LA-UR-25-25247

Los Alamos NATIONAL LABORATORY

$\mu \to e$ conversion in nuclei:

Effective theory and new experimental signals

Evan Rule | CIPANP 2025| June 11, 2025

Berkeley UNIVERSITY OF CALIFORNIA

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries

PHYSICS FRONTIER CENTER

NSF

Charged leptons: e, μ, τ

Standard model:

Muon decay:	$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$
Beta decay:	$n \to p + e^- + \bar{\nu}_e$
Pion decay:	$\pi^+ \to \mu^+ + \nu_\mu$

Charged leptons: e, μ, τ

Standard model: Each flavor conserved

Muon decay: $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$

Beta decay: $n \to p + e^- + \bar{\nu}_e$

Pion decay: $\pi^+ \to \mu^+ + \nu_\mu$

$$\underset{L_\mu = +1}{\boxed{\mu^-}} \to \underset{L_e = +1}{\boxed{e^-}} + \underset{L_e = -1}{\boxed{\bar{\nu}_e}} + \underset{L_\mu = +1}{\boxed{\nu_\mu}}$$

Charged leptons: e, μ, τ

Standard model: Each flavor conserved

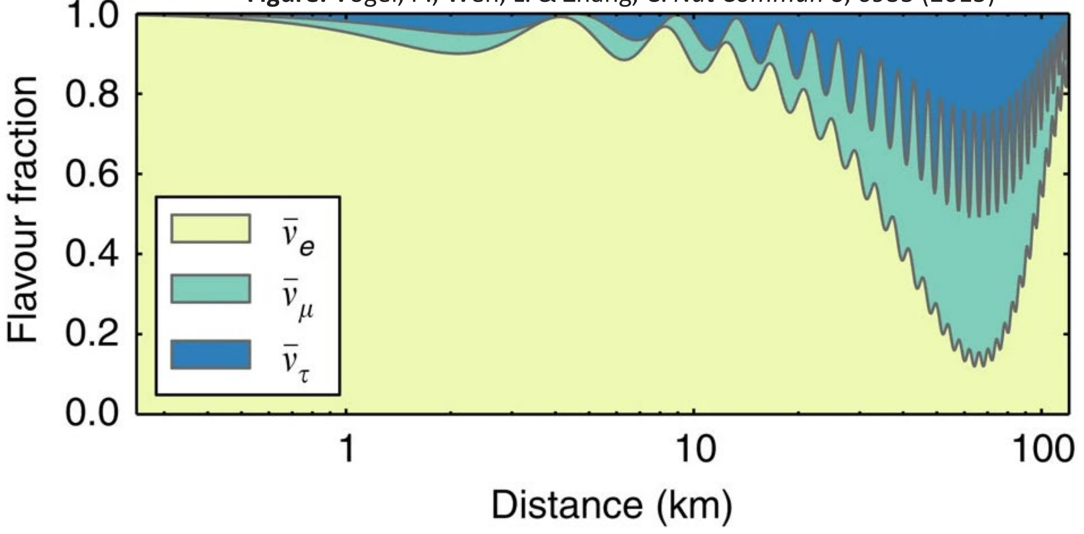
Muon decay: $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

Beta decay: $n \rightarrow p + e^- + \bar{\nu}_e$

Pion decay: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

Neutral leptons: ν_e, ν_μ, ν_τ

Figure: Vogel, P., Wen, L. & Zhang, C. *Nat Commun* **6**, 6935 (2015)



Neutrino oscillations: Flavor NOT conserved

Charged leptons: e, μ, τ

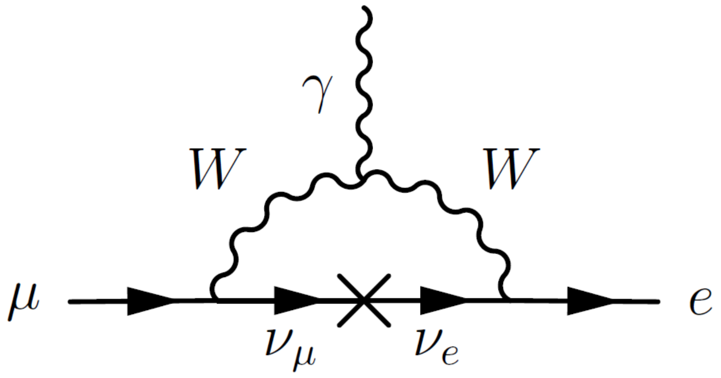
Standard model: Each flavor conserved

Muon decay: $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

Beta decay: $n \rightarrow p + e^- + \bar{\nu}_e$

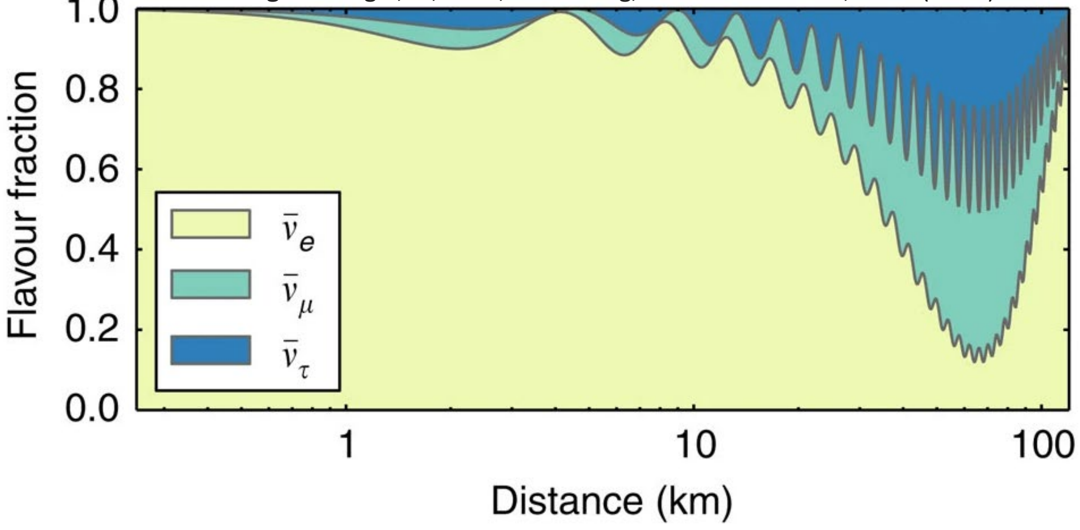
Pion decay: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

Standard model + neutrino oscillations



Neutral leptons: ν_e, ν_μ, ν_τ

Figure: Vogel, P., Wen, L. & Zhang, C. *Nat Commun* **6**, 6935 (2015)



Neutrino oscillations: Flavor NOT conserved

Charged leptons: e, μ, τ

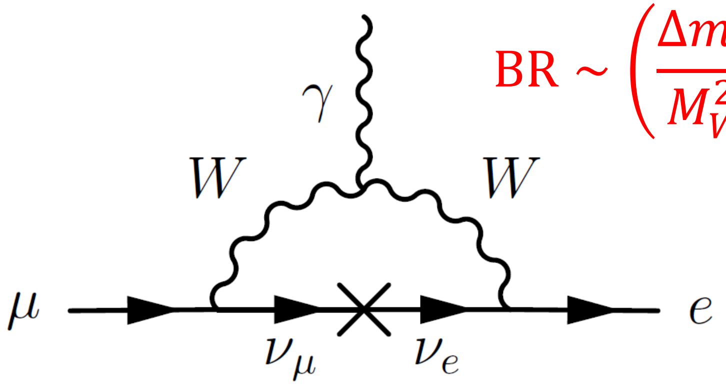
Standard model: Each flavor conserved

Muon decay: $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

Beta decay: $n \rightarrow p + e^- + \bar{\nu}_e$

Pion decay: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

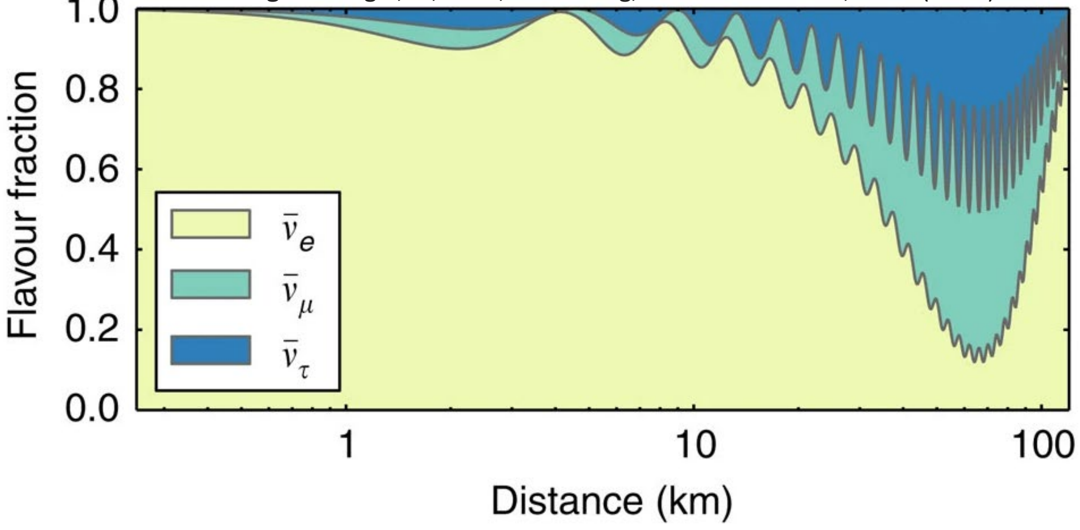
Standard model + neutrino oscillations



$$\mathrm{BR} \sim \left(\frac{\Delta m_\nu^2}{M_W^2}\right)^2 \sim 10^{-54}$$

Neutral leptons: ν_e, ν_μ, ν_τ

Figure: Vogel, P., Wen, L. & Zhang, C. *Nat Commun* **6**, 6935 (2015)



Neutrino oscillations: Flavor NOT conserved

Charged lepton flavor violation (CLFV) → BSM Physics

Charged leptons: e, μ, τ

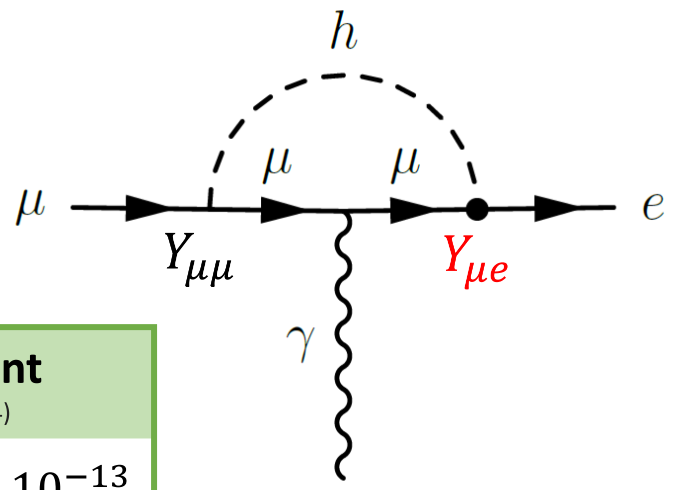
Standard model: Each flavor conserved

Muon decay: $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$

Beta decay: $n \to p + e^- + \bar{\nu}_e$

Pion decay: $\pi^+ \to \mu^+ + \nu_\mu$

BSM model



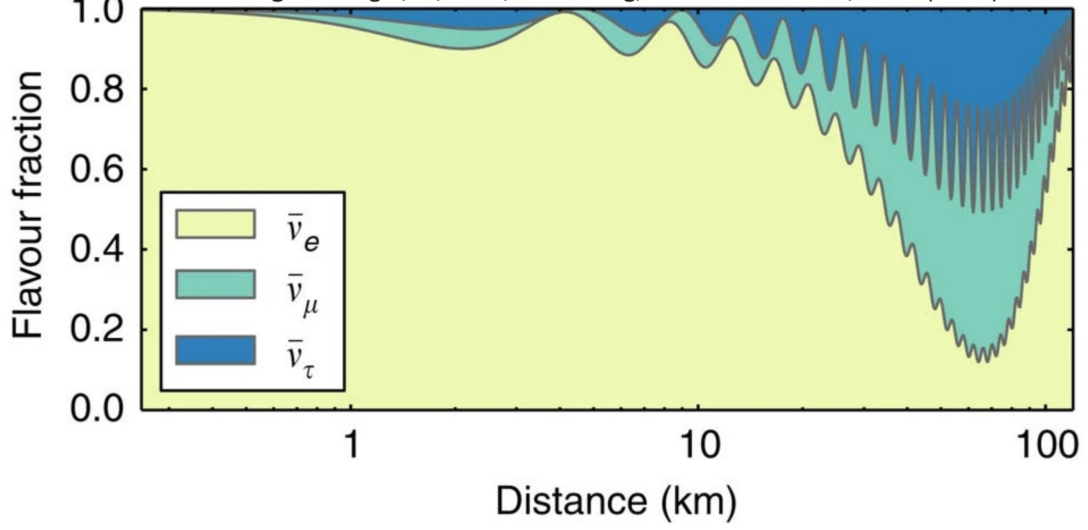
MEG II experiment

Eur. Phys. J. C **84**, 216 (2024)

$\mathrm{BR}(\mu \to e\gamma) < 3.1 \times 10^{-13}$

Neutral leptons: ν_e, ν_μ, ν_τ

Figure: Vogel, P., Wen, L. & Zhang, C. *Nat Commun* **6**, 6935 (2015)



Neutrino oscillations: Flavor NOT conserved

Charged lepton flavor violation (CLFV) → BSM Physics

- 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

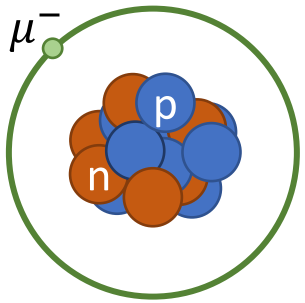
Stopped Muon Constraints

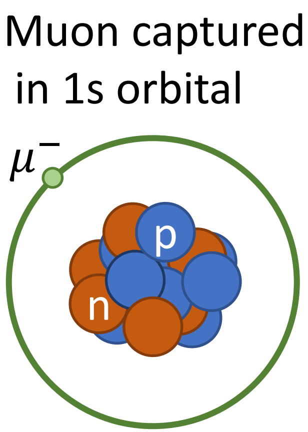
Process	BR Limit	CL	Experiment
$\mu^+ \to e^+\gamma$	3.1×10^{-13}	90%	MEG + MEG II
$\mu^+ \to e^+e^-e^+$	1.0×10^{-12}	90%	SINDRUM
$\boldsymbol{\mu^- + \mathrm{Cu} \to e^- + \mathrm{Cu}}$	1.6×10^{-8}	90%	SINDRUM II
$\boldsymbol{\mu^- + {}^{32}\mathrm{S} \to e^- + {}^{32}\mathrm{S}}$	7×10^{-11}	90%	SIN
$\boldsymbol{\mu^- + \mathrm{Pb} \to e^- + \mathrm{Pb}}$	4.6×10^{-11}	90%	SINDRUM II
$\boldsymbol{\mu^- + \mathrm{Ti} \to e^- + \mathrm{Ti}}$	6.1×10^{-13}	90%	SINDRUM II
$\boldsymbol{\mu^- + \mathrm{Au} \to e^- + \mathrm{Au}}$	7.0×10^{-13}	90%	SINDRUM II

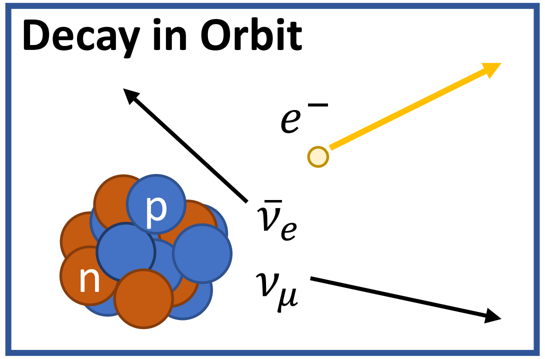
$\mu^+ \to e^+\gamma$	6×10^{-14}	90%	MEG II
$\mu^+ \to e^+e^-e^+$	4×10^{-16}	90%	Mu3e
$\boldsymbol{\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}}$	$\boldsymbol{8 \times 10^{-17}}$	90%	Mu2e
$\boldsymbol{\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}}$	$\boldsymbol{7 \times 10^{-17}}$	90%	COMET

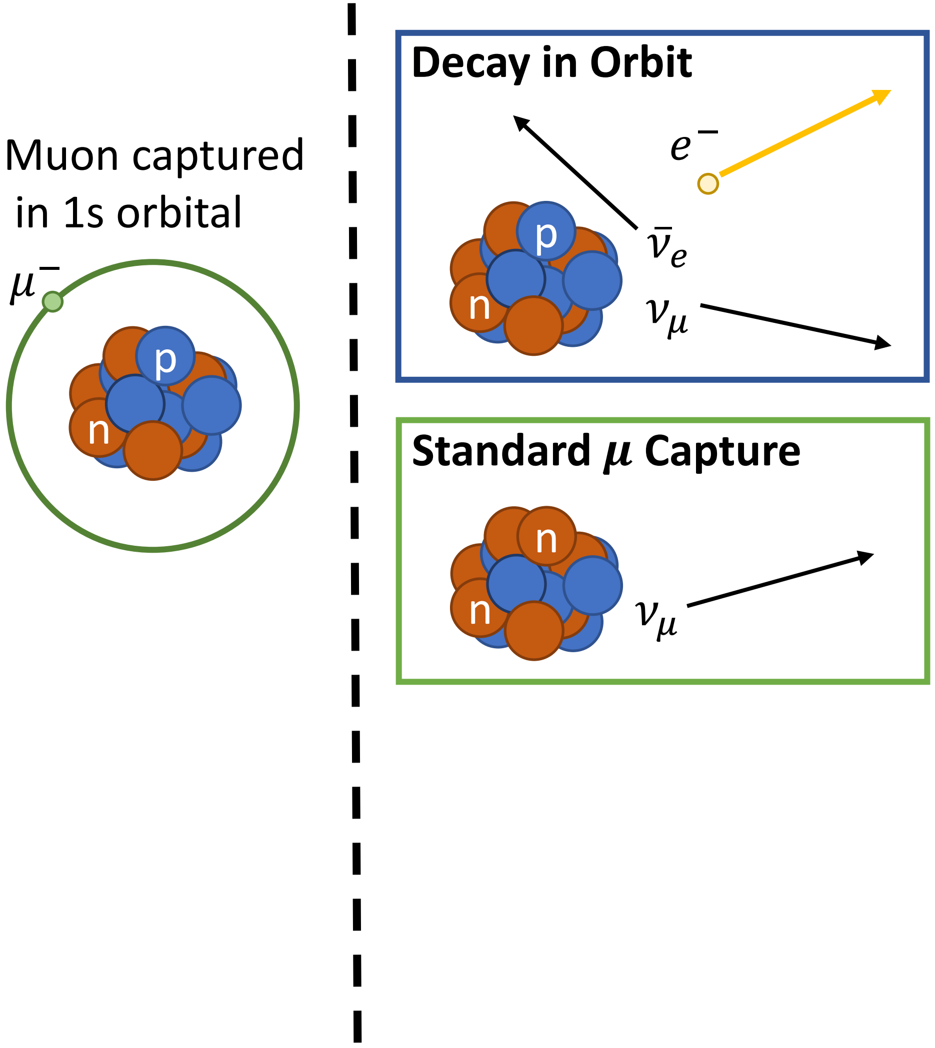
Next-Generation Experiments

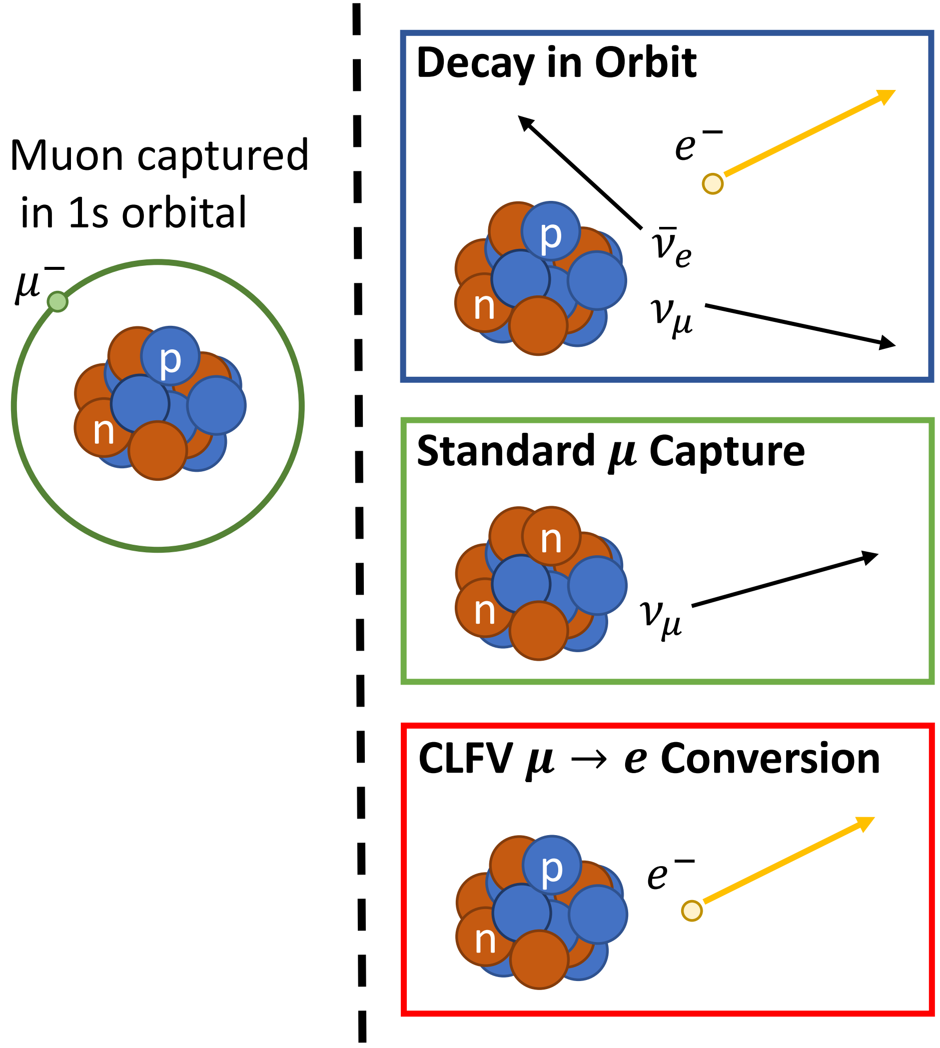
Muon captured
in 1s orbital



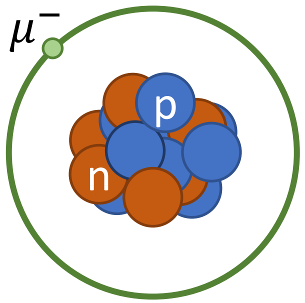

Muon captured
in 1s orbital
μ^-
p
n


Decay in Orbit
e^-
$\bar{\nu}_e$
ν_μ
p
n

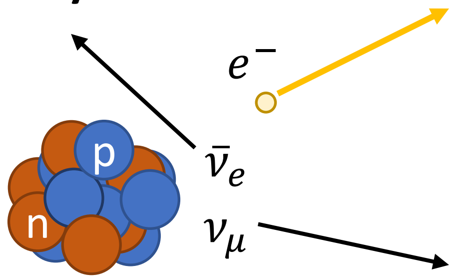

Muon captured
in 1s orbital
μ^-
p
n
Decay in Orbit
e^-
$\bar{\nu}_e$
ν_μ
Standard μ Capture
ν_μ


Muon captured
in 1s orbital
μ^-
p
n
Decay in Orbit
e^-
$\bar{\nu}_e$
ν_μ
p
n
Standard μ Capture
n
n
ν_μ
CLFV $\mu \to e$ Conversion
p
n
e^-

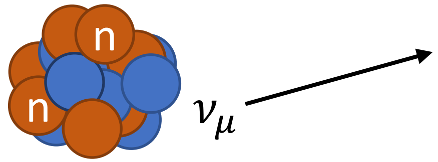
Muon captured
in 1s orbital



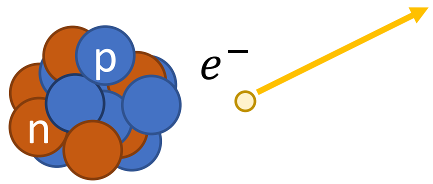
Decay in Orbit



Standard μ Capture

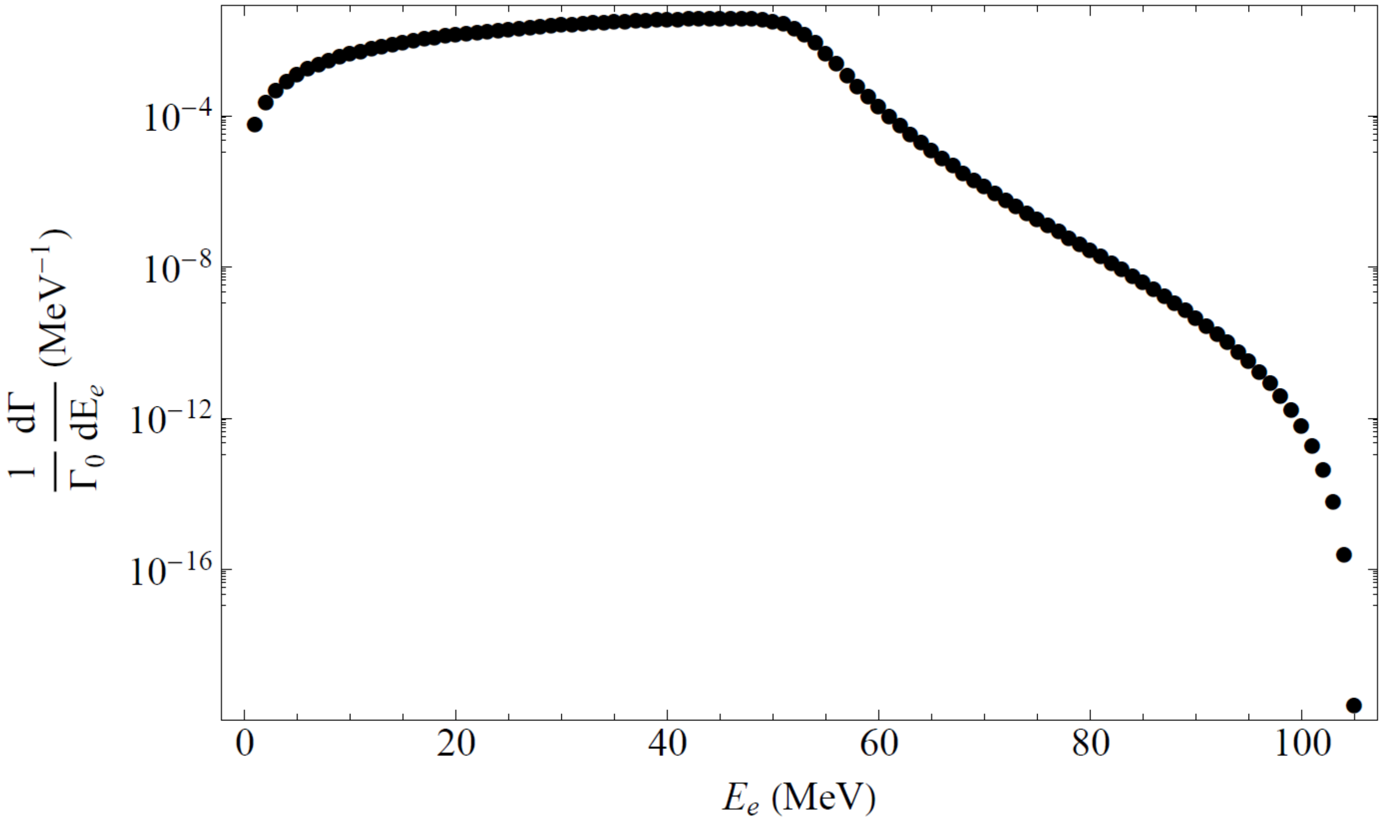


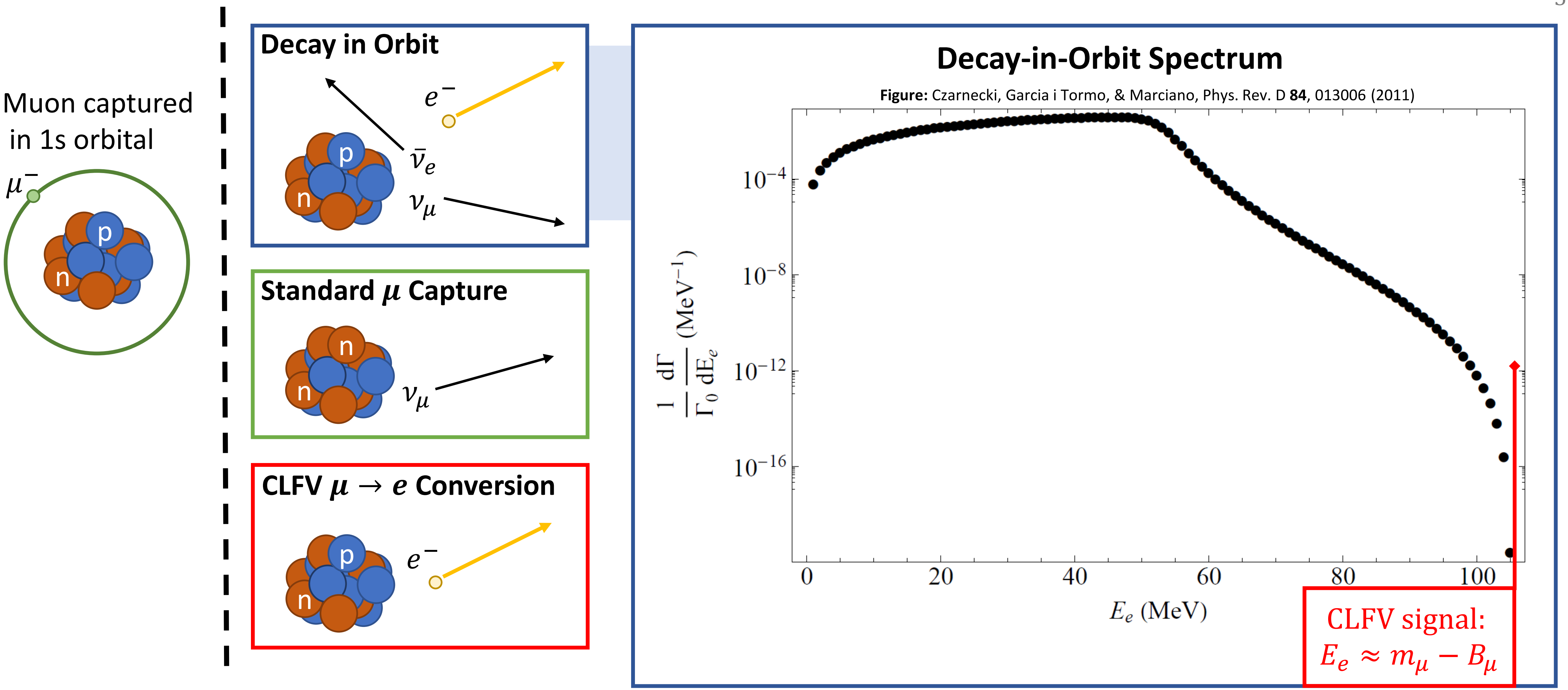
CLFV $\mu \to e$ Conversion



Decay-in-Orbit Spectrum

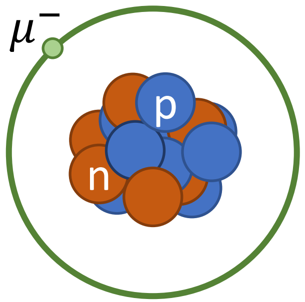
Figure: Czarnecki, Garcia i Tormo, & Marciano, Phys. Rev. D **84**, 013006 (2011)



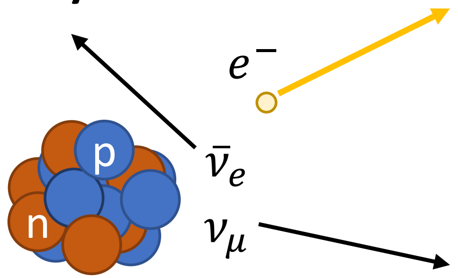


Muon captured in 1s orbital
μ^-
p
n
Decay in Orbit
e^-
$\bar{\nu}_e$
ν_μ
Standard μ Capture
ν_μ
CLFV $\mu \to e$ Conversion
e^-
Decay-in-Orbit Spectrum
Figure: Czarnecki, Garcia i Tormo, & Marciano, Phys. Rev. D **84**, 013006 (2011)
$\frac{1}{\Gamma_0}\frac{d\Gamma}{dE_e}$ (MeV^{-1})
10^{-4}
10^{-8}
10^{-12}
10^{-16}
0
20
40
60
80
100
E_e (MeV)
CLFV signal:
$E_e \approx m_\mu - B_\mu$

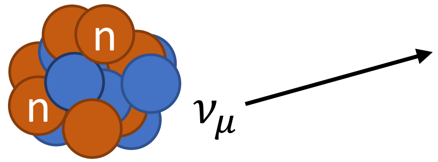
Muon captured in 1s orbital



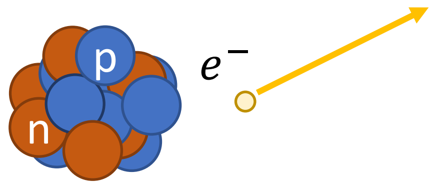
Decay in Orbit



Standard μ Capture

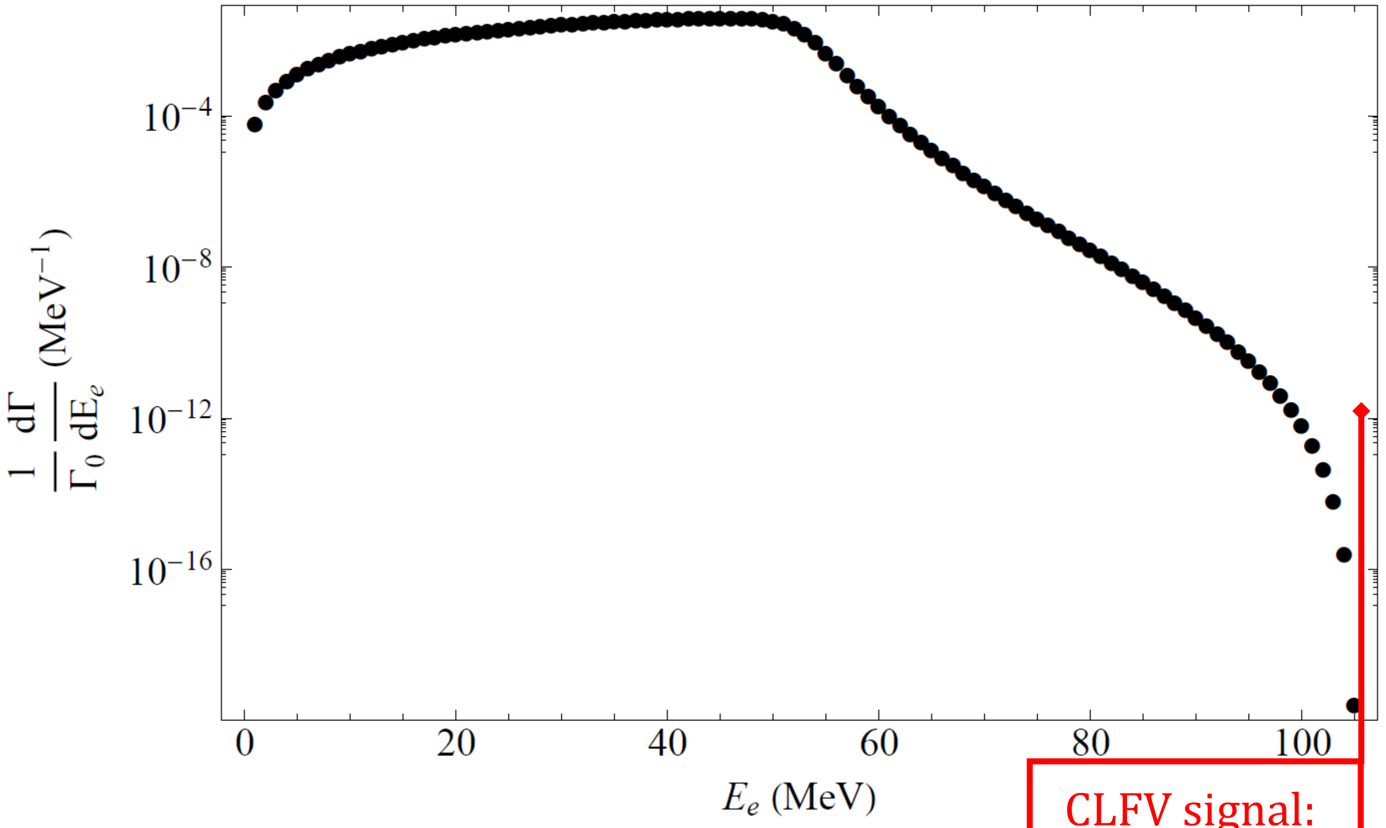


CLFV $\mu \rightarrow e$ Conversion



Decay-in-Orbit Spectrum

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



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

**** Assuming nucleus remains in ground state ****

"Elastic conversion"

Mu2e Experiment

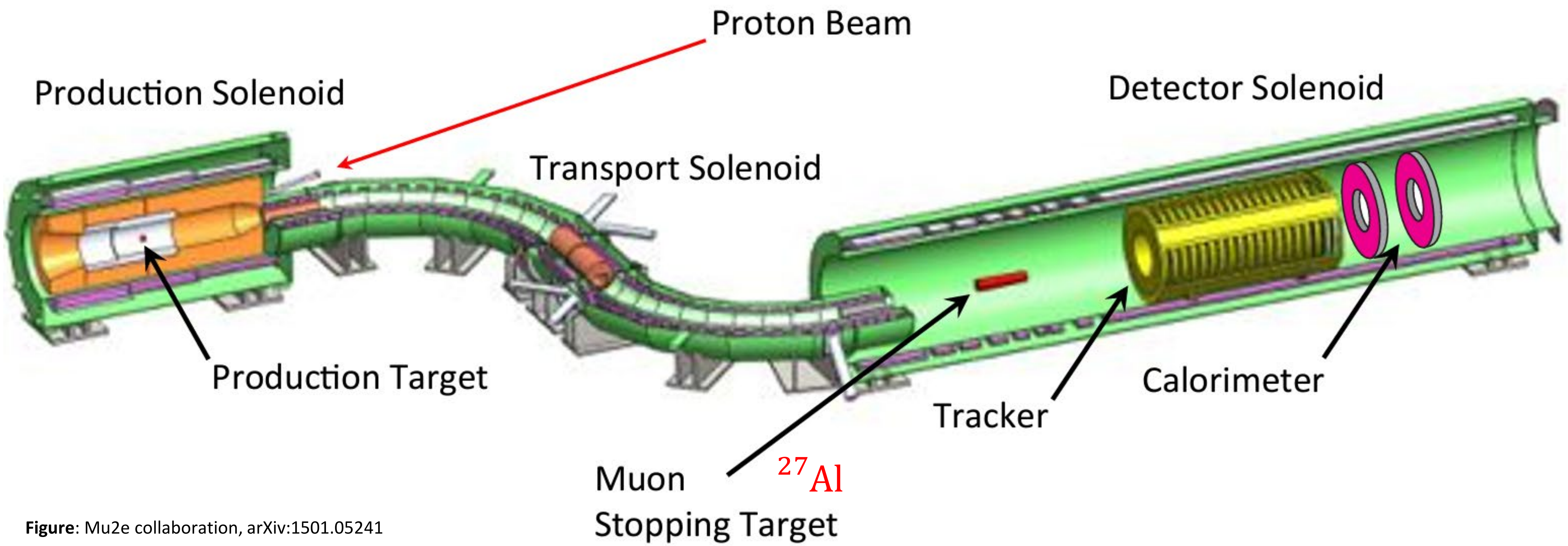
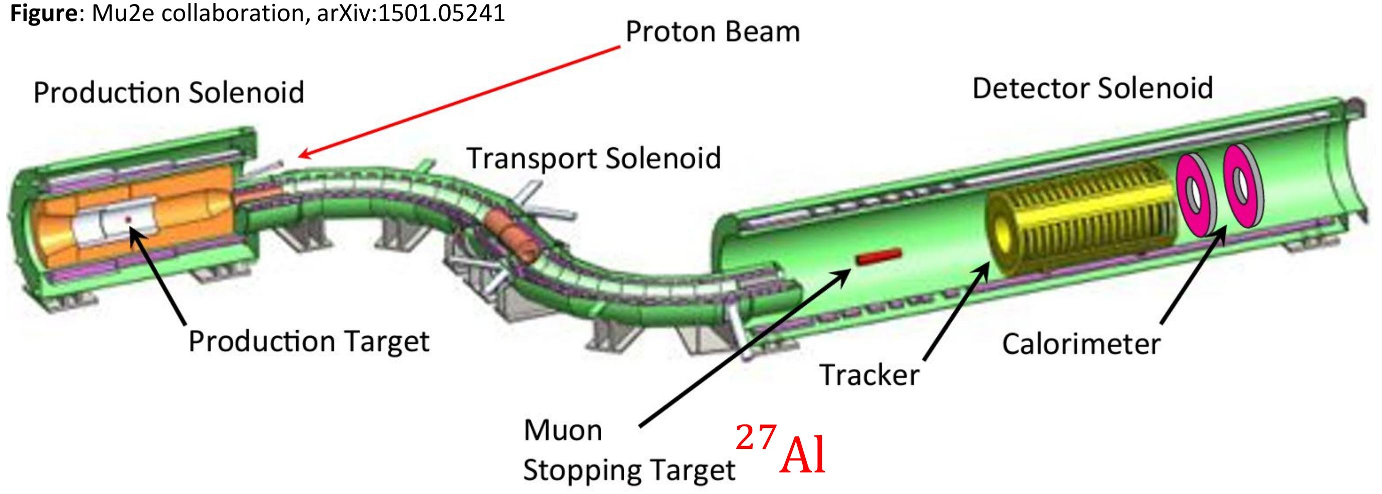


Figure: Mu2e collaboration, arXiv:1501.05241

Mu2e Experiment

Figure: Mu2e collaboration, arXiv:1501.05241



Advantages

Huge Intensity: 10^{18} muons captured

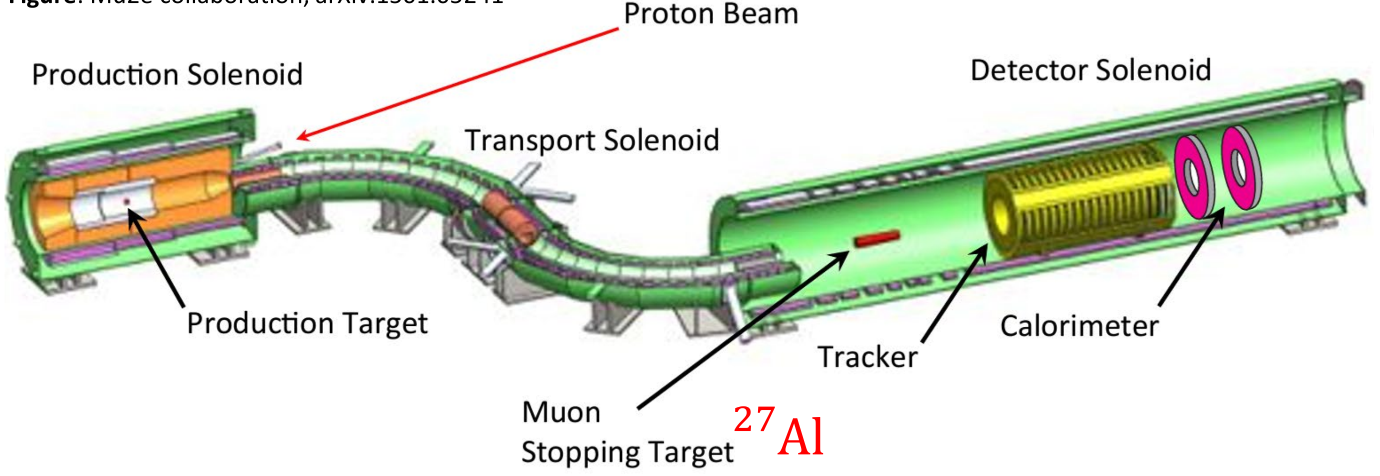
Single-event sensitivity: $\mathrm{BR}(\mu \to e) < 3 \times 10^{-17}$ (1 in 30 quadrillion)

Definitive signal of new physics

Varying nuclear target probes **different** CLFV physics

Mu2e Experiment

Figure: Mu2e collaboration, arXiv:1501.05241



Advantages

Huge Intensity: 10^{18} muons captured

Single-event sensitivity: $\mathrm{BR}(\mu \to e) < 3 \times 10^{-17}$
(1 in 30 quadrillion)

Definitive signal of new physics

Varying nuclear target probes **different** CLFV physics

Challenges

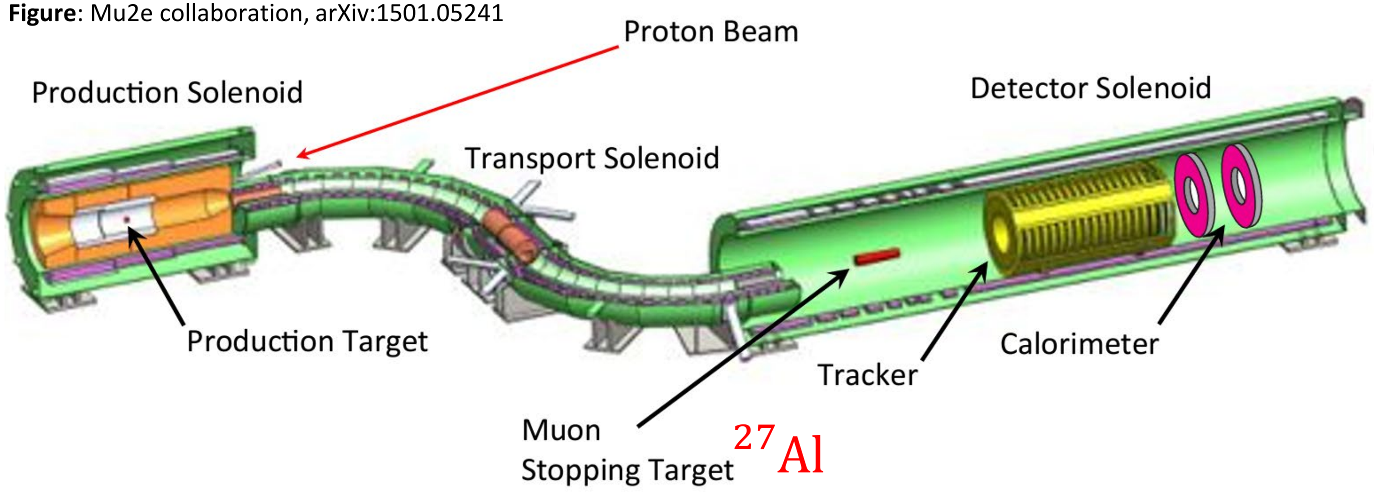
CLFV physics **filtered** by **nuclear** physics

Large scale separation between **experiments** and **UV** theories

Mu2e Experiment

Fermilab

Figure: Mu2e collaboration, arXiv:1501.05241



Advantages

Huge Intensity: 10^{18} muons captured

Single-event sensitivity: $\mathrm{BR}(\mu \to e) < 3 \times 10^{-17}$
(1 in 30 quadrillion)

Definitive signal of new physics

Varying nuclear target probes **different** CLFV physics

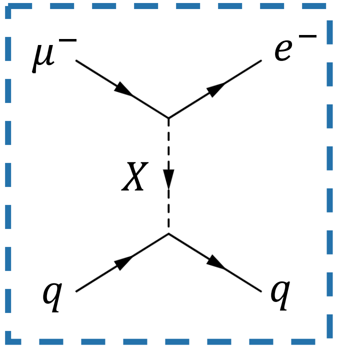
Challenges

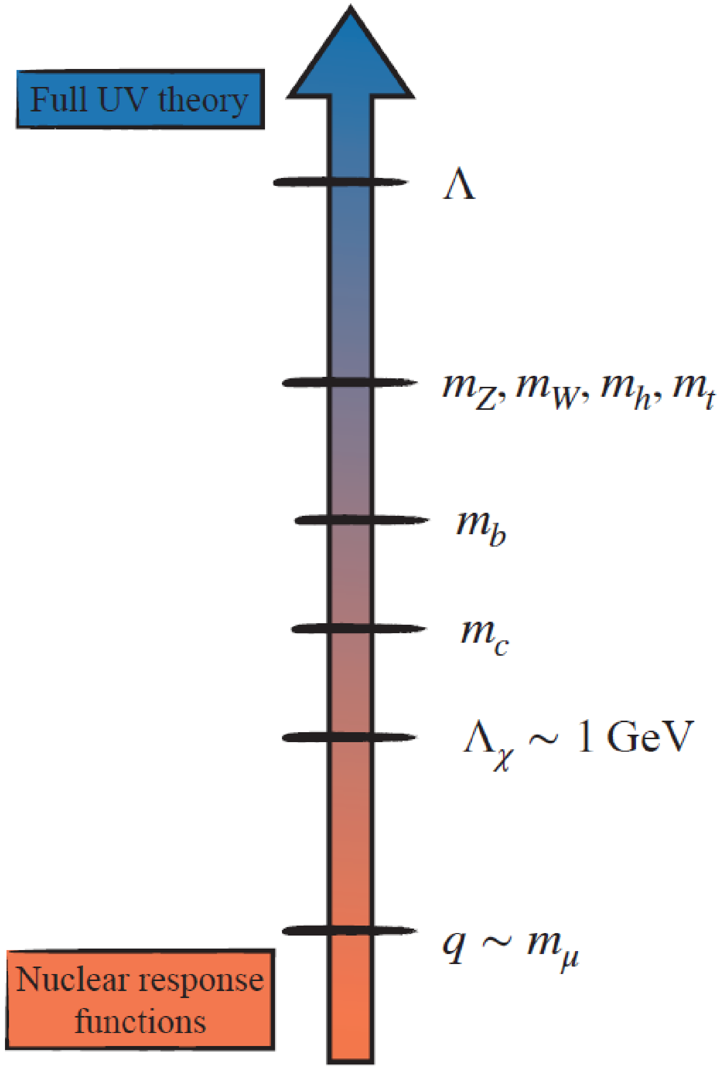
CLFV physics **filtered** by **nuclear** physics

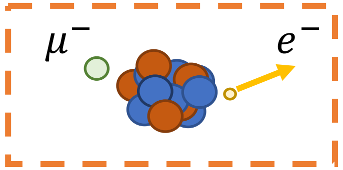
Large scale separation between **experiments** and **UV** theories

Goal: Extract maximum information from experiment

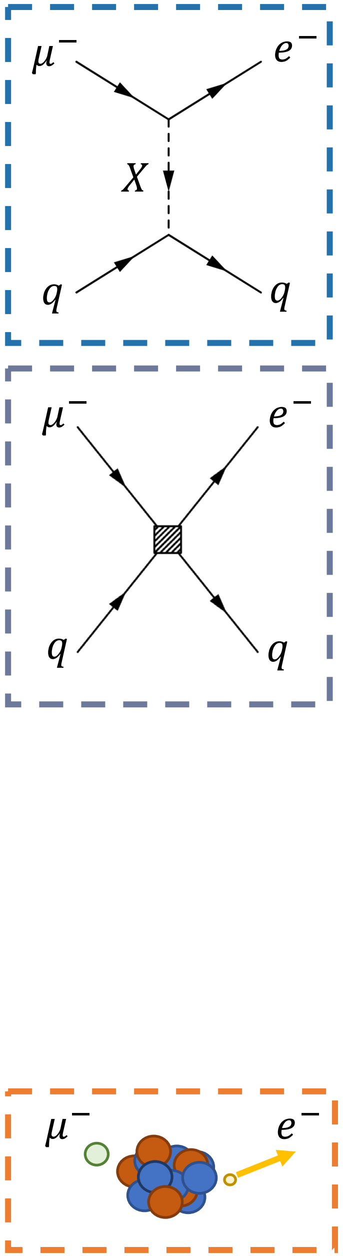
A Tower of Effective Theories

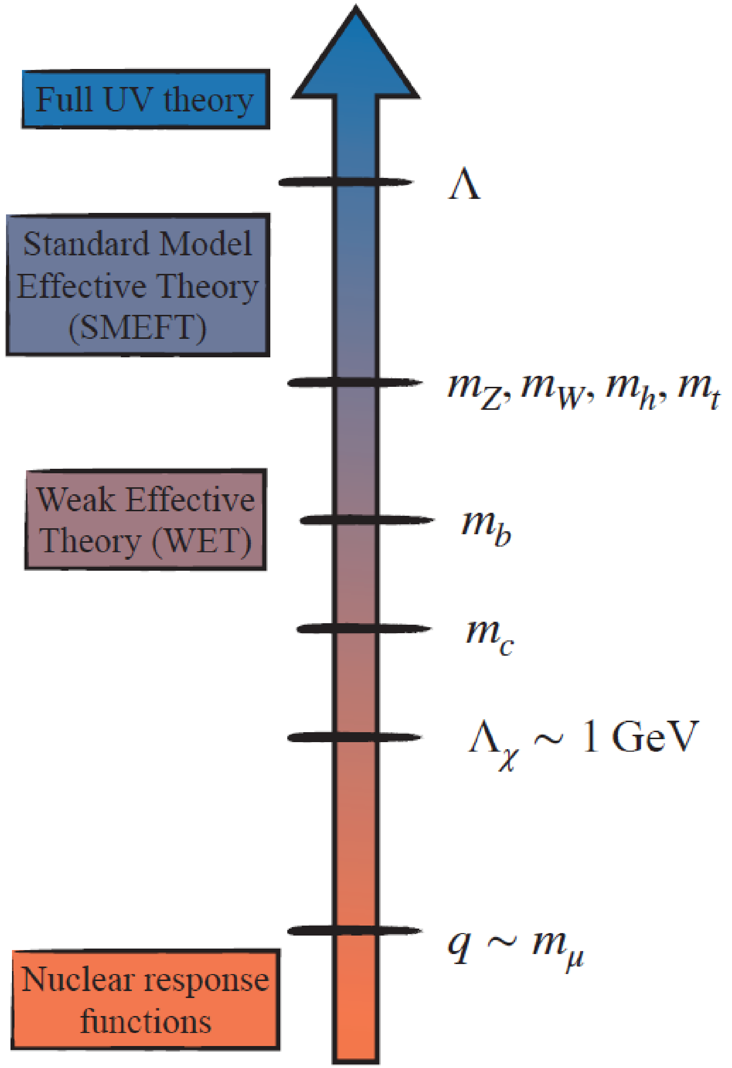




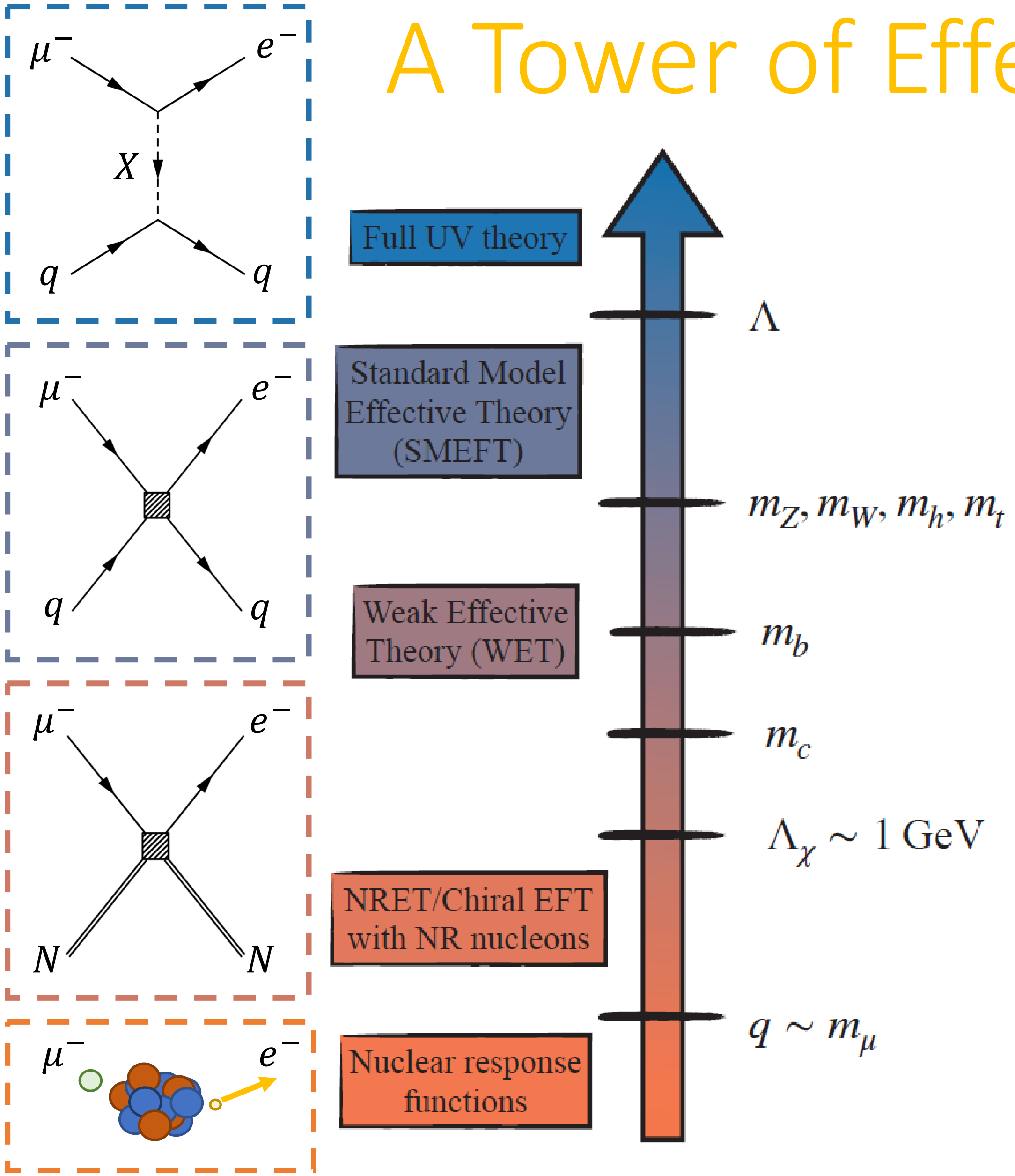


A Tower of Effective Theories

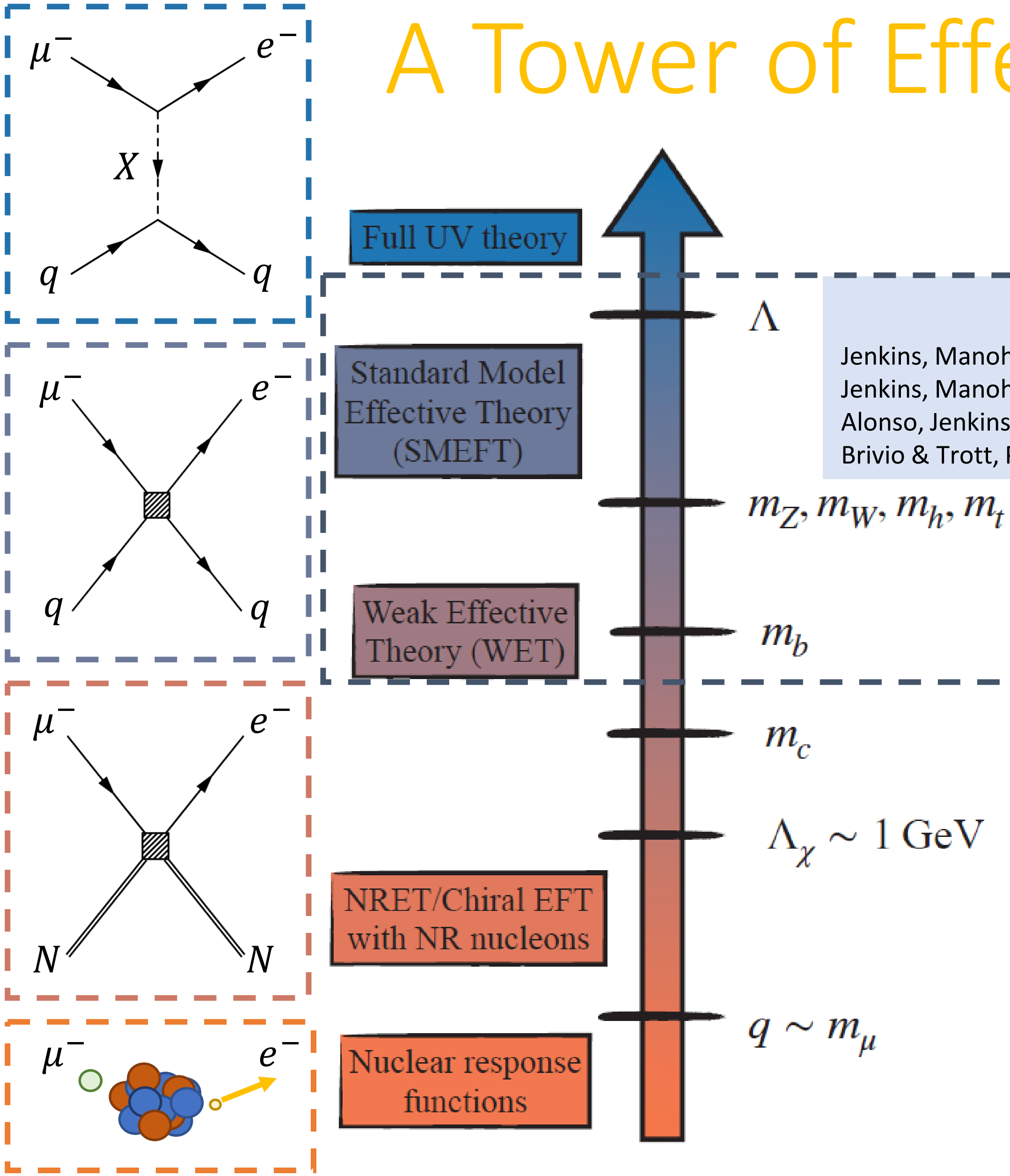




A Tower of Effective Theories



A Tower of Effective Theories



SMEFT

Jenkins, Manohar, & Trott, JHEP **10** (2013) 087
Jenkins, Manohar, & Trott, JHEP **01** (2014) 035
Alonso, Jenkins, Manohar, & Trott, JHEP **04** (2014) 159
Brivio & Trott, Phys. Rept. **793** (2019) 1-98

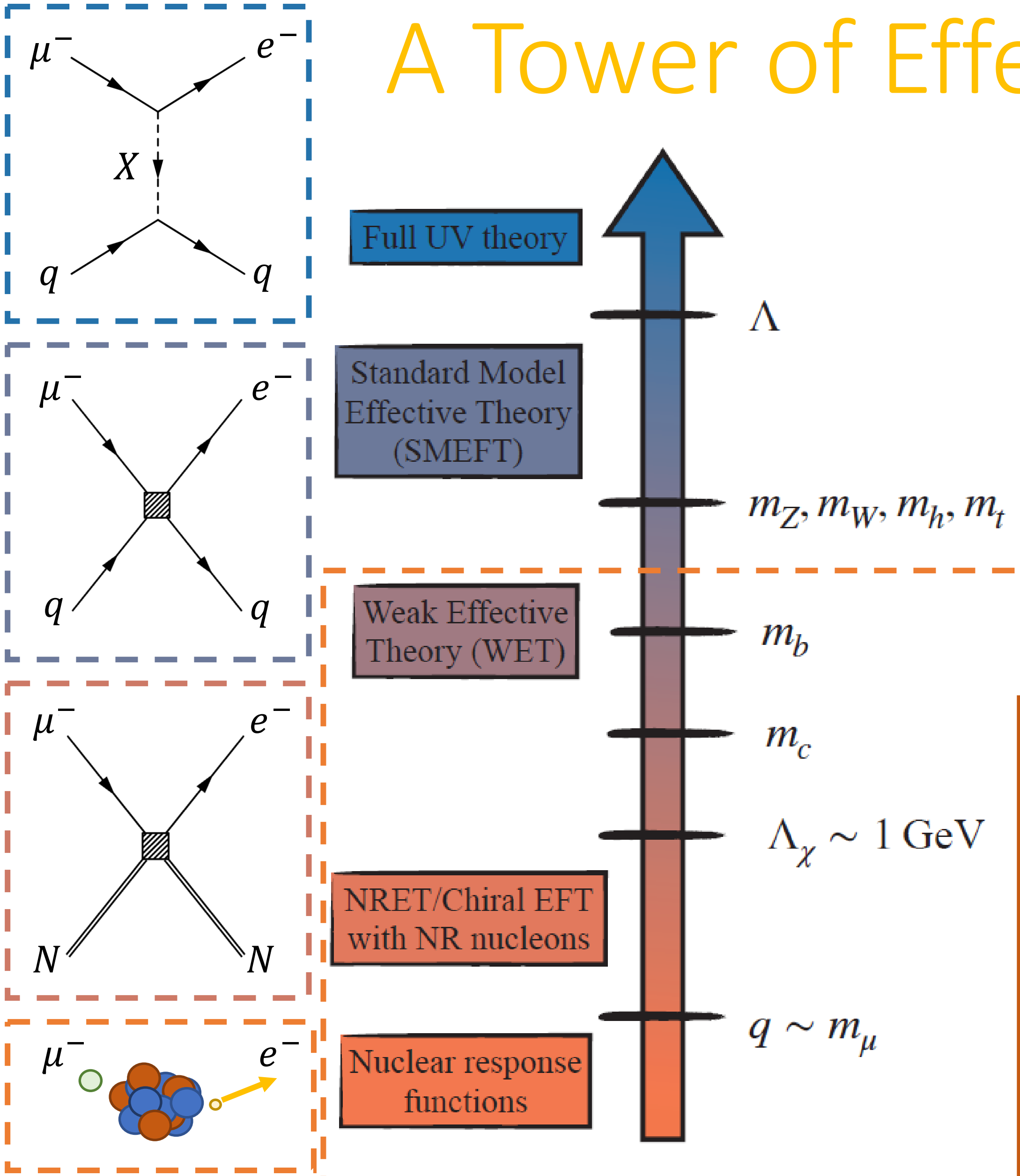
WET

Jenkins, Manohar, & Stoffer, JHEP **03** (2018) 016
Dekens & Stoffer, JHEP **10** (2019) 197

Codes

Wilson: Aebischer, Kumar, & Straub, Eur. Phys. J. C **78** (2018) 1026
DsixTools: Celis, Fuentes-Martin, Vicente, and Virto, Eur. Phys. J. C **77** (2017)
Fuentes-Martin, Ruiz-Femenia, Vicente & Virto, Eur. Phys. J. C **81** (2021)

A Tower of Effective Theories



ER, Haxton, & McElvain, *PRL* **130**, 131901 (2023)
Haxton, **ER**, McElvain, & Ramsey-Musolf, *PRC* **107**, 035504 (2023)
Haxton, McElvain, Menzo, **ER**, & Zupan, *JHEP* **11**, 076 (2024)

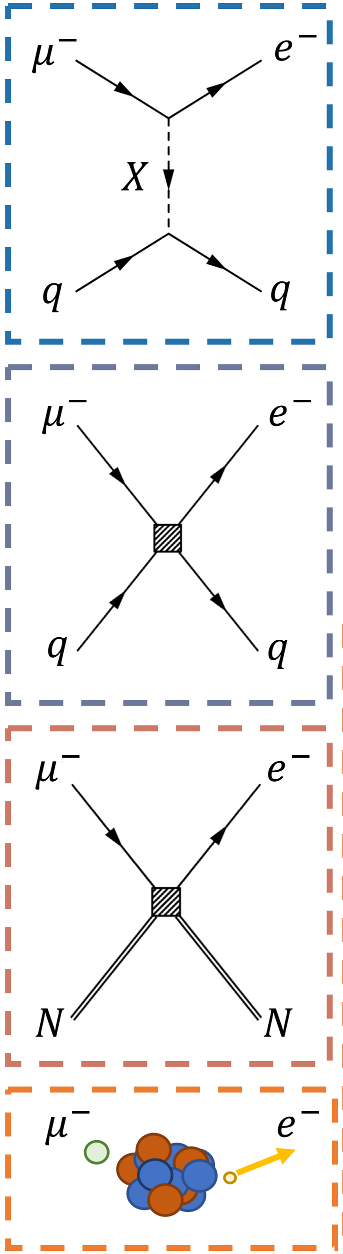
Our Focus

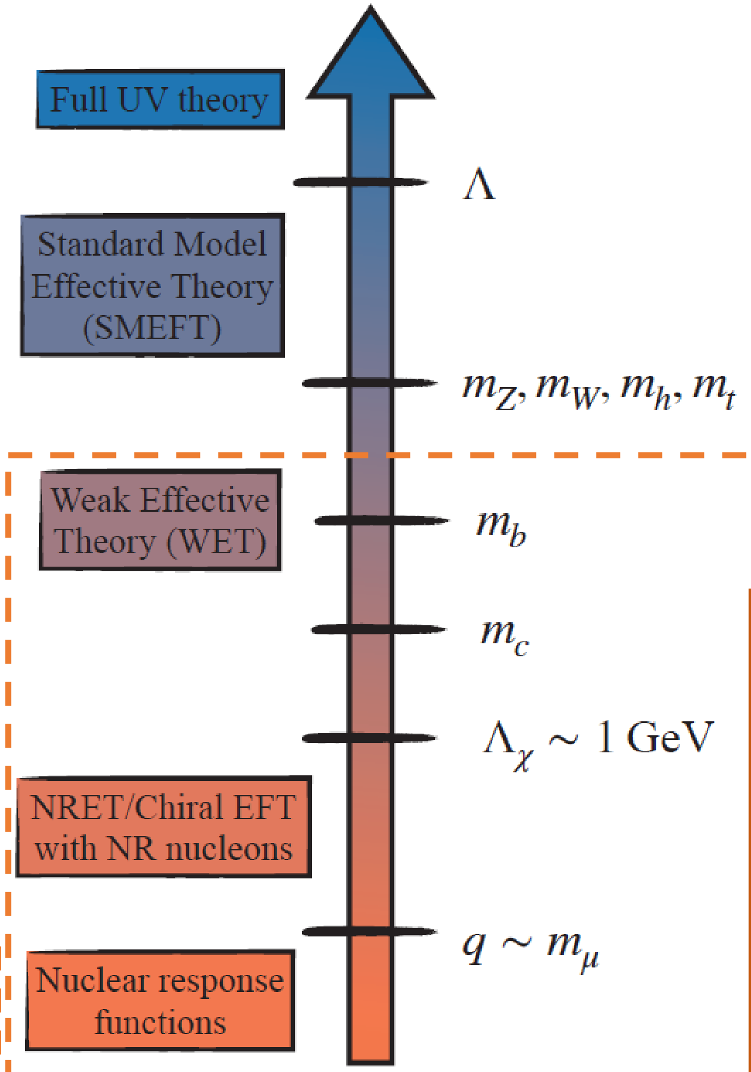
Quarks → Nucleons → Nuclei

Nuclear effective theory

- Interfaces directly with experiment
- Determines how much CLFV information is available

A Tower of Effective Theories





ER, Haxton, & McElvain, *PRL* **130**, 131901 (2023)
Haxton, **ER**, McElvain, & Ramsey-Musolf, *PRC* **107**, 035504 (2023)
Haxton, McElvain, Menzo, **ER**, & Zupan, *JHEP* **11**, 076 (2024)

Our Focus

Quarks → Nucleons → Nuclei

Nuclear effective theory

- Interfaces directly with experiment
- Determines how much CLFV information is available

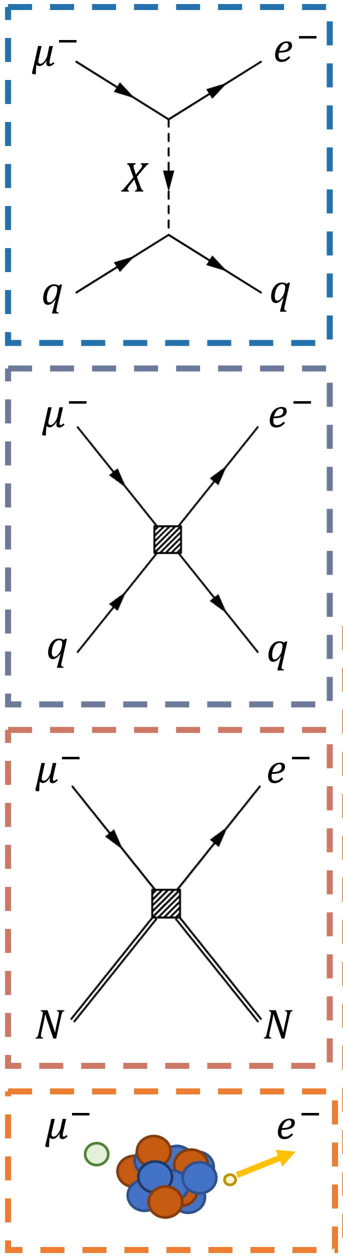
Nuclear: Target-dependent

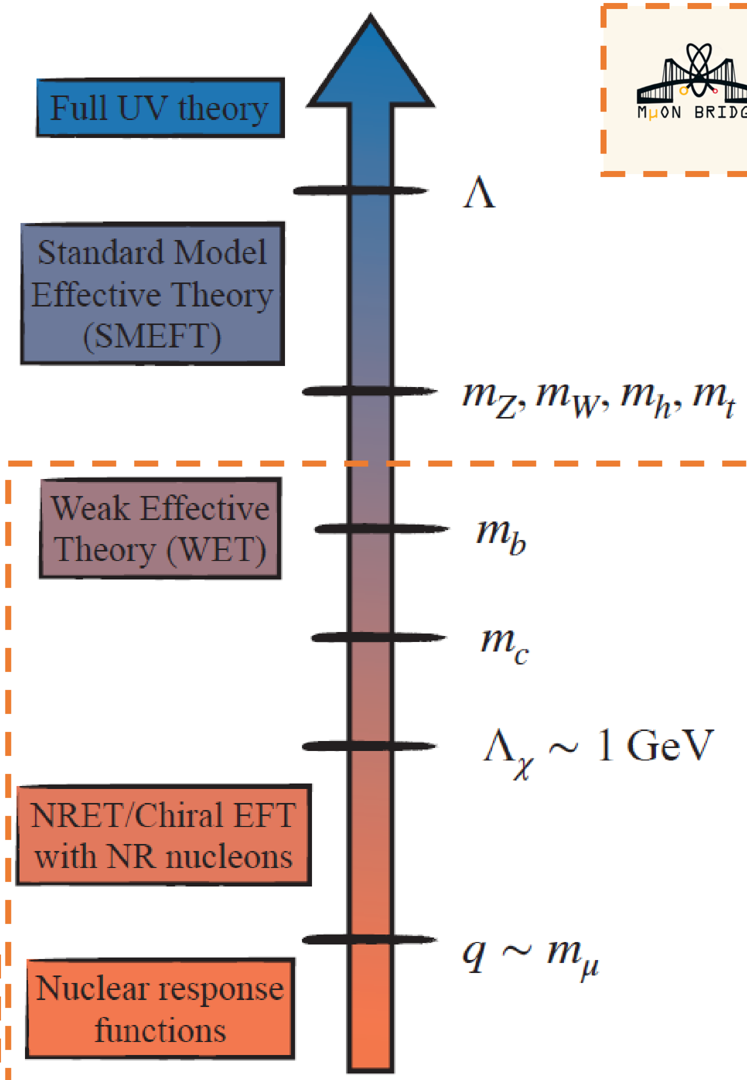
$$\Gamma_{\mu\to e} = \Gamma_0 \sum_i R_i \times W_i$$

CLFV: Target-independent

12 independent (R_i, W_i)

A Tower of Effective Theories





Publicly available analysis code **MuonBridge**

ER, Haxton, & McElvain, *PRL* **130**, 131901 (2023)
Haxton, **ER**, McElvain, & Ramsey-Musolf, *PRC* **107**, 035504 (2023)
Haxton, McElvain, Menzo, **ER**, & Zupan, *JHEP* **11**, 076 (2024)

Our Focus

Quarks → Nucleons → Nuclei

Nuclear effective theory

- Interfaces directly with experiment
- Determines how much CLFV information is available

Nuclear: Target-dependent

$$\Gamma_{\mu\to e} = \Gamma_0 \sum_i R_i \times W_i$$

CLFV: Target-independent

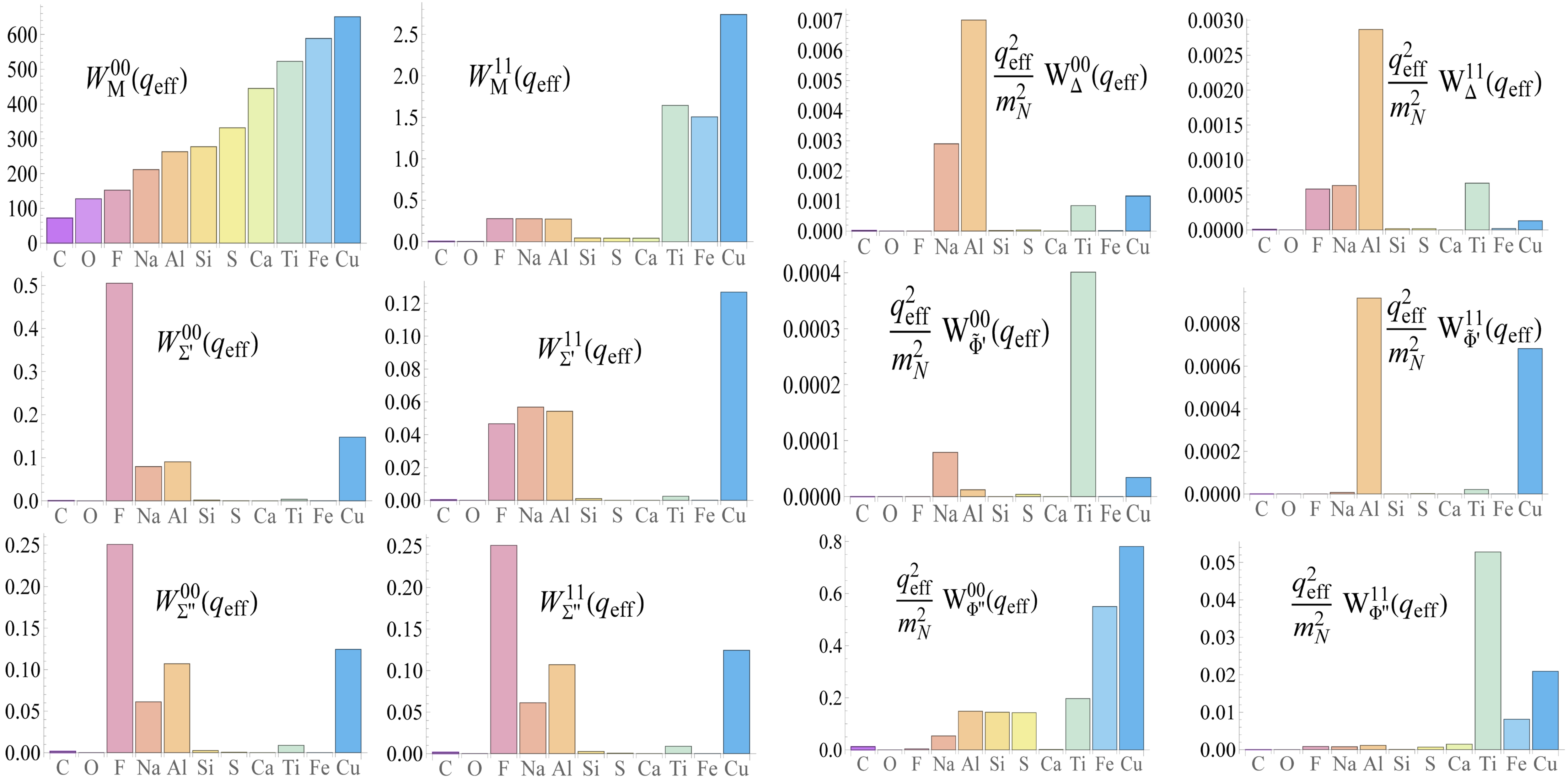
12 independent (R_i, W_i)

Velocity-independent

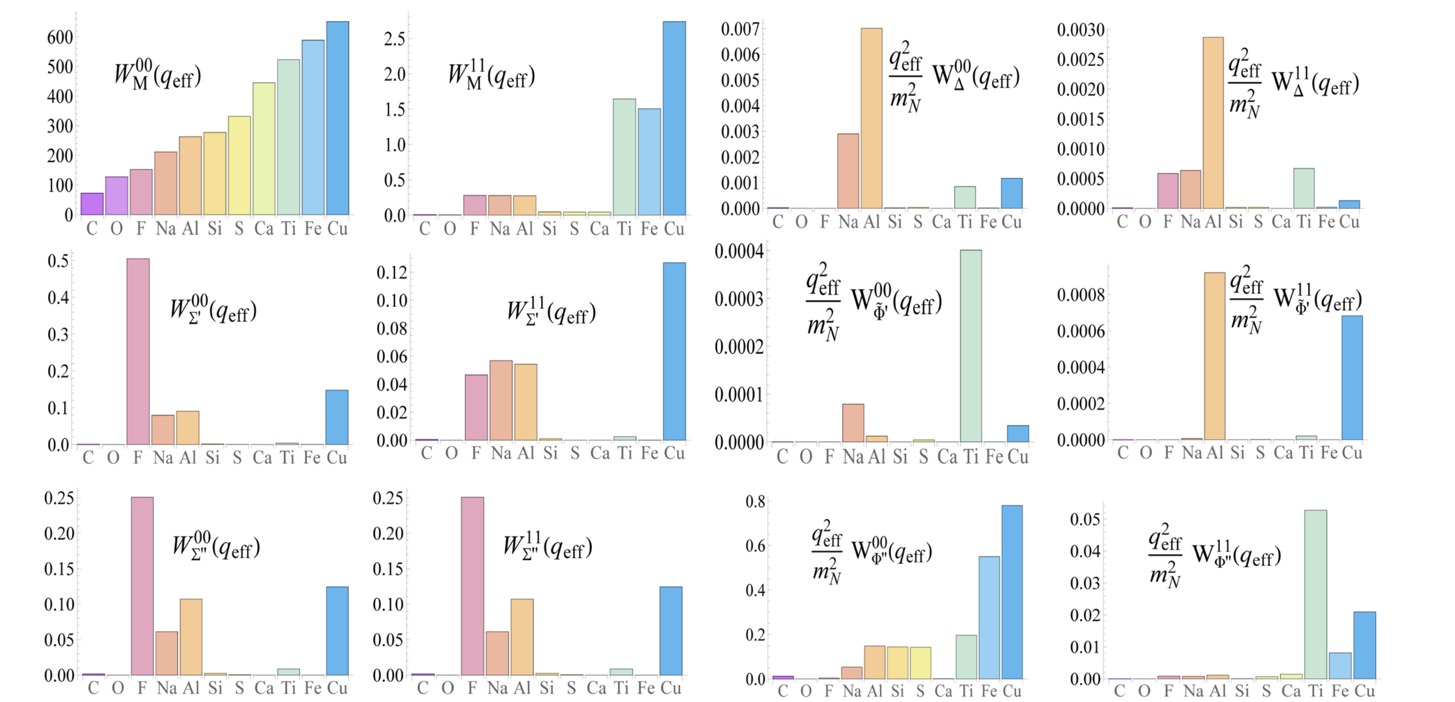
Isoscalar | **Isovector**

Velocity-dependent

Isoscalar | **Isovector**



Many possible CLFV mechanisms can mediate $\mu \to e$ conversion



Requires **multiple experimental programs** with **different target nuclei**

Can we learn more from a single nuclear target?

What about ***inelastic*** $\mu \to e$ conversion?

(Nucleus transitions to excited state)

What about ***inelastic*** $\mu \to e$ conversion?
(Nucleus transitions to excited state)

Large energy transfer
$\Delta E \approx m_\mu \approx 100$ MeV

What about ***inelastic*** $\mu \to e$ conversion?
(Nucleus transitions to excited state)

Large energy transfer
$\Delta E \approx m_\mu \approx 100$ MeV

Relative to nuclear excitation energies
$\Delta E_{\mathrm{nuc}} \sim 1$ MeV

What about ***inelastic*** $\mu \to e$ conversion?
(Nucleus transitions to excited state)

Large energy transfer
$\Delta E \approx m_\mu \approx 100$ MeV

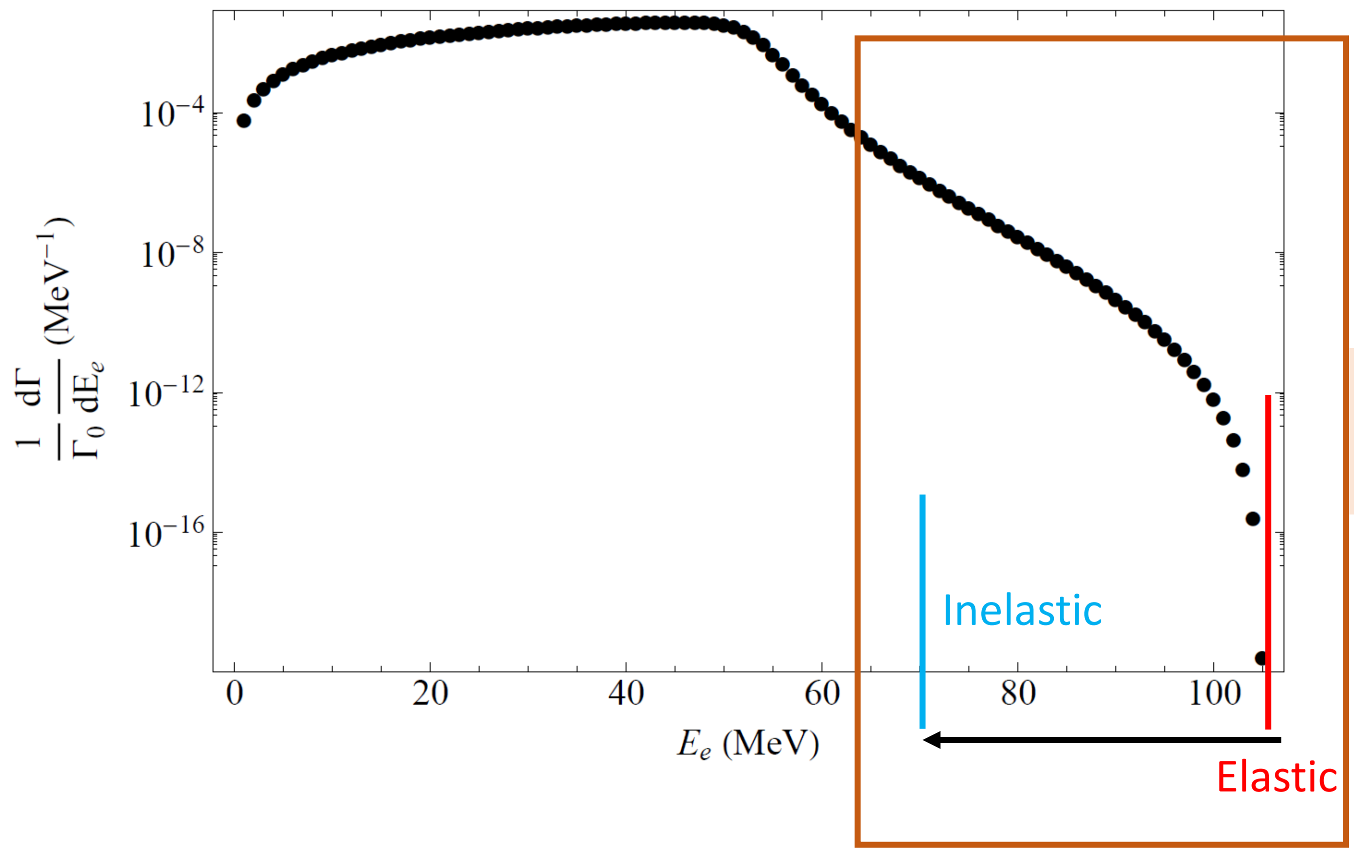
Relative to nuclear excitation energies
$\Delta E_{\text{nuc}} \sim 1$ MeV

Signal electron shifted
$E_e \approx m_\mu - \Delta E_{\text{nuc}}$

What about ***inelastic*** $\mu \to e$ conversion?

(Nucleus transitions to excited state)

Decay-in-Orbit Background



Large energy transfer

$\Delta E \approx m_\mu \approx 100$ MeV

Relative to nuclear excitation energies

$\Delta E_{\text{nuc}} \sim 1$ MeV

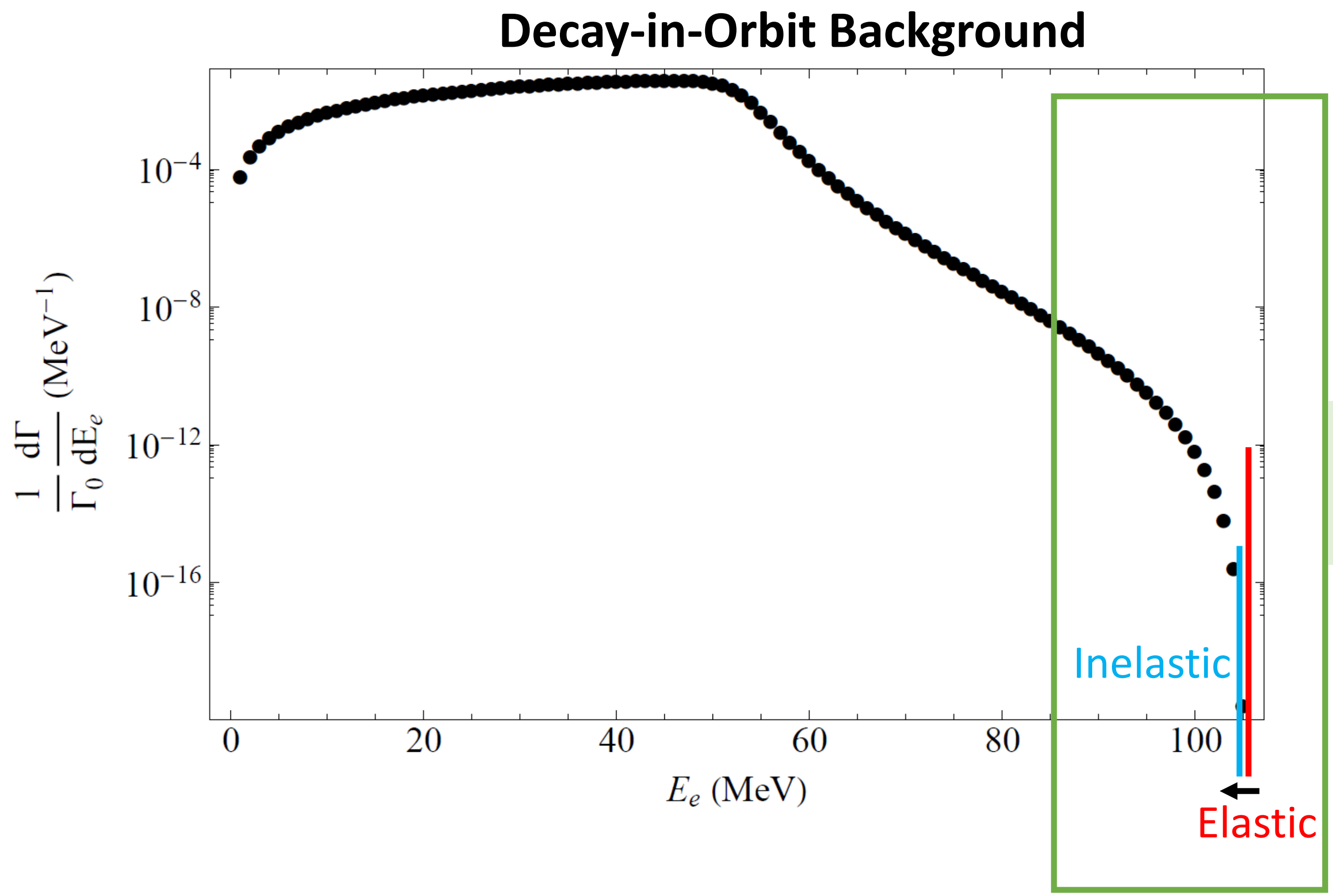
Signal electron shifted

$E_e \approx m_\mu - \Delta E_{\text{nuc}}$

Contributions from high-lying excited states lost in $\mu \to e + 2\nu$ background

What about ***inelastic*** $\mu \to e$ conversion?

(Nucleus transitions to excited state)



Large energy transfer

$\Delta E \approx m_\mu \approx 100$ MeV

Relative to nuclear excitation energies

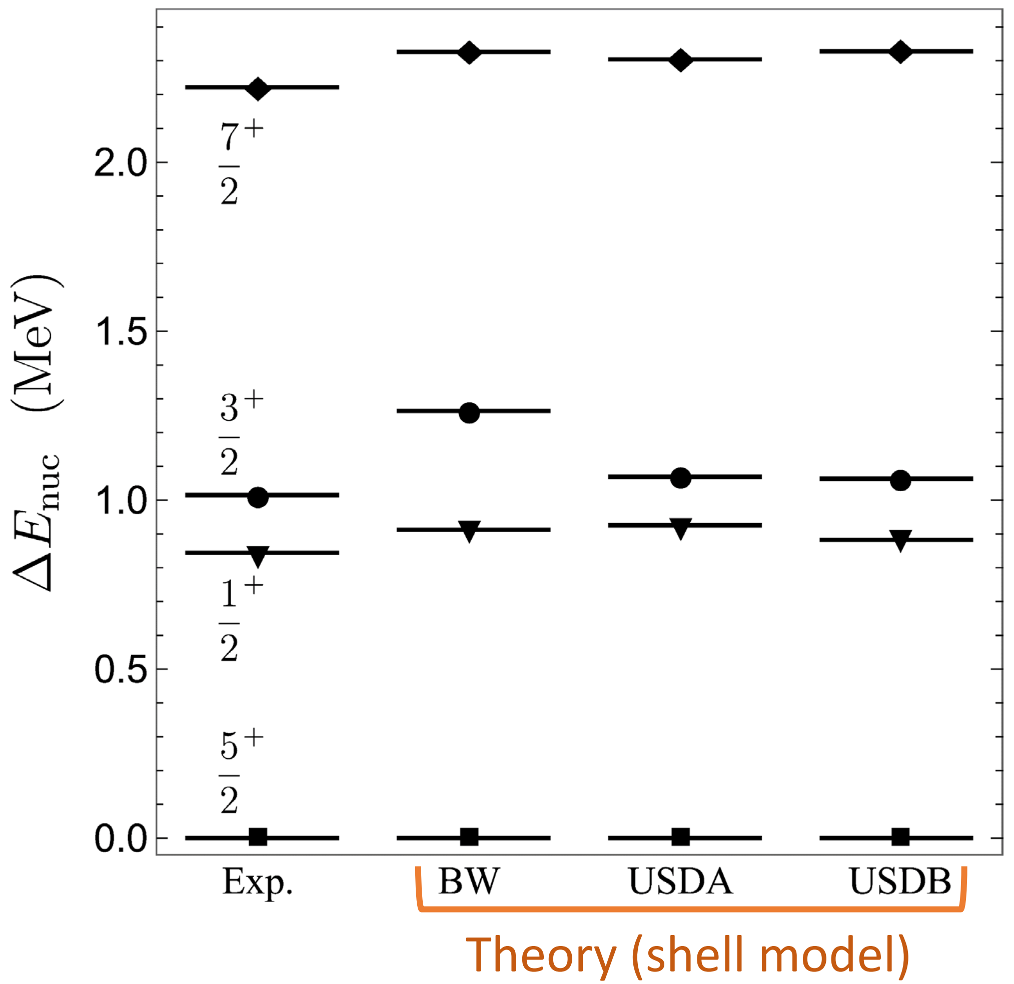
$\Delta E_{\text{nuc}} \sim 1$ MeV

Signal electron shifted

$E_e \approx m_\mu - \Delta E_{\text{nuc}}$

Can low-lying excited states affect the observed electron spectrum?

Spectrum of ^{27}Al



Large energy transfer

$\Delta E \approx m_\mu \approx 100$ MeV

Relative to nuclear excitation energies

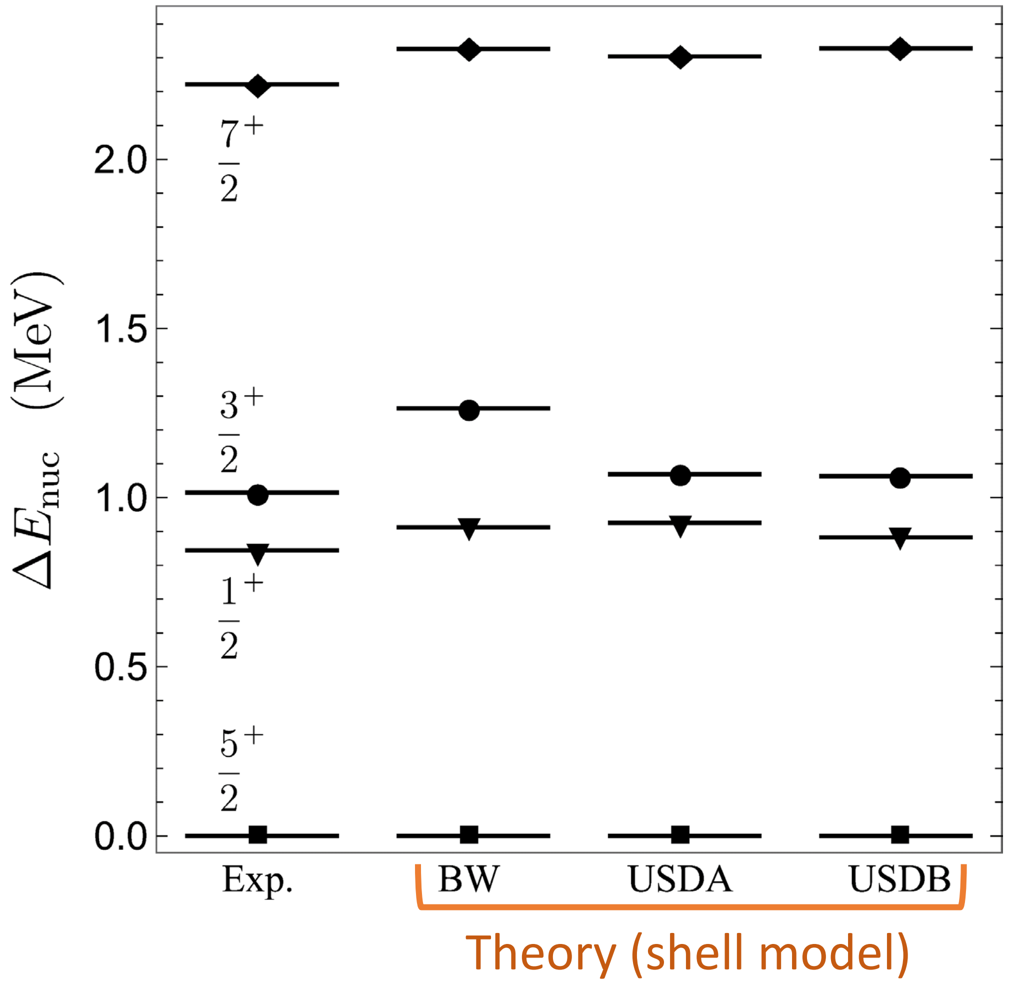
$\Delta E_{\rm nuc} \sim 1$ MeV

Signal electron shifted

$E_e \approx m_\mu - \Delta E_{\rm nuc}$

Can low-lying excited states affect the observed electron spectrum?

Spectrum of ^{27}Al



Large energy transfer

$\Delta E \approx m_\mu \approx 100$ MeV

Relative to nuclear excitation energies

$\Delta E_{\mathrm{nuc}} \sim 1$ MeV

Signal electron shifted

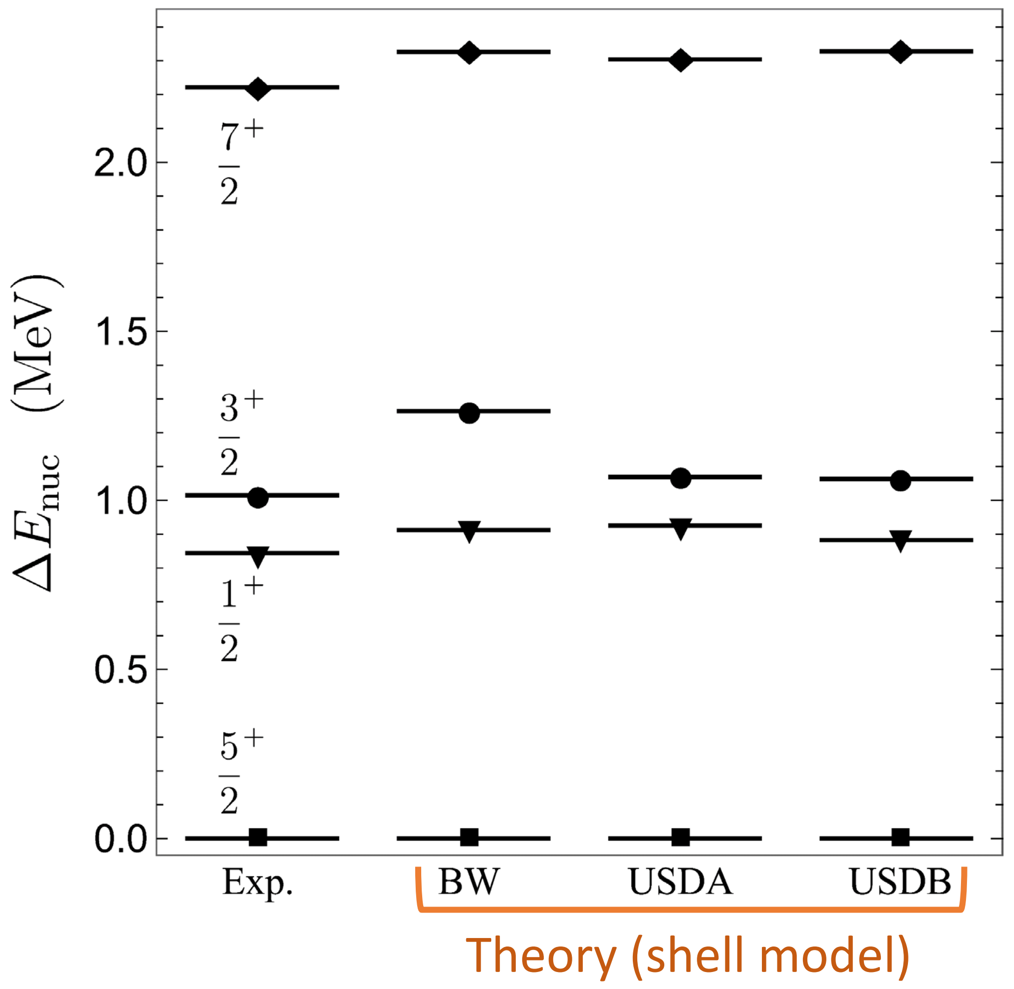
$E_e \approx m_\mu - \Delta E_{\mathrm{nuc}}$

Can low-lying excited states affect the observed electron spectrum?

YES...

but it depends on the CLFV physics

Spectrum of ^{27}Al



Large energy transfer

$\Delta E \approx m_\mu \approx 100$ MeV

Relative to nuclear excitation energies

$\Delta E_{\rm nuc} \sim 1$ MeV

Signal electron shifted

$E_e \approx m_\mu - \Delta E_{\rm nuc}$

Can low-lying excited states affect the observed electron spectrum?

YES…

but it depends on the CLFV physics

New experimental information!

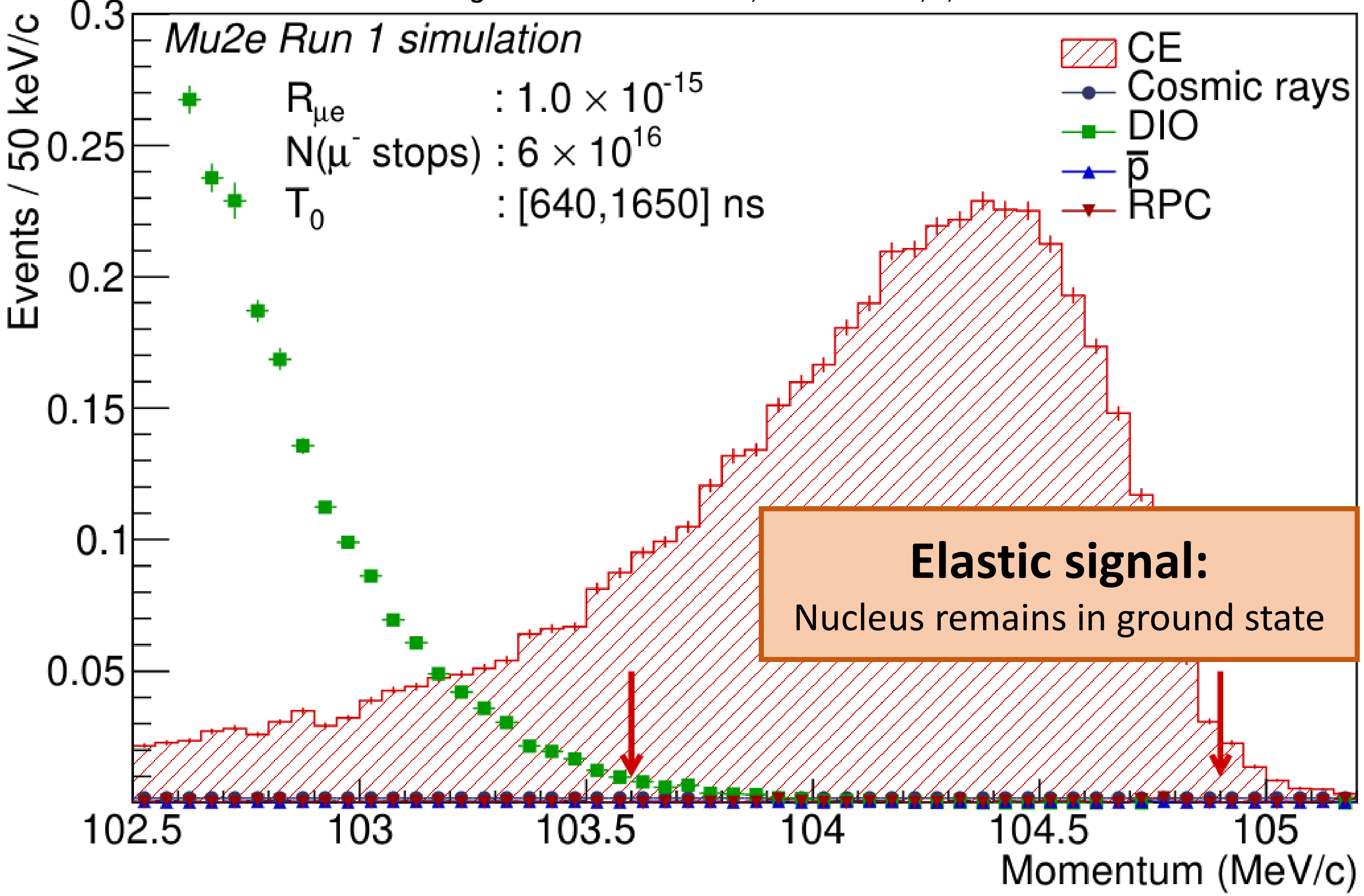
Expected Mu2e signal

Monte Carlo simulation of Mu2e experimental pipeline

Including all backgrounds and cuts

1. Protons on production target
2. Pions decay to muons
3. Muons captured on target
4. Electrons detected by calorimeter

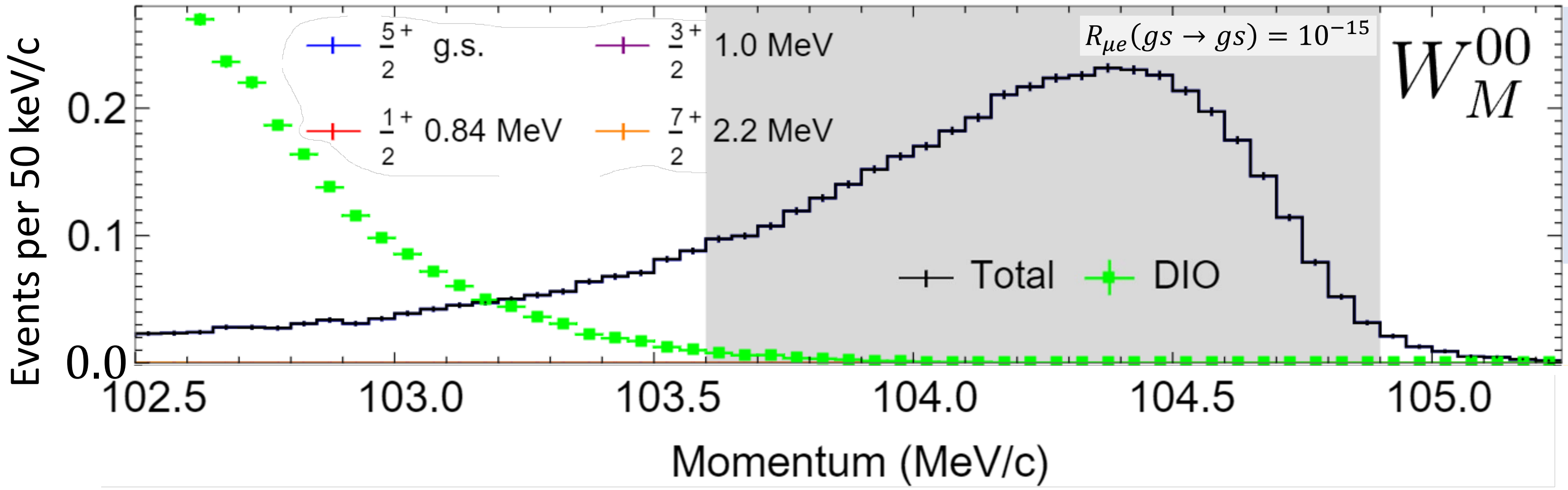
Figure: Mu2e collaboration, *Universe* **2023**, 9, 54



Elastic signal:

Nucleus remains in ground state

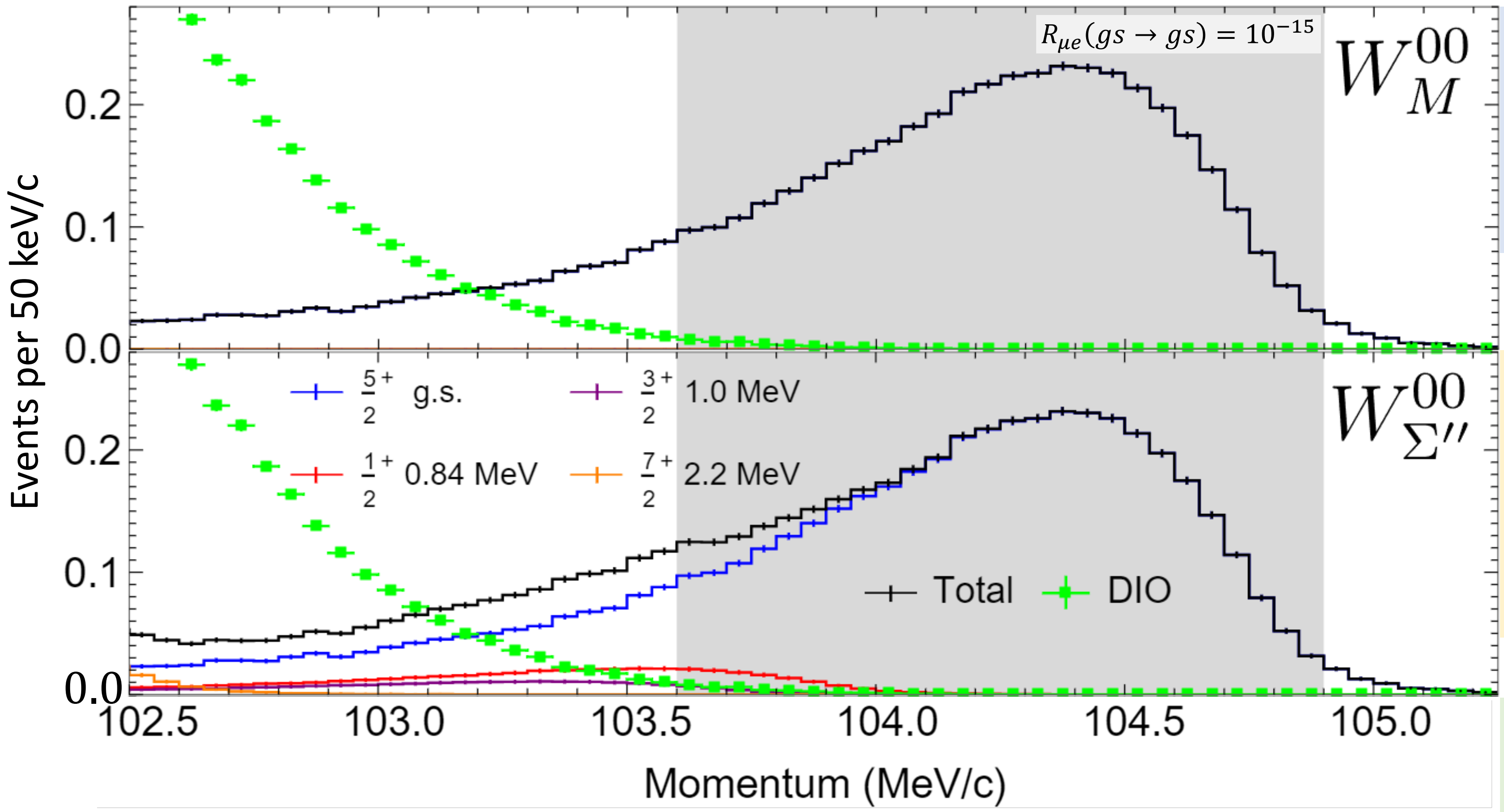
Figure: Haxton & ER, PRL 133, 261801 (2024)



Coherent conversion

- Elastic process enhanced
- Ground state dominates

Figure: Haxton & **ER**, *PRL* **133**, 261801 (2024)



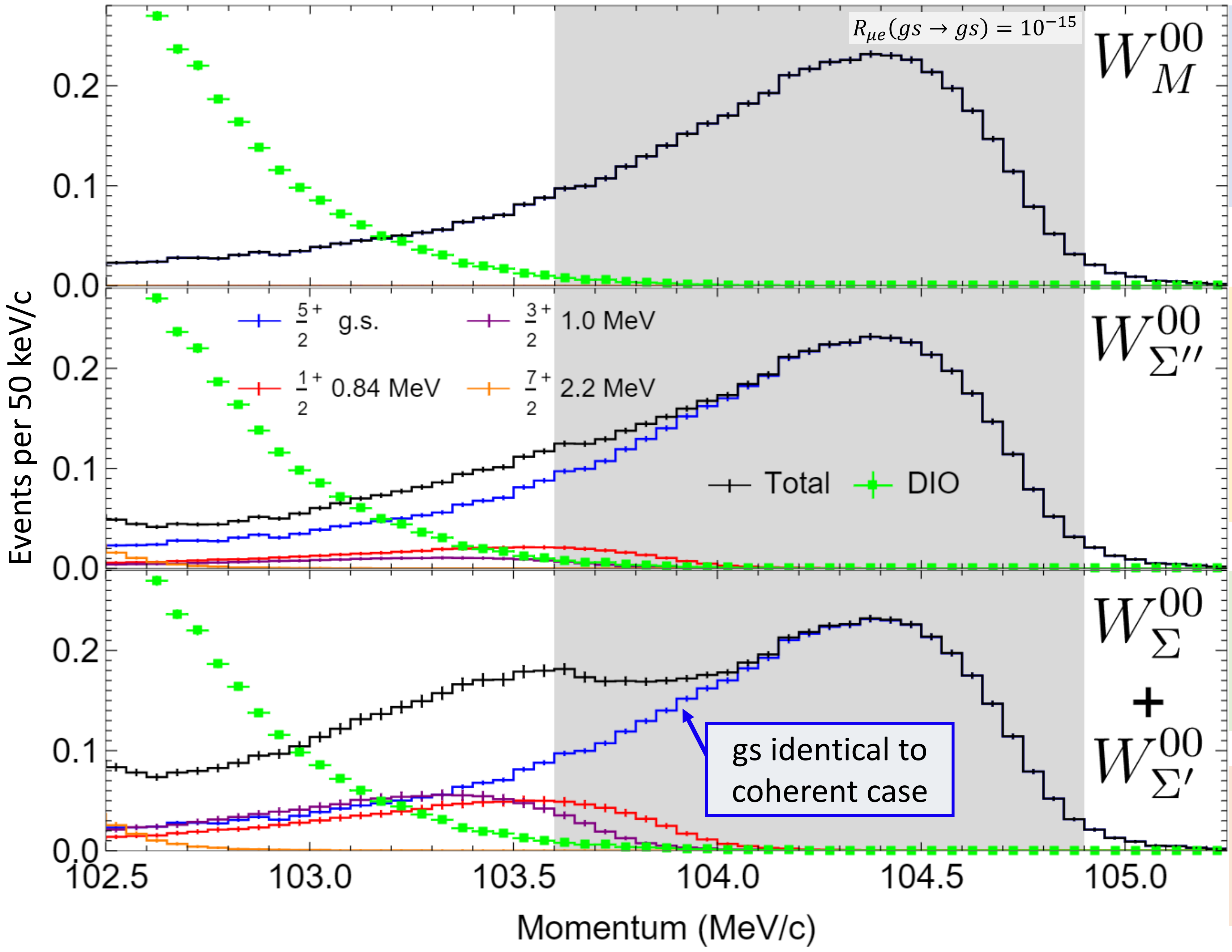
Coherent conversion

- Elastic process enhanced
- Ground state dominates

CLFV ALP

- Forbidden transition to $1/2^+$ state is significant
- 40% enhancement in electron counts near $q \approx 103.5$ MeV

Figure: Haxton & **ER**, *PRL* **133**, 261801 (2024)



Coherent conversion

- Elastic process enhanced
- Ground state dominates

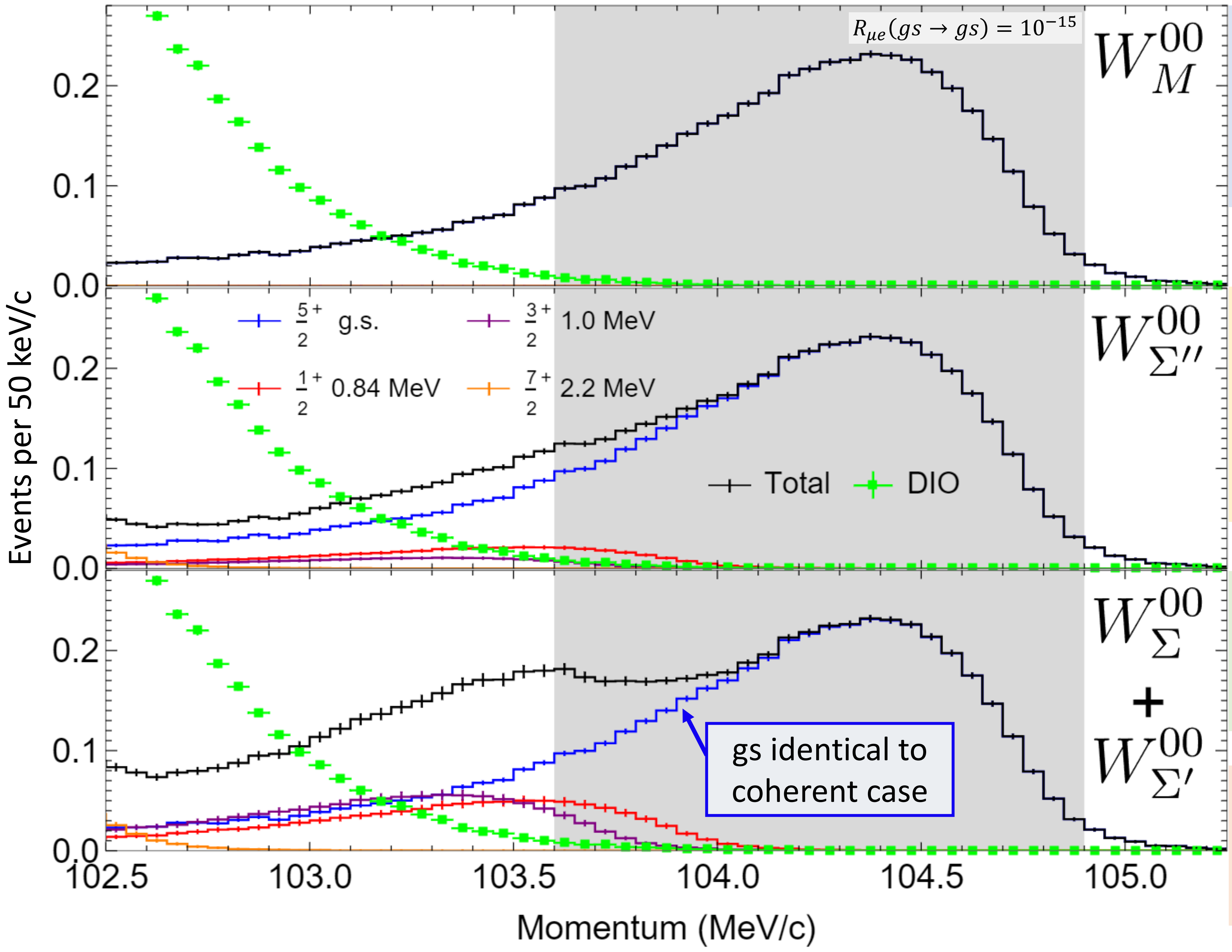
CLFV ALP

- Forbidden transition to $1/2^+$ state is significant
- 40% enhancement in electron counts near $q \approx 103.5$ MeV

Transverse spin-dependent

- Distinct 2nd peak near $q \approx 103.5$ MeV

Figure: Haxton & **ER**, *PRL* **133**, 261801 (2024)



Coherent conversion

- Elastic process enhanced
- Ground state dominates

CLFV ALP

- Forbidden transition to $1/2^+$ state is significant
- 40% enhancement in electron counts near $q \approx 103.5$ MeV

Transverse spin-dependent

- Distinct 2nd peak near $q \approx 103.5$ MeV

Mu2e Run I:	$\mathbf{6 \times 10^{16}}$ **muons**
Mu2e lifetime:	10^{18} muons
Mu2e-II:	10^{19} muons

Summary

$\mu \to e$ conversion in nuclei

Collaborators: Vincenzo Cirigliano, Kaori Fuyuto, Wick Haxton, Ken McElvain, Tony Menzo, Michael Ramsey-Musolf, Jure Zupan

Mu2e and **COMET** will probe **CLFV** at **energies** $\lesssim$ **10,000 TeV**

Complete effective theory: Experiment to **UV**

Inelastic conversion: new signal + new information

See also:

Ab initio overlap integrals for μ → e conversion in nuclei	*Matthias Heinz*
Multicultural Greek	13:30 - 13:55
Searching for Lepton Flavor Violation	*Kaori Fuyuto*
Multicultural Greek	13:55 - 14:20
Mu2e at Fermilab : Charged Lepton Flavor Violation Experiment	*Mamta Jangra*
Multicultural Greek	14:20 - 14:45
A new method to calibrate the momentum scale of the Mu2e experiment	*Pavel Murat*
Multicultural Greek	14:45 - 15:10

Summary

$\mu \to e$ conversion in nuclei

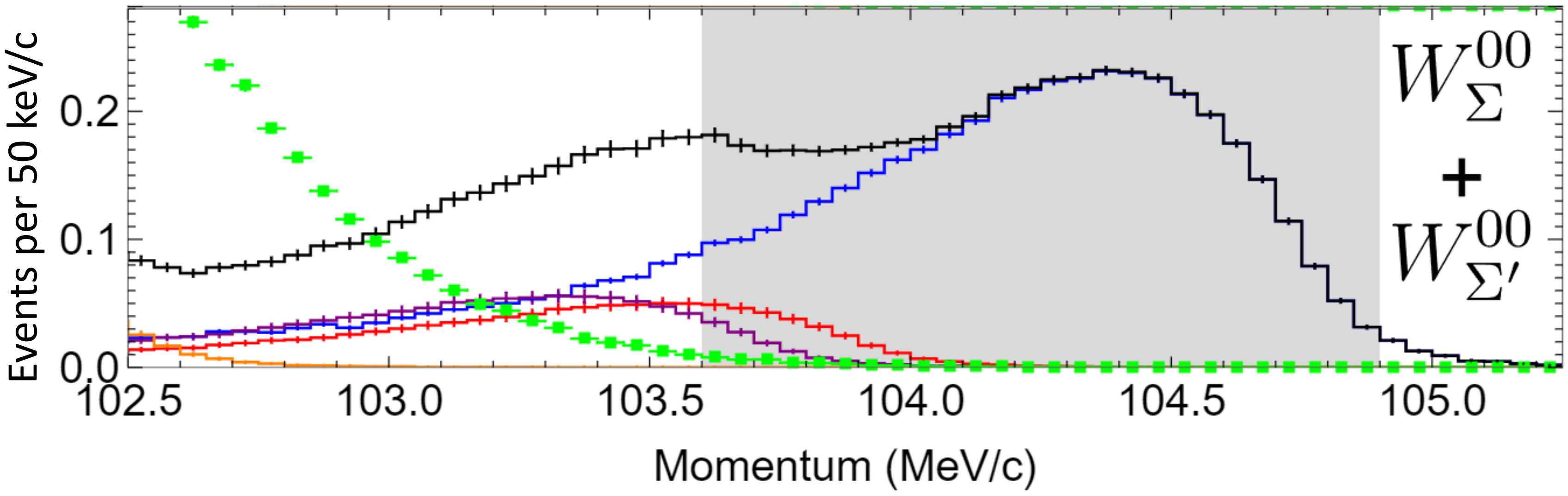
Collaborators: Vincenzo Cirigliano, Kaori Fuyuto, Wick Haxton, Ken McElvain, Tony Menzo, Michael Ramsey-Musolf, Jure Zupan

Mu2e and **COMET** will probe **CLFV** at **energies** $\lesssim$ **10,000 TeV**

Complete effective theory: Experiment to **UV**

Inelastic conversion: new signal + new information

Publicly available codes
EFT: MuonBridge
Inelastic: Mu2e_Inelastic



Backup Slides

Coherent Conversion

Dipole:

$$\frac{1}{\Lambda^2} C_{D\alpha} m_\mu \, \bar{\boldsymbol{e}} \boldsymbol{\sigma}^{\lambda\nu} \boldsymbol{P}_\alpha \boldsymbol{\mu} \, \boldsymbol{F}_{\lambda\nu}$$

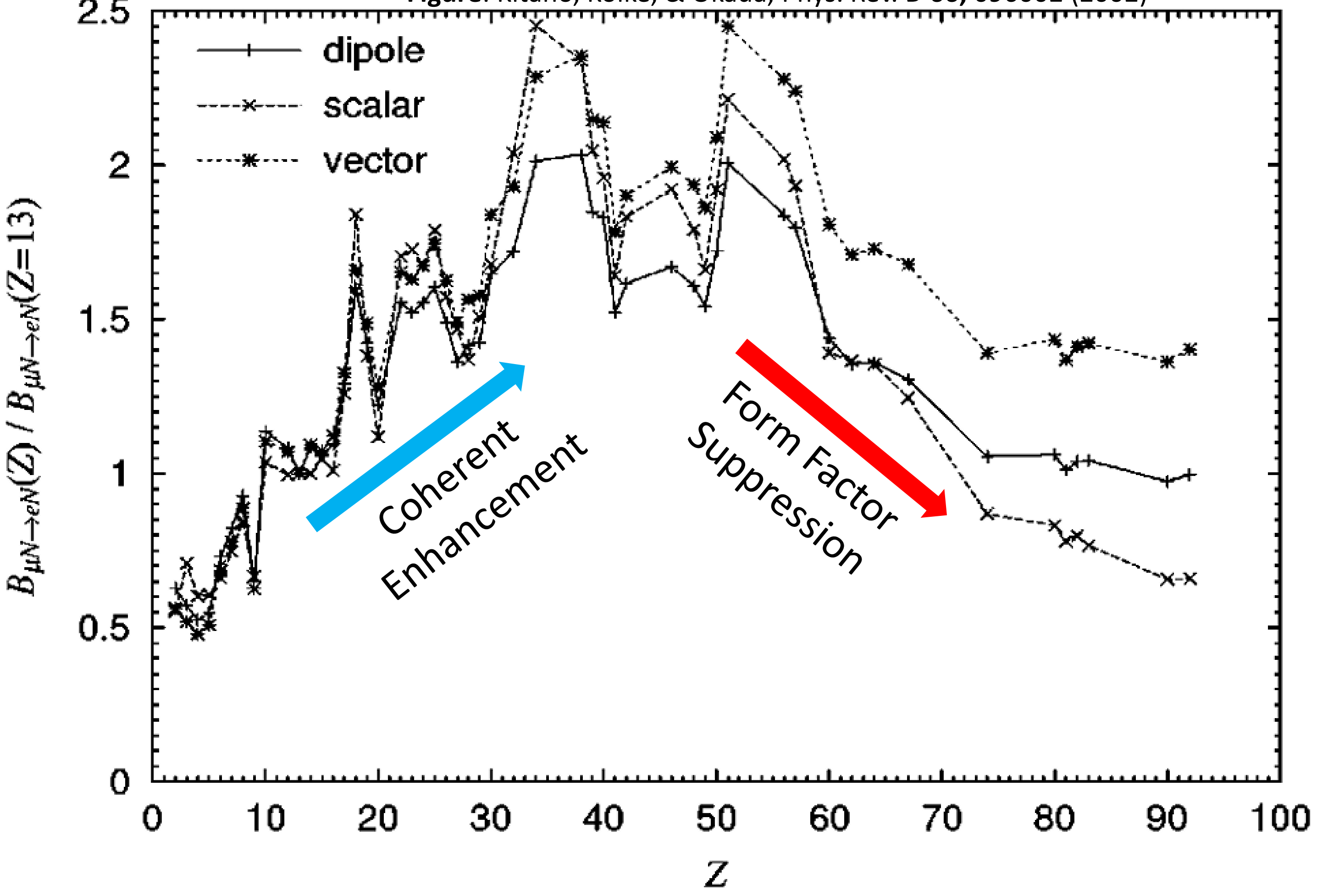
Scalar:

$$\frac{1}{\Lambda^2} \sum_q C_{S\alpha}^{(q)} G_F m_\mu m_q \, \bar{\boldsymbol{q}} \boldsymbol{q} \, \bar{\boldsymbol{e}} \boldsymbol{P}_\alpha \boldsymbol{\mu}$$

Vector:

$$\frac{1}{\Lambda^2} \sum_q C_{V\alpha}^{(q)} G_F m_\mu m_q \, \bar{\boldsymbol{q}} \boldsymbol{\gamma}^\nu \boldsymbol{q} \, \bar{\boldsymbol{e}} \boldsymbol{\gamma}_\nu \boldsymbol{P}_\alpha \boldsymbol{\mu}$$

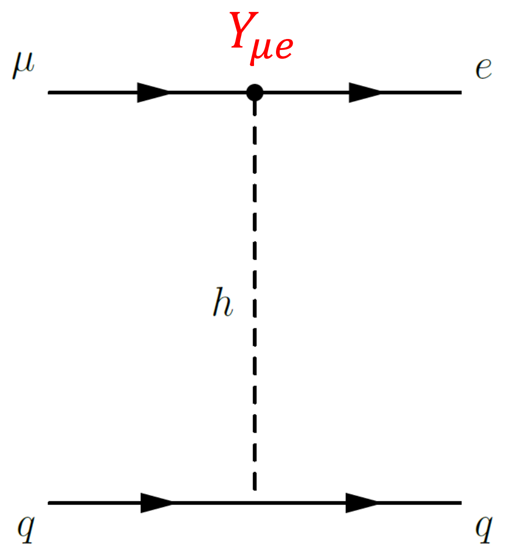
Figure: Kitano, Koike, & Okada, Phys. Rev. D **66,** 096002 (2002)

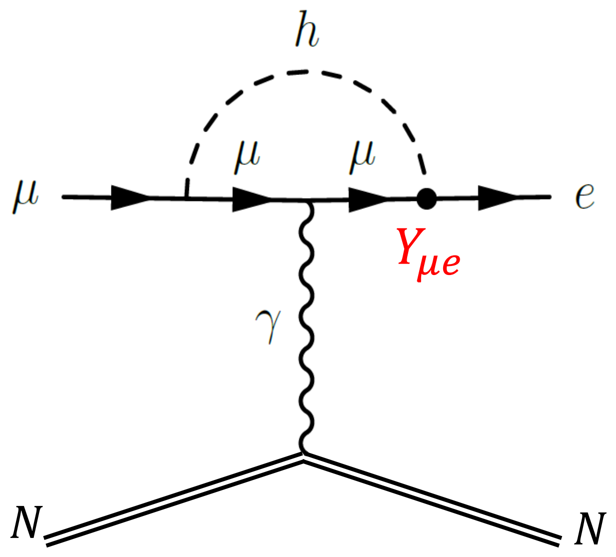


Nuclear operator: isoscalar charge monopole $\boldsymbol{M_0(q)}$

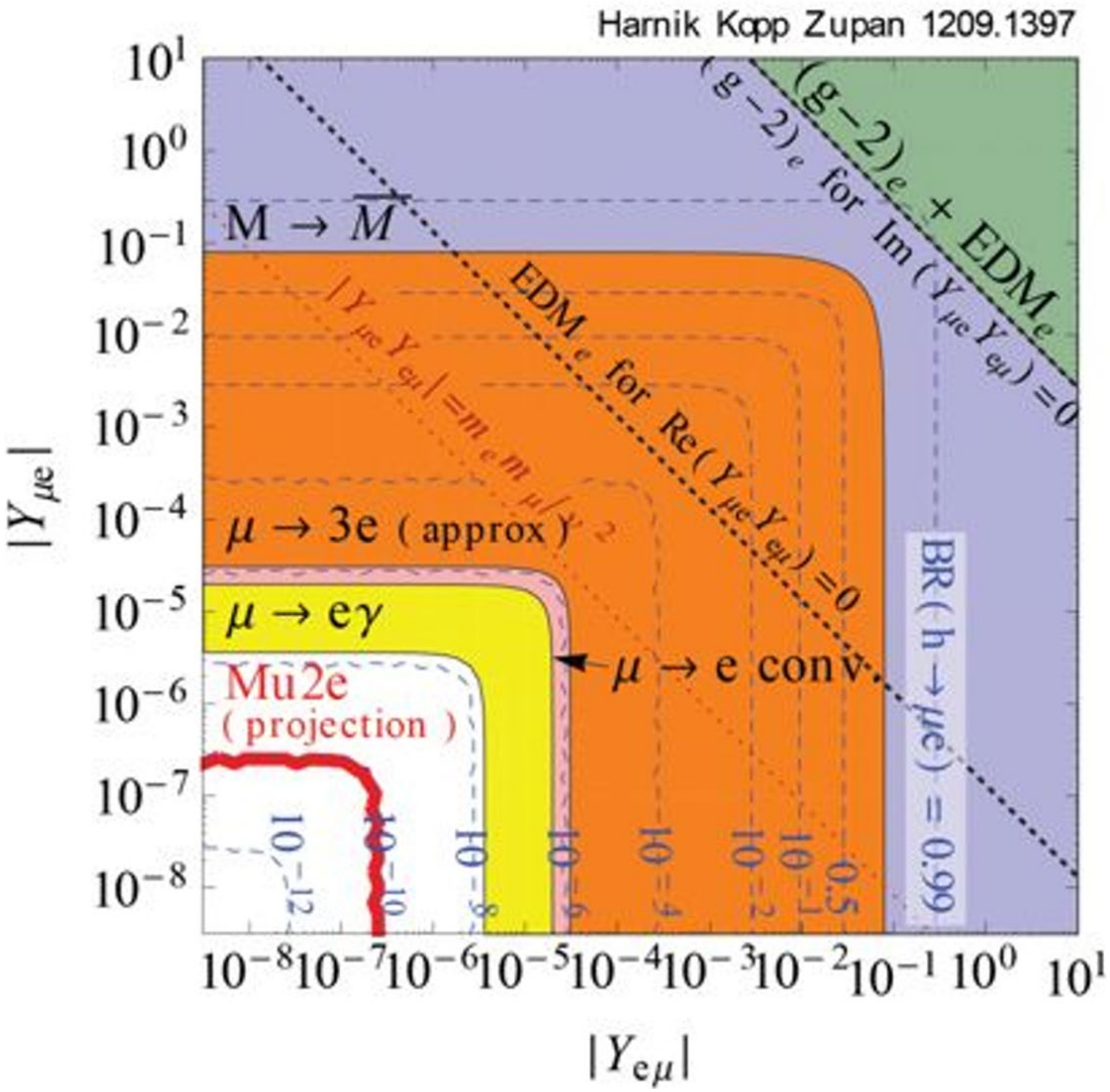
- Rate enhanced by A^2
- Nuclear matrix elements constrained by electron scattering, πN scattering, pionic atoms,…

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





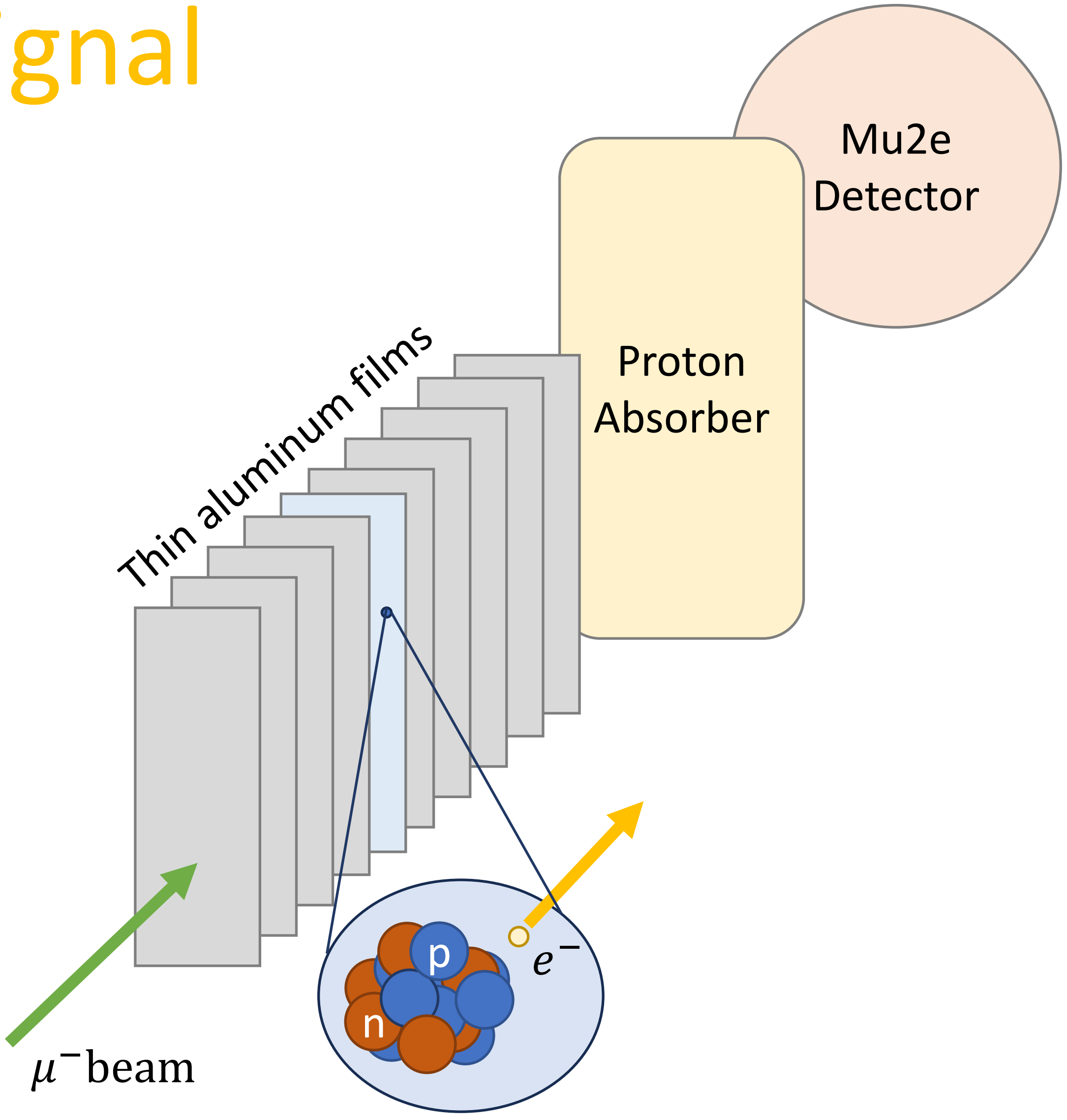
$\mu \to e$ provides better constraint than $h \to e\mu, \mu \to e\gamma, \mu \to 3e$



Expected Mu2e signal

Monte Carlo simulation of
Mu2e experimental pipeline
Including all backgrounds and cuts

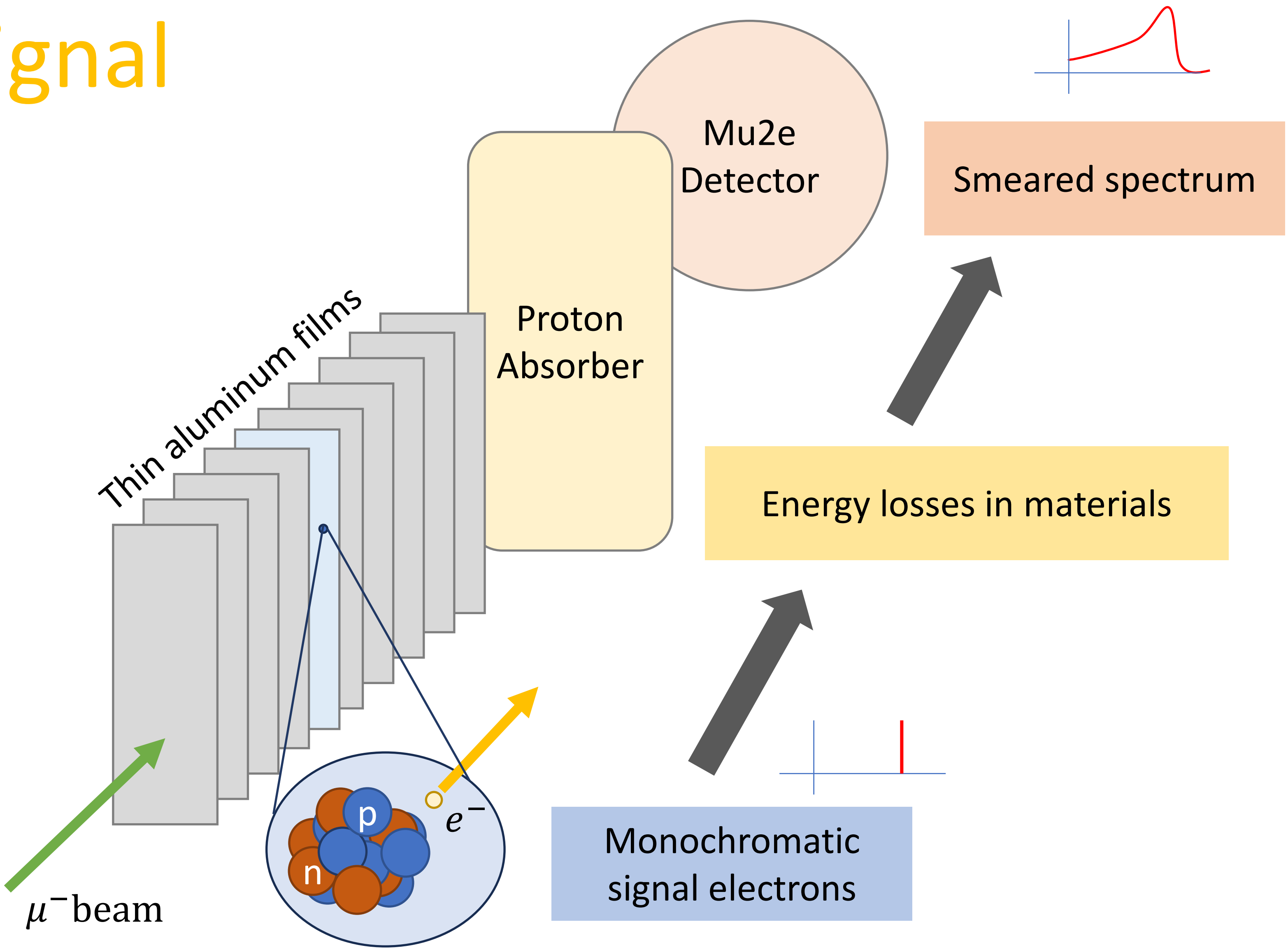
1. Protons on production target
2. Pions decay to muons
3. Muons captured on target
4. Electrons detected by calorimeter



Expected Mu2e signal

Monte Carlo simulation of
Mu2e experimental pipeline
Including all backgrounds and cuts

1. Protons on production target
2. Pions decay to muons
3. Muons captured on target
4. Electrons detected by calorimeter

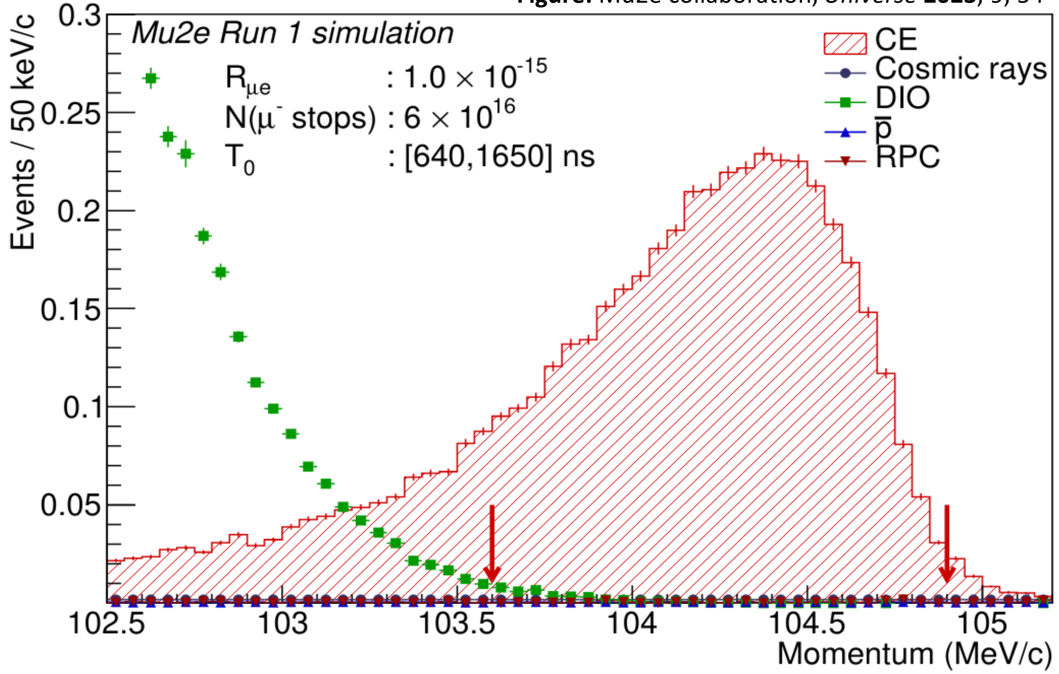


Combined elastic + inelastic electron spectrum

Individual spectral shapes

Fixed by e^- interactions before hitting detector

Figure: Mu2e collaboration, *Universe* **2023**, 9, 54



Combined elastic + inelastic electron spectrum

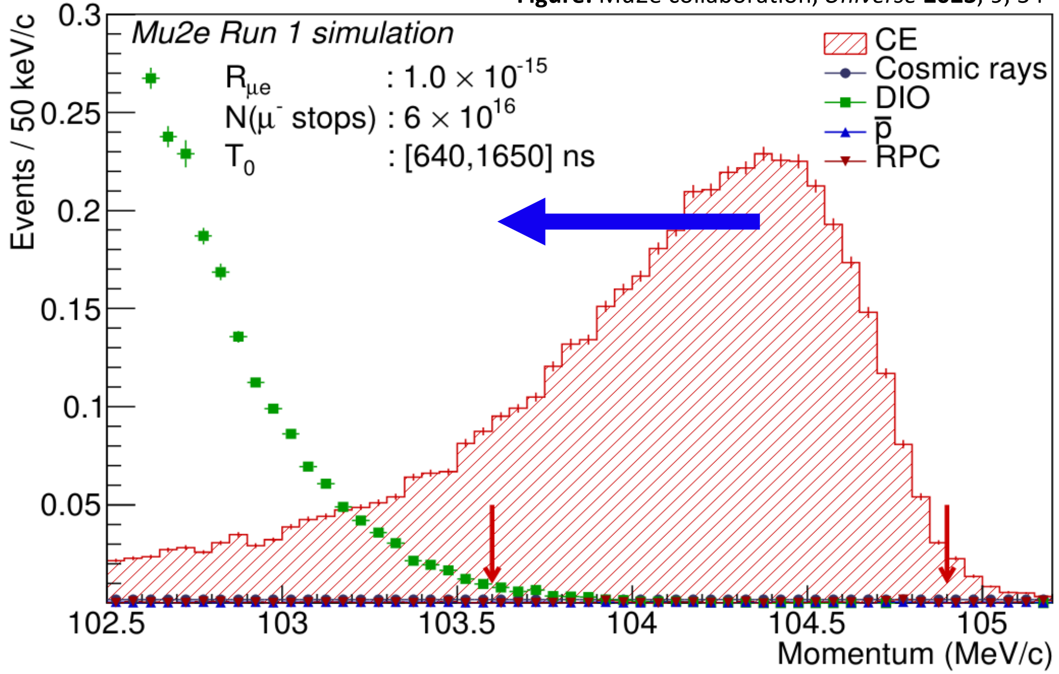
Individual spectral shapes

Momentum of peak

Shifts by **excitation energy:**

$$E_e \approx m_\mu - \Delta E_{\text{nuc}}$$

Figure: Mu2e collaboration, *Universe* **2023**, 9, 54



Combined elastic + inelastic electron spectrum

Individual spectral shapes

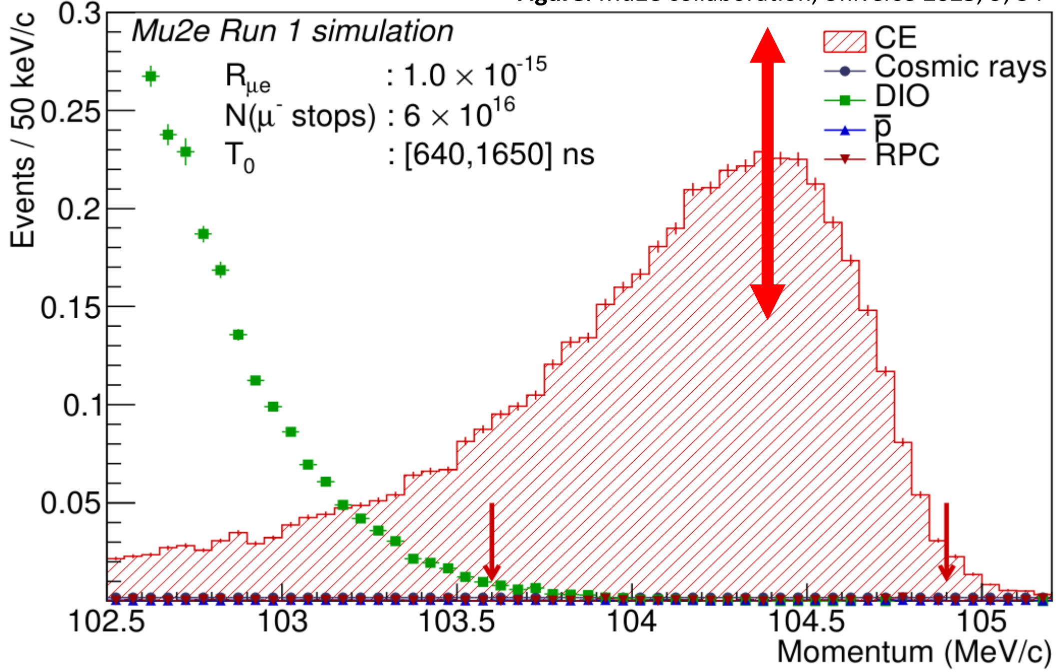
Momentum of peak

Amplitude relative to elastic signal

Scaled by **relative branching ratio:**

$$\frac{R_{\mu\to e}(gs\to f)}{R_{\mu\to e}(gs\to gs)} = \frac{\Gamma_{\mu\to e}(gs\to f)}{\Gamma_{\mu\to e}(gs\to gs)}$$

Figure: Mu2e collaboration, *Universe* **2023**, 9, 54



Combined elastic + inelastic electron spectrum

Individual spectral shapes	**Fixed** by e^- interactions before hitting detector
Momentum of peak	**Shifts** by **excitation energy:** $E_e \approx m_\mu - \Delta E_{\text{nuc}}$
Amplitude relative to elastic signal	Scaled by relative branching ratio: $\frac{R_{\mu\to e}(gs\to f)}{R_{\mu\to e}(gs\to gs)}$

Depend on nuclear target

Combined elastic + inelastic electron spectrum

Individual spectral shapes	**Fixed** by e^- interactions before hitting detector
Momentum of peak	**Shifts** by **excitation energy:** $E_e \approx m_\mu - \Delta E_{\text{nuc}}$
Amplitude relative to elastic signal	**Scaled** by **relative branching ratio:** $\dfrac{R_{\mu\to e}(gs\to f)}{R_{\mu\to e}(gs\to gs)}$

Depends on nuclear target and CLFV physics

Spin-dependent $\mu \to e$ Conversion

Flavor-violating ALPs

Fuyuto & Mereghetti, arXiv:2307:13076

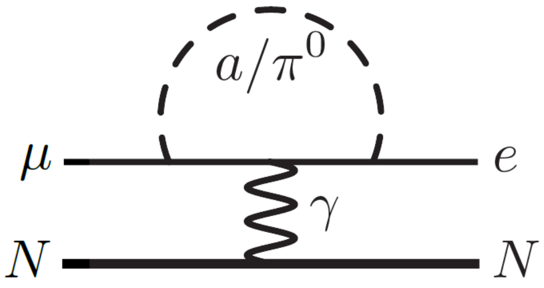
$$\mathcal{L}^a \supset -2i\frac{a}{f_a}m_\mu a_{\mu\mu}\bar{\mu}\gamma_5\mu - i\frac{a}{f_a}m_\mu\bar{e}\left(v_{e\mu} + a_{e\mu}\gamma_5\right)\mu$$

Spin-dependent $\mu \to e$ Conversion

Flavor-violating ALPs

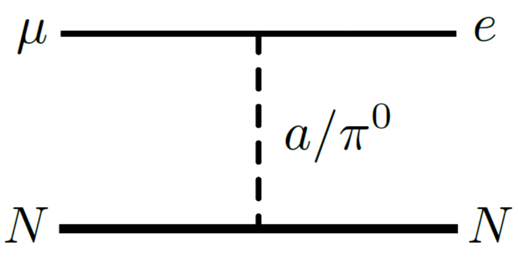
Fuyuto & Mereghetti, arXiv:2307:13076

$$\mathcal{L}^a \supset -2i\frac{a}{f_a}m_\mu a_{\mu\mu}\bar{\mu}\gamma_5\mu - i\frac{a}{f_a}m_\mu\bar{e}(v_{e\mu} + a_{e\mu}\gamma_5)\mu$$



Coherent

$\langle M_0 \rangle$



Spin-dependent

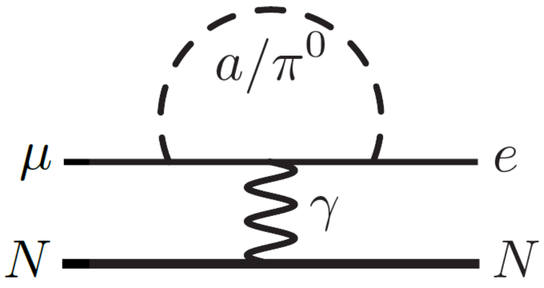
$\langle \Sigma''_J \rangle$

Spin-dependent $\mu \to e$ Conversion

Flavor-violating ALPs

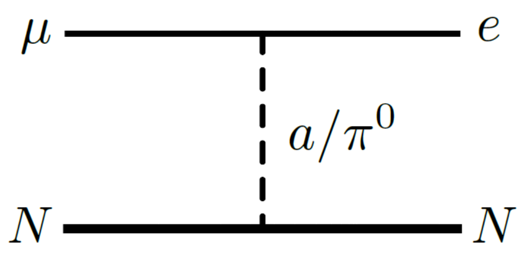
Fuyuto & Mereghetti, arXiv:2307:13076

$$\mathcal{L}^a \supset -2i\frac{a}{f_a} m_\mu a_{\mu\mu} \bar{\mu}\gamma_5 \mu - i\frac{a}{f_a} m_\mu \bar{e}\left(v_{e\mu} + a_{e\mu}\gamma_5\right)\mu$$



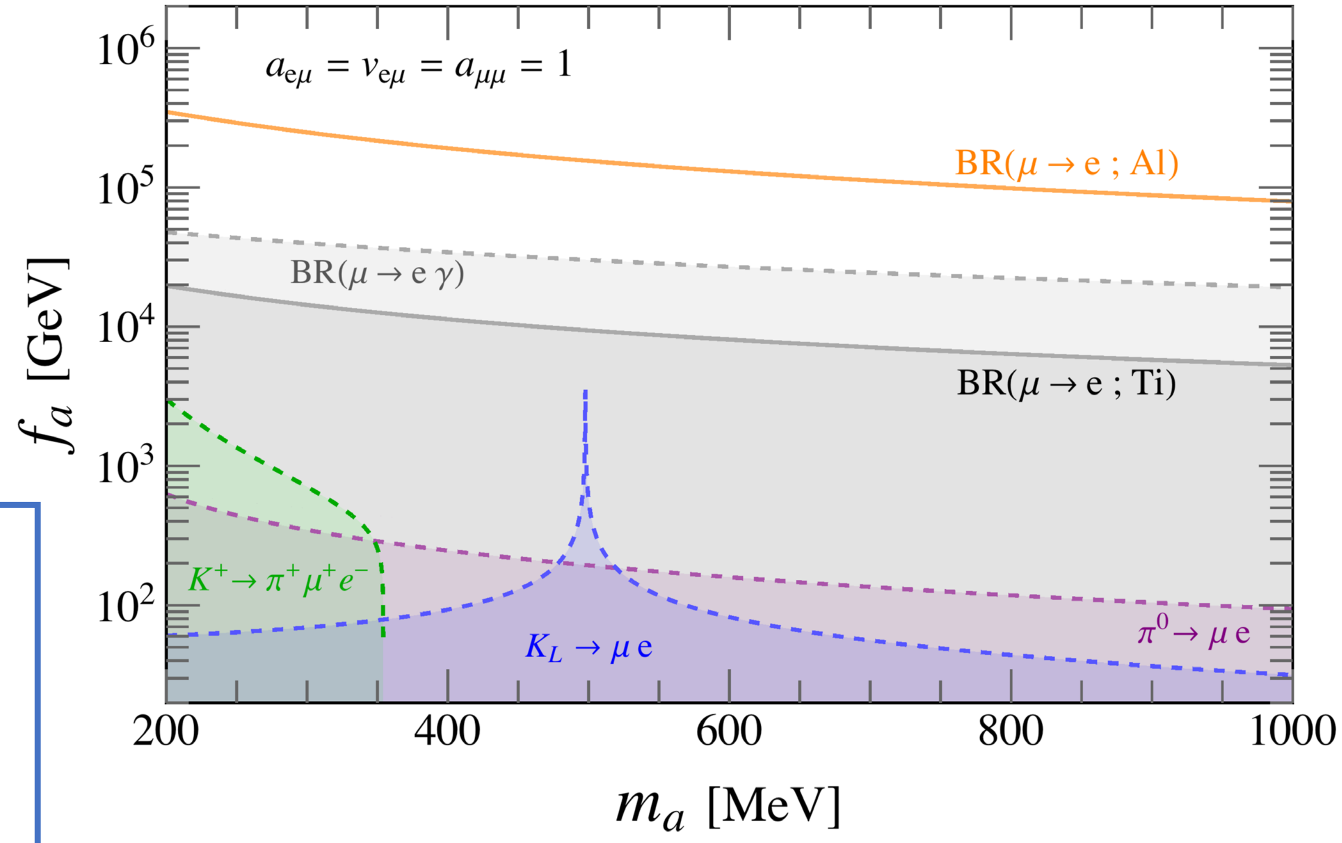
Coherent

$\langle M_0 \rangle$



Spin-dependent

$\langle \Sigma_J'' \rangle$



- Coherent dipole is suppressed by $\approx \left(\frac{\alpha_{EM}}{4\pi}\right)^2$
  - Spin-dependent process dominates