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A new experiment for the $\mu \to e\gamma$ search
Letter of Interest for Snowmass 2021

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Charged Lepton Flavour Violation provides a very clean environment to search for beyond the standard model physics. In the next few years, the MEG-II experiment will investigate the $\mu \to e\gamma$ decay down to a sensitivity of $6 \cdot 10^{-14}$. A next generation of $\mu \to e\gamma$ experiments at future high intensity muon facilities could further improve the sensitivity by at least an order of magnitude beyond MEG-II. In this letter of interest, we present a new experimental concept to search for $\mu \to e\gamma$ decay with a sensitivity of $\lesssim 10^{-15}$. Crucial element for achieving this goal is the innovative approach to the precise measurement of the ∼53 MeV photon by a sequence of high resolution photon spectrometers, each made of a thin layer of photon converter, followed by a few layers of scintillating fibres and an ultra-light drift chamber. The precise reconstruction of the converted electron-positron pair will result in a photon energy resolution of ∼0.6%, a factor 2 better that the current highly performing liquid-Xe calorimeter of MEG-II, as well as an excellent photon angular resolution. An ultra-light tracker, surrounding the stopping target and inside the converting photon spectrometers, precisely reconstructs momentum and angles of the fully contained positron tracks with a ∼90% geometrical acceptance.

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Charged Lepton Flavour Violation (CLFV) provides a very clean environment to search for physics beyond the standard model (BSM). These decays are extremely suppressed in the standard model due the small neutrino mass and the GIM mechanism, and an observation would be an unambiguous sign of new physics. The mass scales probed by current and future measurements [1], up to thousands of TeV, extend far beyond those directly accessible at high-energy colliders.

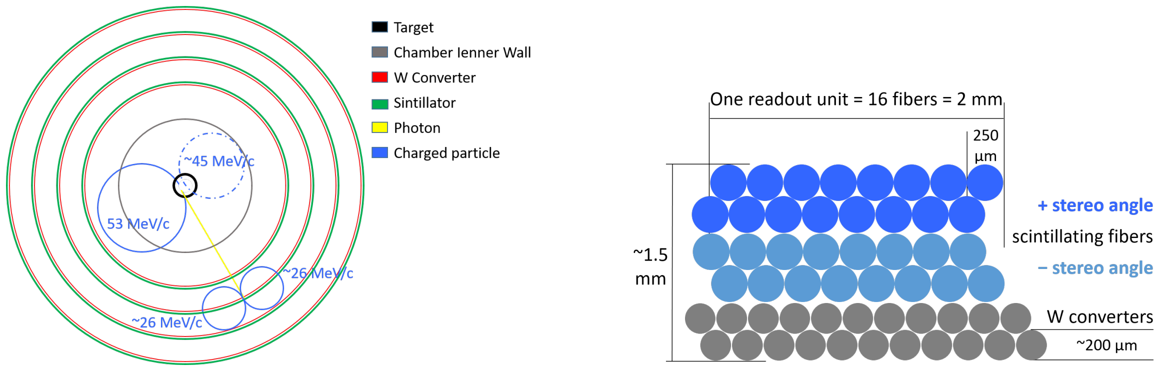
Searches for CLFV in the muon sector has been performed since the second half of the last century, investigating the neutrino-less $\mu^+ \to e^+\gamma$, the $\mu^- N \to e^- N$ and the $\mu^+ \to e^+e^+e^-$ processes. The MEG [2] and SINDRUM I/II [3, 4] experiments at Paul Scherrer Institute (PSI) have measured the current world best upper limits (at 90% of CL) of $4.2 \cdot 10^{-13}$, $7.0 \cdot 10^{-13}$ and $1.0 \cdot 10^{-12}$, respectively. A world wide effort is underway to improve these limits by orders of magnitude. The MEG-II experiment [5] at PSI (under commissioning) projects to reach a sensitivity of $\sim 6 \cdot 10^{-14}$ for $\mu^+ \to e^+\gamma$ decays, while the Mu3e experiment [6] at PSI (under construction) aims to probe limits of the order of 10^{-16} for $\mu^+ \to e^+e^+e^-$ decays. The Mu2e experiment [7] at Fermilab and the COMET experiment [8] at J-PARC are, both under construction, will search for $\mu^- \to e^-$ conversion with a single event sensitivity of $\sim 3 \cdot 10^{-17}$.

The MEG-II experiment will explore $\mu^+ \to e^+\gamma$ decays using state of the art of detection techniques, including a Liquid-Xe calorimeter to measure the energy, the time and the direction of the 52.8 MeV γ, and an ultra-light drift chamber assisted by scintillating counters to accurately and efficiently measure the momentum, the direction, the origin and the emission time of the positron. The main background arises from the accidental coincidence in the same time window of a photon and positron originating from different muon decays. A next generation of experiments at future high intensity muon facilities [9–11] could further improve the $\mu^+ \to e^+\gamma$ sensitivity by several orders of magnitude. However, no experimental concept beyond MEG-II have been proposed so far.

The factors limiting the search of $\mu \to e\gamma$ decays have been studied in Ref. [12]. The overall performance of the MEG-II tracking system, a signal reconstruction efficiency of $\sim 70\%$, a momentum resolution of $\sim$110 keV/c and an angular resolution of $\sim$5 mrad, should still be adequate to improve the sensitivity by an order of magnitude. However, exploiting a muon stopping rates up to $10^{10}\mu$/s would require to improve the rate capability of the innermost tracking layers up to the level of $\sim$MHz/cm^2. A possible solution could be to use a He based drift chamber with drift cells ($\sim$ 6 mm wide) disposed orthogonally with respect to the beam axis. Assuming a B-field of 1T and the overall dimensions of the MEG-II drift chamber, the innermost cells will at most 40 cm long, so that particle fluxes of $\gtrsim$200 kHz/cm^2 are sustainable with a total collected drift time of 200 ns, although aging may limit the optimal gas amplification. The material budget amounts to $\sim 2 \cdot 10^{-5} X/X_0$ per single cell, so that a track hitting 80 cells will cross approximately the same amount of material as in the MEG-II tracker (new wire materials, currently under investigation, may further reduce this value). The main issue is related to the non-uniform distribution of the support material and readout electronics in the volume before the photon spectrometer, potentially degrading the measurement. We plan to investigate the construction feasibility of such a design, together with other possible tracking technologies.

On the other hand, the calorimetric approach to identify and measure the 52.8 MeV photon cannot be used at muon stopping rates $\gtrsim 5 \cdot 10^8 \mu$/s and only a limited improvement in the sensitivity is foreseeable [12]. An alternative way is based on the photon conversion in electron-positron pairs and in reconstructing the low energy tracks created. The MEGA experiment [13] used two photon spectrometers made of a lead foil of 0.045 X_0 equivalent thickness preceded by a scintillator layer for timing and followed by 4 layers of drift cells to measure the emerging charged tracks. They were able to reach a photon energy resolution of $\sim$ 1.7 MeV, an angular resolutions on the aperture angle between the positron and the photon of 35 mrad, a resolution on the photon direction of 180 mrad, and a resolution of the time difference between the photon and positron of 1.6 ns. Applying the same approach to modern detector technology [10, 14], it should be possible to reach resolutions of $\sim$ 300 keV, $\lesssim$ 8 mrad, $\sim$ 5 mrad and $\gtrsim$ 50 ps, respectively. The main challenge consists of maximizing the photon conversion and low-momentum electron/positron reconstruction efficiencies. In this LOI, we propose an experiment with large photon conversion probability ($\sim$ 50%) and geometrical acceptance ($\sim$ 90%), together with a photon energy resolution better than 350 keV. The experimental concept is sketched in fig. 1(a).

A central low mass tracker system (a drift chamber and, eventually, a vertex detector) surrounds the



(a) (b)

Figure 1. Sketch of: a) the layout of a possible experiment for the $\mu \to e\gamma$ search; b) the layout of a possible construction strategy of the photon conversion layer.

stopping target. The inner and outer radii of the tracker are chosen to cut off all the positron tracks with momenta <45 MeV/c, and fully contain those with momenta of 52.8 MeV/c. Assuming a magnetic filed similar to that of MEG-II, the inner and outer radii are 20 cm and 30 cm, respectively. The tracker is surrounded by a sequence of co-axial cylindrical photon spectrometers. Each photon spectrometer can be made by using tungsten (W) wires to create a thin, $\sim 0.1X/X_0$, conversion layer followed by a layer of scintillating fibers[1] (see fig. 1(b)) to measure the conversion time and vertex, and by some layers of a light, highly granular drift chamber to precisely measure the track parameters of the $e^+ - e^-$ pair. A possible construction strategy could be to insert the radiator shells in the drift chamber volume, without creating dead regions, by placing bundles of W wires at the same stereo angle as the drift chamber layers. A layer of 250 μm diameter scintillating fibers with the same stereo orientations could be placed immediately after the converter shell in two close-packed layers for triggering the photon conversion and defining an approximate position of the conversion point. A sufficient number of alternating sign stereo layers (about 12-16) of $\sim$ 1cm square drift cells can be located between two radiator shells in order to efficiently and precisely reconstruct the looping electron-positron pairs, each producing several dozens of hits. Assuming a magnetic field of 0.6-1 T, about 10 photon spectrometer modules could be located in a volume of 2.5-3 m radius. Using the construction technique of the MEG-II drift chamber [5], a spectrometer with a total length of ~3 m should be feasible. Preliminary Geant4 simulations show that this detector will allow to obtain resolutions of the order of 300 keV on the photon energy, $\sim 500\mu$m on the transverse and ~2 mm on the longitudinal position of the photon conversion vertex, and a time resolution better than 150 ps. Moreover, this tracking-based method provides also the measurement of the photon direction, unlike a homogeneous calorimeter where only the shower impact point is measured, thus further reducing the accidental background.

Assuming an acquisition time equivalent to the one of MEG-II, the expected sensitivity has been evaluated with a toy Monte Carlo method based on the calculation done in Ref. [12]. The expected sensitivity of the proposed design, with very conservative assumptions, is at the level of $3 \cdot 10^{-15}$, outperforming the calorimetric approach. An improvement by a factor of 3 could be envisioned with a better vertex performance and a muon stopping rates of $\sim 10^9 \mu$/s. By exploiting the potential of the PIP II at Fermilab, as well as increasing the accidental background rejection and optimizing the photon reconstruction strategy, branching fractions down to $\mathcal{O}(10^{-16})$ could be within reach.

[1] Using fast Si sensors for the photon converter will be considered too.

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