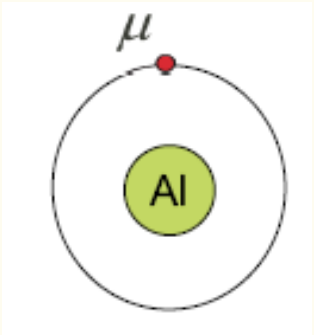
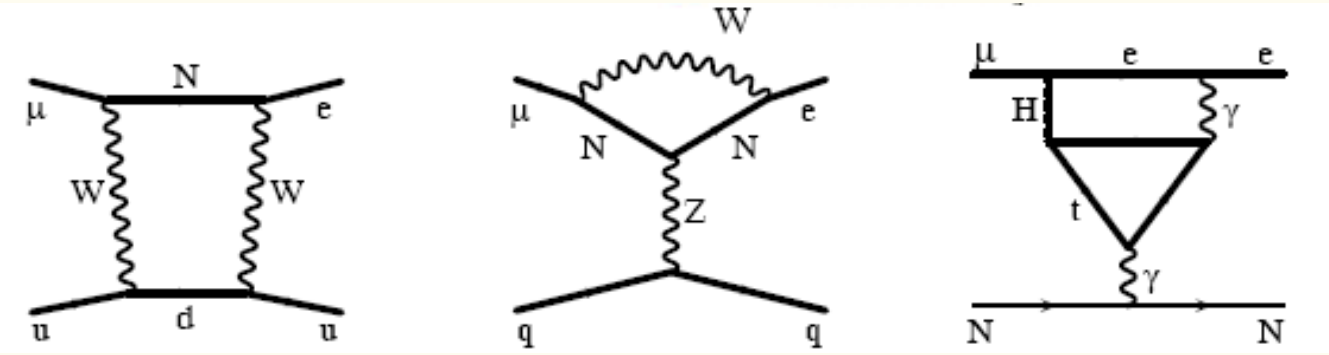
Spectrum of the muon decay in orbit





EXA 2011

Vienna, September 2011

Andrzej Czarnecki University of Alberta

Outline

- Muon electron conversion near nuclei
- Muon decay in orbit
- Decay $\mu \rightarrow e$+majoron

Muon-electron conversion

Muon g-2: ~3.6σ discrepancy

Encouragement for lepton flavor violation searches:

$$a_\mu^{\mathrm{NP}} \frac{e}{2m} \bar{\mu} \sigma \cdot F \mu \;\rightarrow\; \frac{e}{2m} \bar{e} \left(f_M + f_E \gamma_5 \right) \sigma \cdot F \mu$$

$$f_{M,E} \sim a_\mu^{\mathrm{NP}} \cdot \delta$$

$$BR\left(\mu \rightarrow e\gamma \right) \sim 10^{-3} \delta^2$$

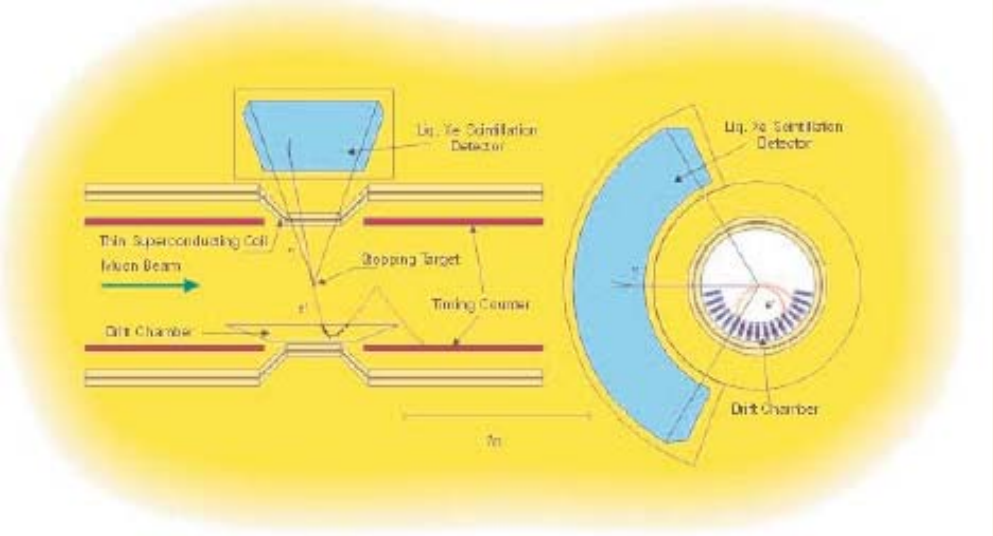
(Also lots of theoretical encouragement from "new physics" models.)

Muon decay to an electron and photon, $\mu \to e\gamma$

Until recently (MEGA @ Los Alamos):

$$BR(\mu \to e\gamma) < 10^{-11}$$

New bound (MEG @ Paul Scherrer Institute)



$$< 2.4 \times 10^{-12}$$

arXiv:1107.5547

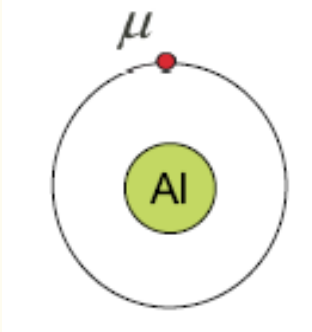
Note: unusual QED suppression ~15% (large log of the new physics scale Λ)

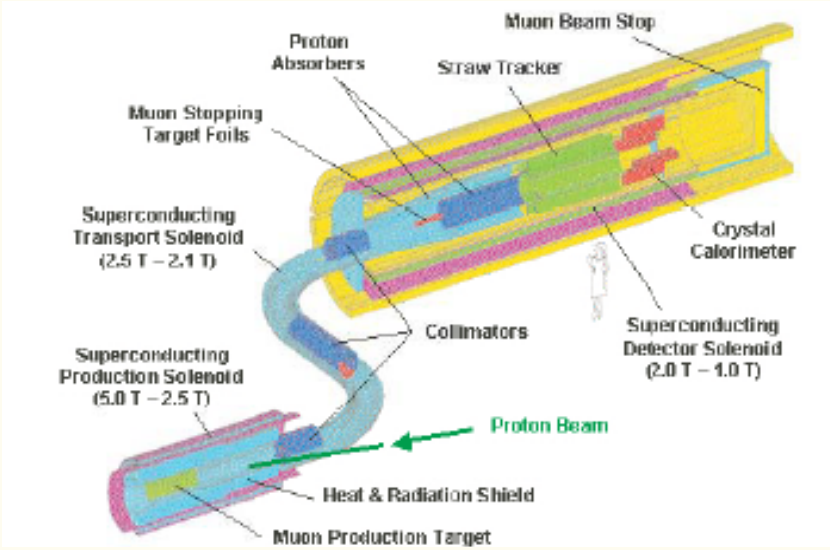
$$\Gamma(\mu \to e\gamma) \simeq \left(1 - \frac{8\alpha}{\pi} \ln \frac{\Lambda}{m_\mu}\right) \Gamma^{(0)}(\mu \to e\gamma)$$

Phys. Rev. D 65, 113004

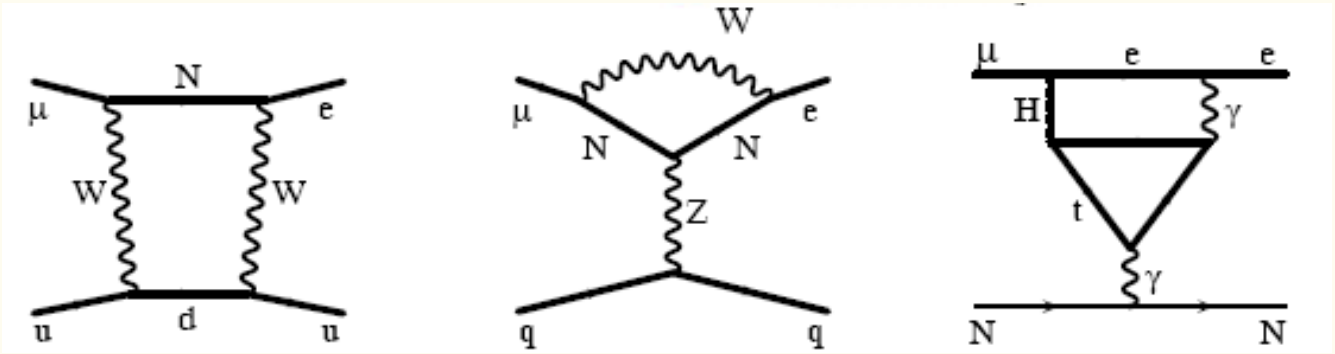
Muon-electron conversion

"The best rare process"
No accidental bkgd
(single monochromatic e^-);
10^{-17} sensitivity envisioned





Variety of mechanisms:

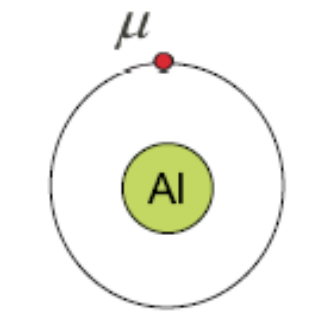


Comparison with scattering experiments

Typical luminosity in fixed-target experiments

$$\sim 10^{37\ldots38} \,/\left(\mathrm{cm}^2 \cdot \mathrm{s}\right)$$

In a single muonic atom



$$= \text{density} \times \text{velocity}$$

$$= \left|\psi(0)\right|^2 \cdot Z\alpha = \frac{m_\mu^3 Z^4 \alpha^4}{\pi} \sim Z^4 \cdot 4 \cdot 10^{39} \,/\left(\mathrm{cm}^2 \cdot \mathrm{s}\right)$$

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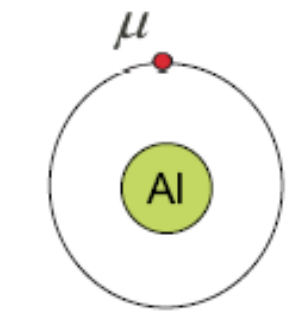

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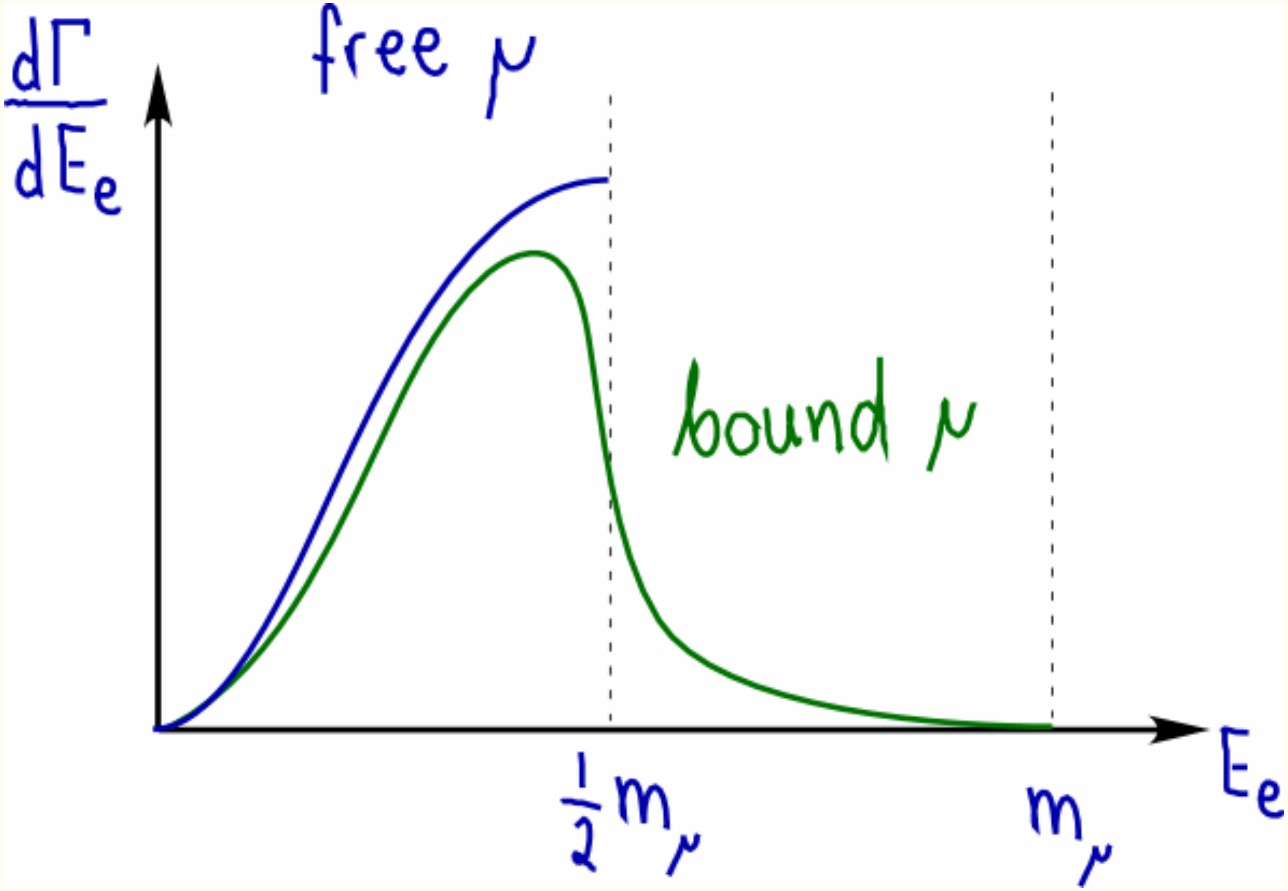
Many atoms are studied in parallel: ~10^{11} muons stopped per second, each lives about 10^{-6} seconds: 10^5 atoms present:

$$\sim 10^{49} \,/\left(\mathrm{cm}^2 \cdot \mathrm{s}\right)$$

Background from the standard muon decay



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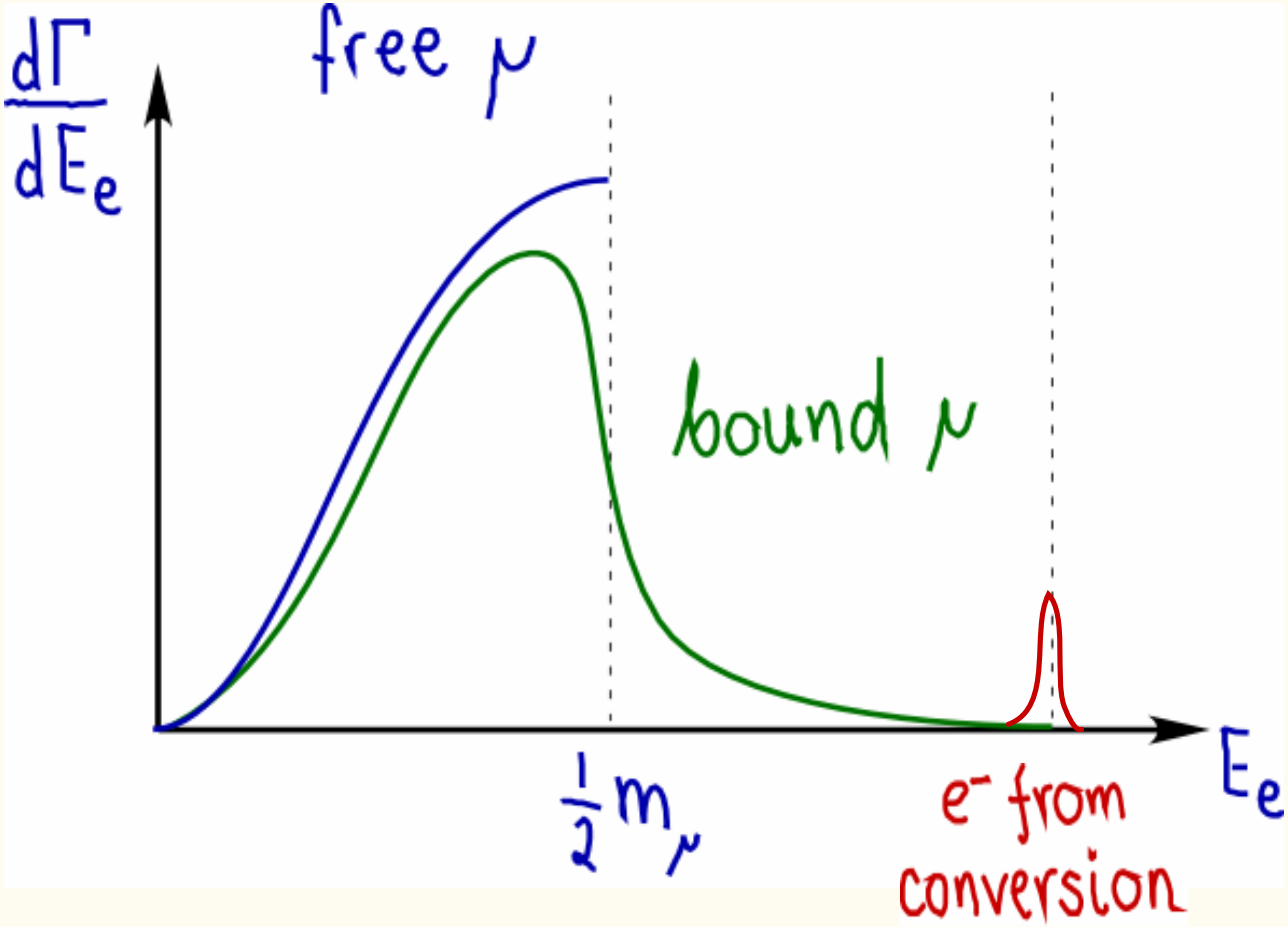
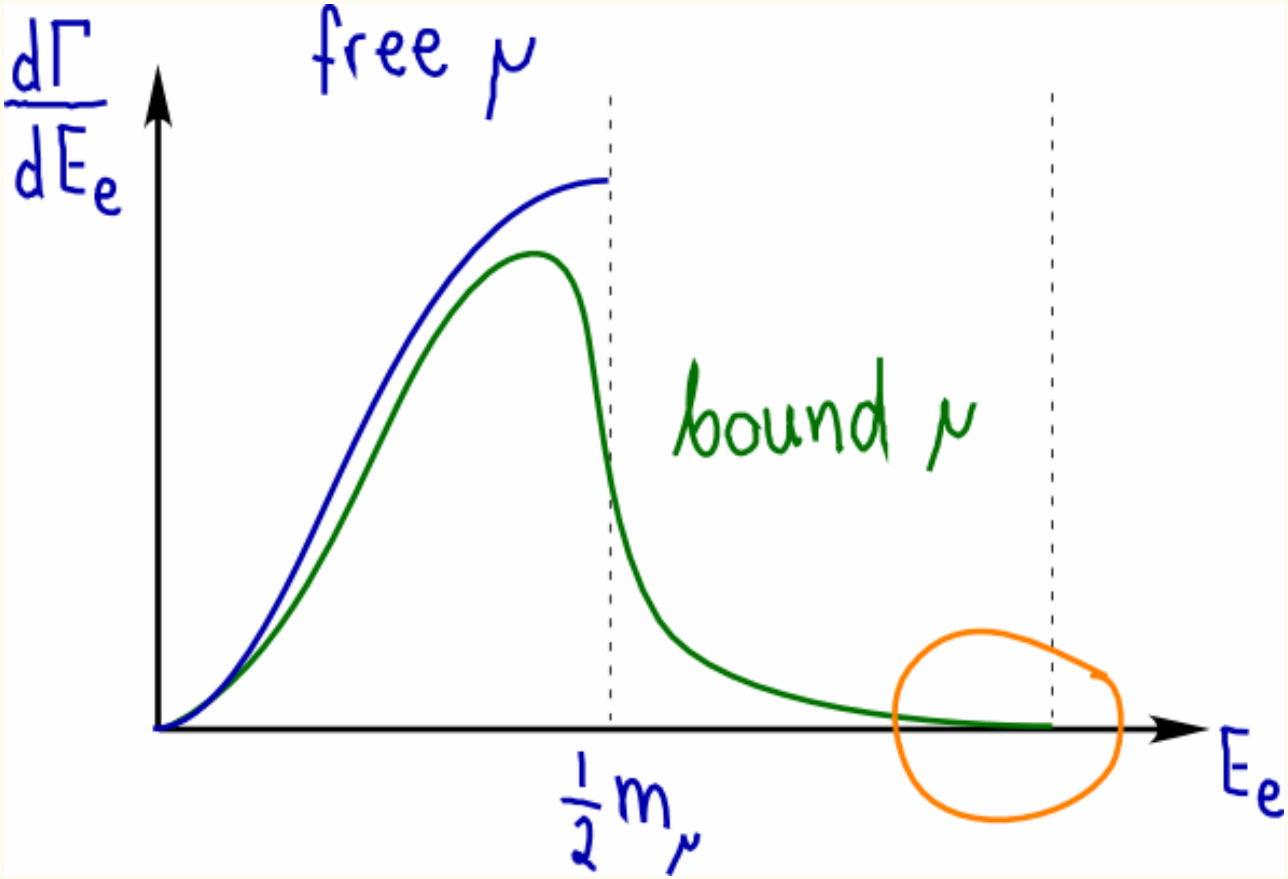


End point spectrum must be well understood



$$\frac{d\Gamma}{dE_e} \sim (Z\alpha)^5 (E_{\max} - E)^5$$

End point spectrum

Previous studies: Shanker & Roy, Hänggi et al., Herzog & Alder

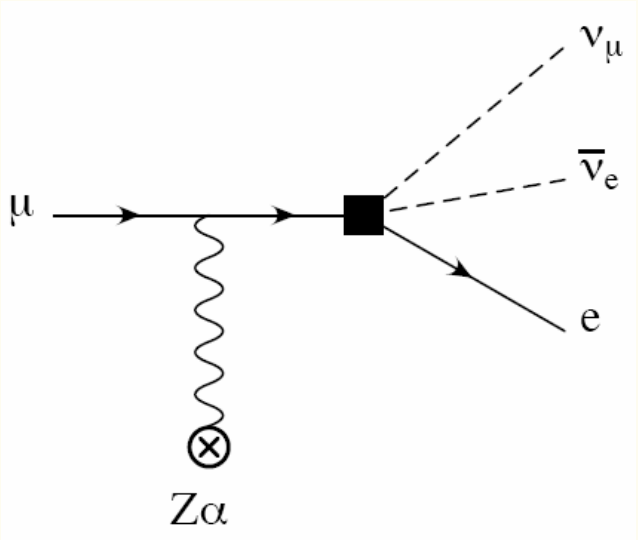
Relativistic muon wave function, nuclear size and recoil, electron final state interactions: all taken into account.

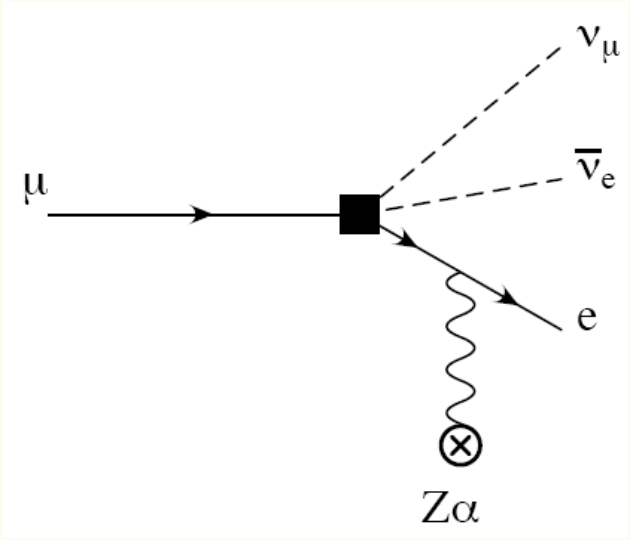
$$N\left(E_e\right)dE_e \simeq 0.4{\cdot}10^{-21}\left(1-\frac{E_e}{E_{\max}}\right)^5 dE_e$$

New evaluation: AC, X. Garcia i Tormo, W. J. Marciano PRD84,013006,2011

Planned energy resolution in Mu2e: ~250 keV → 0.22 background events.

How can the electron get muon's whole energy?





Neutrinos get no energy;
The nucleus balances electron's momentum, takes no energy.
Near the end point:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e} \sim |\psi(0)|^2 (Z\alpha)^2 \frac{\mathrm{d}^3\nu_e}{\nu_e}\frac{\mathrm{d}^3\nu_\mu}{\nu_\mu}\delta(E_{\max}-E_e-\nu_e-\nu_\mu)\,\mathrm{Tr}\ldots\psi_e\ldots\psi_\mu$$

$$\sim (Z\alpha)^5 (E_{\max}-E_e)^5$$

μ-e conversion may be caused by a majoron

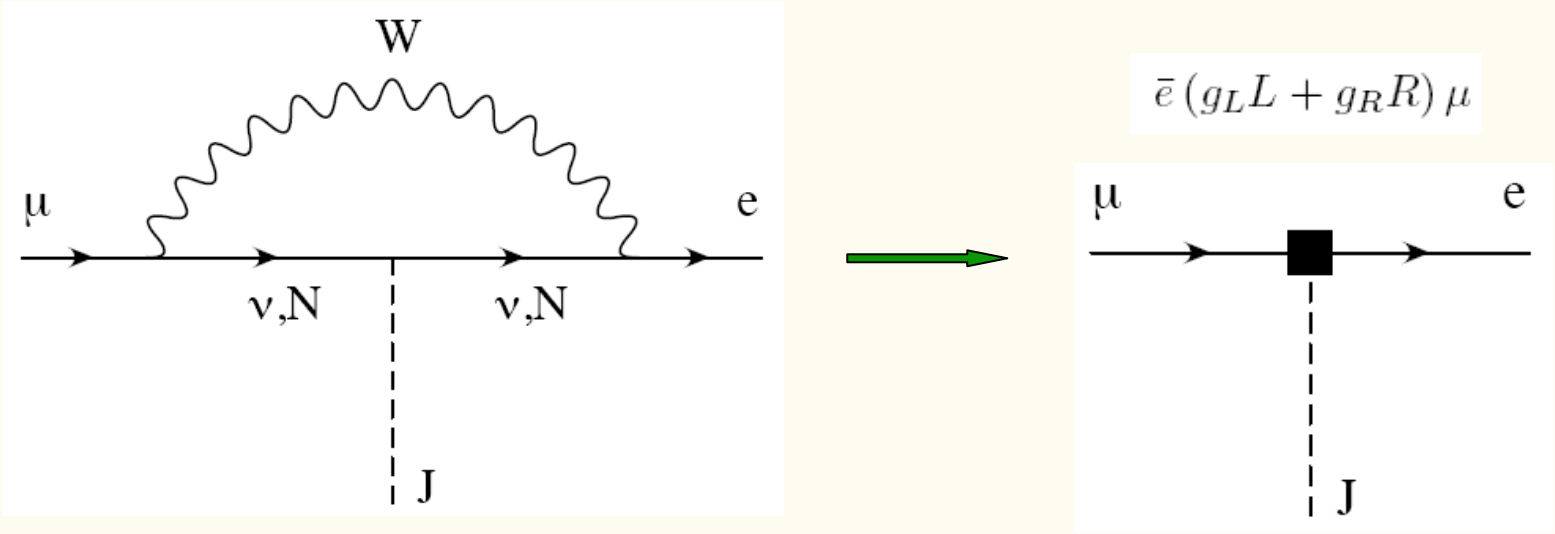
What is the majoron?

If neutrinos have Majorana masses: lepton number is not conserved.

How can lepton conservation be broken?

* explicitly by the Majorana mass term;
* spontaneously, locally; or
* spontaneously, globally → Goldstone boson.

Majoron can violate lepton flavor number

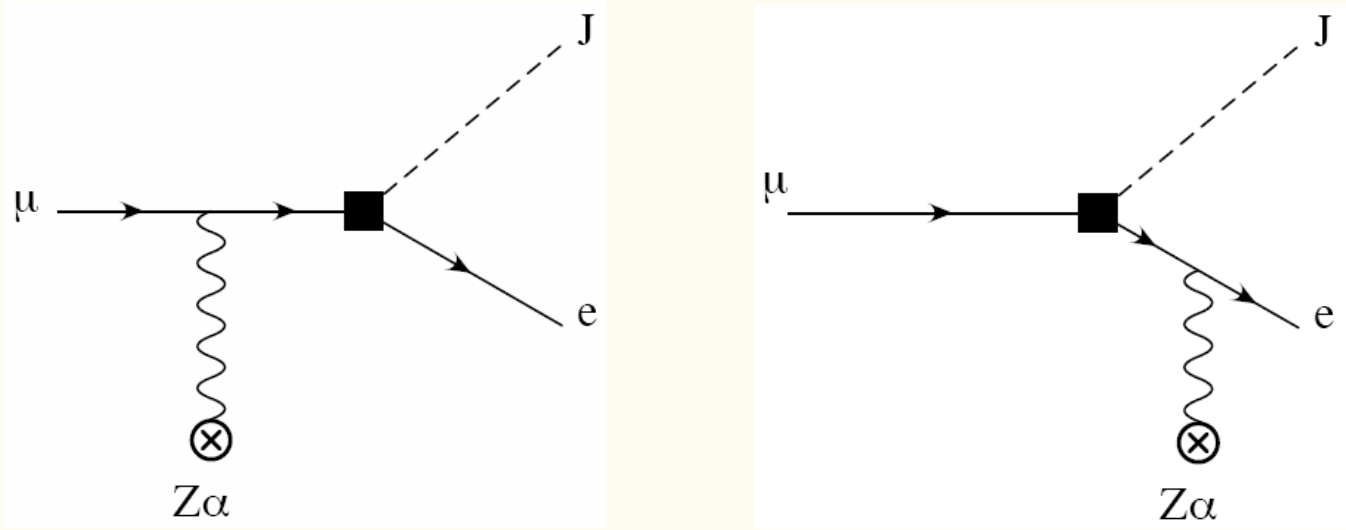


The resulting extra muon decay rate:

$$\Gamma\left(\mu \to eJ\right) = \frac{m_\mu}{32\pi}\left(g_L^2 + g_R^2\right)$$

What is the electron spectrum in $\mu \to e + J$?

Free muon: monoenergetic electron, $E_e = m_\mu/2$
Muon bound in an atom: spread out up to m_μ



$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e} \sim |\psi(0)|^2 (Z\alpha)^2 \frac{\mathrm{d}^3 J}{J} \delta(E_{\max} - E_e - J) |\mathcal{M}|^2$$

$$\sim (Z\alpha)^5 (E_{\max} - E_e)^3$$

Vanishes at end point

With D. Bryman, M. Dowling, X. Garcia i Tormo

Summary

We have determined spectra of daughter electrons in decays of bound muons.

Simple interpretation of the high-energy tail: hard photon exchange with the nucleus.

The signal of possible decays into majorons is enhanced by two powers of $(E_{max} - E_e)$ but not by four powers.