Muon charged Lepton Flavor Violation search in Europe: the $\mu^+ \rightarrow \mathrm{e}^+\gamma$ and the $\mu^+ \rightarrow \mathrm{e}^+\mathrm{e}^-\mathrm{e}^+$ decays

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Abstract. Lepton flavor violation (LFV) research is currently one of the most exciting branches of particle physics. Flavor violating processes, such as $\mu^+ \rightarrow \mathrm{e}^+\gamma$ and $\mu^+ \rightarrow \mathrm{e}^+\mathrm{e}^-\mathrm{e}^+$, which are strongly suppressed in the Standard Model (SM), in which massive neutrinos are included to take into account neutrino oscillations, are very sensitive to "new physics". The MEG experiment and the Mu3e experiment, which search for the $\mu^+ \rightarrow \mathrm{e}^+\gamma$ and the $\mu^+ \rightarrow \mathrm{e}^+\mathrm{e}^-\mathrm{e}^+$ decay respectively, are two precision physics experiments at the forefront of field. They are housed at the Paul Scherrer Institut (PSI), in Switzerland, which provides the most intense continuous muon beam in the world. A summary of the status of the two experiments is given.

1. Introduction

The Standard Model supplemented with massive neutrinos (SM) and enriched by the latest great discovery of the Higgs-like particle at the Large Hadron Collider (LHC), summarizes our present best knowledge of particle physics. In spite of its extraordinary success, being able to account for a huge bulk of experimental data, there exist both strong theoretical reasons in particle physics and significant observational hints from astro-particle physics for new physics beyond the SM [1].

Different experimental approaches can be pursued to address these fundamental physics questions. Amongst others a powerful way is to search for SM forbidden or strongly suppressed (rare) processes which can reveal new physics via indirect production of Beyond Standard Model (BSM) particles, strongly enhancing the probability of these processes to occur [2, 3]. Although for indirect processes new particles are only virtual in the loop and will not be directly observed (contrary to the case of direct searches as at LHC), the physics energy scale explored following this approach ($\mathcal{O} \geq 1000$ TeV) is orders of magnitude higher than what can be done at the state-of-the-art accelerator machines ($\mathcal{O} \approx 10$ TeV).

In the last years, flavor physics became one of the most exciting branches of particle physics due to the high sensitivity to new physics in the so called charged lepton flavor violation (cLFV) processes. Indeed, the simplest and most reliable theoretical SM extensions predict measurable charged lepton flavor violating processes. Furthermore, the observation of neutrino oscillations has clearly demonstrated that neutral lepton flavor is not conserved.

Muonic rare channels such as the $\mu^+ \rightarrow e^+\gamma$ decay, the $\mu^+ \rightarrow e^+e^+e^-$ decay and $\mu^-N \rightarrow e^-N$ conversion in nuclei are the most promising LFV processes, the so called "golden muonic

Table 1. Resolutions (Gaussian σ) and efficiencies comparison between the current MEG detector and the MEGII detector.

Detector Resolutions	Present MEG	Upgrade scenario
e^+ energy (keV)	305 (core = 85%)	130
e^+ timing (ps)	70	35
e^+ θ (mrad)	10.6	5.3
e^+ ϕ (mrad)	7.5	5.0
e^+ vertex (mm) Z/Y(core)	1.9 / 1.3	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.6 / 1.7	1.3 / 1.0
γ timing (ps)	67	similar
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	127	84
Detector Efficiency (%)		
e^+	40	90
γ	63	69
trigger	$\approx$ 99	$\approx$ 99

channels" [4]. The effective lagrangian, which describes in a model independent way the above processes, contains two possible terms contributing to cLFV:

$$\mathcal{L}_{cLFV} = \frac{m_\mu}{(k+1)\Lambda^2}\overline{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{k}{(k+1)\Lambda^2}\overline{\mu}_R\gamma_\mu e_L \overline{f}\gamma^\mu f \quad (1)$$

While $\mu^+ \to e^+\gamma$ proceeds only via the first term, the $\mu^+ \to e^+e^+e^-$ decay and the $\mu^- N \to e^- N$ conversion may occur also through the second one. If nature prefers the $k = 0$ case, the $\mu^+ \to e^+\gamma$ decay is favored and appears as the most sensitive discovery channel. On the other hand for the $k \neq 0$ cases the $\mu^+ \to e^+e^+e^-$ decay and the $\mu^- N \to e^- N$ conversion become more and more prominent as k grows. A complementary search approach is the only way to reveal the nature of the physics which induces cLFV if an evidence of it is found.

Rare decay searches require the use of high beam intensities and demand detectors able to work in critically high background environments. Two of the three golden processes can be studied in Europe, at the Paul Scherrer Institut (PSI) as the unique laboratory in the world delivering the highest continuous positive muon beam. We will focus on them, starting from the experiment that has just completed its data acquisition and is presently finalizing the data analysis.

2. The MEG experiment and its upgrade

The MEG experiment [5] searches for the $\mu^+ \to e^+\gamma$ decay and has recently set the most stringent upper limit on its branching ratio $\mathcal{B}(\mu^+ \to e^+\gamma) < 5.6 \times 10^{-13}$ [6]. It is a factor 20 better than the previous limit set by the MEGA experiment and also the strongest upper limit among all the other decays.

The signature of a $\mu^+ \to e^+\gamma$ decay at rest is a back-to-back, mono-energetic, time coincident photon and positron pair.

The strong scientific motivation of searching for cLFV pushed the collaboration to think about an upgrade of the experiment, aiming at enhancing the sensitivity by a factor 10 [7]. The upgrade preserves the general idea of the previous experiment in terms of the $\mu^+ \to e^+\gamma$

signature and the detectors used to extract it. In the following a summary of the MEG upgrade is given.

The positron tracker is a unique volume, low mass cylindrical drift chamber placed inside the magnet. The positron trajectory is measured up to the point where the positron reaches the new TC tiles, with minimum presence of passive material and an increased number of hits per track. The new TC are made by a large number of small ultra-fast scintillator plates coupled with silicon photomultiplier (SiPM). The high segmentation allows to work at a higher muon rate and to reach a better timing resolution. An upgrade of the LXe calorimeter involving a denser allocation of photo-detectors on the front face, replacing the current PMTs (2 inch diameter) with smaller Muti-Pixel Photon Counter (MPPC Hamamatsu) 12×12 mm^2 is ongoing for expected better energy and position resolutions.

Two completely new detectors are considered to be added to the framework of the MEGII experiment: (a) an active target which provides a continuous beam monitoring and a direct measurement of the vertex decay; (b) a radiative decay counters, enabling to increase the capability of rejecting the accidental background by tagging low energy positrons associated with the high energy photons in the signal region.

The upgraded detectors demand also new calibration and monitoring methods: (a) a dedicated monochromatic positron beam with an energy very close to the MEG signal has been proposed and is already under study to fully explore the new DCH; (b) a timing calibration at level of 15 ps for the new TC pixels has been suggested, based on the cyclotron Radio Frequency (RF) signal associated to the positron beam.

Finally, MEG II requires improvements also on the existing DAQ system in terms of an increased number of channels and a higher bandwidth of the waveform digitization system: a new DAQ board (WaveDREAM), based on the current DRS chip, is under construction

A summary of the current detector performances and the expected ones for the MEG II are summarized in Tab. 1.

3. The Mu3e experiment

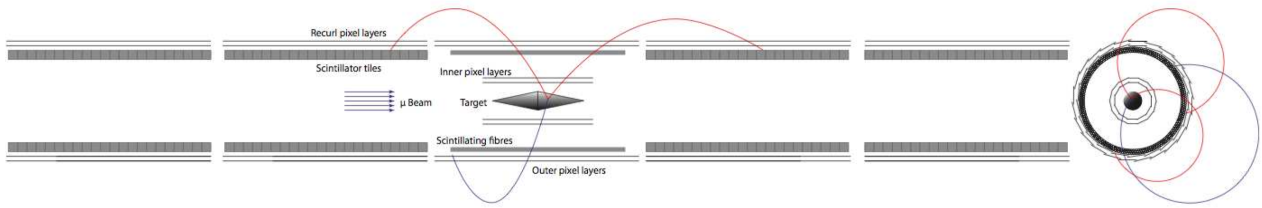

Figure 1. Schematic view of the final Mu3e experimental setup.

The approved Mu3e experiment [8] will search for the $\mu^+ \to e^+e^+e^-$ decay aiming at a sensitivity of a few $\times\ 10^{-16}$, four orders of magnitude better than the previous upper limit on the $\mu^+ \to e^+e^+e^-$ decay set by the SINDRUM experiment $\mathcal{B}(\mu^+ \to e^+e^+e^-) < 1.0 \times 10^{-12}$. This expected strong improvement is possible because the previous experiment was limited only by statistics. Indeed the development of new technologies, one of the key elements of the novel Mu3e design, allows to enhance the sensitivity at least by two orders of magnitude using the presently available beam intensity (10^8 muons/s). In order to explore the mentioned few $\times\ 10^{-16}$ region, two big issues have to be addressed: an available continuous positive muon beam intensity of 10^9 muons/s and a tracking device working at such as high rates.

Currently there are no such (pulsed or continuous, DC) high-intensity muon sources available in the world. A new concept has been proposed at PSI and it is at present at a feasibility study stage, aiming at 10^{10} muons/s, DC.

The Mu3e experiment is thought to run in two different phases: the so called "low" beam intensity phase, with the current beam intensities and the "high" beam intensity phase, with a completely new beam line, able to reach at least 10^9 muons/s.

The $\mu^+ \to e^+e^+e^-$ decay signal is defined by its final state: two positrons and one electron without any additional neutrinos. All the tracks originating from the decay share a single common vertex and they are coincident in time. The invariant mass of the three tracks, measured at the vertex position, is identical to the muon mass. The muons are stopped in the target implying that the vectorial sum of the positron momenta must vanish. Any background to the signal comes from accidental and internal conversion processes that mimic signal. The accidental background is not coincident in time or space and the total momentum does not fulfill the requirements given above. To suppress these kinds of backgrounds a high vertex and time resolution are needed. The other type of background comes from internal conversion decays, as the $\mu^+ \to e^+e^+e^-\nu\overline{\nu}$. These are radiative decays where the radiated photon immediately converts to an electron-positron pair. In some parts of the phase-space the measurable final state is nearly identical to the signal. There are three electron tracks, one of which has a negative charge, they share a common vertex and they are coincident in time. This arrangement is indistinguishable from the signal decay. However, there are two additional neutrinos in the final state and the three electron tracks do not fulfill the required energy and momentum relations. To suppress these backgrounds to an acceptable level, a momentum resolution for the sum of the three electron momenta below 1 MeV/c is needed.

The proposed Mu3e detector is based on two double layers of High Voltage Monolithic Active Pixel Sensors (HV-MAPS) [9] around a hollow double cone target. The outer two pixel sensor layers are extended upstream and downstream to provide precise momentum measurements in an extended region with the help of re-curling electrons. The silicon detector layers are supplemented by two timing systems, a scintillating fibre tracker in the central part and scintillating tiles inside the re-curl layers. Precise timing of all tracks is necessary for event building and to suppress accidental combinatorial background. The entire detector is built in a cylindrical shape around a beam pipe, with a total length of approximately 2 m, inside a 1 T solenoid magnet with 1 m inside diameter and 2.5 m total length.

A schematic view of the final detector with two sets of re-curl stations for high intensity physics runs is shown in Fig. 1.

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