A New Charged Lepton Flavor Violation Program at Fermilab

RPF Town Hall
2 October 2020

ENIGMA: nExt geNeration experIments with hiGh intensity Muon beAms

more references in backup;
Johnstone/Pasternak/Prebys talks in this session; also Papa, Tassielli talks
and Middleton, Mackenzie, Borrel, Chislett on Mu2e/Mu2e-II

https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0-AF5_AF0_Robert_Bernstein-027.pdf

Overview

- Charged Lepton Flavor Violation, or transitions from $\tau \rightarrow \mu \rightarrow e$ without neutrinos have never been observed

- we've seen quark mixing and neutral lepton mixing (oscillations). Why not charged leptons?

    - fundamental puzzle dating to the discovery of the muon

    - really about the generation/flavor puzzles

    - CLFV is forbidden in the Standard Model but it is a extremely common in extensions, particularly SUSY.

    - *Observation and study of CLFV could drive the choice of the next high-energy collider*

Muons And CLFV

- Three main modes (note there are no neutrinos, hence charged lepton flavor violation!)
  - $\mu^+ \to e\gamma$ at PSI (MEG)
  - $\mu^+ \to 3e$ at PSI (Mu3e)
  - $\mu^- N \to e^- N$ at FNAL (Mu2e) and J-PARC (COMET)
    - Muons have a unique advantage since you can make beams, effective luminosity 10^{48}/cm^2/sec in Mu2e or COMET
    - Note: two *decay* experiments with μ^+ and a *capture* experiment with μ^-

Advantage of Multiple Experiments

- Each of these experiments probes new physics in different ways
  - complementary, not competing
- Z-dependence of $\mu^- N \to e^- N$ can reveal nature of new physics
  - need to go to high atomic number like Au(Z=79)
  - Mu2e and COMET are for Al (Z=13) or Ti (Z=22)

Goals of this Effort

- A facility for
  - one muon beam for the decay experiments $\mu \to e\gamma$ and $\mu \to 3e$
    - this is similar to existing beams at PSI
  - a second muon beam for the $\mu^- N \to e^- N$ experiment that can go to high *Z*
    - this is a new beam, and probing high *Z* not possible with Mu2e/COMET beams
- Reaching orders of magnitude beyond current experiments to mass scales $\mathcal{O}(10^5)$ TeV

Comparisons

- For a sense of scale: how many stopped muons for the decay experiments could we make (under reasonable assumptions)?
  - approximate, but ratios are the take-away
  - PIP-II is transformative

Facility	Stopped Muon Rate/
Current PSI	2×10^8
HiMB at PSI	10^{10}
Mu2e Design (+ mode)	10^{11}
PIP-II	$>10^{12}$

Beam I: decay experiments

- Decay Experiments: stop μ^+ and let them decay
  - these muon beams are old technology. A 1.4 MW-target is already the source for the PSI muon program, but PSI muon program only receives small fraction; we do not have similar competition
    - the statistics are so high that one can convert the γ so $\mu \to e\gamma, \gamma \to e^+e^-$ which greatly improves momentum resolution and reduces background
    - x100 better than MEG-II, probing $\mathcal{O}$ (10^4) TeV in SUSY-like models

Beam II: capture experiments

- Protons hit target in a solenoid, making $\pi \rightarrow \mu$ (capture solenoid)
- PRISM concept:
  - and place μ^- in a fixed-field, alternating gradient ring (FFA)
  - phase rotate muons to have a narrow momentum spread
    - slow down leading edge, speed up trailing edge of bunches
- Extract muons to detector system
- PIP-II time structure requires a compressor ring to rebunch the beam, since phase rotation takes time and PIP-II is too fast

Challenges:

- Target 1MW of beam inside a superconducting solenoid to capture pions and create muon beam.
  - A lot of study has gone into this for muon colliders! *Many overlaps and synergies with muon colliders and neutrino factories throughout*
- FFA built at small scale at Osaka (MUSIC)
- Injection/Extraction to FFA
  - Kickers to transfer beam around 1 kHz

Forming Collaboration

- This LOI has people from the different programs and Labs: J-PARC, PSI, FNAL experiments
  - $\mu \to e\gamma, \mu \to 3e$, and $\mu^- N \to e^- N$
- Beam and Detector Groups for decay and conversion experiments being formed
- Discussions with Proponents for Low-Energy Muon Facility about overall Muon Program (see C. Johnstone talk)
  - muonium-antimuonium (Tang & Petcov)

Preliminary Groups

- Decay Experiments:
  - Beam: use CDR for HiMB at PSI for starting point; HiMB planned for funding 2025-2028, this would follow that generation
  - Detectors: it possible to build one detector for both $\mu \to e\gamma$ and $\mu \to 3e$? Multiple stopping targets?
    - tracking? aging? calorimetry? timing? γ converter design?

Preliminary Groups

- Capture Experiment
  - Beam: compressor ring preliminary design underway; adapt FFA design from PRISM group; kickers, injection/extraction, and targeting
    - need to form connection to muon collider work (https://indico.cern.ch/event/930508/)
  - Detector: is a Mu2e/COMET-style detector best? Can crystal calorimetry handle the rates without excessive pile-up? Tracker lifetime?

Muons are a Community Priority

- Just from this session, we see:
  - two muonium-antimuonium talks (Tang/Petcov)
  - rare muon decays and light physics (Redigolo)
  - $\mu \to e\gamma$ (Papa, Tassielli)
  - $\mu^- N \to e^- N$ Mu2e and Mu2e-II (Middleton, Chislett, Prebys)
  - $\mu^- N \to e^+ N$ ($\Delta L = 2$ process!) at Mu2e and Mu2e-II (MacKenzie)
  - General Low Energy Muon Facility (Johnstone)
- ***A large community committed to muon physics over Snowmass period and beyond***

What We Want from Snowmass/P5

- Snowmass:
  - Set “requirements”. Collaboration will work on a coherent early-stage design of both beams and detectors
  - we would like the Snowmass report to discuss the physics case for a large-scale new muon program at PIP-II and to include this opportunity in the report
- P5:
  - we would like P5 to endorse the physics concept and resources for design studies

Backup

Some Relevant Papers

- Experimental Limiting Factors for the Search of $\mu \to e\gamma$ at Future Facilities, Renga et al., 1811.12324
- Towards a High Intensity Muon Beam (HiMB) at PSI
  - https://indico.cern.ch/event/577856/contributions/3420391/attachments/1879682/3097488/Papa_HiMB_EPS2019.pdf
- A Phase Rotated Source of Muons (PRISM) for a $\mu \to e$ Conversion Experiment
  - https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0-AF5_AF0_J_Pasternak-096.pdf
- Bunch Compressor for the PIP-II Linac
  - https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF5_AF0-RF5_RF0_Prebys2-203.pdf

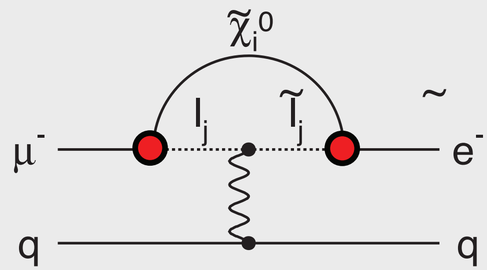
Some Relevant Papers (2)

- An Upgraded Low-Energy Muon Facility at Fermilab
    - https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF0-AF0-007.pdf
- The MEG-II Experiment and its Future Developments
    - https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0_MEGII-062.pdf
- Mu2e-II
    - https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0_Frank_Porter-106.pdf
- A New Experiment for the $\mu \to e\gamma$ Search
    - https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0_Tassielli-067.pdf

Contributions to μe Conversion

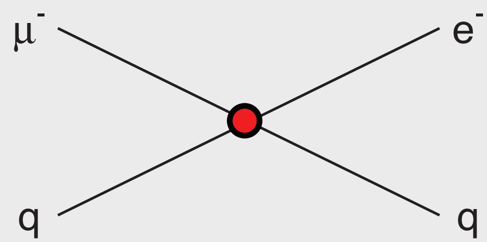
Supersymmetry

rate ~ 10^{-15}



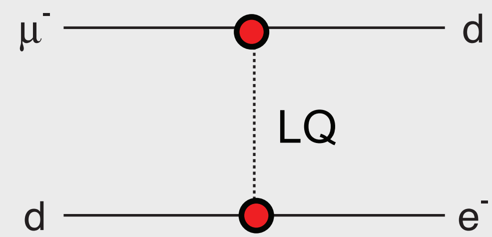
Compositeness

Λ_c ~ 3000 TeV



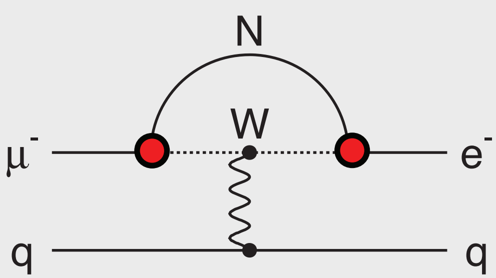
Leptoquark

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



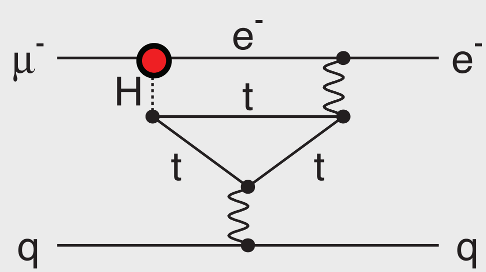
Heavy Neutrinos

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



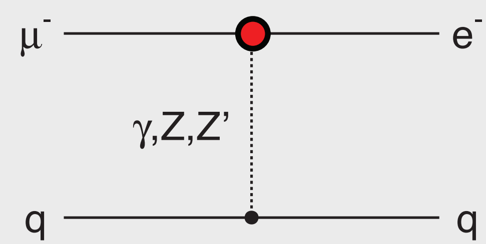
Second Higgs Doublet

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



Heavy Z' Anomal. Z Coupling

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

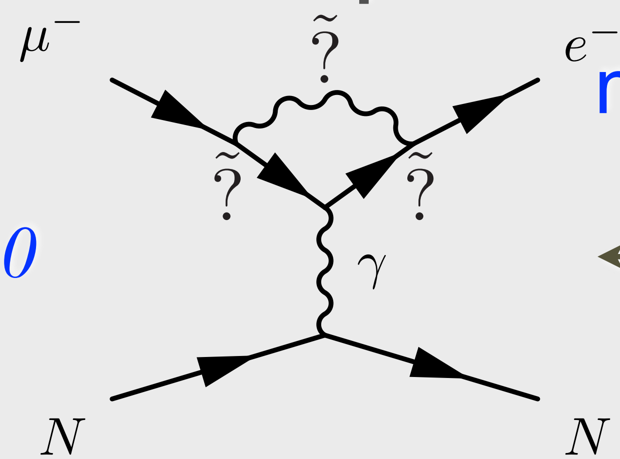


also see Flavour physics of leptons and dipole moments, arXiv:0801.1826 ;
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:10.1146/annurev.nucl.58.110707.171126 ;

Effective Lagrangian

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

"Loops"



$\kappa = 0$

Supersymmetry and Heavy Neutrinos

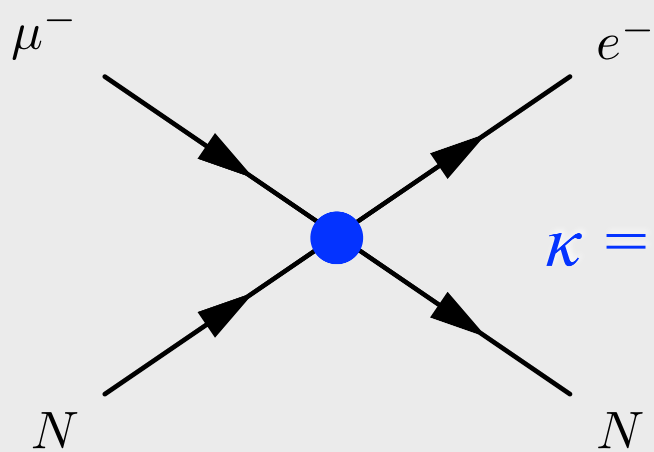
Contributes to $\mu \to e\gamma$

(just imagine the photon is real)

mass scale Λ

κ

"Contact Terms"



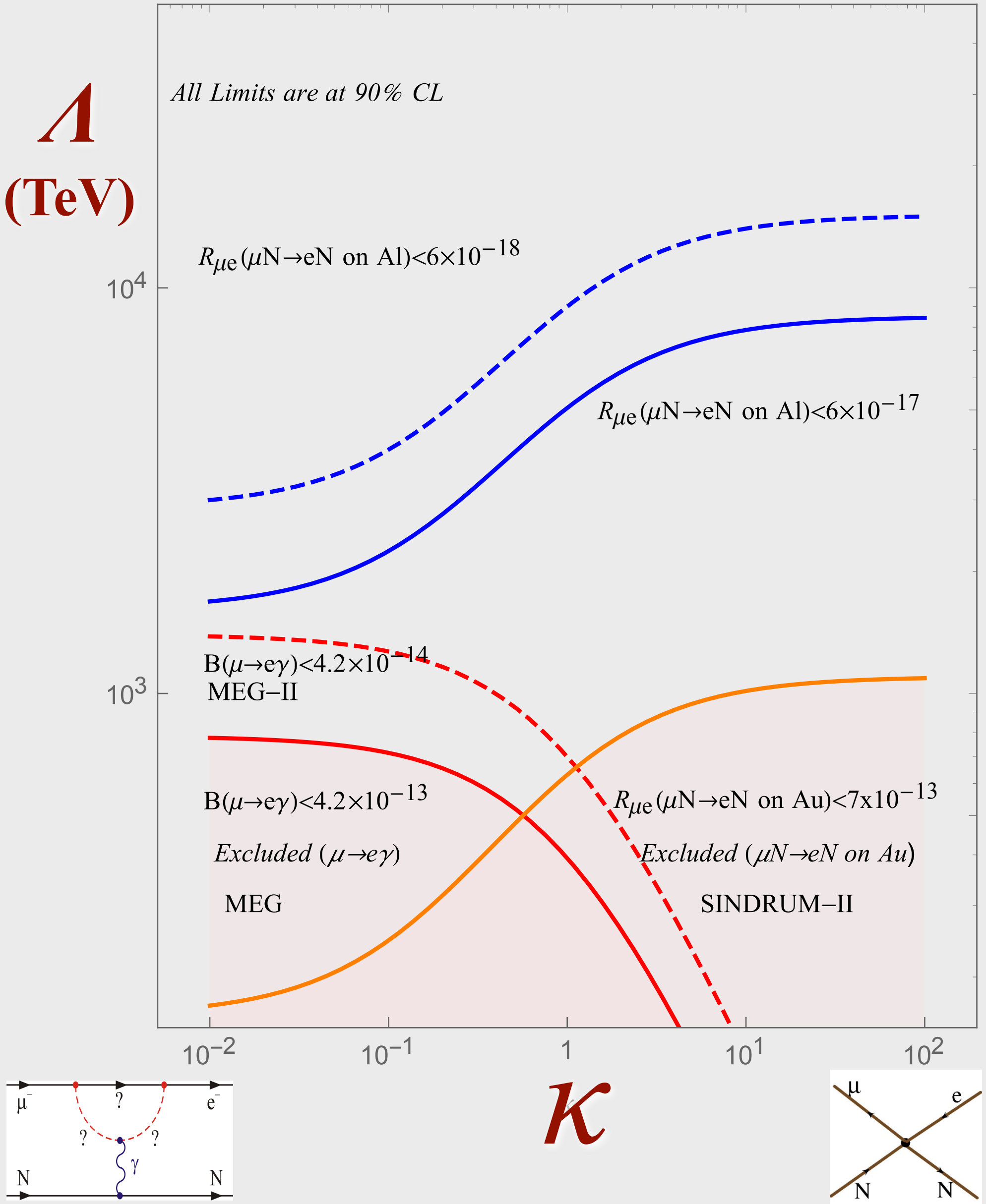
$\kappa = \infty$

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

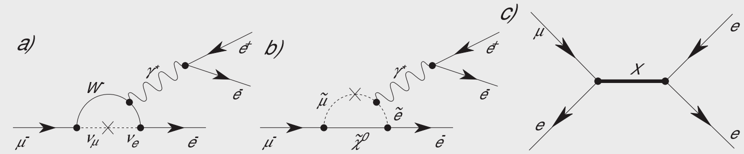
Does not produce $\mu \to e\gamma$

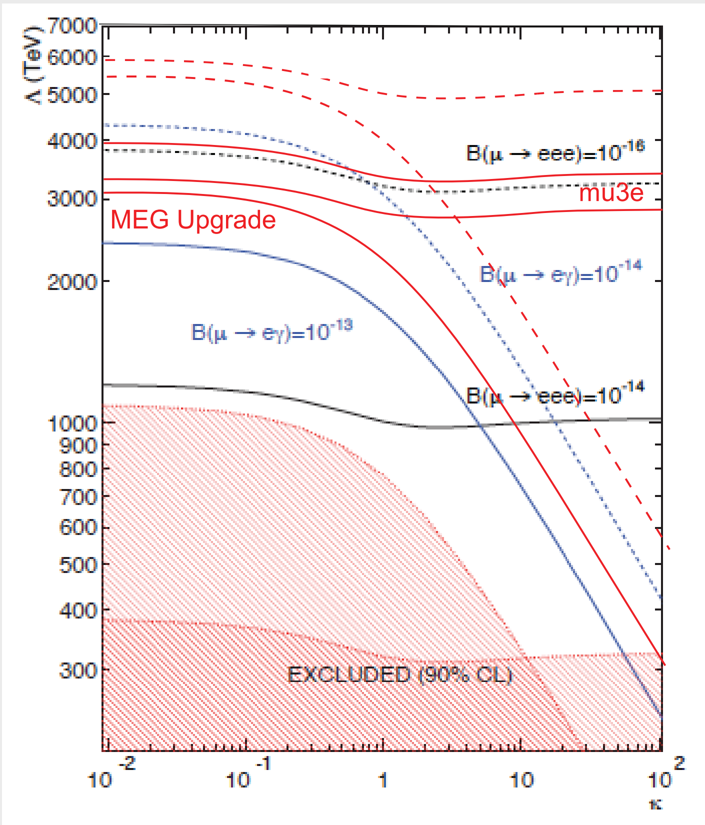
from André deGouvêa

Simplistic Comparsion



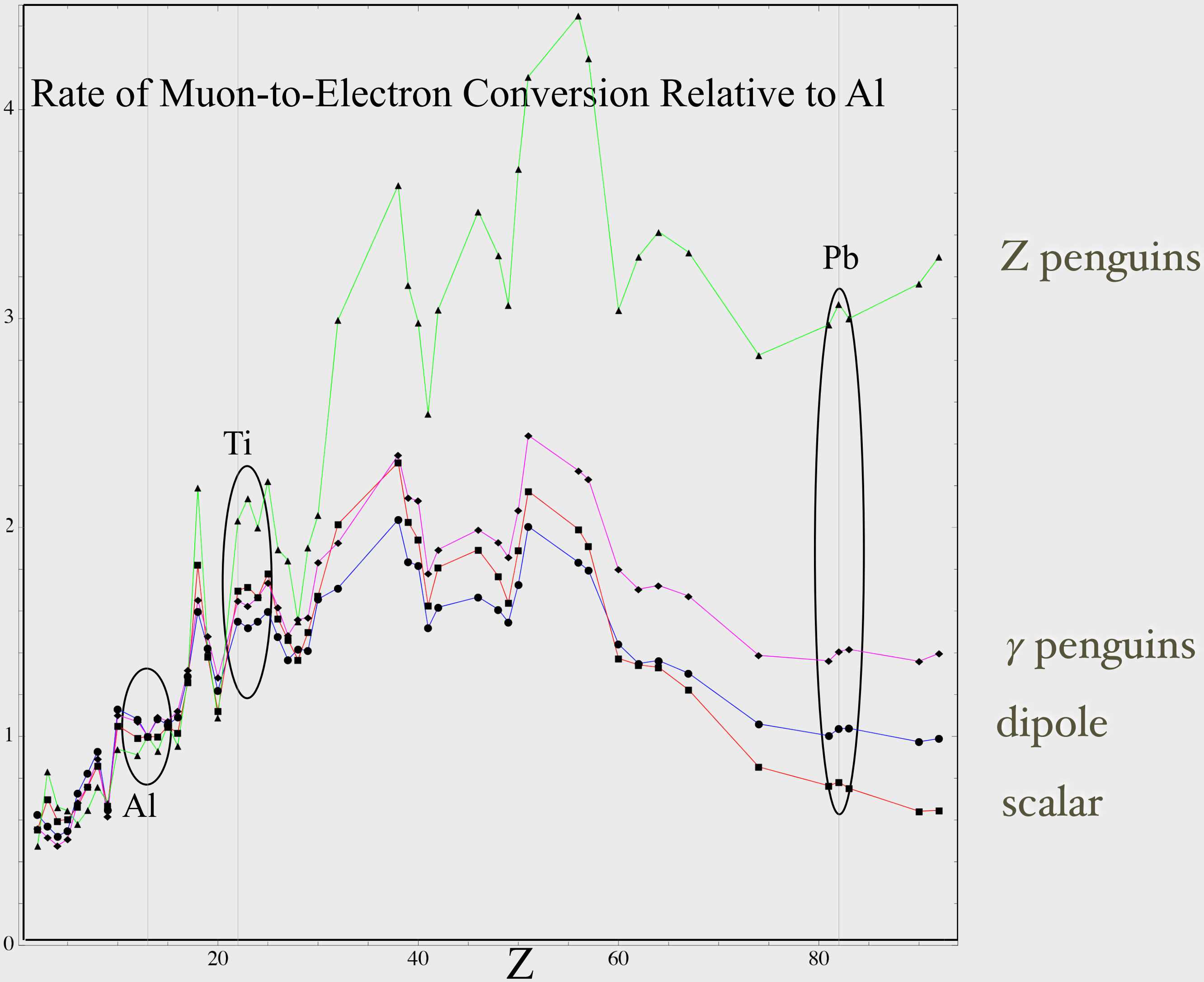
higher mass scale





after Andre deGouvea

Mu2e Upgrades and Z-Dependence



5% measurement on Al/Ti needed to see split

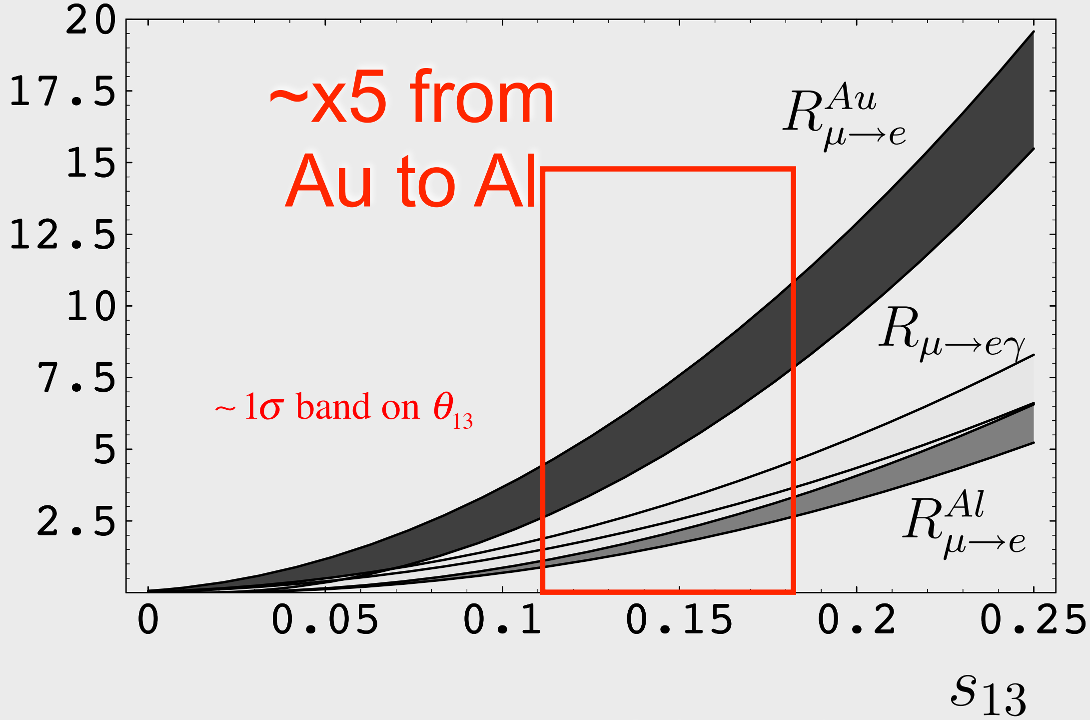
- Different Operators have different Z-dependence
- Combine depending on the particular model

Lepton flavor violating mu - e conversion rate for various nuclei
M. Koike et al., J.Phys. G29 (2003) 2051-2054
DOI: 10.1088/0954-3899/29/8/401

Example of Physics Reach

- just one example

PDG 2017



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