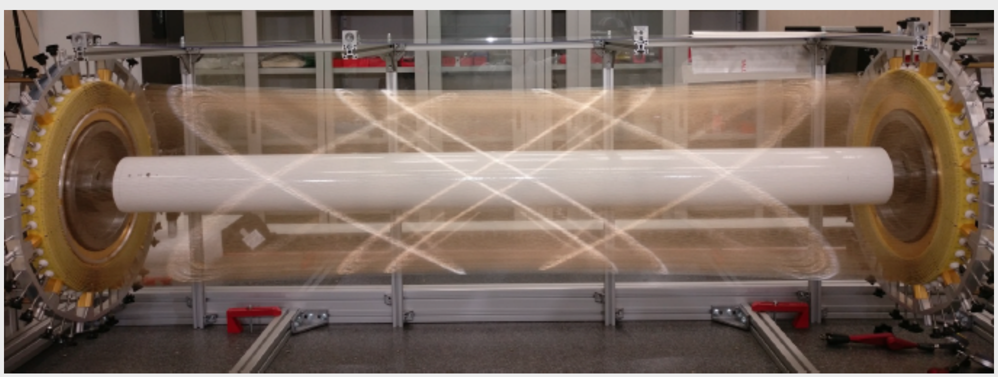
N_{acc}= 7684 ± 103
N_{RMD}= 663 ± 59
N_{sig}(best fit) = -2.2
BR < 4.2 x 10^{-13} @ 90% C.L.
Eur. Phys. J. C76, 434 (2016)

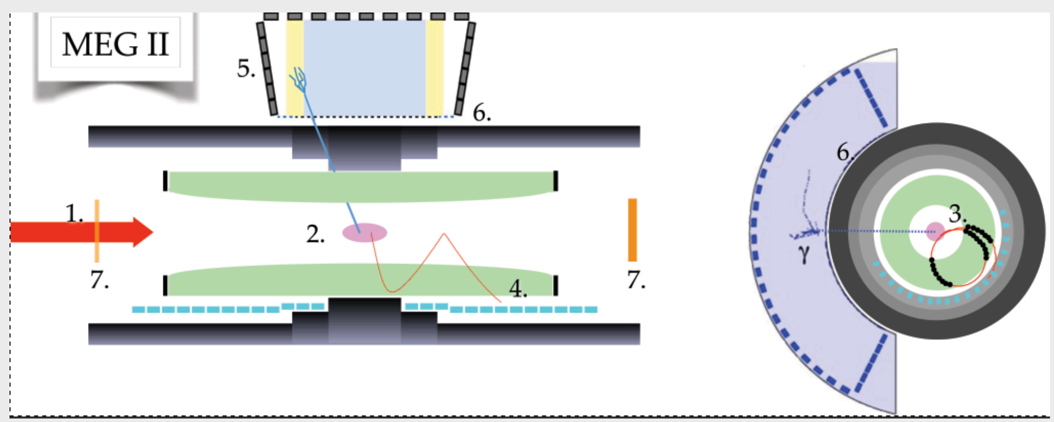


MEG-II Upgrade

Renga, 10.22323/1.405.0058

- Improve Calorimeter, Timing, Drift Chamber, Trigger
- First physics run in 2021, analysis underway
- x10 improvement to 4×10^{-14} @ $90\,\%$ CL



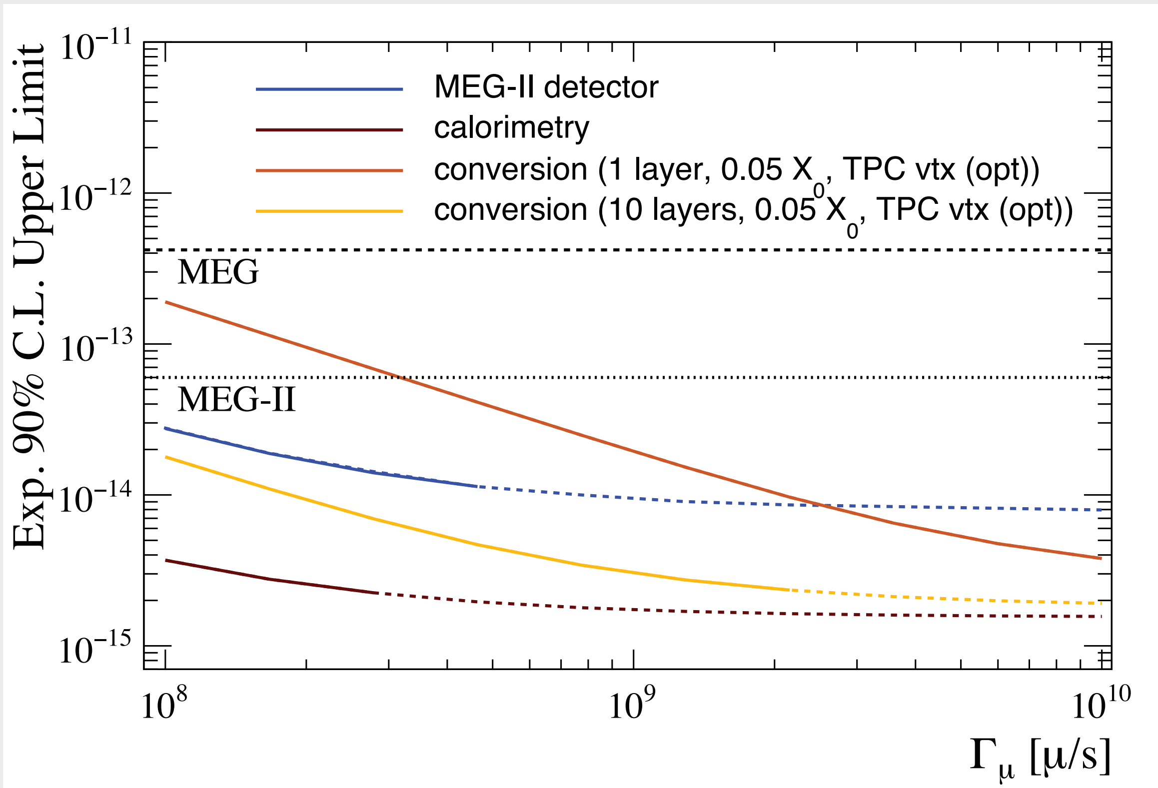


What's Next?

- HiMB PSI upgrade will increase muon rate by x10 post 2028
- but at some point resolutions make experiment background-dominated
- converting photon would allow forming a vertex
  - right now don't know vertex since the calorimeter measures a space point far from decay point
- but conversion loses ~x100 in rate
  - need a thin converter or too much dE/dx, MS

Limits on Experiment

- Methods level out after $\mathcal{O}(10^9)\mu/\mathrm{sec}$ with or without conversion



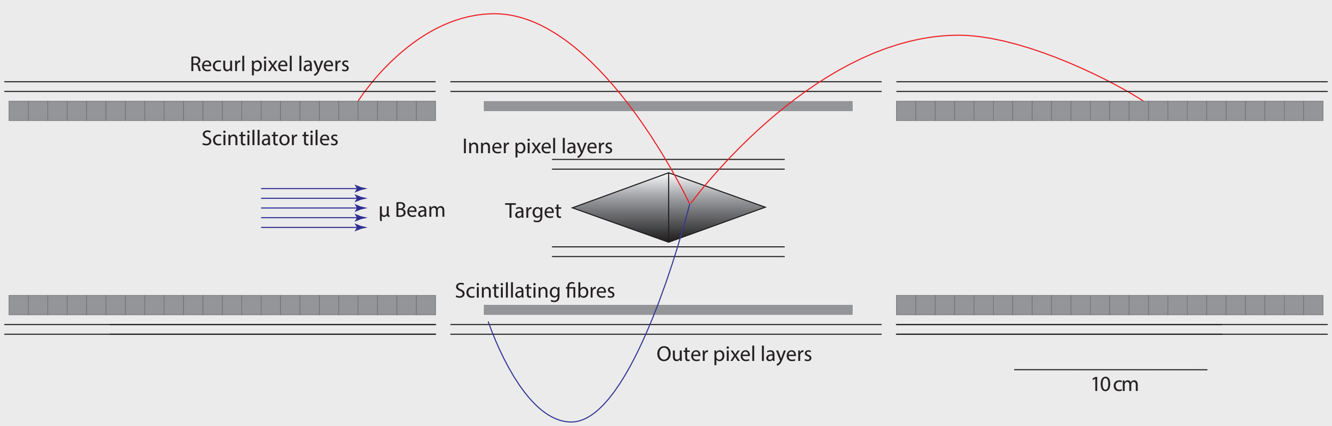
Renga et al., https://arxiv.org/pdf/1707.01805.pdf

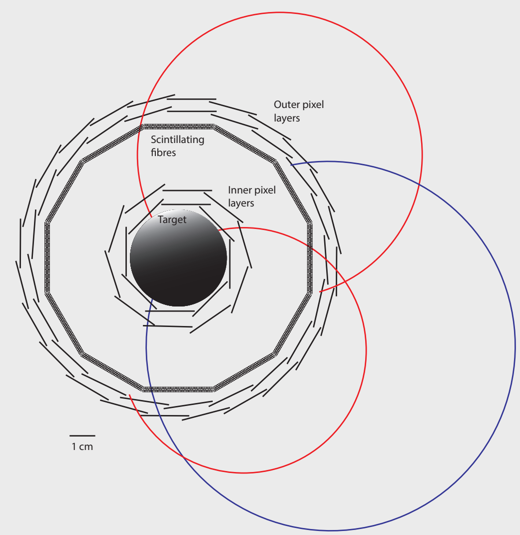
MEG-III?

- New experimental concepts required for use of HiMB rate
  - decay ring?
  - Active target/better vertexing?
  - Under study
  - Can it use AMF at FNAL?

Mu3e: $\mu \rightarrow 3e$

- We established this is different physics from $\mu \rightarrow e\gamma$ and $\mu^- N \rightarrow e^- N$
- Get a vertex from three tracks, but lose back-to-back constraint of $\mu \rightarrow e\gamma$
- Background is $\mu^+ \rightarrow e^+(e^+e^-)\bar{\nu}_\mu \nu_e$ with small neutrino four-momenta



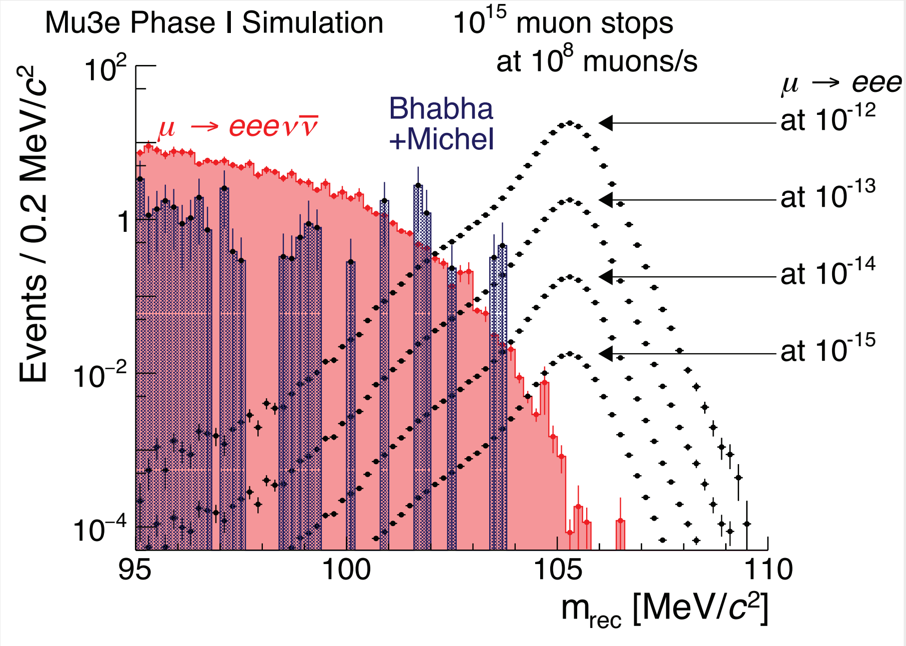


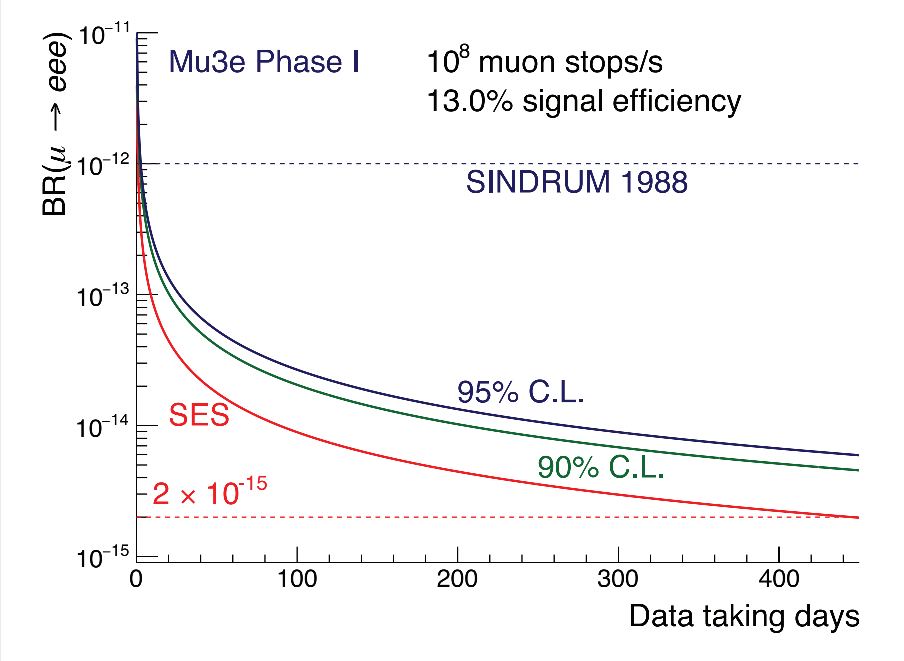
Hesketh et al., 2204.0001

Mu3e Outlook

- Phase-I 2024 is before HiMB at 2×10^{-15} @ 90 % CL

- Phase-II post 2028 at $\mathcal{O}(10^{-16})$





- also $\mu^+ \to e^+ X$ and into long-lived $X \to e^+ e^-$

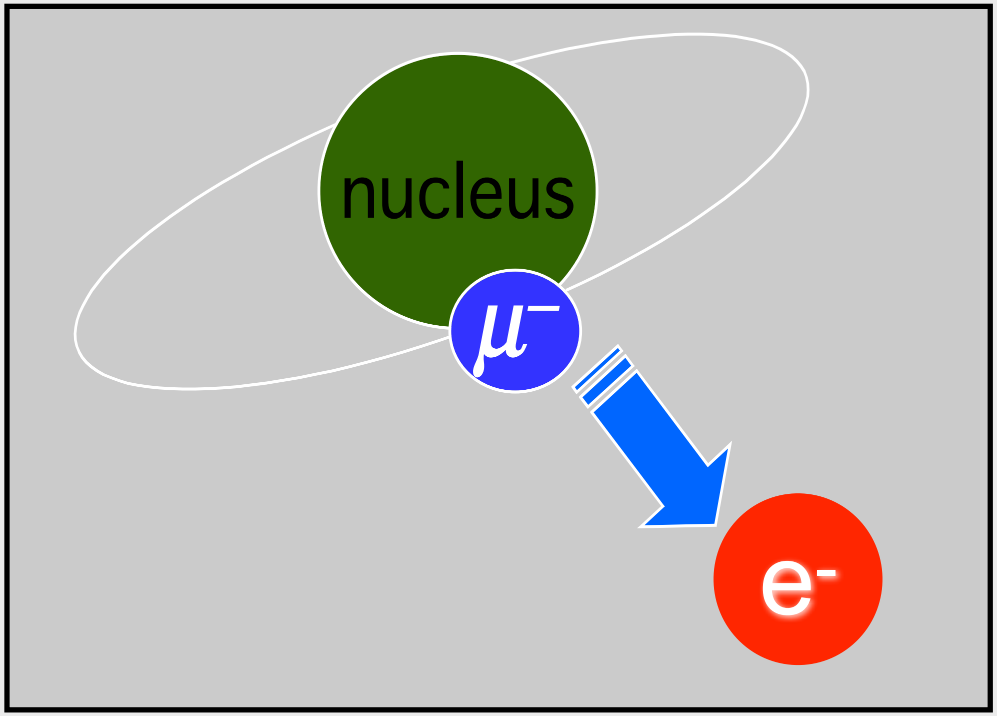
What is Muon to Electron Conversion?

$$\mu^- N \to e^- N$$

- Muon converts to an electron in the field of a nucleus

- Signal is mono-energetic electron ~ muon mass

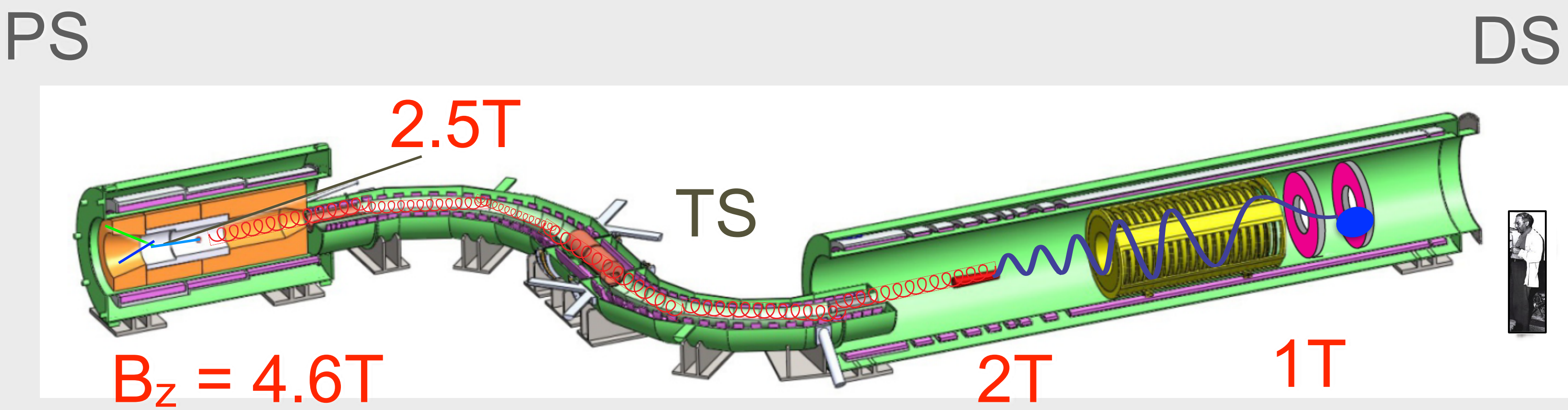
- Mu2e or COMET
  $90\,\%\ \mathrm{CL} \Rightarrow 8 \times 10^{-17}$;
  $5\sigma \Rightarrow 2 \times 10^{-16}$



Mu2e Method

with apologies to our COMET friends; experiments are similar but important differences; ask me

- Three solenoids
  - produce and capture muons (PS)
  - transport to Al stopping target (TS)
  - detect signal electrons (DS)

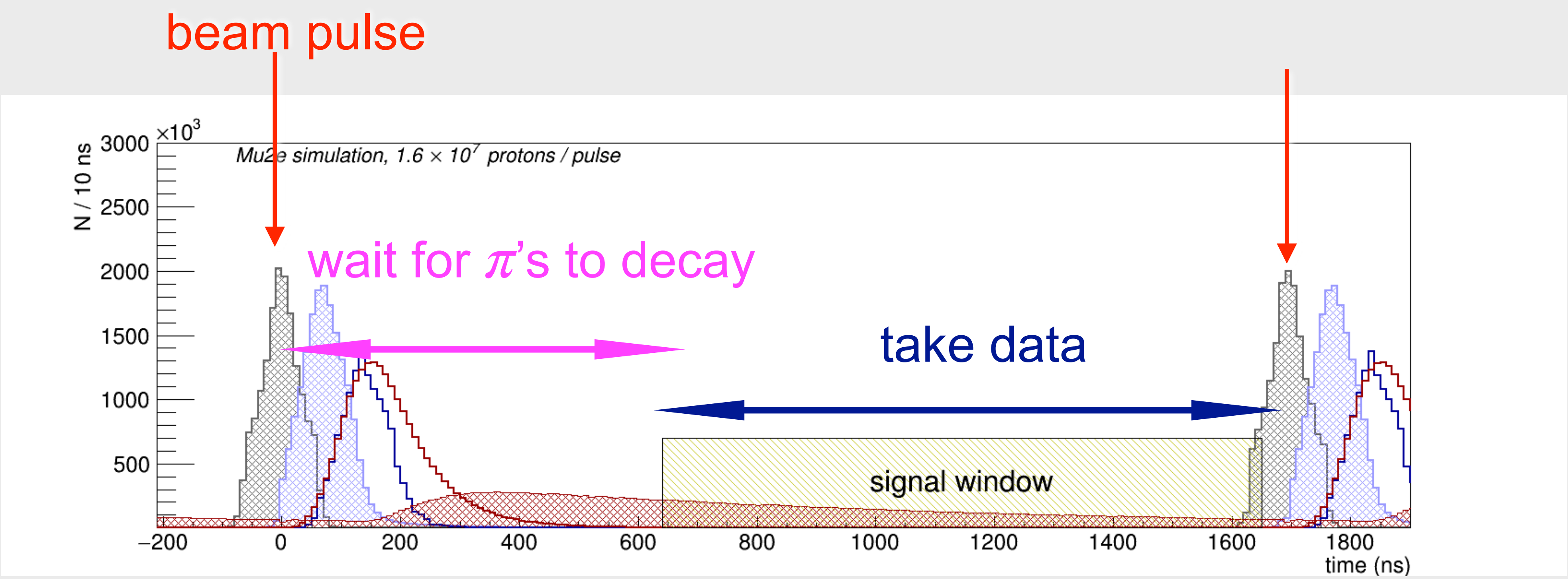


Mu2e Time Structure

- We get μ's from pN in production target:
  $p + \text{ Target} \rightarrow \pi$, then $\pi \rightarrow \mu$
- sometimes π's live long enough to make it to Al target
  - Radiative Pion Capture: $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+ e^-$
  - if we see only e^- and it is near muon mass, it is a background
- this limited PSI versions since their beam is "DC" and can't take advantage of short π lifetime relative to μ

Pulsed Beam

- Beam pulses are 1695 ns apart, set by FNAL rings
  - fortunate coincidence when compared to 2.2 μs lifetime!

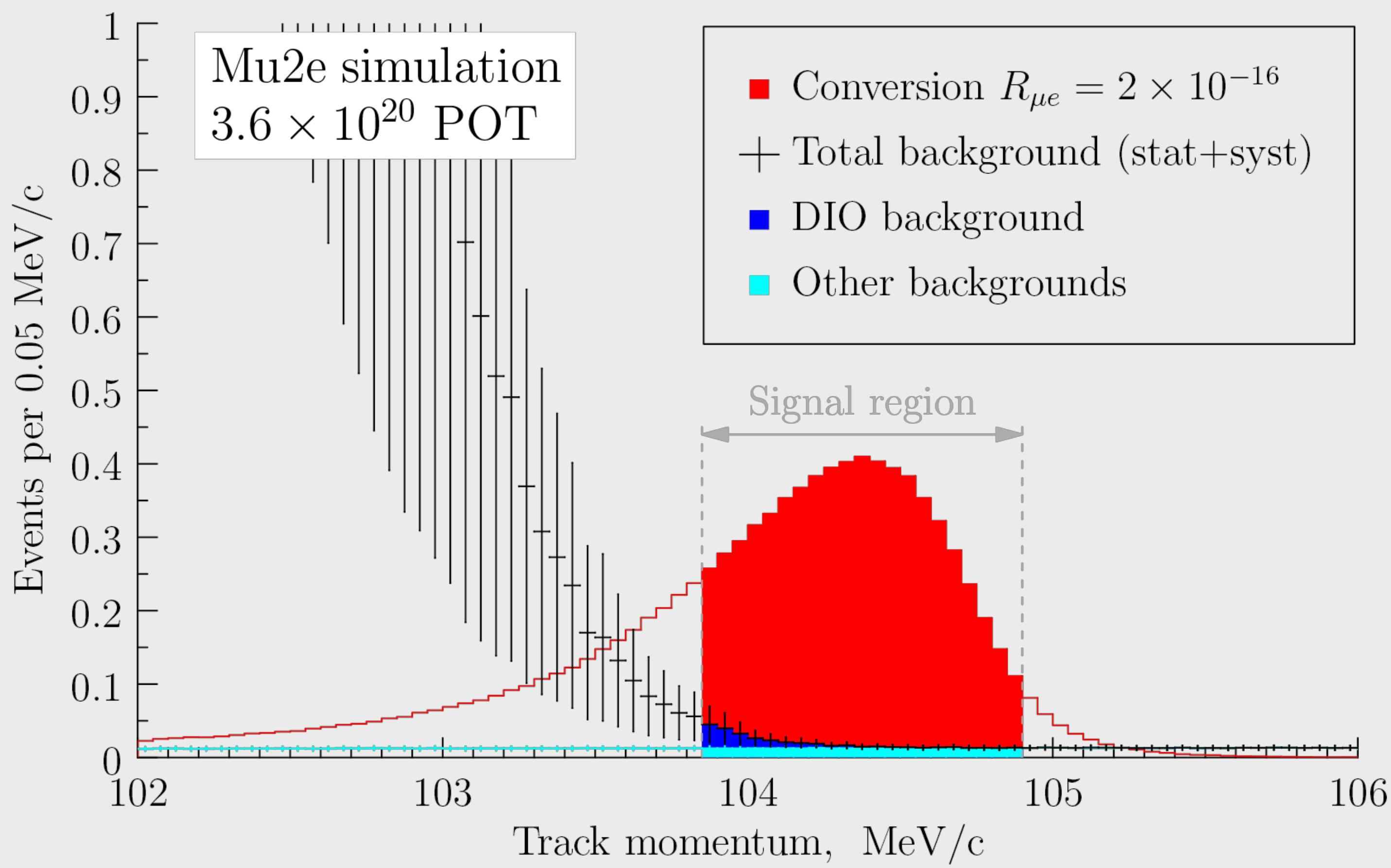


Mu2e Reach

90% CL ~ 8 x 10^{-17} 5σ~ 2 x 10^{-16}

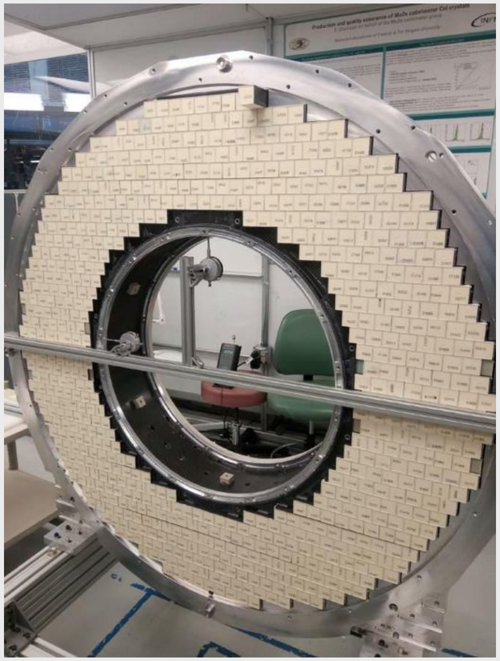
x10000 better than existing limit

Mu2e

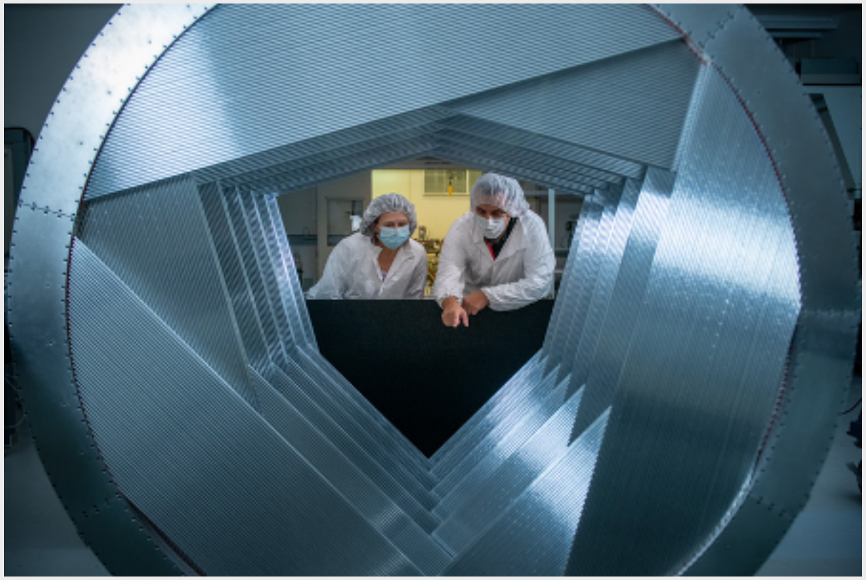


typical SUSY at 10^{-15}: 40 events vs 0.4 bkg

Mu2e Schedule



- x1000 existing experiments by 2025
  - in construction!
- x10000 by end-of-decade

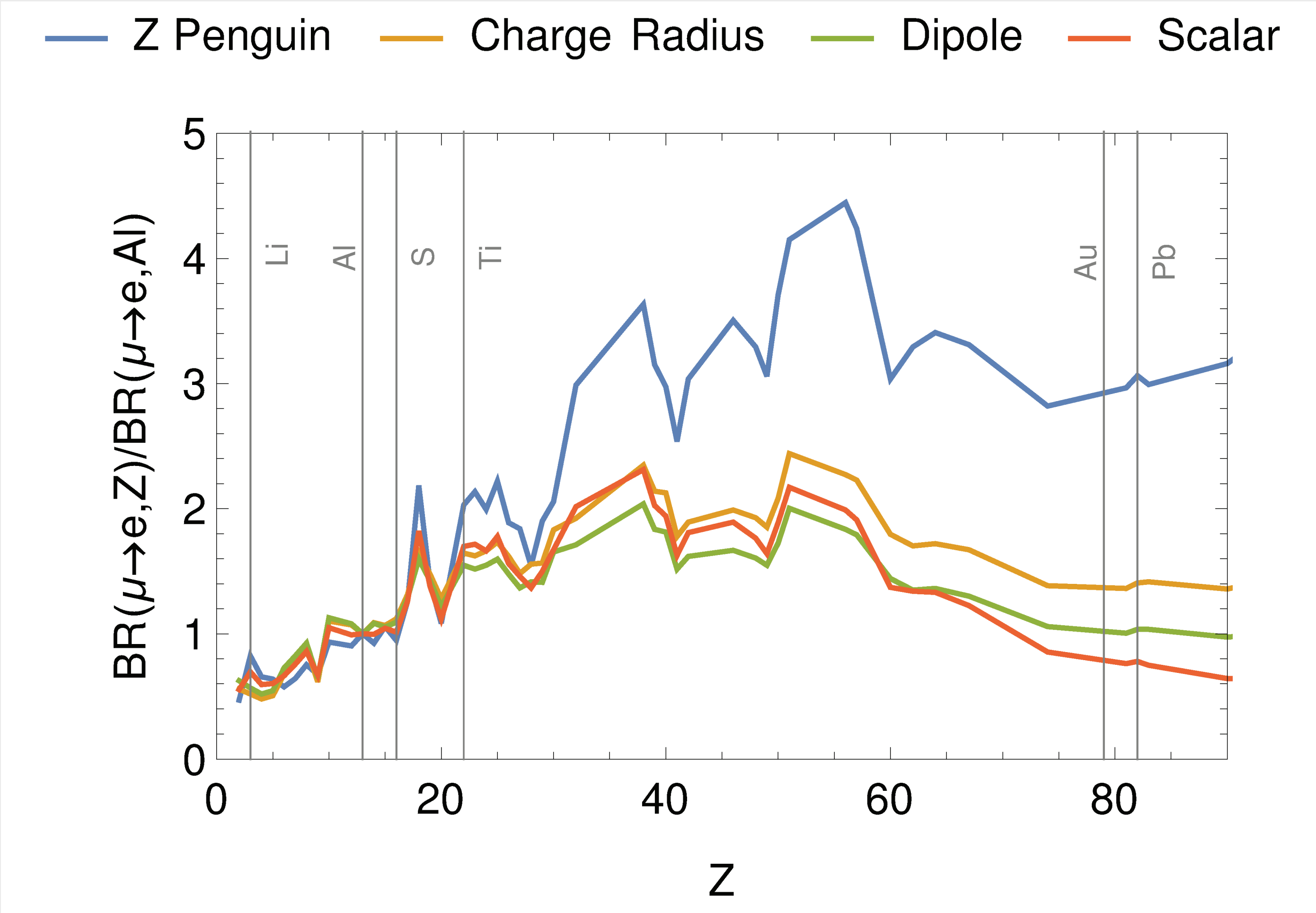


What Next?

- Mu2e-II
  - x10 limits and move to Ti; about x2 higher rate
  - re-use Mu2e as much as possible
  - being designed, will run after Mu2e
- Mu2e and Mu2e-II can’t probe high *Z*

Probing High Z

- different operators split at high *Z*, distinguishing among models

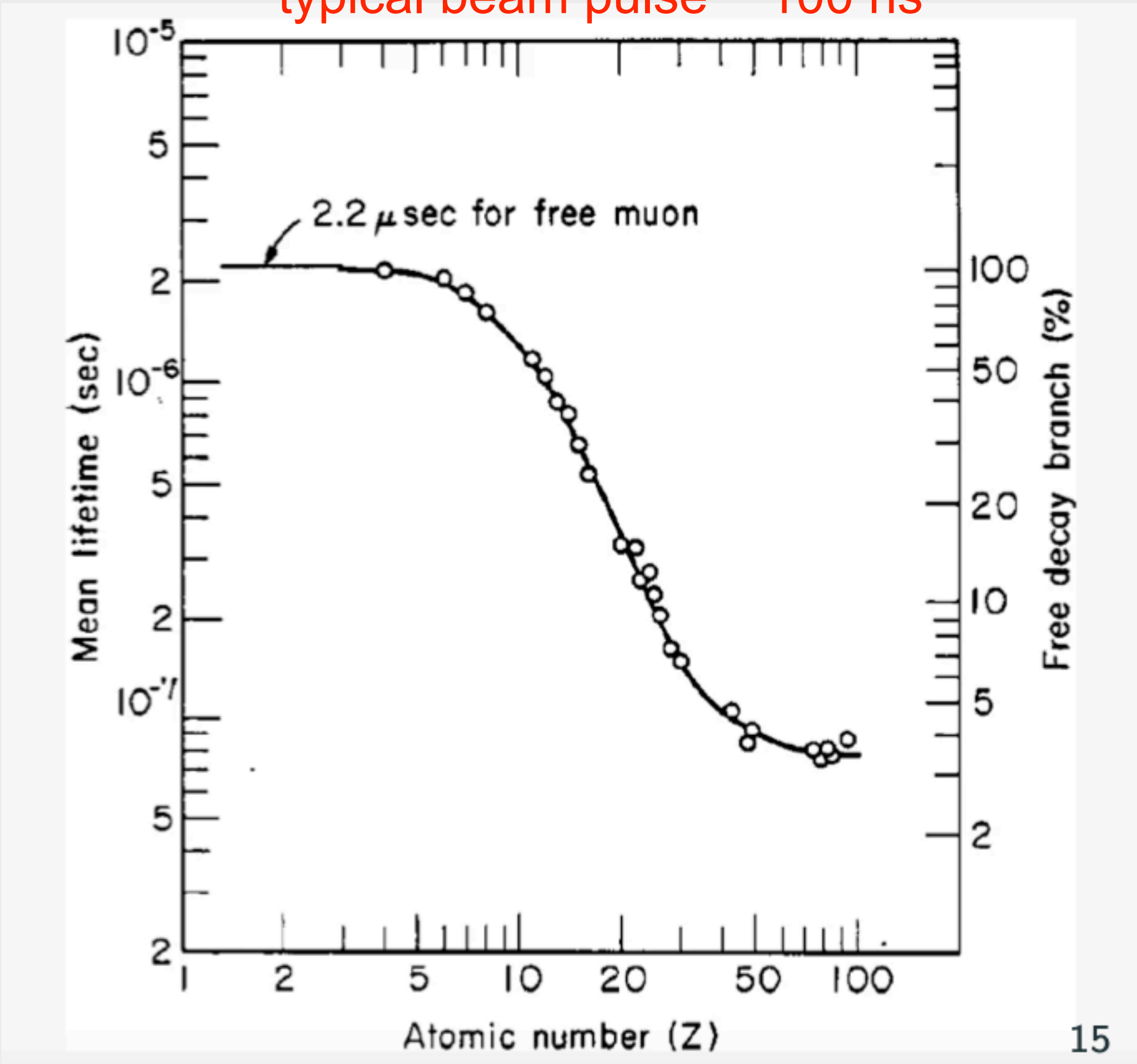


adapted from V. Cirigliano, B. Grinstein, G. Isidori, M. Wise **Nucl.Phys.B728:121-134,2005**

Mu2e Method Limitation

- Captured μ lifetime depends on Z
- Can't probe high Z at Mu2e, since lifetime is within beam pulse

typical beam pulse ~ 100 ns



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 $\mu N \to eN$ at high Z and additional x100 in rate
      - with a possible DM experiment
    - x100-1000 more beam for $\mu \to e\gamma$ and $\mu \to 3e$ than are possible at PSI
  - Possible muonium-antimuonium and muon EDM

Conclusions

- 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.

- We hope for P5 to recommend design of the program with submission to next P5