Looking for an axion in a haystack of muons

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New Frontiers in Lepton Flavor

Pisa – 16 May 2023

Based on arXiv:2211.01040

McMule

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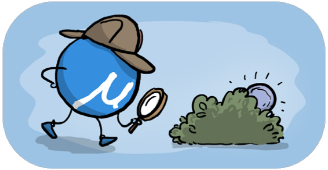
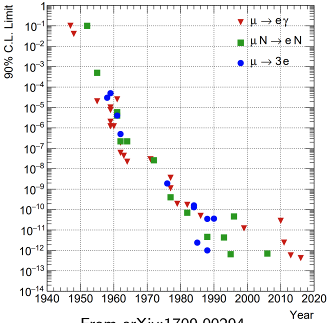
Looking for a needle in a haystack

- 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: $\boldsymbol{5 \cdot 10^8\ \mu^+/s} \longrightarrow 10^{10}\ \mu^+/s$ (future goal).
  $\hookrightarrow$ Ideal setting for studying rare muon decays beyond the SM.
- **MEG II** experiment: $\boldsymbol{\mu^+ \rightarrow e^+\gamma}$ with BR $\sim 6 \cdot 10^{-14}$ at 90% CL.
- **Mu3e** experiment: $\boldsymbol{\mu^+ \rightarrow e^+e^+e^-}$ with BR $\sim 10^{-15}$ at 90% CL.
- Can these two experiments search for other cLFV processes? **Yes!**
- Both might be sensitive to decays of a muon into an invisible **axion-like particle** (ALP), arising from the spontaneous symmetry breaking (SSB) of a global $U(1)$ symmetry (e.g. axion, majoron, familon).

$\hookrightarrow\ \mu \rightarrow e\,X\,\gamma,\ \mu \rightarrow e\,(X \rightarrow \gamma\,\gamma),\ \boldsymbol{\mu \rightarrow e\,X},\ \mu \rightarrow e\,(X \rightarrow e\,e)$

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





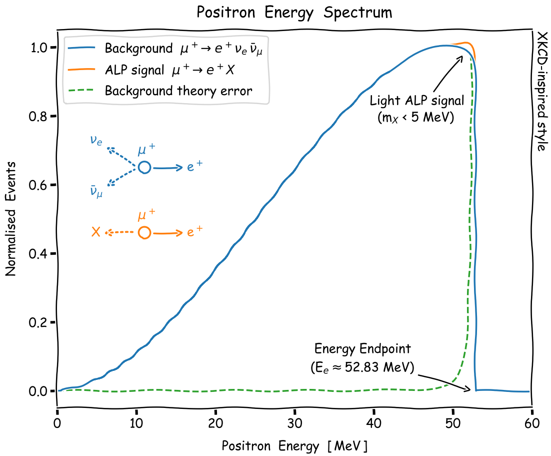
From arXiv:1709.00294

Search for $\mu \to e\,X$ with MEG II and Mu3e

- This talk: focus on $\boldsymbol{\mu^+ \to e^+ X}$ (simple but elusive!)
  $\hookrightarrow$ TWIST limit: $\mathrm{BR} < 5.8 \cdot 10^{-5}$ for $m_X < 10$ MeV.
- The signature is a **monochromatic** $\boldsymbol{e^+}$ 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.
  $\hookrightarrow$ Limiting factor for signal with small m_X.
- This search requires extremely accurate theoretical predictions for the generation of positron events in experimental simulations.



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).
  $\hookrightarrow$ McMule $\longrightarrow$ **M**onte **C**arlo for **MU**ons and other **LE**ptons [arXiv:2007.01654].

- A framework for the numerical computation of **fully differential QED corrections** for decay and scattering processes involving leptons, mainly at low energies.

- Based on the **FKS$^\ell$ subtraction scheme** for soft singularities [arXiv:1909.10244].

- For an implemented process the output is the distribution $d^n\sigma/dx_1 \dots dx_n$ for *any* set of IR-safe observables $x_1 \dots x_n$ that can be constrained with *any* cut.
  $\hookrightarrow$ Can reproduce detector acceptances, analysis cuts, trigger preselections etc.

- Many experiments of interest:
  - $\rightarrow$ MEG II and Mu3e (cLFV decays)
  - $\rightarrow$ MUonE (hadronic muon g - 2)
  - $\rightarrow$ Belle II (flavour physics)
  - $\rightarrow$ MUSE and PRad II (proton radius)
  - $\rightarrow$ P2 and QWeak (weak mixing angle)

McMule

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
$\tau \to \ell\,\nu\,\bar\nu$	NNLO
$\tau \to \ell\,\nu\,\bar\nu\,\gamma$	NLO
$\tau \to \ell\nu\bar\nu ll$	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

An inclusive e^+ event from a **polarised** μ^+ decay is fully characterised by the double differential cross section:

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

$P_\mu \longrightarrow$ Muon polarisation rate (85% for MEG II & Mu3e).

$F\,(E_e) \longrightarrow$ Contribution **independent** on μ^+ polarisation.

$G\,(E_e) \longrightarrow$ Contribution **dependent** on μ^+ polarisation.

Effective model for the signal $\boldsymbol{\mu^+ \to e^+ X}$:

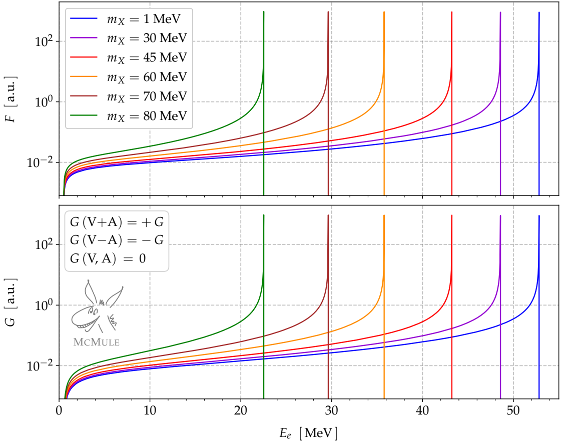
$$\mathcal{L}_\mathrm{X} = \frac{1}{\Lambda}\,(\partial_\rho \mathrm{X})\,\bar{\psi}_\mu\,(\mathrm{g_V}\,\gamma^\rho + \mathrm{g_A}\,\gamma^\rho\gamma^5)\,\psi_\mathrm{e} + \mathcal{L}_\mathrm{QED}$$

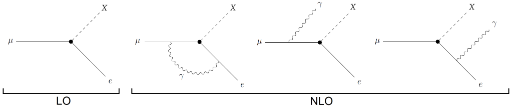
$\mathrm{g_V} = -\,\mathrm{g_A} \longrightarrow$ V−A coupling (left-handed, like SM)

$\mathrm{g_V} = +\,\mathrm{g_A} \longrightarrow$ V+A coupling (right-handed, unlike SM)

$\mathrm{g_A} = 0 \longrightarrow$ V coupling (no muon polarisation effect)

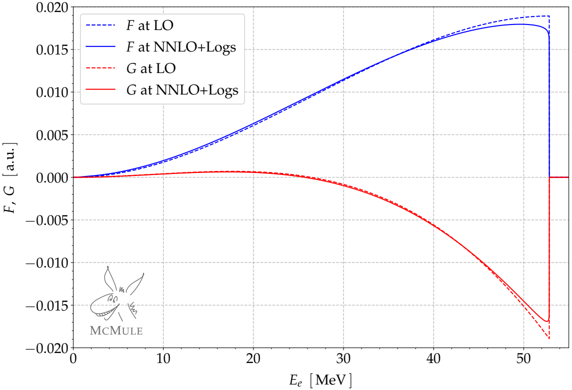
$\mathrm{g_V} = 0 \longrightarrow$ A coupling (no muon polarisation effect)

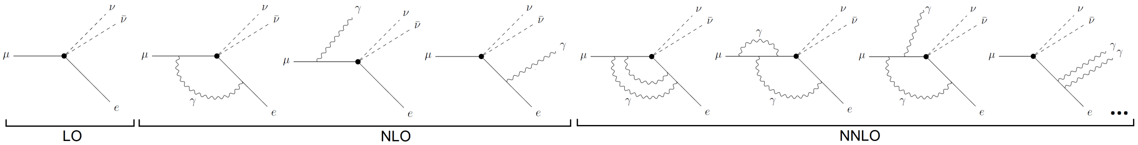




Background $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ at NNLO+Logs

- 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 NNLL accuracy (YFS exponentiation).
- (Hadronic) Vacuum Polarisation effects at $\mathcal{O}(\alpha^2)$.
- Resulting theory error of $10^{-5} \div 10^{-6}$ on F and G.

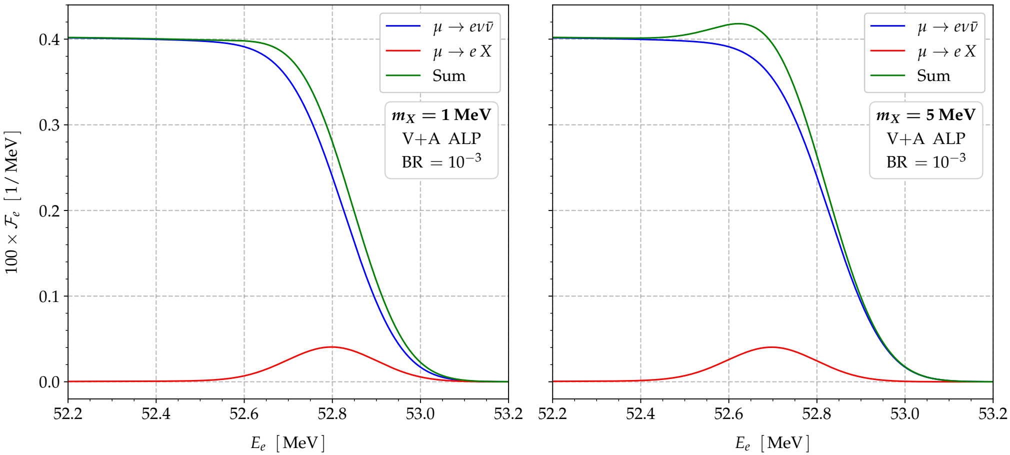




Signal vs. Background for MEG II

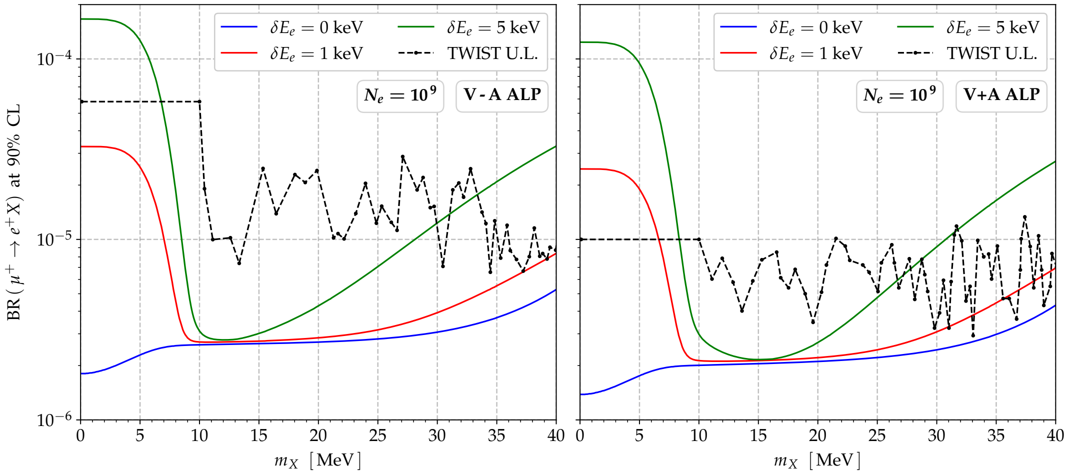
$\mathcal{F}_e = (\,\mathcal{E}_e \times \mathcal{A}_e\,) \otimes \mathcal{S}_e \quad \longrightarrow$

$\mathcal{F}_e$: Expected energy spectrum, $\mathcal{A}_e$: Positron energy acceptance,
$\mathcal{E}_e$: Theoretical energy spectrum, $\mathcal{S}_e$: Positron energy resolution.



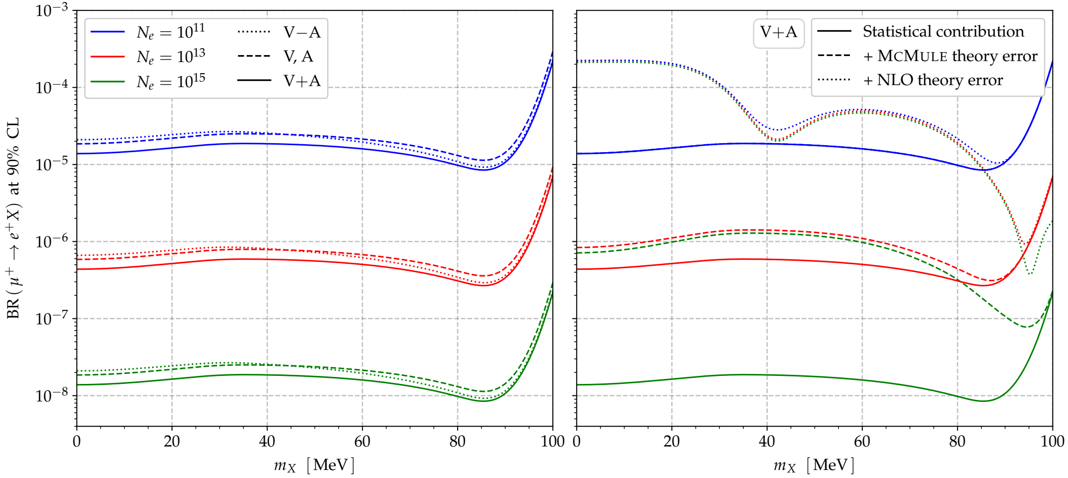
Expected sensitivity for MEG II

Sensitivity on $\mu \to e\,X$ at 90% CL for MEG II, assuming different offsets on E_e calibration $\longrightarrow$ Signal biases for $m_X \simeq 0$



Expected 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 tackled with McMule, leading to **a new state-of-the-art computation of $\boldsymbol{\mu \to e\,\nu\,\bar{\nu}}$** for polarised muons [arXiv:2211.01040].

- The results have been implemented in the MEG II framework for more detailed studies [arXiv:2211.02030].

- Work in progress for $\boldsymbol{\mu \to e\,X\,\gamma}$ and processes involving BSM neutrinos.

- The current McMule 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

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