Search for cLFV mediated by a new light particle at PSI

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UNIVERSITÀ DI PAVIA

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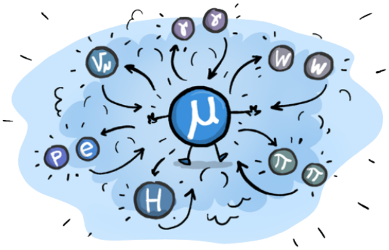
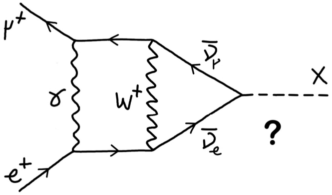
Looking for the ~~needle~~ muon in the haystack

- The search for **charged Lepton Flavour Violation** (cLFV) in **muon decays** is a sensitive tool to test the Standard Model (SM) at the **intensity frontier**.
- The Paul Scherrer Institute features the **most intense** continuous muon beam in the world: $\mathbf{5 \cdot 10^8\ \mu^+/s} \longrightarrow 10^{10}\ \mu^+/s$ (future goal).
  $\hookrightarrow$ Ideal setting for studying rare muon decays beyond the SM.
- **MEG II** experiment: $\boldsymbol{\mu^+ \rightarrow e^+\gamma}$ with a sensitivity of $6 \cdot 10^{-14}$ at 90% CL.
  $\hookrightarrow$ MEG upper limit: BR $< 4.2 \cdot 10^{-13}$ at 90% CL.
- **Mu3e** experiment: $\boldsymbol{\mu^+ \rightarrow e^+e^+e^-}$ with a sensitivity of 10^{-15} at 90% CL.
  $\hookrightarrow$ SINDRUM upper limit: BR $< 1.0 \cdot 10^{-12}$ at 90% CL.
- Can these two experiments search for other cLFV processes? **Yes!**
- Both are competitive in searching for muon decays involving a light **axion-like particle** (ALP) arising from the spontaneous symmetry breaking (SSB) of a global model-dependent U(1) symmetry (e.g. axion, majoron, familon etc).
  $\hookrightarrow$ $\mu \rightarrow e\,X\,\gamma$, $\mu \rightarrow e\,(X \rightarrow \gamma\,\gamma)$, $\boldsymbol{\mu \rightarrow e\,X}$, $\mu \rightarrow e\,(X \rightarrow e\,e)$

MEG II (first three processes) — Mu3e (last two processes)

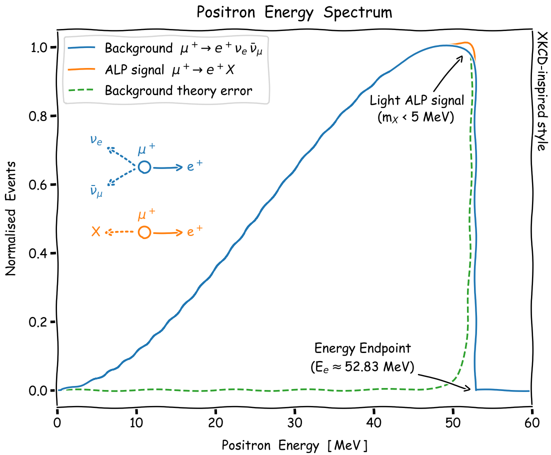




- This talk: focus on $\boldsymbol{\mu^+ \to e^+ X}$ (simple but elusive!)
  $\hookrightarrow$ TWIST limit: BR $< 5.8 \cdot 10^{-5}$ for $m_X < 10$ MeV.
- The signature is a **monochromatic e^+** close to the **energy endpoint** of the $\boldsymbol{\mu^+ \to e^+ \nu_e \bar{\nu}_\mu}$ background:

$$E_e^{max} = \frac{m_\mu}{2}\left[1 + \left(\frac{m_e}{m_\mu}\right)^2\right] \approx 52.83 \text{ MeV}$$

- The higher-order QED corrections for $E_e \to E_e^{max}$ are enhanced by the emission of **soft photons**.
- The background theory error is large at the endpoint.
  $\hookrightarrow$ It covers the signal for low BRs for any experiment.
- The background theory error is a peak at the endpoint.
  $\hookrightarrow$ It resembles a false signal, leading to possible biases.
- This search requires extremely accurate theoretical predictions, both for $\mu \to e\,X$ and $\mu \to e\,\nu\,\bar{\nu}$.



Signal energy: $E_e^X(m_X) = \dfrac{m_\mu^2 + m_e^2 - m_X^2}{2m_\mu}$

We need a Mule to do the hard work

- The new generation of precision experiments with leptons needs extremely accurate predictions for the SM processes, usually at the **next-to-next-leading order** (NNLO).
  $\hookrightarrow$ Required a **unified framework** including all the relevant processes in one "box".
- Here it comes... McMule $\longrightarrow$ **M**onte **C**arlo for **MU**ons and other **LE**ptons
- A framework for the numerical computation of **fully-differential QED corrections** for decay and scattering processes involving leptons, mainly at low energies.
- For an implemented process the output is the distribution $\boldsymbol{d^n\sigma/dx_1 \dots dx_n}$ for *any* set of IR-safe observables $\boldsymbol{x_1 \dots x_n}$ that can be constrained with *any* cut.
  $\hookrightarrow$ Can reproduce detector acceptances, analysis cuts, trigger preselections etc.
- Collinear singularities regularised by keeping finite the fermion masses (e.g. $m_e \neq 0$).
- Soft singularities subtracted by using the **FKS$^\ell$ scheme** (YFS + ξ_c parameter).
- Numerical integration of phase space based on the Vegas adaptive algorithm.
- **Open source** code and user library available here: `https://gitlab.com/mule-tools`

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Process	Precision
$\mu \to e\,\nu\,\bar\nu$	NNLO †
$\mu \to e\,\nu\,\bar\nu\,\gamma$	NLO †
$\mu \to e\nu\bar\nu ee$	NLO †
$\mu \to e\,X$	NLO †
$e\,e \to e\,e$	NNLO
$e\,e \to \nu\,\bar\nu$	NNLO
$e\,e \to \gamma\,\gamma$	NNLO ⋆
$e\,e \to \mu\,\mu$	NNLO ⋆
$e\,p \to e\,p$	NNLO
$\mu\,p \to \mu\,p$	NNLO
$\mu\,e \to \mu\,e$	NNLO ⋆

† τ decays as well
⋆ Work in progress

Signal $\mu^+ \to e^+ X$ at NLO

$$\mathcal{L}_X = \frac{1}{\Lambda} (\partial_\rho X)\, \bar{\psi}_\mu \left(\gamma^\rho\, g_V + \gamma^\rho \gamma^5\, g_A \right) \psi_e$$

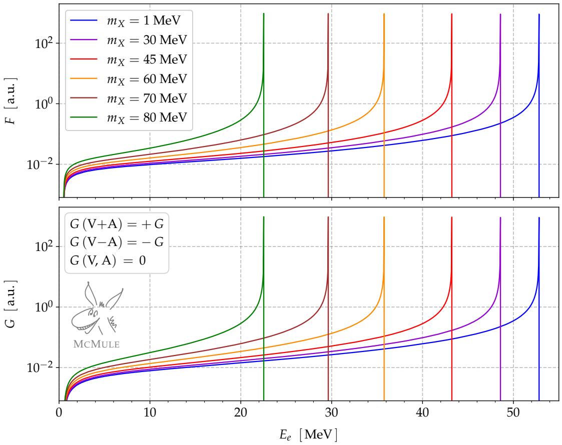
- $\Lambda \longrightarrow$ Large mass scale $\sim$ SSB scale
- $g_V = -g_A \longrightarrow$ V−A coupling (left-handed, like SM)
- $g_V = +g_A \longrightarrow$ V+A coupling (right-handed, unlike SM)
- $g_A = 0 \longrightarrow$ V coupling (no muon polarisation effect)
- $g_V = 0 \longrightarrow$ A coupling (no muon polarisation effect)

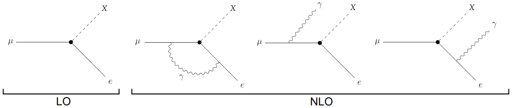
An inclusive **polarised** muon decay is fully characterised by

$$\frac{d^2\Gamma}{dE_e\, d\cos\theta_e} = \frac{G_F^2\, m_\mu^5}{192\,\pi^3} \left[F(E_e) + P_\mu \cos\theta_e\, G(E_e) \right]$$

- $\theta_e \longrightarrow$ Angle between e^+ momentum and μ^+ polarisation
- $P_\mu \longrightarrow$ μ^+ polarisation rate (85% for MEG II and Mu3e)
- $F \longrightarrow$ Contribution **independent** on μ^+ polarisation
- $G \longrightarrow$ Contribution **dependent** on μ^+ polarisation

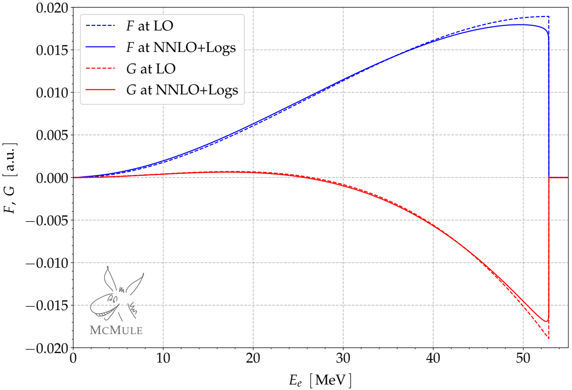
+ QED corrections up to next-to-leading order (NLO) $\Longrightarrow$

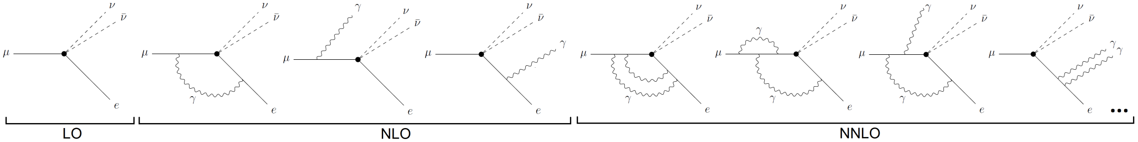




Background $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ at NNLO+Logs

- LO computed with the (dear old) Fermi theory.
- Leading EW correction: $G_F \to G_F\,(1 + 3m_\mu^2\,/\,5m_W^2)$.
- Full **QED corrections at NNLO** with $m_e \neq 0$.
- Inclusion of **collinear logarithms** $\log(m_e\,/\,m_\mu)$ up to $\mathcal{O}(\alpha^5)$ with next-to-leading logarithm (NLL) accuracy.
- Resummation of **soft logarithms** $\log(1 - 2E_e/m_\mu)$ with a NNLL accuracy $\to$ YFS exponentiation.
- (Hadronic) Vacuum Polarisation effects at $\mathcal{O}(\alpha^2)$.
- The final theory error on positron spectrum is $\sim 10^{-5}$.





Simplified model for MEG II and Mu3e positron trackers:

$$\mathcal{F}_e\left(E_e\right) = \int dE_e' \left[\mathcal{E}_e\left(E_e'\right) \times \mathcal{A}_e\left(E_e'\right) \times \mathcal{S}_e\left(E_e - E_e'\right)\right]$$
$$\equiv \left[\mathcal{E}_e \times \mathcal{A}_e\right] \otimes \mathcal{S}_e\left(E_e\right)$$

$\mathcal{F}_e$: Expected e^+ energy spectrum
$\mathcal{E}_e$: Theoretical e^+ energy spectrum
$\mathcal{A}_e$: Positron energy **acceptance** function
$\mathcal{S}_e$: Positron energy **resolution** function

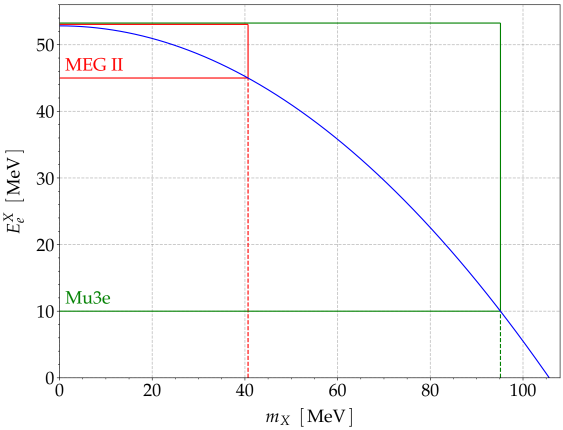
MEG II acceptance: $|\cos\theta_e| < 0.35,\ E_e \gtrsim 45$ MeV
Mu3e acceptance: $|\cos\theta_e| < 0.8,\ E_e \gtrsim 10$ MeV

$$\mathcal{S}_e\left(E_e\,;\,\sigma_e\right) = \frac{1}{\sigma_e\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{E_e}{\sigma_e}\right)^2\right]$$

MEG II resolution: $\sigma_e \simeq 100$ keV at $E_e = 52.83$ MeV
Mu3e resolution: $\sigma_e \simeq 300$ keV (offline), 2 MeV (online)

(No experiments were harmed in making this analysis)

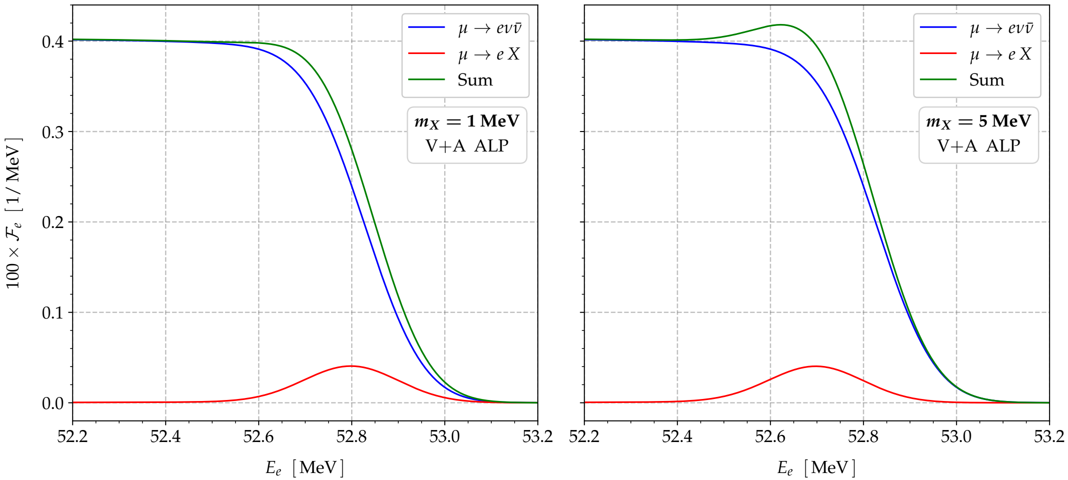
ALP mass acceptance in MEG II and Mu3e



Signal energy at LO: $E_e^X(m_X) = \dfrac{m_\mu^2 + m_e^2 - m_X^2}{2m_\mu}$

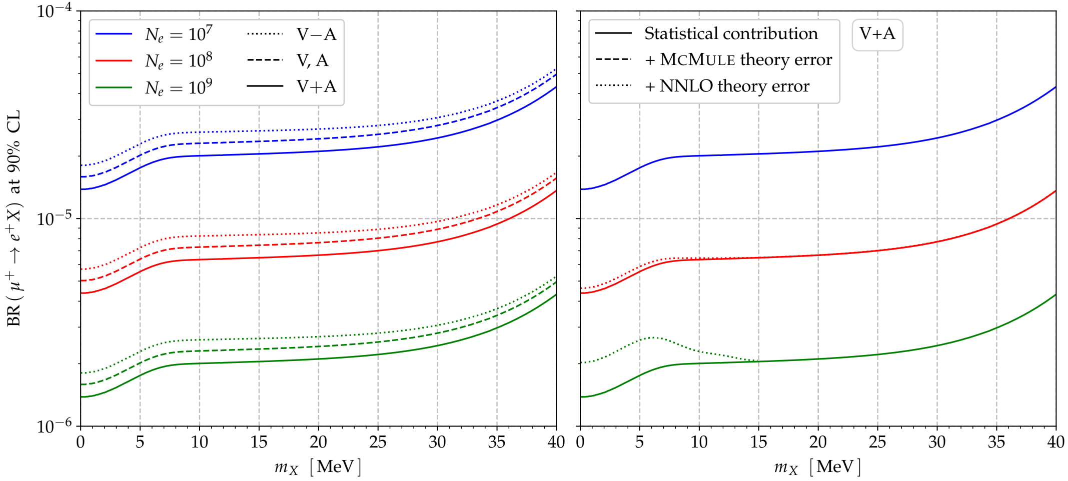
Signal vs. Background in MEG II

Comparison between background and signal for $\text{BR}(\mu \to e X) = 10^{-3}$ (large to be visible) in MEG II experiment.



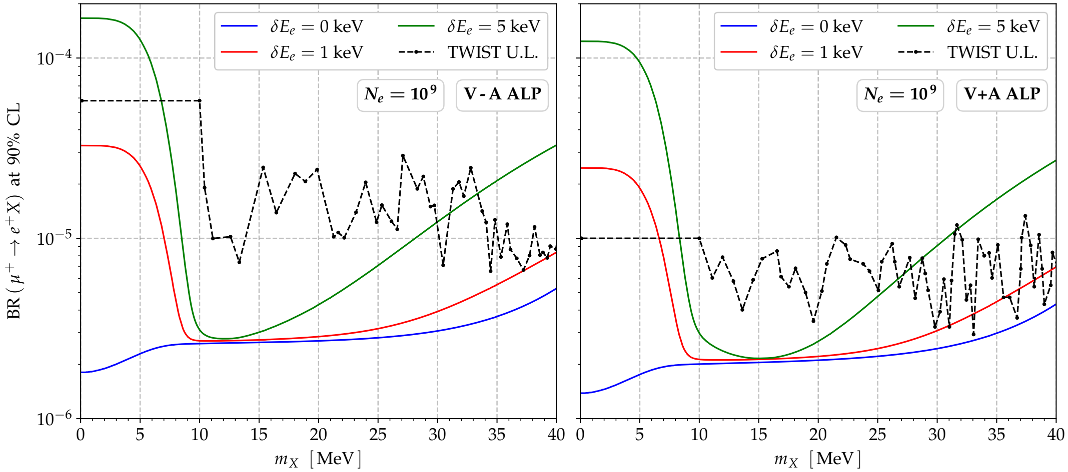
Preliminary sensitivity for MEG II

Sensitivity on $\mu \to e\,X$ at 90% CL for MEG II, assuming different numbers of e^+ events and ALP masses and couplings.



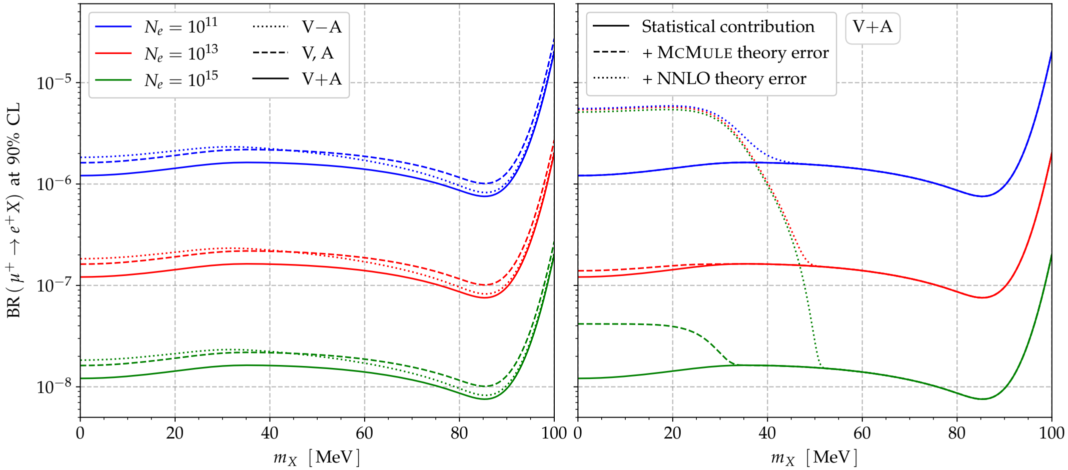
Preliminary sensitivity for MEG II with systematics

Sensitivity on $\mu \to e\,X$ at 90% CL for MEG II, assuming different offsets in the positron energy scale → signal biases!



Preliminary sensitivity for Mu3e

Sensitivity on $\mu \to e\,X$ at 90% CL for Mu3e, assuming different numbers of e^+ events and ALP masses and couplings.



Conclusion and outlook

- The search for cLFV ALPs in muon decays such as $\mu \to e\,X$, $\mu \to e\,X\,\gamma$, $\mu \to e\,(X \to \gamma\,\gamma)$, $\mu \to e\,(X \to e\,e)$ is an excellent opportunity for MEG II and Mu3e to **extend their physics programme** beyond their main channels.
- The theoretical challenges for the very elusive $\mu \to e\,X$ have been successfully tackled with McMule, leading to **a new state-of-the-art computation of $\boldsymbol{\mu \to e\,\nu\,\bar\nu}$** for polarised muons.
  ↪ P. Banerjee et al., *High-precision muon decay predictions for ALP searches* (in preparation, 2022).
- The new predictions are under implementation in simulation frameworks for **more detailed experimental studies**.
  ↪ A. Gurgone et al., *Improved muon decay simulation with McMule and Geant4* (in preparation, 2022).
- McMule aims to provide accurate theoretical predictions for high-precision experiments with leptons.
  ↪ Collaboration with **MEG II** ($\mu \to e\nu\bar\nu$, $\mu \to e\nu\bar\nu\gamma$, $\mu \to e\nu\bar\nu\gamma\gamma$), **Mu3e** ($\mu \to e\nu\bar\nu$, $\mu \to e\nu\bar\nu ee$), **MUonE** ($\mu\,e \to \mu\,e$), **MUSE** ($\mu\,p \to \mu\,p$), **PRad** ($e\,p \to e\,p$, $e\,e \to e\,e$), **P2** ($e\,p \to e\,p$), **PADME** ($e\,e \to \gamma\,\gamma$), Luminosity at **future ℓ-colliders** ($e\,e \to e\,e$, $e\,e \to \gamma\,\gamma$)...
- The current target is the **NNLO** accuracy, but the first **N^{3}LO** calculations are foreseen in the near future, as well as the implementation of a **QED parton shower** matched to the fixed-order contributions.
- As everyone knows, once a Mule has made up its mind, it is difficult to stop...

The McMule team, a.k.a. the “Mules”

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