The McMule framework and the search for ALPs at PSI

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McMule

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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: $\mathbf{5 \cdot 10^8}$ $\boldsymbol{\mu^+/s}$ $\longrightarrow$ $10^{10}\ \mu^+/s$ (future goal).

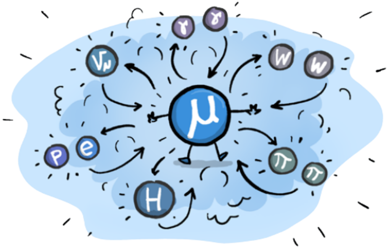
  $\hookrightarrow$ Ideal setting for studying rare muon decays beyond the SM.
- **MEG II** experiment: $\boldsymbol{\mu^+ \to e^+\gamma}$ with a sensitivity of $6 \cdot 10^{-14}$ at 90% CL.

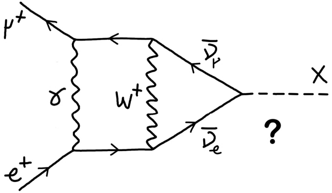
  $\hookrightarrow$ MEG upper limit: $\mathrm{BR} < 4.2 \cdot 10^{-13}$ at 90% CL.
- **Mu3e** experiment: $\boldsymbol{\mu^+ \to e^+e^+e^-}$ with a sensitivity of 10^{-15} at 90% CL.

  $\hookrightarrow$ SINDRUM upper limit: $\mathrm{BR} < 1.0 \cdot 10^{-12}$ 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).

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

  MEG II (first three) Mu3e (last two)



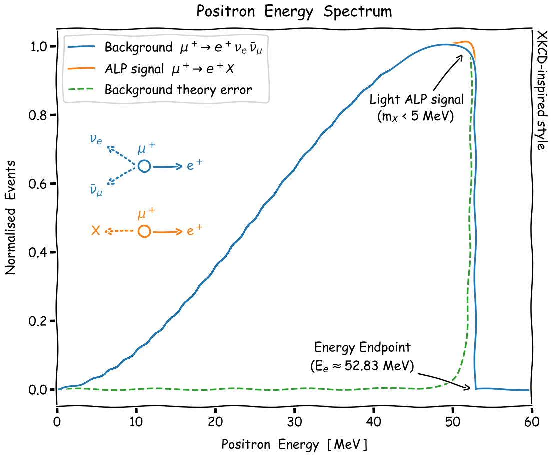


Search for $\mu \to e\,X$ with MEG II and Mu3e

- This talk: focus on $\boldsymbol{\mu^+ \to e^+ X}$ (simple but elusive!)
  $\hookrightarrow$ TWIST limit: 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.
  $\hookrightarrow$ 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).
  $\hookrightarrow$ 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.

- An inclusive e^+ event from a **polarised** μ^+ decay is fully characterised by

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

$P_\mu \longrightarrow$ Muon polarisation rate (85% for MEG II and Mu3e).
$F\,(E_e) \longrightarrow$ Contribution **independent** on μ^+ polarisation.
$G\,(E_e) \longrightarrow$ Contribution **dependent** on μ^+ polarisation.

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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

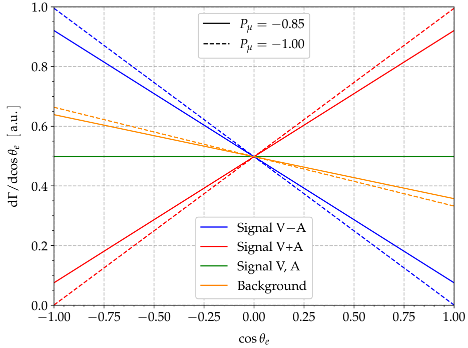
$$\mathcal{L}_X = \frac{1}{\Lambda} (\partial_\rho X)\, \bar{\psi}_\mu \,(\gamma^\rho\, g_V + \gamma^\rho \gamma^5\, g_A)\, \psi_e + \mathcal{L}_{QED}$$

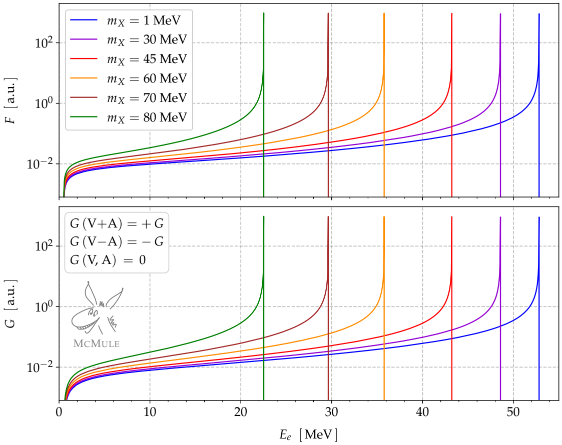
$g_V = -g_A \longrightarrow$ V−A coupling (left-handed, like SM)

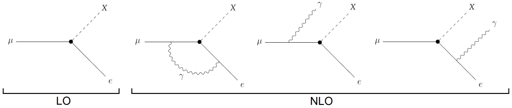
$g_V = +g_A \longrightarrow$ V+A coupling (right-handed, unlike SM)

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

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

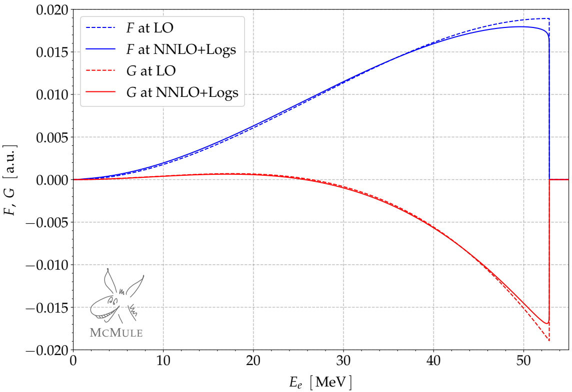


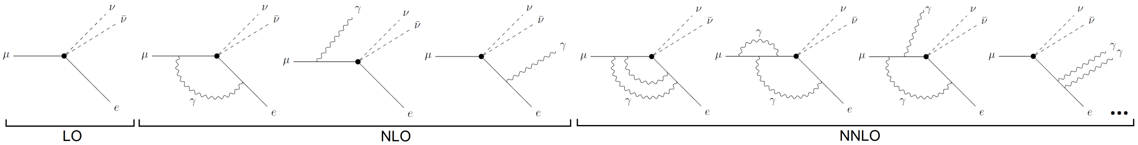




Background $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ at NNLO+Logs

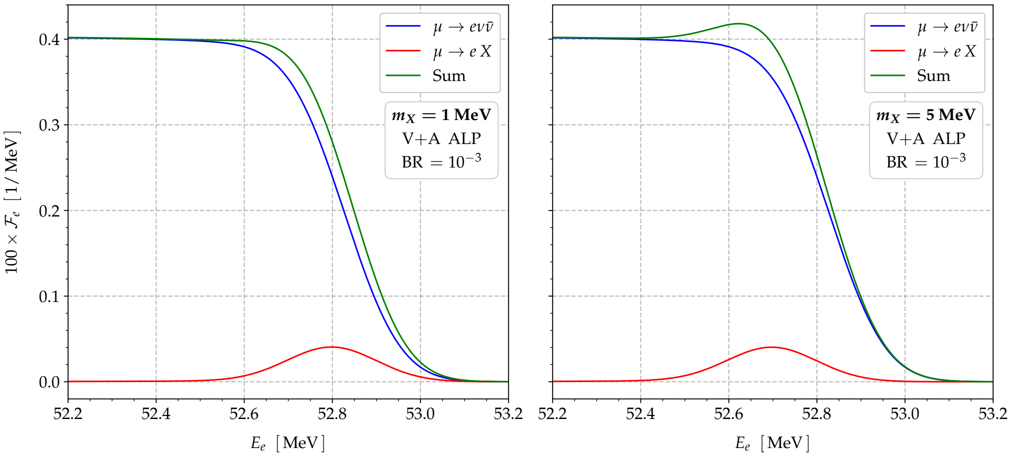
- LO computed with the (dear old) Fermi theory.
- Leading EW correction: $G_F \to G_F \,(1 + 3m_\mu^2 \,/\, 5m_W^2)$.
- Full **QED corrections at NNLO** with $m_e \neq 0$.
- Inclusion of **collinear logarithms** $\log(m_e \,/\, m_\mu)$ up to $\mathcal{O}(\alpha^5)$ with next-to-leading logarithm (NLL) 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 $\sim 10^{-5}$.





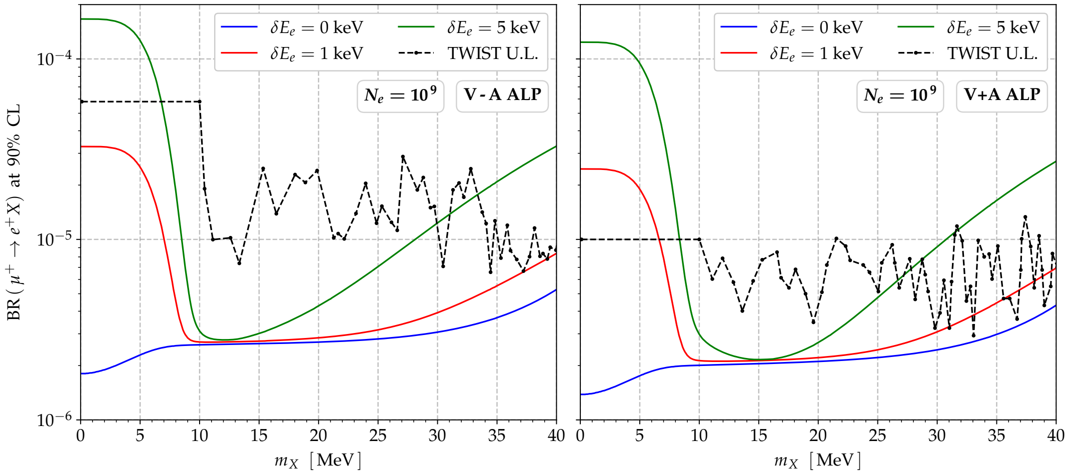
$$\mathcal{F}_e = (\,\mathcal{E}_e \times \mathcal{A}_e\,) \otimes \mathcal{S}_e \quad \longrightarrow$$

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



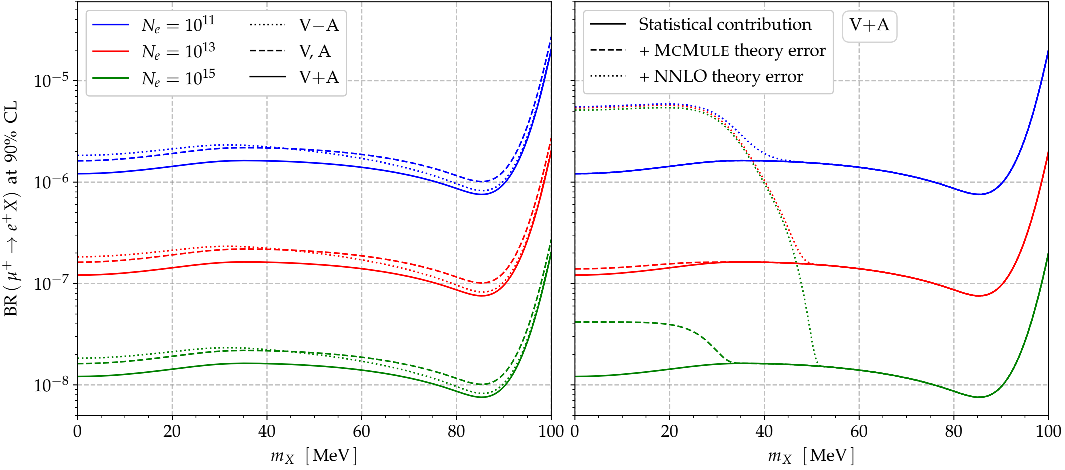
Preliminary sensitivity for MEG II

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



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 $\mu \to e\,\nu\,\bar{\nu}$** 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...

McMule

P. Banerjee[1], A. Coutinho[2], T. Engel[2,3], A. Gurgone[4,5], F. Hagelstein[6,2], S. Kollatzsch[7], L. Naterop[3], A. Proust[8], M. Rocco[2], N. Schalch[9], V. Sharkovska[2,3], A. Signer[2,3], Y. Ulrich[10]

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Visit our website: `https://mule-tools.gitlab.io`

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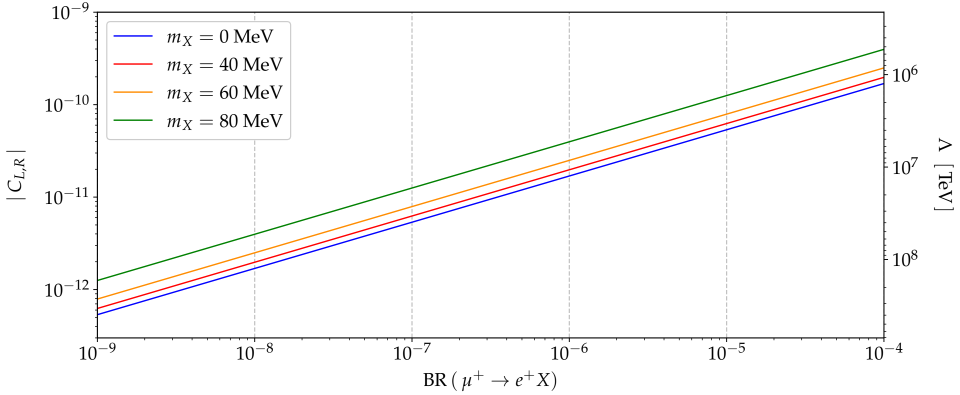
Backup

$\mathrm{BR}(\mu \to e X) \longleftrightarrow \Lambda \longleftrightarrow C_L, C_R$

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

$$\mathrm{C_L} \equiv \mathrm{g_V}\,\frac{\mathrm{i}\,(m_e - m_\mu)}{\Lambda} + \mathrm{g_A}\,\frac{\mathrm{i}\,(m_e + m_\mu)}{\Lambda} \qquad \mathrm{C_R} \equiv \mathrm{g_V}\,\frac{\mathrm{i}\,(m_e - m_\mu)}{\Lambda} - \mathrm{g_A}\,\frac{\mathrm{i}\,(m_e + m_\mu)}{\Lambda}$$



Theorist's toy analysis for MEG II and Mu3e

Simplified model for MEG II and Mu3e positron trackers:

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

$\mathcal{F}_e$: 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

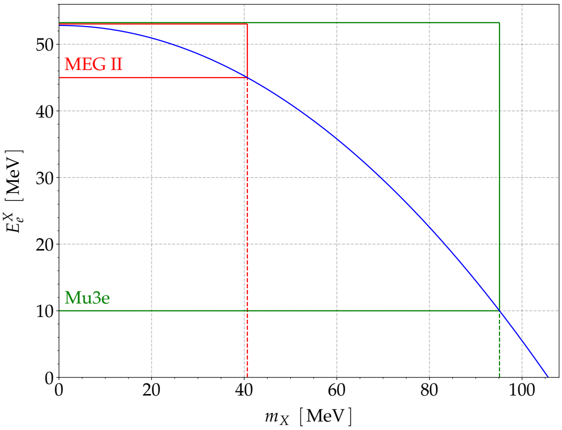
MEG II acceptance: $|\cos\theta_e| < 0.35$, $E_e \gtrsim 45$ MeV
Mu3e acceptance: $|\cos\theta_e| < 0.8$, $E_e \gtrsim 10$ MeV

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

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)

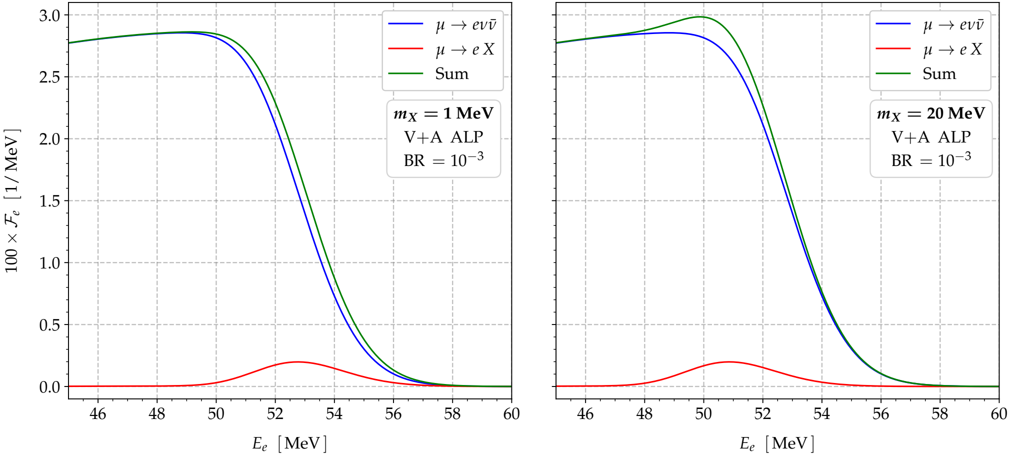
ALP mass acceptance in MEG II and Mu3e



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

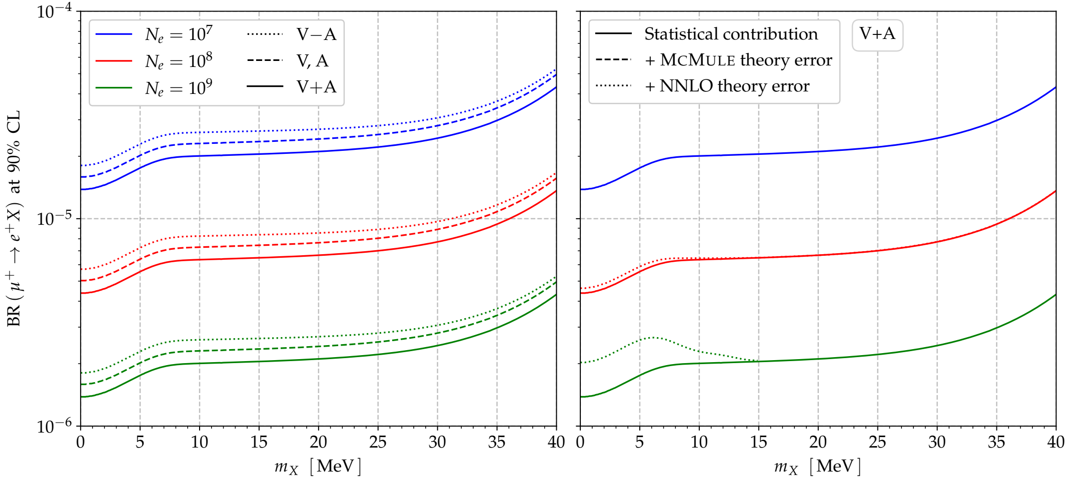
Signal vs. Background in Mu3e

$\mathcal{F}_e = (\mathcal{E}_e \times \mathcal{A}_e) \otimes \mathcal{S}_e \longrightarrow$ $\mathcal{F}_e$: Expected energy spectrum, $\mathcal{A}_e$: Positron energy acceptance, $\mathcal{E}_e$: Theoretical energy spectrum, $\mathcal{S}_e$: Positron energy resolution.

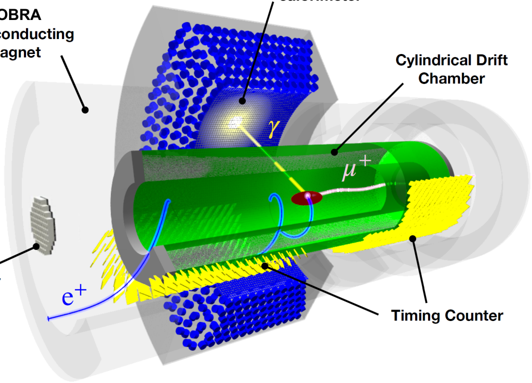


Preliminary sensitivity for MEG II without systematic effects

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



The MEG II experiment at PSI



The Mu3e experiment at PSI