Improved muon decay simulation with GEANT4 and MCMULE

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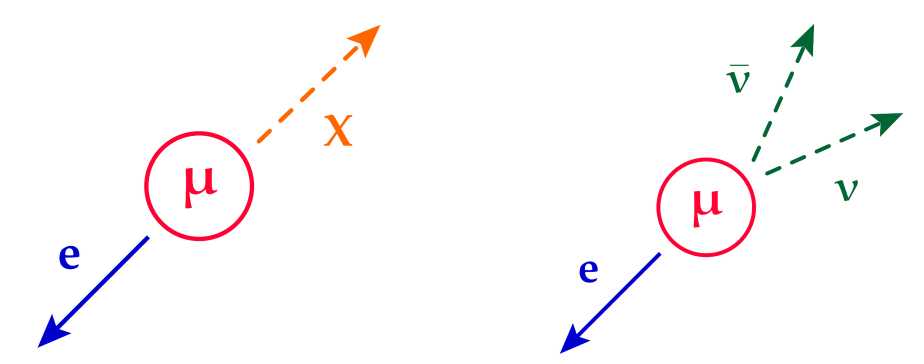
Motivations

The search for **charged Lepton Flavour Violation** (cLFV) in muon decays is a key tool to probe the SM. The **MEG II experiment** at PSI searches for $\mu^+ \to e^+\gamma$ with a BR sensitivity of $6 \cdot 10^{-14}$ at 90% of CL. Furthermore, the experiment appears to be competitive in searching for processes in which cLFV occurs in the presence of a light neutral scalar boson X, possibly an **axion-like particle** (ALP). Since MEG II is designed for a two-body signal, a promising process is $\boldsymbol{\mu^+ \to e^+X}$. Unfortunately, its only signature is a monochromatic positron close to the kinematic endpoint of the $\boldsymbol{\mu^+ \to e^+\nu_e\bar{\nu}_\mu}$ background ($E_e^{max} \simeq 52.83$ MeV). The hunt for such an elusive signal requires an exhaustive **MC simulation** to fully characterise the detector response. Since the higher-order radiative corrections for $E_e \to E_e^{max}$ are enhanced by the emission of **soft photons**, the simulation must include extremely accurate theoretical predictions for the event generation of both decays.



ALP Signal   Background

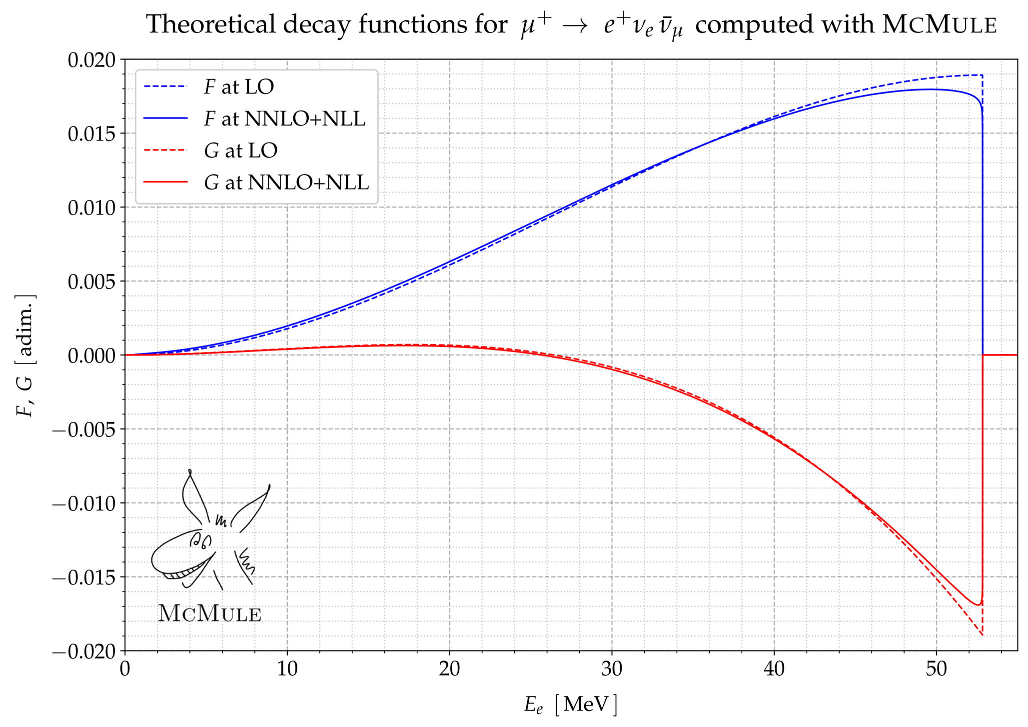
Theory input

The required theoretical accuracy is achieved with **MCMULE**, a framework for the numerical computation of **QED corrections** for low-energy processes involving leptons. The only two relevant observables in **polarised muon decay** are the positron energy E_e and the angle θ_e between the positron momentum $\vec{p}_e$ and the muon polarisation $\vec{n}_\mu$. The corresponding differential decay width can be written as

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

The two functions $F(E_e)$ and $G(E_e)$ provide all the information required to generate positron events. In MCMULE the signal $\mu^+ \to e^+X$ is implemented assuming a **generic mass and coupling** for the ALP and including the QED corrections at next-to-leading order (NLO). The background $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ includes the leading weak and hadronic corrections, exact QED corrections at **next-to-next-leading order** (NNLO) and approximated at higher orders with a **next-to-leading logarithm** (NLL) accuracy. The result is a theory error of $10^{-5} \div 10^{-6}$ on the positron energy spectrum, the smallest achieved so far.

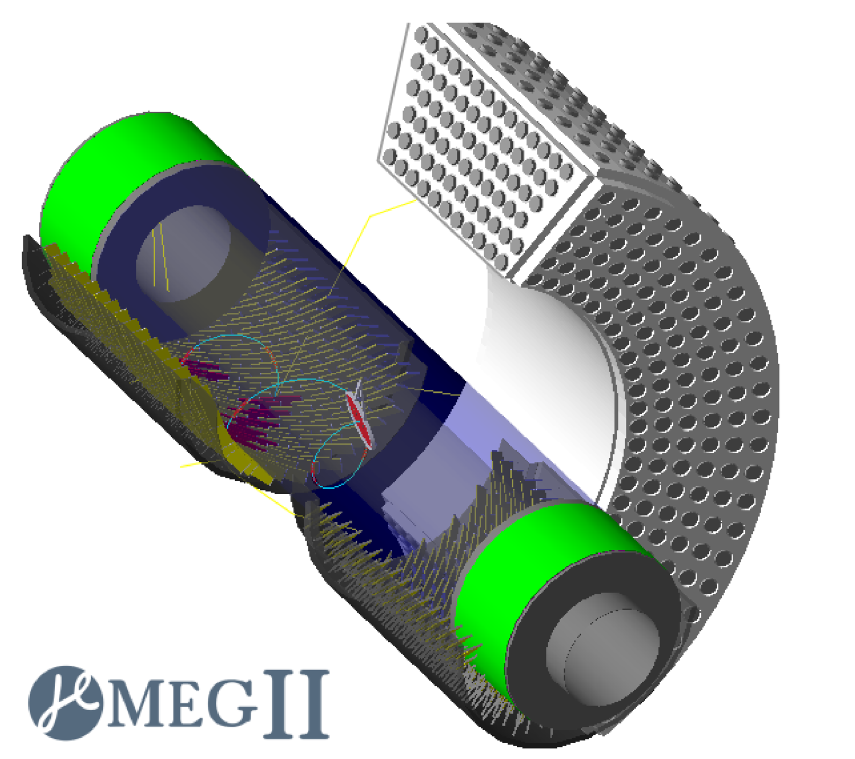
Theoretical decay functions for $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ computed with MCMULE



Event generation

The MCMULE predictions are used to implement an improved **positron event generator** for MEG II. The incoming muon is assumed to decay at rest inside the MEG II target. The **decay vertex** is found by intersecting the muon beam distribution with the target surface. The depth of the decay is determined by simulating the interactions between the incoming muon and the target material. The **energy** $\boldsymbol{E_e}$ and the **polar angle** $\boldsymbol{\theta_e}$ of the outgoing positron are generated according to their correlated distribution in MCMULE. To this end, the two functions $F(E_e)$ and $G(E_e)$ are implemented as discrete probability distributions with a negligible energy bin width (2 keV). The **azimuthal angle** $\boldsymbol{\phi_e}$ is generated uniformly, being perpendicular to the muon polarisation. This set of observables completely specifies the event kinematics, both for $\mu^+ \to e^+X$ and $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$.

Simulation of a $\mu^+ \to e^+X$ event in the MEG II software



Positron reconstruction

In MEG II the outgoing positrons are tracked with a **spectrometer** consisting of three elements:

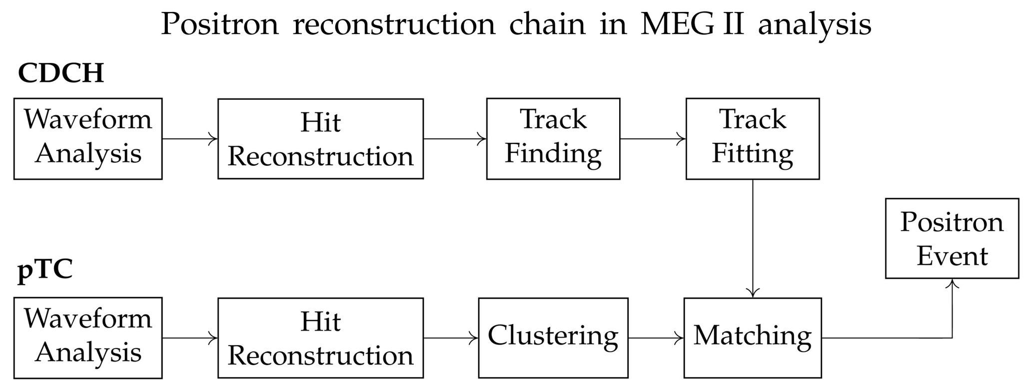
1. The **COnstant Bending RAdius** (COBRA) magnetic field, a solenoid with a longitudinal gradient to sweep the positrons away after a few turns.
2. The **Cylindrical Drift CHamber** (CDCH) for the precise measurement of the muon decay vertex and the positron momentum ($\delta p_e \sim 100$ keV).
3. The **pixelated Timing Counter** (pTC) for the precise measurement of positron time ($\delta t_e \sim 70$ ps).

In the **MEG II software**, the event reconstruction is simulated in three conceptual steps:

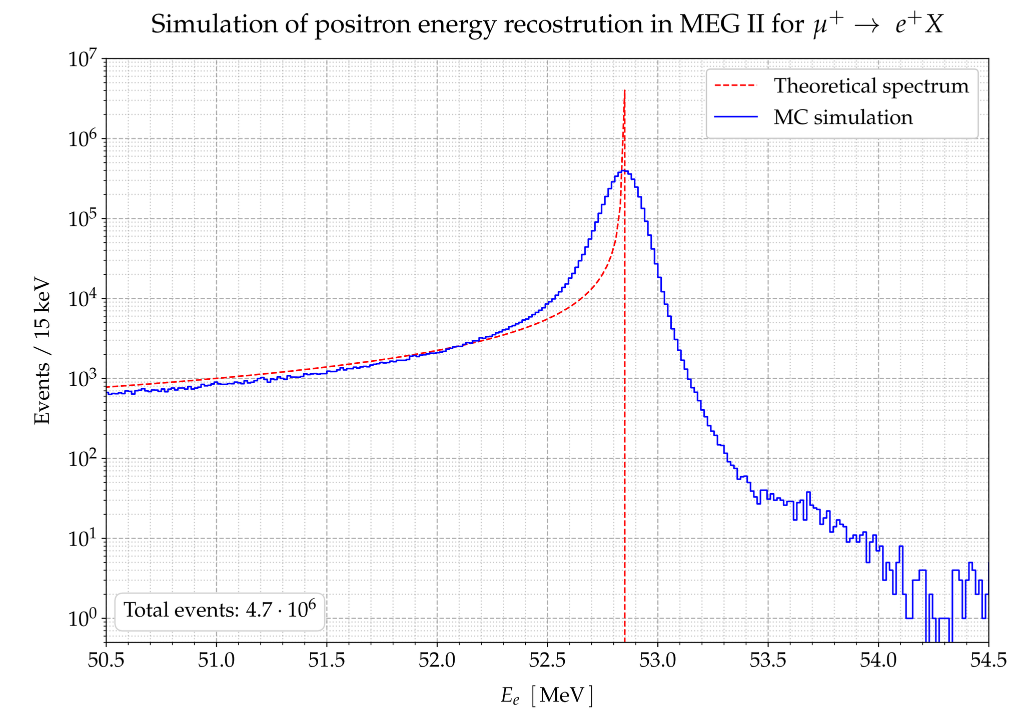
1. Event generation and simulation of the detector response with GEANT4 and other toolkits.
2. Simulation of the readout electronics and event mixing to include pile-up effects.
3. Reconstruction of physical observables from waveforms and raw data.

Positron tracks are identified with a pattern recognition algorithm and fitted with a Kalman filter.

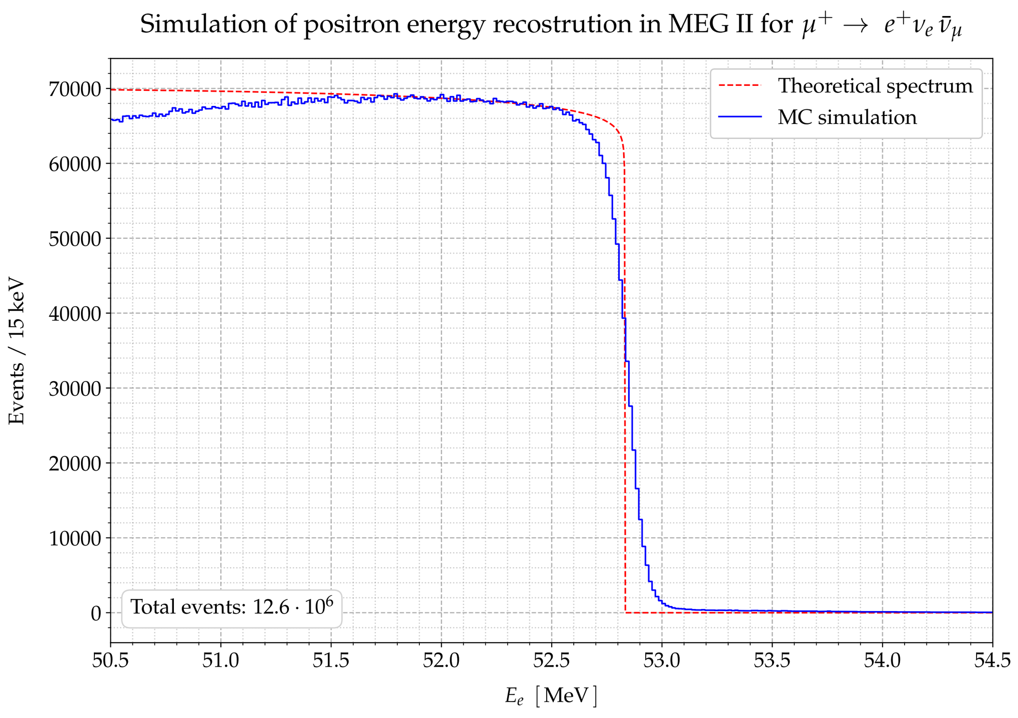
Positron reconstruction chain in MEG II analysis



Simulation of positron energy recostrution in MEG II for $\mu^+ \to e^+X$



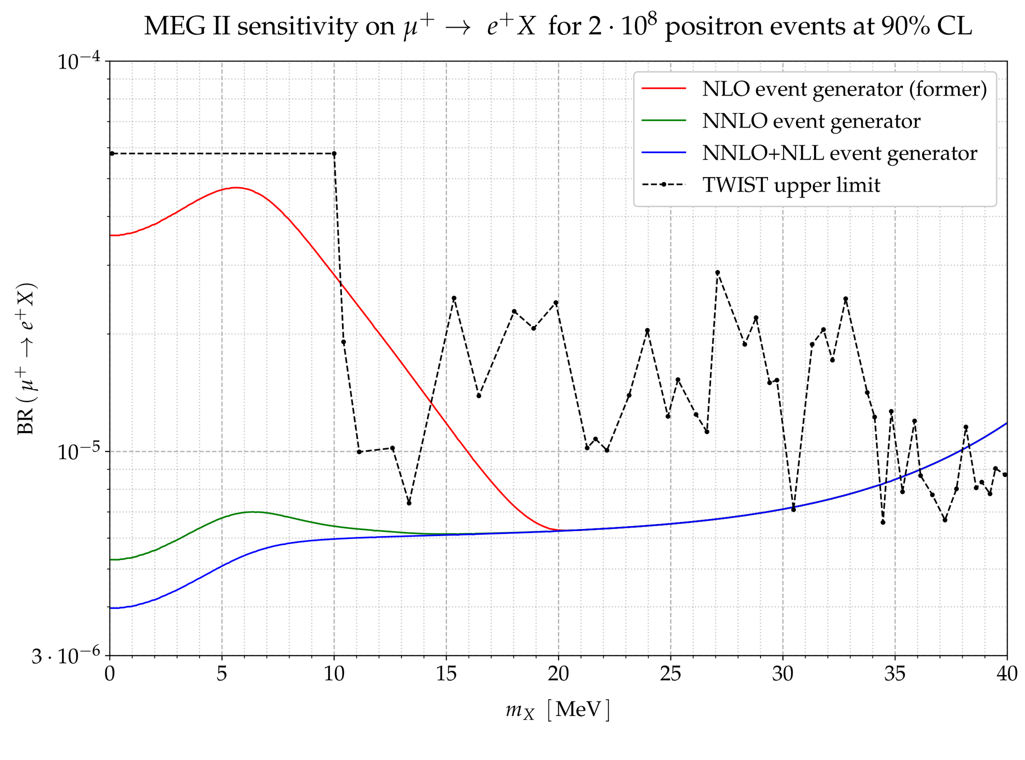
Simulation of positron energy recostrution in MEG II for $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$



Conclusions

The search for lepton flavour violating ALPs in muon decays such as $\mu^+ \to e^+X$, $\mu^+ \to e^+X\gamma$ or $\mu^+ \to e^+(X \to \gamma\gamma)$ is an excellent opportunity to **extend the MEG II physics programme** beyond $\mu^+ \to e^+\gamma$. The first process is particularly elusive given the presence of only one detectable particle. On the other side, the MEG II spectrometer is specifically designed to detect positrons at the kinematic endpoint, as occurs for $\mu^+ \to e^+X$ with $m_X \to 0$.

MEG II sensitivity on $\mu^+ \to e^+X$ for $2 \cdot 10^8$ positron events at 90% CL



The presented MC simulation can be used to study the feasibility of this additional search. A preliminary study shows a **competitive sensitivity**, close to the upper limit set by the TWIST experiment. Since the **theoretical error on the background** covers the signal for low BRs, the new NNLO+NLL generator considerably improves the sensitivity w.r.t. the former NLO generator. The effect is larger for low m_X, as the QED corrections are logarithmically enhanced at the endpoint. Furthermore, an offset on the absolute positron energy scale results in a false signal at the endpoint. For this reason, a rigorous control of the **systematic effects** on the positron energy reconstruction is required to avoid signal biases. To this end, **new calibration tools** for the MEG II spectrometer are currently in development.

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