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Muon charged Lepton Flavor Violation search in Europe: the $\mu^+ \to \mathrm{e}^+\gamma$ and the $\mu^+ \to \mathrm{e}^+\mathrm{e}^-\mathrm{e}^+$ 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 $\mu^+ \to \mathrm{e}^+\gamma$ and $\mu^+ \to \mathrm{e}^+\mathrm{e}^-\mathrm{e}^+$, which are strongly suppressed in the Standard Model (SM), are very sensitive to new physics. The MEG experiment and the Mu3e experiment, which search for the $\mu^+ \to \mathrm{e}^+\gamma$ and the $\mu^+ \to \mathrm{e}^+\mathrm{e}^-\mathrm{e}^+$ 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 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 and ability to account for a huge quantity 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.

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 [1, 2], exploring physics energy scales up to $\approx 10^4$ 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 $\mu^+ \to e^+\gamma$ decay, the $\mu^+ \to e^+e^+e^-$ decay and $\mu^-N \to e^-N$ conversion are the most promising LFV processes, the so called "golden muonic channels" [3]. The effective lagrangian, which describes in a model independent way the above processes, contains two possible terms contributing to cLFV [4]:

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

where the first term describes the photonic interaction, associated with the photon field $F^{\mu\nu}$, while the second term describes the fermionic interaction, associated with the fermion f. In the formula m_μ is the muon mass, Λ represents the effective mass scale and k governs the relative size of the two different types of operators. 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 [5]. 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 (DC) 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 [6] searches for the $\mu^+ \to e^+\gamma$ decay and has recently set the most stringent upper limit on its branching ratio $\mathcal{B}(\mu^+ \to e^+\gamma) < 5.7 \times 10^{-13}$ at 90 % C.L. [7], using the 2009-2011 data sample. It is a factor 20 better than the previous limit set by the MEGA experiment [8] and also the strongest upper limit among all the other particle decays. The sample statistic has been increased by a factor two adding the 2012-2013 data sample to the previous one and the analysis is ongoing. We reached the planned sensitivity, whose limit comes from the accidental background. 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 [9]. The upgrade preserves the general idea of the previous experiment in terms of the $\mu^+ \to \mathrm{e}^+\gamma$ signature and the detectors used to extract it.

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

A new positron-tracking chamber (DCH) with significantly improved acceptance, resolutions and efficiency is under construction. The DCH provides a measurement of the positron momentum and the emission direction (which is described by the polar θ and azimuthal ϕ angles), from which the positron energy (E_e) and the decay vertex coordinates on the target plane ($Z_{proj,e}$ and Y_e) are extracted[1]. The positron trajectory is measured up to the point where the positron reaches the new timing counter (TC), with a strong reduced presence of passive material and an increased number of hits per track with respect to the current detector. The new TC, which provides a measurements of the positron time t_e, is 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 beam rate and to reach a better timing resolution. The energy (E_γ), the time (t_γ) and the interaction point (described by the (u, v) coordinates on the LXe front face and the depth w) of the photon are measured with a large (900 liters) homogeneous liquid xenon calorimeter (LXe). The LXe upgrade namely refers to the replacement of the current PMTs (2 inch diameter) of the calorimeter front face with smaller Muti-Pixel Photon Counter (MPPC Hamamatsu) 12×12 mm^2 for 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

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[1] We refer to a cylindrical coordinate system (r,ϕ,z) with origin in the centre of the DCH. The z-axis is along the incoming muon beam. The axis defining $\phi = 0$ (the x-axis of the corresponding Cartesian coordinate system) is directed opposite to the centre of the liquid xenon detector.

Table 1. Comparison between the MEG and the MEGII detector.

Detector Resolutions (σ)	MEG	MEGII (Upgrade scenario)
e^+ energy (keV)	305	130
e^+ timing (ps)	70	35
e^+ θ (mrad)	10.6	5.3
e^+ ϕ (mrad)	7.5	5.0
e^+ vertex (mm) Z_{proj}/Y	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

decay vertex; b) a radiative decay counters, enabling to increase the capability of rejecting the accidental background. The upgraded detectors demand also new calibration and monitoring methods: a dedicated monochromatic positron beam with an energy very close to the MEG signal is under study to fully explore the new DCH and TC. A new DAQ system (WaveDREAM) will provide a larger bandwidth of the waveform digitization and a better channel inter-calibration implying better detector resolutions. A summary of the current detector performances and the expected ones for the MEG II is given in Tab. 1.

3. The Mu3e experiment

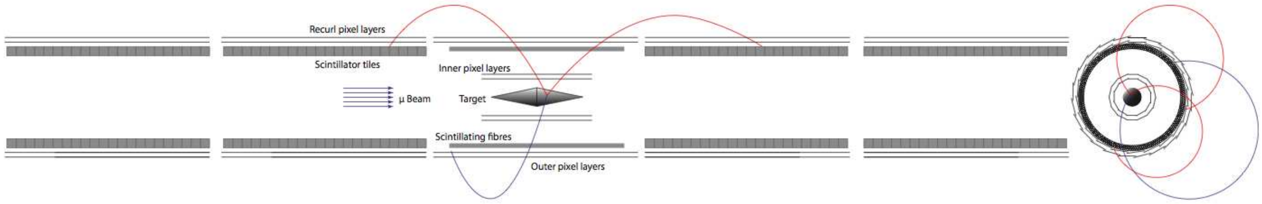

Figure 1. Schematic view of the final Mu3e experimental setup.

The approved Mu3e experiment [10] 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 $\mathcal{B}(\mu^+ \to e^+e^+e^-) < 1.0 \times 10^{-12}$ [11]. This expected strong improvement is possible because the previous experiment was limited only by statistics. Furthermore the achieved momentum resolution of the SINDRUM tracking system (4.2 % in σ) leaves space for a large improvement. Indeed the Mu3e experiment, based on a silicon tracker, 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 10^{-16} sensitivity region a DC positive muon beam delivering 10^9 muons/s is required. Currently there are no such (pulsed or DC) high-intensity muon sources available in the world. A feasibility study for a DC muon beam aiming at 10^{10} muons/s (more than what is required by Mu3e to cover other physics programmes) is undergoing at PSI.

The $\mu^+ \rightarrow e^+e^+e^-$ decay signal is defined by its final state: two positrons and one electron without any additional neutrinos. The muons are stopped in the target. 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. Any background to the signal comes from internal conversion and accidental processes that mimic the signal. The main background source is given by the $\mu^+ \rightarrow e^+e^+e^-\nu\overline{\nu}$ decay. In order to reject that a very good energy resolution is requested (below 1 MeV/c on the reconstructed momentum sum resolution). 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 (200 μm) and time resolution (100 ps) are needed.

The proposed Mu3e detector is based on two double layers of High Voltage Monolithic Active Pixel Sensors (HV-MAPS) [12] 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 detector with two sets of re-curl stations for high intensity physics runs is shown in Fig. 1.

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