

# Charged Lepton Flavour Violation: An Introduction to Muon Experiments

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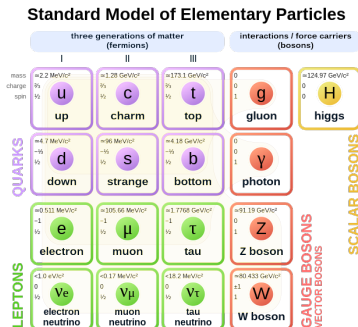
# Standard Model conserved quantities

There are a few quantities that are strictly conserved in SM processes:

- Electric & colour charge
- Baryon number  $B$
- Lepton number  $L$

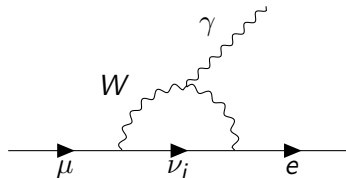
If neutrinos were massless, individual lepton flavour numbers  $L_e$ ,  $L_\mu$ , and  $L_\tau$  would be conserved<sup>1</sup>. With massive neutrinos, only  $L$  is conserved. (Provided neutrinos are Dirac fermions and not Majorana fermions)

<sup>1</sup>M.E. Peskin, 2018, p.286



# Charged Lepton Flavour Violation (CLFV)

- We already see lepton flavour being violated in neutrino oscillation
- Best estimates of  $\mu \rightarrow e\gamma$  rates by the same mechanism are  $<10^{-54}$ , which are not realistically measurable<sup>2</sup>. Similar for other processes
- Thus observing these processes implies new physics is at play!
- Example processes would be  $\mu \rightarrow e e e$ ,  $\mu \rightarrow e\gamma$ , and  $\tau \rightarrow \mu, e + X$
- Muons are much easier to study than tau leptons

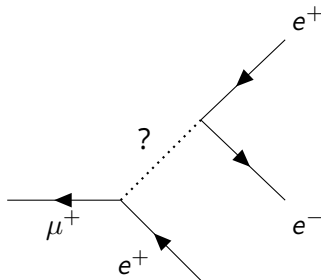
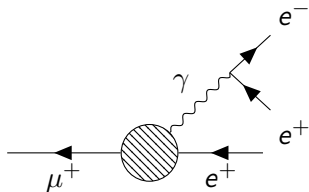


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<sup>2</sup>de Gouvea, A., & Vogel, P. (2013). Lepton Flavor and Number Conservation, and Physics Beyond the Standard Model.

$$\mu \rightarrow e e e$$

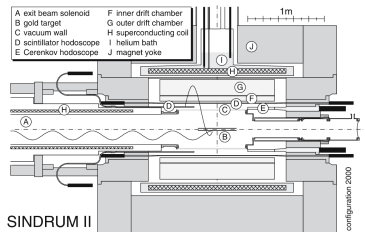
- We could see this as  $\mu^+ \rightarrow e^+ e^+ e^- \nu_\mu \bar{\nu}_e$  and not be new physics
- Thus we look for this with no missing energy
- Could be  $\mu \rightarrow e \gamma$  with more steps, or could be something else entirely
- The SINDRUM experiment put a rate limit of  $10^{-12}$  with future experiments (Mu3e) aiming for  $10^{-16}$ .<sup>3</sup>



<sup>3</sup>Ardu, M., & Pezzullo, G. (2022). Introduction to Charged Lepton Flavour Violation

$$\mu^- N \rightarrow e^- N$$

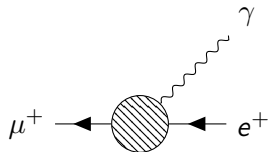
- Conversion of a muon captured by a nucleus into an electron
- Bombarding nuclei with muons to see an outgoing electron
- Should result in a monoenergetic electron,  $\approx 105$  MeV for most nuclei
- Important to ignore  $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$
- Rates for gold and titanium are  $\lesssim 10^{-13}$  from SINDRUM-II<sup>4</sup>
- Has potential to get to  $10^{-18}$  at Fermilab and J-PARC with Al target



<sup>4</sup>Bertl, W., Engfer, R., Hermes, E. et al. A search for  $\mu$ -e conversion in muonic gold. (2006)

$$\mu^+ \rightarrow e^+ \gamma$$

- Longest studied process and with the most potential to reduce limits
- Background events are  $\mu^+ \rightarrow e^+ \bar{\nu}_e \nu_\mu$
- Must look for total energy of  $e + \gamma$  to be  $m_\mu$
- MEG experiment reduced limits to  $4.2 \times 10^{-13}$  in 2016<sup>5</sup>

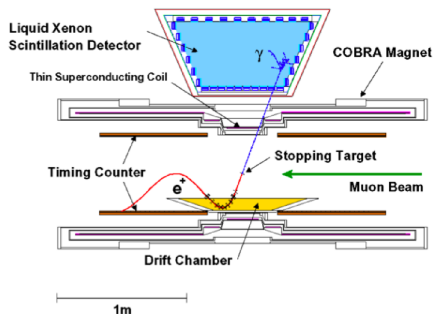


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<sup>5</sup>Meucci, M. (2022). MEG II experiment status and prospect.

# What the heck is MEG?

- Muon Electron Gamma detector at PSI in Zurich
- $3 \times 10^7 \mu^+$  per second beam incident onto polyethylene stopping target
- Looks for coincident  $e^+$  and  $\gamma$  events, each with energy 52.8 MeV
- MEG-II (Electric Boogaloo) aims to bring the limit down to  $6 \times 10^{-14}$
- Large scintillation detector for photons and a drift chamber for positron spectrometry



# Conclusion

- CLFV is allowed in the SM, but with rates far too low to be detected
- Seeing CLFV implies new physics is at play and could also help explain neutrino mass and oscillation
- Muon processes are most commonly studied, with upper limits on rates nearing  $10^{-14}$  in some cases
- The new MEG-II detector and A1 target muon conversion experiments show promise to greatly reduce those limits



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