ER, Haxton, and McElvain, arXiv:2109.13503, accepted at PRL
Haxton, **ER**, McElvain, and Ramsey-Musolf, arXiv:2208.07945, accepted at PRC
Haxton, McElvain, Menzo, **ER**, and Zupan, in prep.

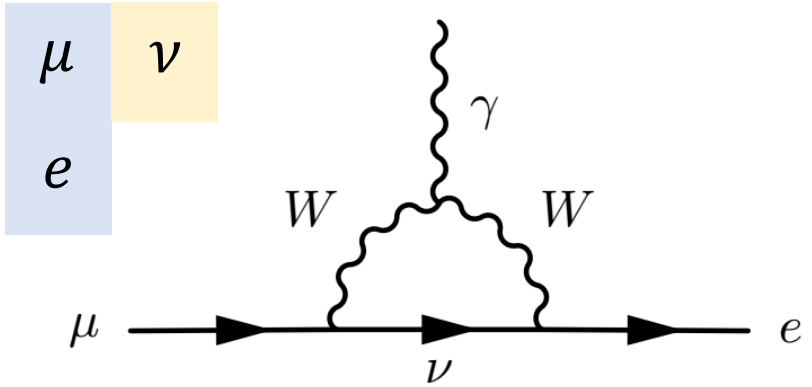
Connecting Low-energy Experiments to UV Theories of Charged Lepton Flavor Violation

Evan Rule | N3AS Annual Meeting| March 18, 2023

Berkeley
UNIVERSITY OF CALIFORNIA

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

NSF



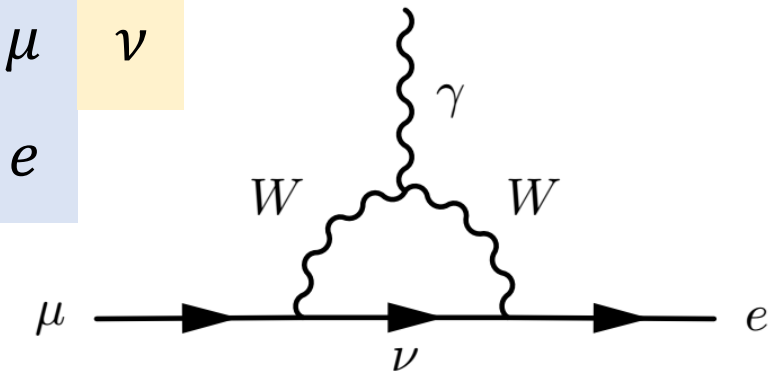
Theory Predicts: $\mathrm{BR}(\mu^+ \to e^+\gamma) \approx 10^{-4}$

Feinberg, Phys. Rev. **110**, 1482 (1958)

Nevis Cyclotron: $\mathrm{BR}(\mu^+ \to e^+\gamma) < 2 \times 10^{-5}$

Lokanathan & Steinberger, Phys. Rev. **98**, 240 (A) (1955)

μ	ν
e	



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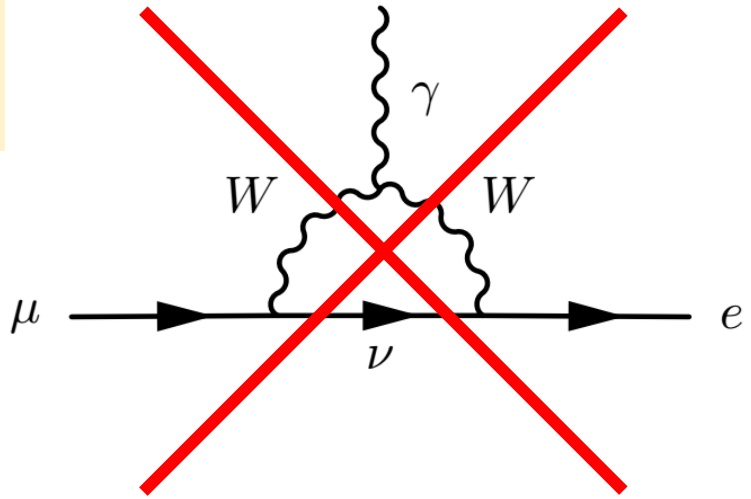
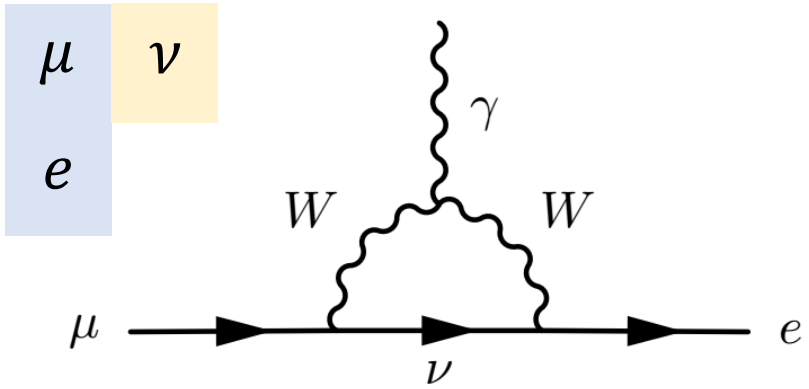
2 Neutrino Hypothesis

Pontecorvo, Zh. Eksp. Teor. Fiz. **37**, 1751–1757 (1959).

μ	ν_μ
e	ν_e





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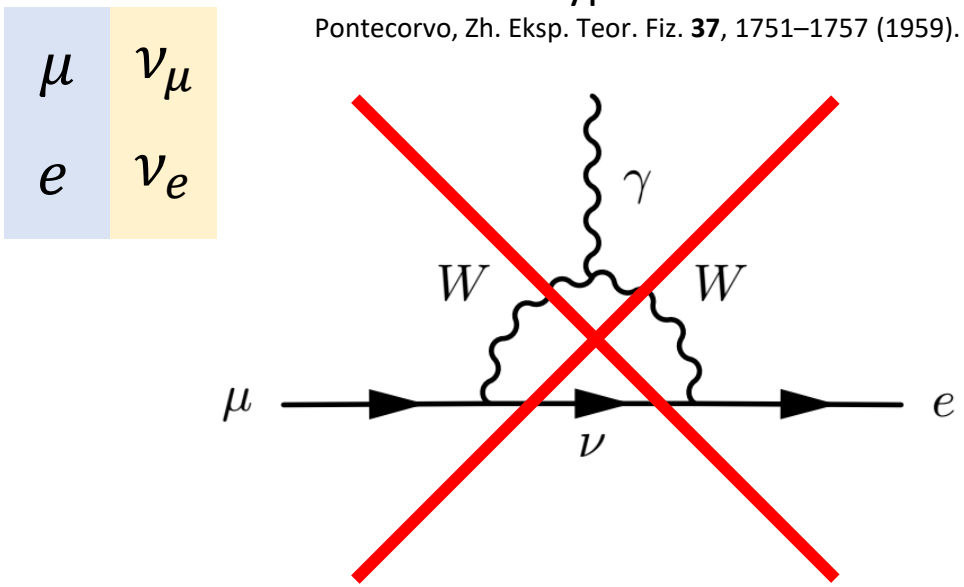
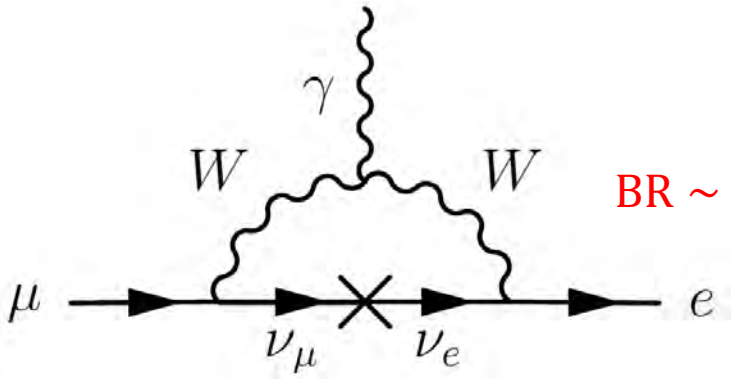




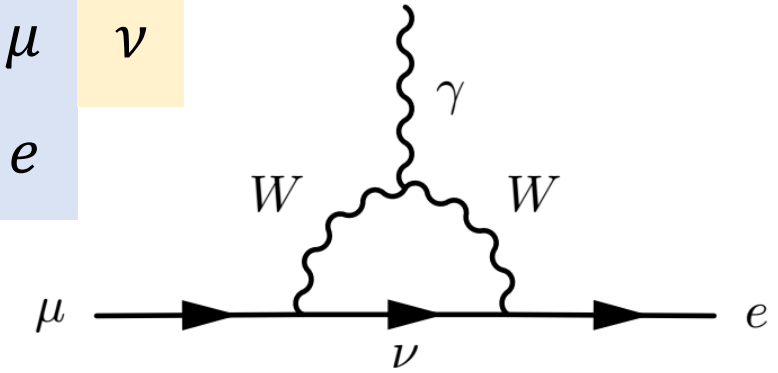
$$\mathrm{BR} \sim \left(\frac{m_\nu}{M_W}\right)^4$$

Super-K, SNO

- Neutrino flavor oscillations → lepton flavor not conserved
- Charged lepton flavor violation (CLFV) extremely suppressed

μ ν

e



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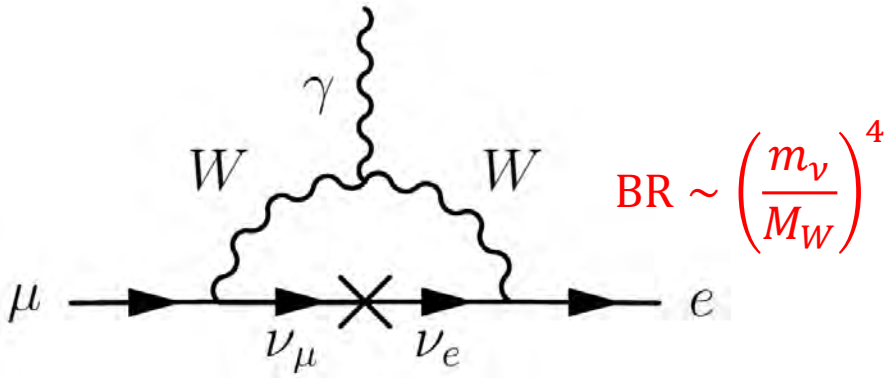

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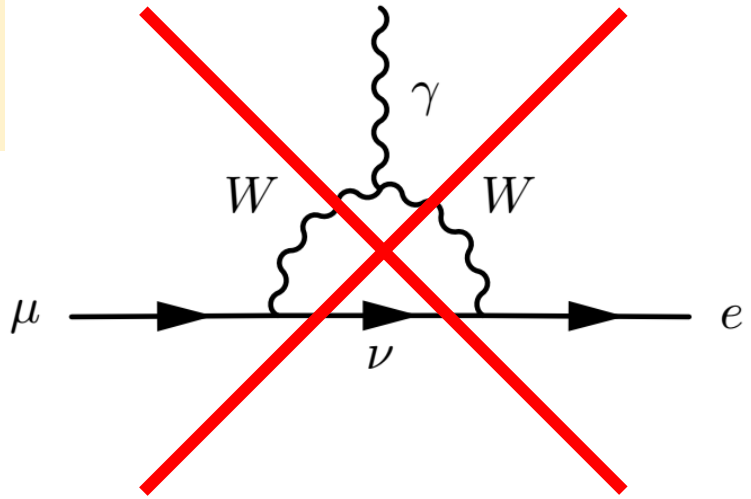
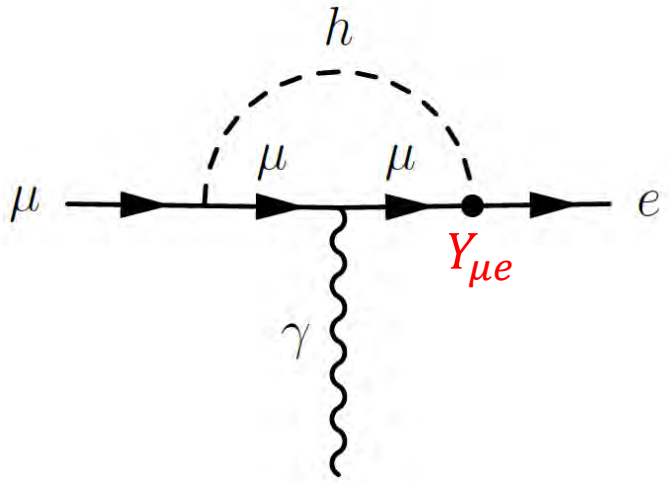




CLFV limits constrain BSM theories

Collider Constraints

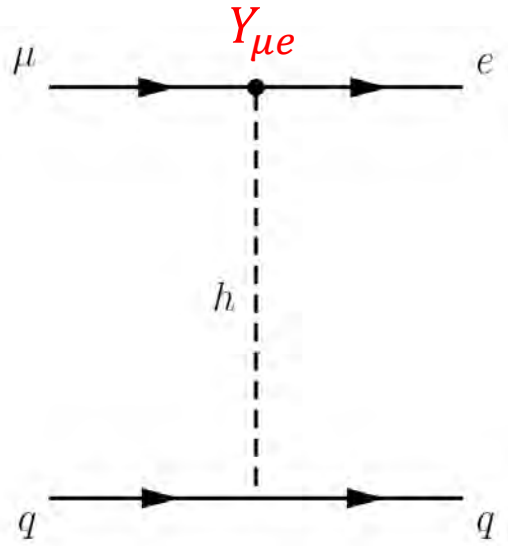
Process	BR Limit	CL	Experiment
$Z \to e\tau$	5.0×10^{-6}	95%	ATLAS
$Z \to \mu\tau$	6.5×10^{-6}	95%	ATLAS
$Z \to e\mu$	7.5×10^{-7}	95%	ATLAS
$h \to e\tau$	2.2×10^{-3}	95%	CMS
$h \to \mu\tau$	1.5×10^{-3}	95%	CMS
$h \to e\mu$	6.1×10^{-5}	95%	ATLAS
$B^+ \to K^+\mu^-\tau^+$	2.8×10^{-5}	90%	BaBar
$B^+ \to K^+e^-\mu^+$	6.4×10^{-9}	90%	LHCb
$D^+ \to K^+e^+\mu^-$	7.5×10^{-8}	90%	LHCb
$\tau^- \to e^-\gamma$	3.3×10^{-8}	90%	BaBar
$\tau^- \to \mu^-\gamma$	4.2×10^{-8}	90%	Belle
$\tau^- \to e^-e^+e^-$	2.7×10^{-8}	90%	Belle

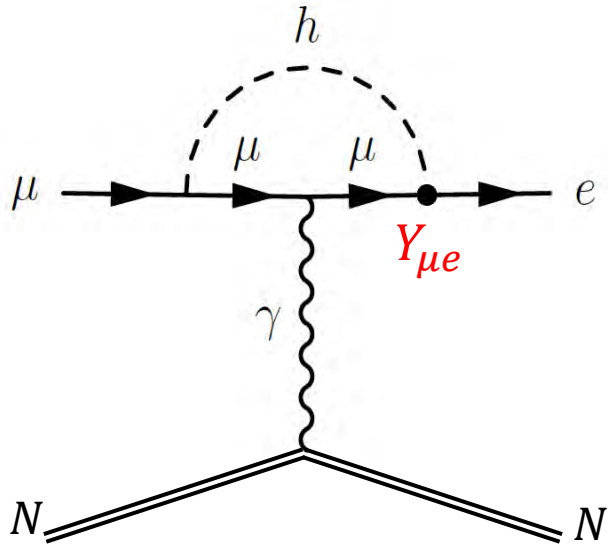
Stopped Muon Constraints

Process	BR Limit	CL	Experiment
$\mu^+ \to e^+\gamma$	4.2×10^{-13}	90%	MEG
$\mu^+ \to e^+e^-e^+$	1.0×10^{-12}	90%	SINDRUM
$\mu^- + \mathrm{Cu} \to e^- + \mathrm{Cu}$	1.6×10^{-8}	90%	SINDRUM II
$\mu^- + {}^{32}\mathrm{S} \to e^- + {}^{32}\mathrm{S}$	7×10^{-11}	90%	SIN
$\mu^- + \mathrm{Pb} \to e^- + \mathrm{Pb}$	4.6×10^{-11}	90%	SINDRUM II
$\mu^- + \mathrm{Ti} \to e^- + \mathrm{Ti}$	6.1×10^{-13}	90%	SINDRUM II
$\mu^- + \mathrm{Au} \to e^- + \mathrm{Au}$	7.0×10^{-13}	90%	SINDRUM II
$\mu^+ \to e^+\gamma$	6×10^{-14}	90%	MEG II
$\mu^+ \to e^+e^-e^+$	4×10^{-16}	90%	Mu3e
$\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}$	8×10^{-17}	90%	Mu2e
$\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}$	7×10^{-17}	90%	COMET

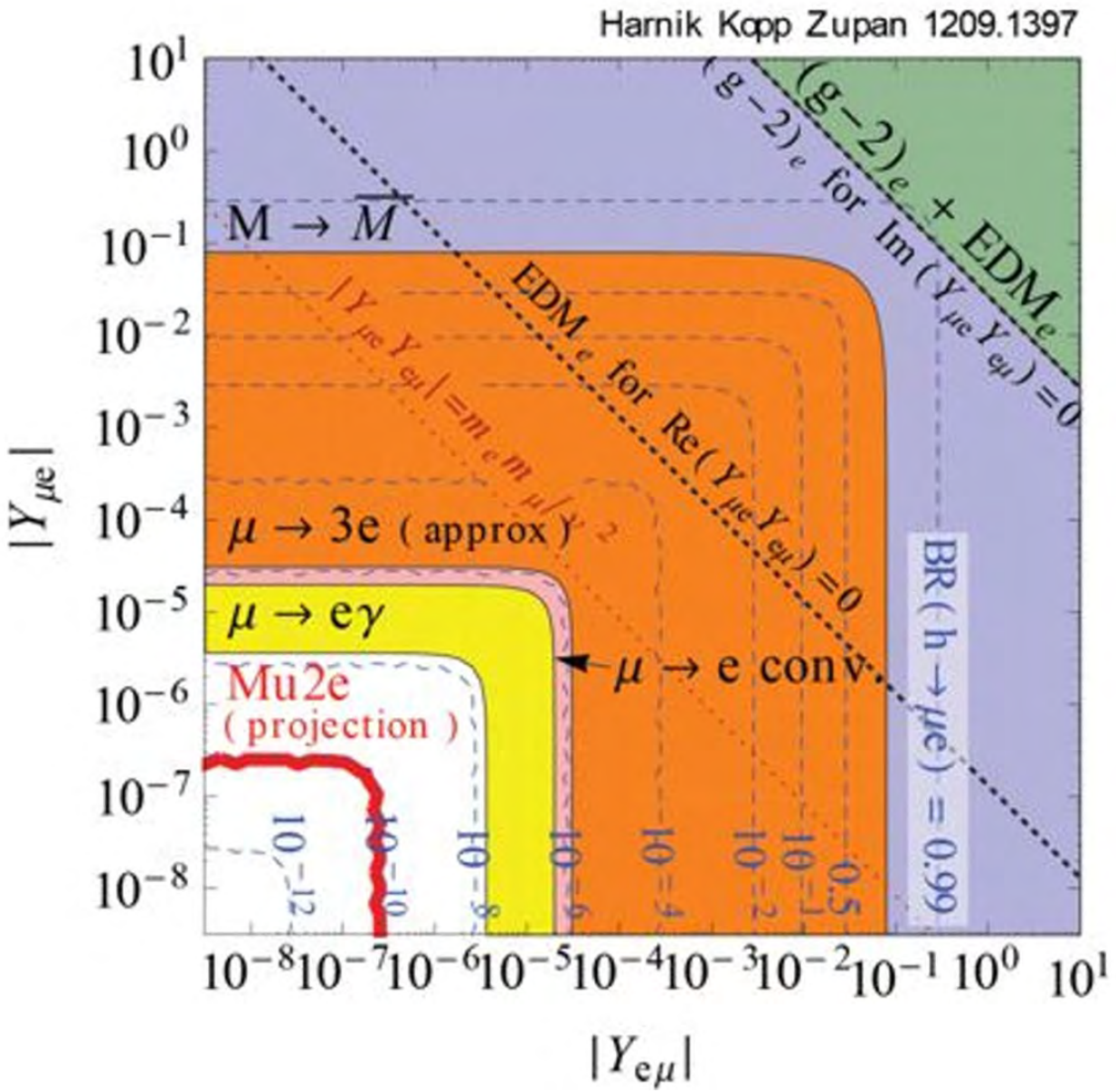
Next-Generation Experiments

Process	BR Limit	CL	Experiment
$h \to e\mu$	6.1×10^{-5}	95%	ATLAS
$\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}$	8×10^{-17}	90%	Mu2e

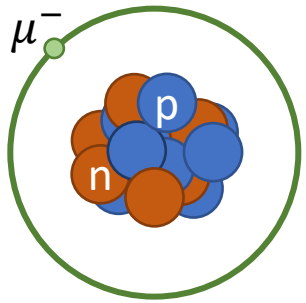




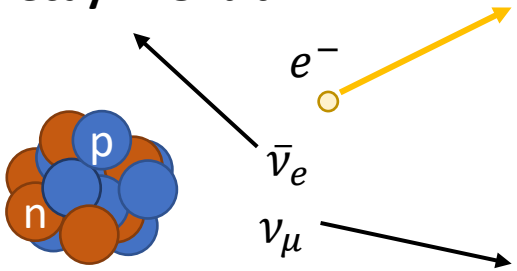
$\mu \to e$ provides better constraint than $h \to e\mu, \mu \to e\gamma, \mu \to 3e$



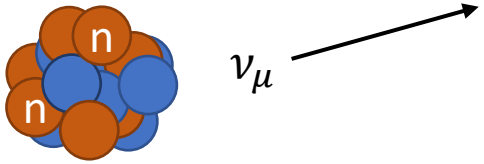
Muon captured in 1s orbital



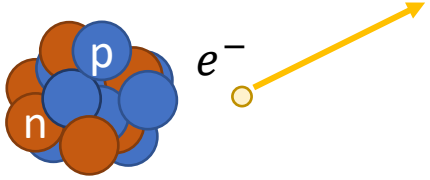
Decay in Orbit



Standard μ Capture

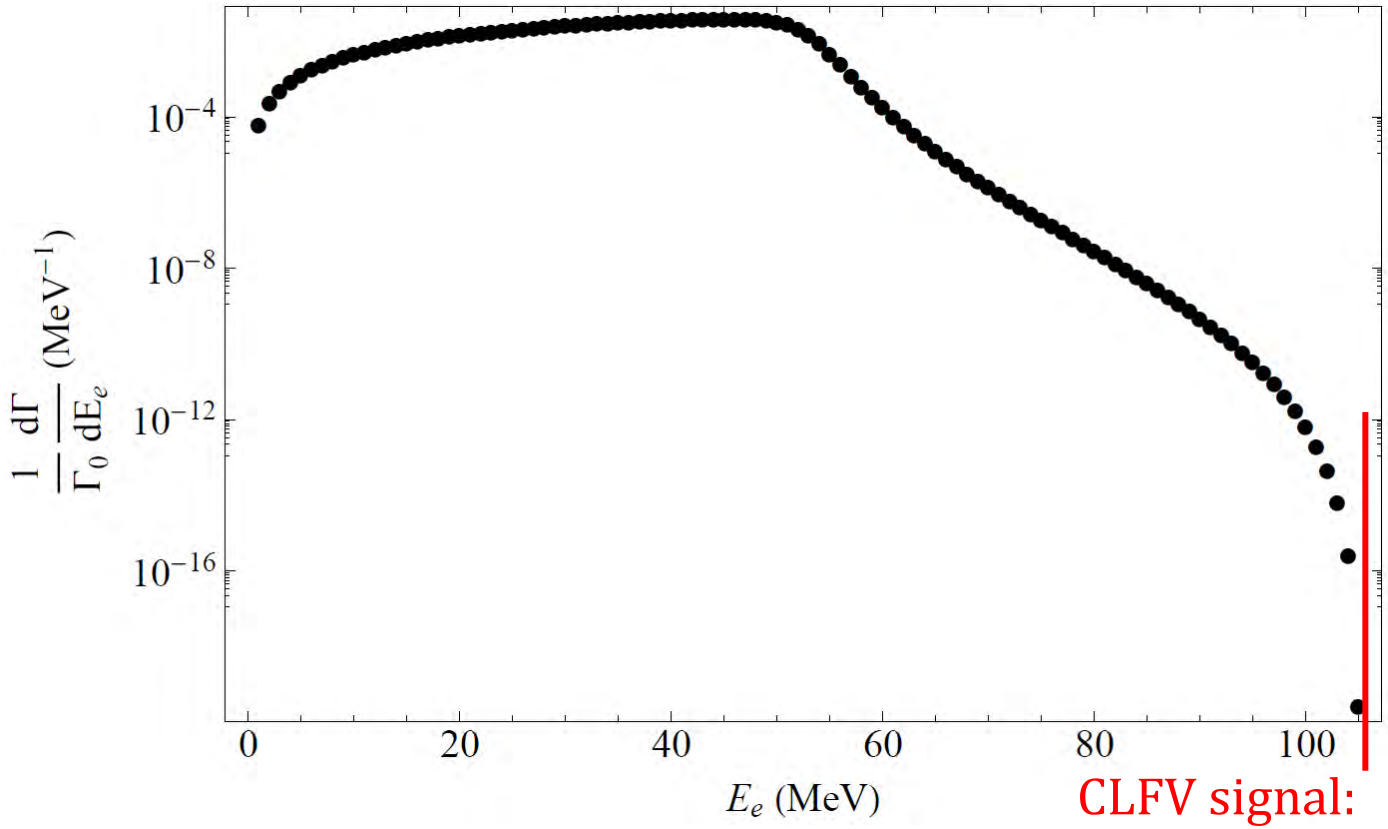


CLFV $\mu \to e$ Conversion



Decay-in-Orbit Spectrum

Figure: Czarnecki, Garcia i Tormo, & Marciano, Phys. Rev. D **84**, 013006 (2011)

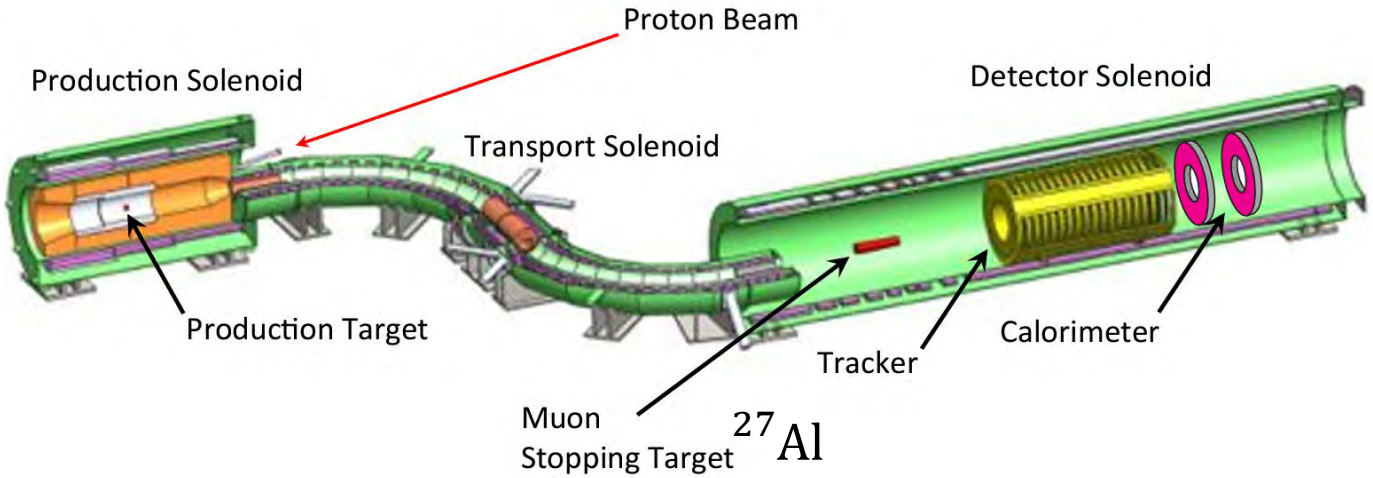


CLFV signal:
$E_e \approx m_\mu - B_\mu$

$$\mathrm{BR}\left(\mu^- + (A,Z) \to e^- + (A,Z)\right) \equiv \frac{\Gamma\left(\mu^- + (A,Z) \to e^- + (A,Z)\right)}{\Gamma\left(\mu^- + (A,Z) \to \nu_\mu + (A,Z-1)\right)}$$

** Assuming nucleus remains in ground state **
"Elastic conversion"

Mu2e Experiment



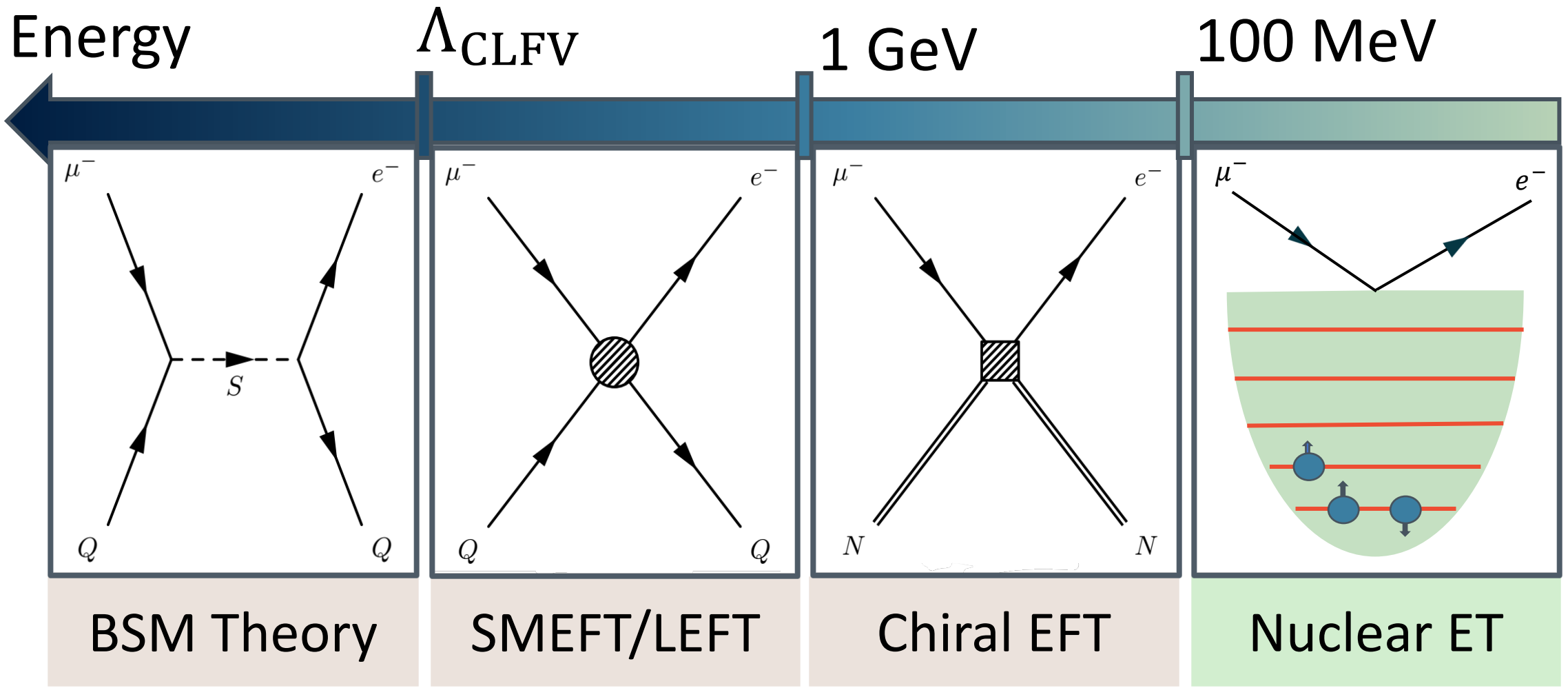
Advantages

- Huge Intensity: 10^{18} muons captured over lifetime
- Clean CLFV signal, free of standard model backgrounds
- Target can be varied to obtain complimentary constraints

Challenges

- CLFV physics polluted by nuclear physics
- Nuclear ground state restricts operators that contribute
  - Parity **P** and time-reversal **T** symmetries
- Large scale separation between experiments and UV theories

How can we extract the most information about underlying CLFV operators from observations of elastic $\mu \to e$ conversion in nuclei?



Nuclear-Scale Effective Theory:

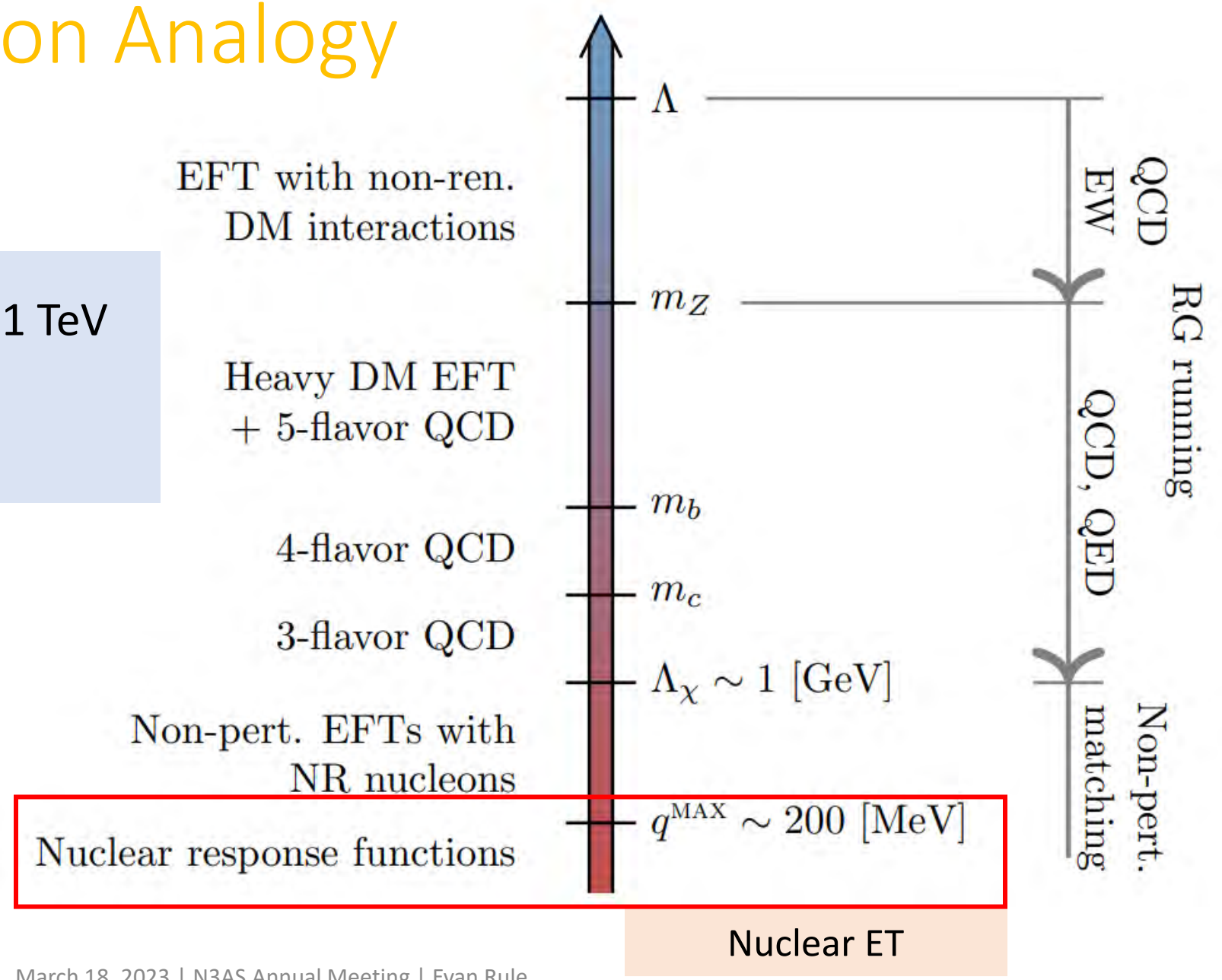
- Interfaces directly with experiment
- Factorizes CLFV physics from nuclear physics
- Many-body calculations require nucleon degrees of freedom

DM Direct Detection Analogy

- UV theories at high energy $\gtrsim$ 1 TeV
- Experiments at nuclear scale

UV Theory Parameters

DM Recoil Event Rate



Nuclear ET

Fitzpatrick, Haxton, Katz, Lubbers, Xu JCAP **02,** 004 (2013)

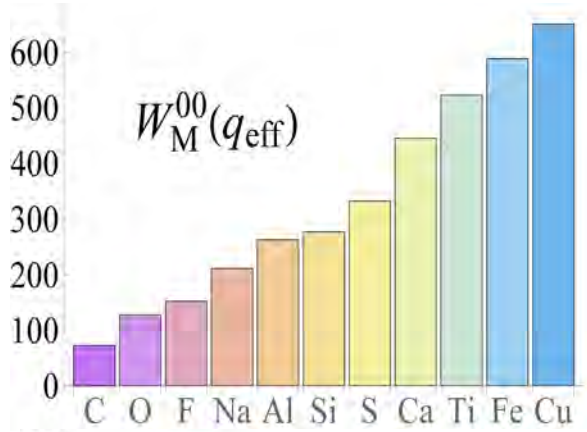
Nuclear ET

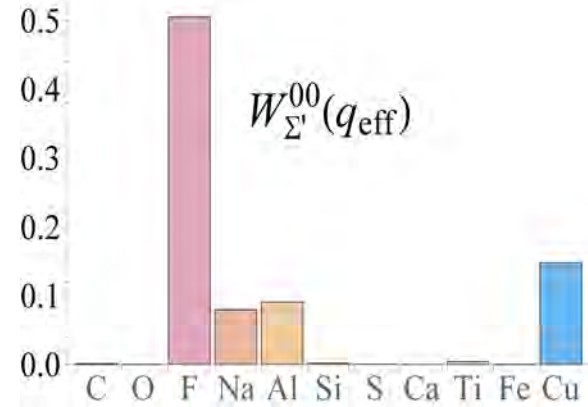
	Velocity-independent	Velocity-dependent
Spin-independent	M_J	Δ_J
Spin-dependent	Σ'_J, Σ''_J	$\tilde{\Phi}'_J, \Phi''_J$
Interference	$M_J \sim \Phi''_J$	$\Sigma'_J \sim \Delta_J$

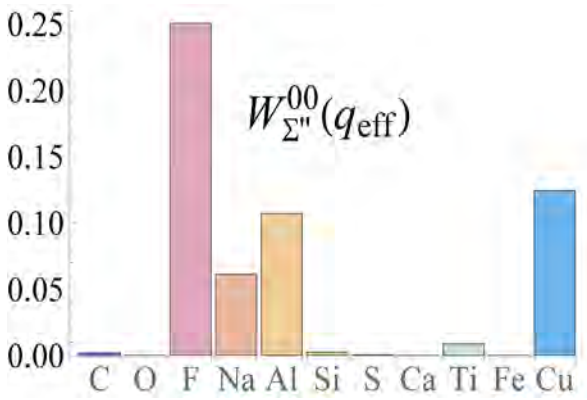
8 independent quantities measured in elastic $\mu \to e$ conversion
($\times$ 2 for isospin)

Velocity-independent

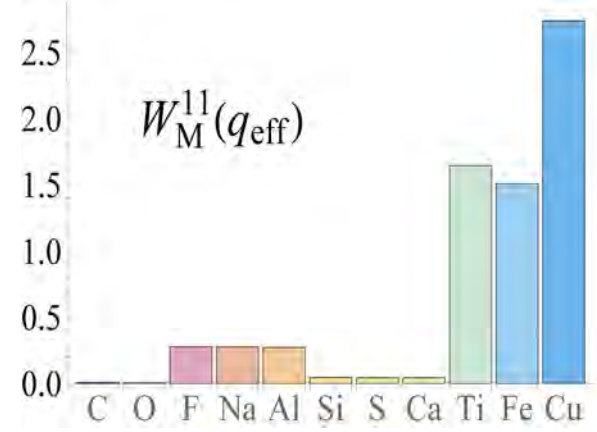
Isoscalar

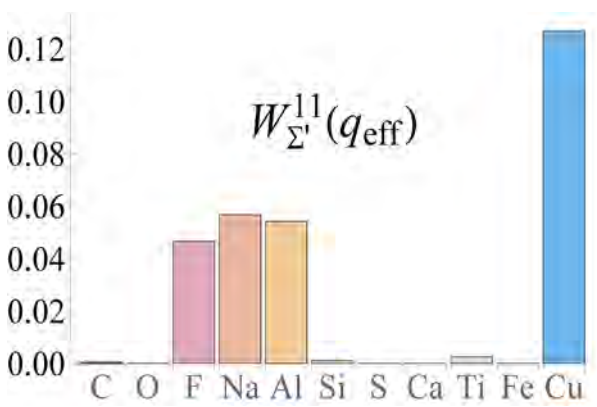


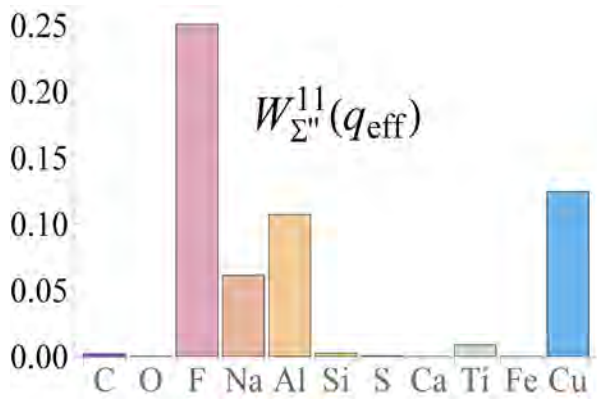




Isovector

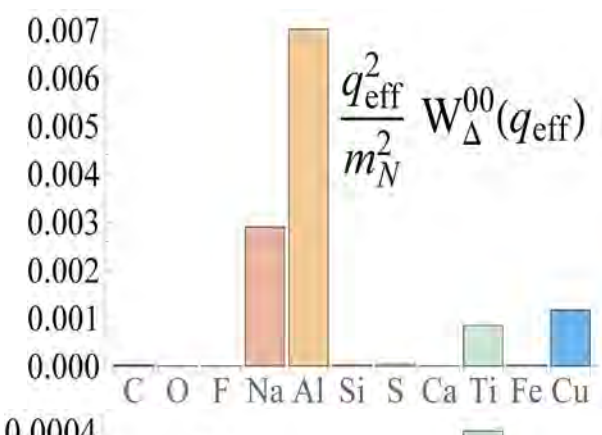


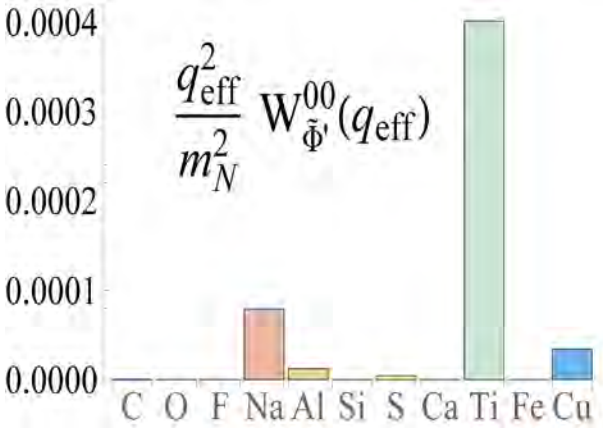


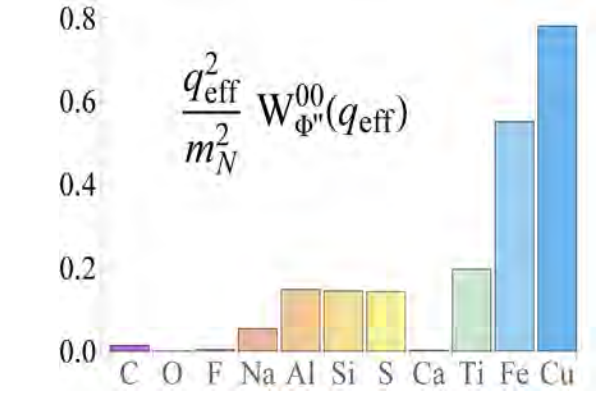


Velocity-dependent

Isoscalar







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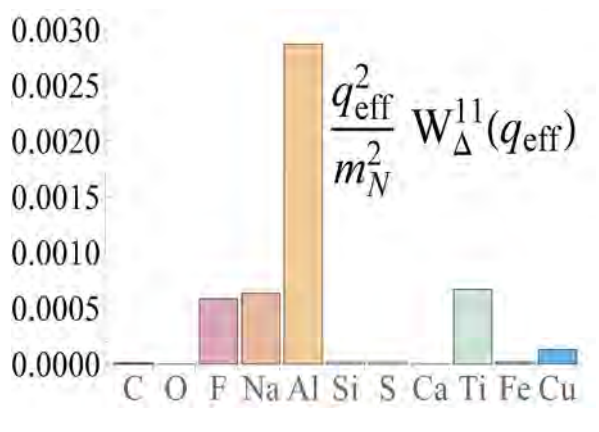
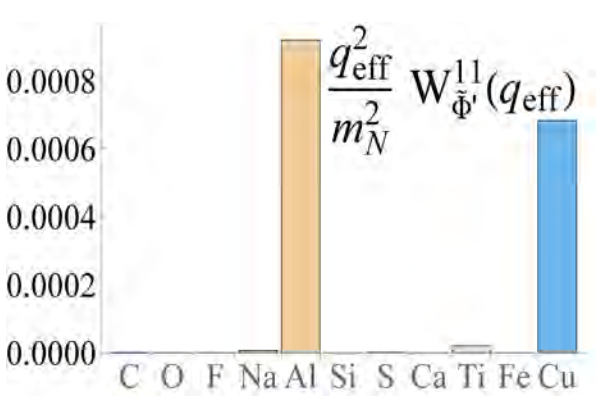
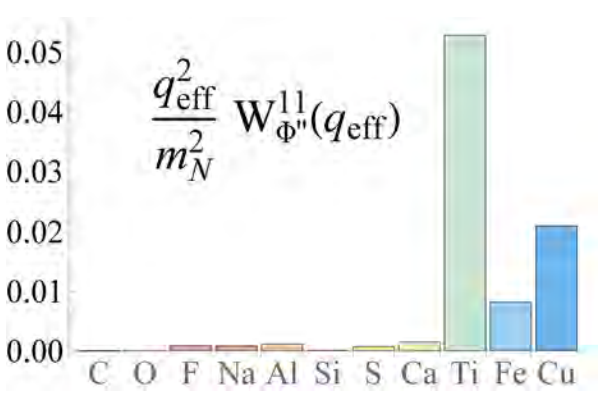




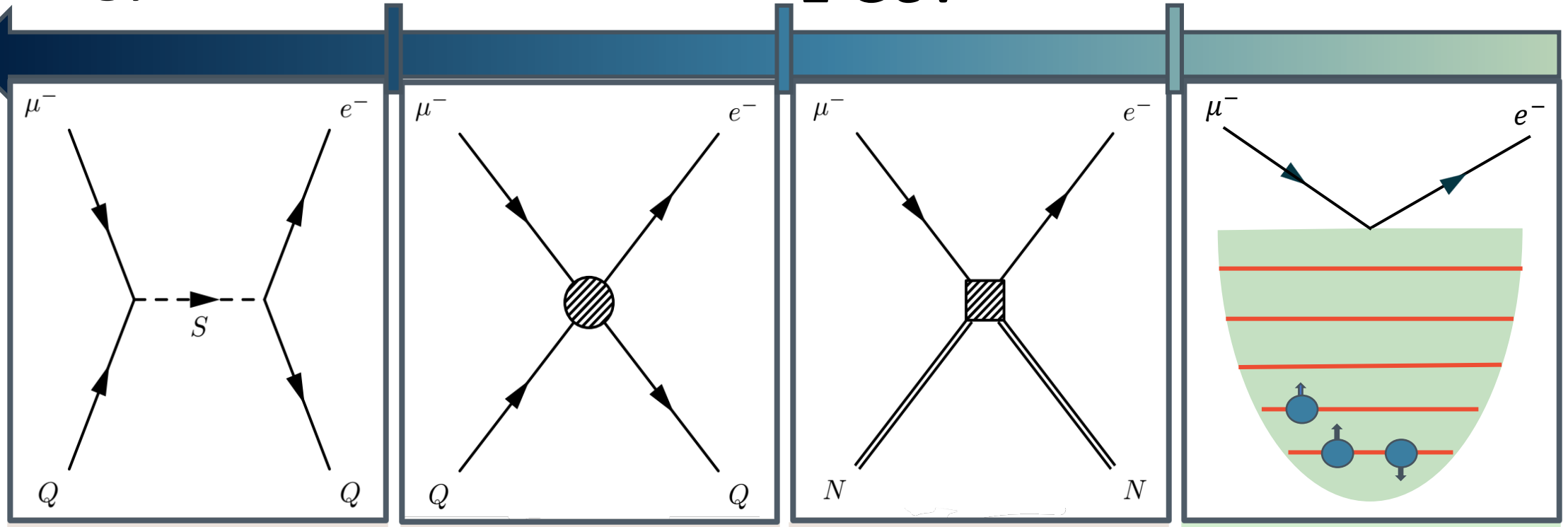


Energy

Λ_{CLFV}

1 GeV

100 MeV



BSM Theory | SMEFT/LEFT | Chiral EFT | Nuclear ET

UV Theory Parameters → $\mathrm{BR}(\mu^- + A \to e^- + A)$