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The McMule framework and the search for axion-like particles at PSI

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Precision measurements of flavour-violating processes are a sensitive tool to search for signals beyond the Standard Model (SM). In this context, the MEG II and Mu3e experiments at the Paul Scherrer Institut (PSI) search for the two muon decays $\mu^+ \rightarrow e^+ \gamma$ and $\mu^+ \rightarrow e^+ e^- e^+$, respectively. In addition to their main channels, both experiments appear to be competitive in searching for more exotic processes, in which lepton flavour violation (LFV) occurs in presence of an invisible axion-like particle (ALP), denoted with X . A suitable candidate is the two-body decay $\mu^+ \rightarrow e^+ X$, whose only signature is a monochromatic positron close to kinematic endpoint of the $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ background. Since the higher-order radiative corrections in this region are greatly enhanced by the emission of soft photons, the experimental hunt for such an elusive signal requires extremely accurate theoretical predictions.

This is one of the problems that led to the development of McMule, acronym of Monte Carlo for MUons and other LEptons. McMule is a generic framework for the numerical computation of fully-differential QED corrections for low-energy processes involving leptons, based on the FKS² subtraction scheme. In addition to muon and tau decays, the code includes scatterings such as $ee \rightarrow ee$, $ee \rightarrow \gamma\gamma$ and $ep \rightarrow ep$ with next-to-next-to-leading order (NNLO) accuracy, while $e\mu \rightarrow e\mu$ and $ee \rightarrow \mu\mu$ are currently in development at the same precision.

In this contribution, we focus on the implementation of $\mu \rightarrow eX$ and $\mu \rightarrow e\nu\bar{\nu}$ in the McMule framework. In both cases the muons are assumed to be polarised and the electron mass is kept at its physical value. The signal $\mu \rightarrow eX$ is computed using an effective field approach, including the QED corrections at next-to-leading order (NLO). The background $\mu \rightarrow e\nu\bar{\nu}$ includes weak corrections at NLO, hadronic contributions at LO, exact QED corrections at NNLO and logarithmically approximated at N³LO and N⁴LO. Going beyond fixed-order calculations, an analytical resummation of soft emissions is also included. This results in a theoretical error on the positron energy spectrum below 10^{-6} , the smallest achieved so far for the polarised muon decay.

As a preliminary study, we assume the nominal performances of the MEG II and Mu3e experiments to estimate their sensitivity on $\mu \rightarrow eX$ for different masses and couplings of the ALP. The branching ratio of this hypothetical process has been limited to $5.8 \cdot 10^{-5}$ by the TWIST experiment. We show that MEG II can provide an independent measurement close to this limit, while Mu3e can improve it up to three orders of magnitude. In this regard, the McMule predictions are currently being implemented in the experimental analysis codes for more detailed studies.

In-person participation

Yes

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