PROCEEDINGS OF SCIENCE

Future $\mu \to e\gamma$ experiments

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Experiments with muons are a unique window to investigate the Standard Model of particle physics and to look for New Physics effects with high sensitivity. The search for the lepton flavor violating $\mu^+ \to e^+\gamma$ decay will reach a sensitivity of few 10^{-14} within the next three years thanks to the MEG II experiment, presently taking data at the Paul Scherrer Institut, with a beam intensity of 4×10^7 muons/s. On the other hand, there is a world-wide effort to increase the muon beams intensity at present facilities by a factor 100. In order to exploit such intense muon beams a new generation of experiments has to be designed, since the present experimental concept is not adequate to deal with the expected increase in rate, radiation and background. An international study group has been recently set, the Study Group for Future $\mu \to e\gamma$ search experiments, to organize this effort. This paper reviews the present main experimental directions identified, the results of simulations and R&D studies made so far.

Muon4Future Workshop (Muon4Future2023)
29–31 May, 2023
Venezia, Italy

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PoS(Muon4Future2023)025

1. Introduction

The study of the flavor sector of the Standard Model (SM) of particle physics plays a crucial role in the search of New Physics (NP) effects. Lepton flavor conservation is associated to an approximated symmetry of the SM due to the tiny neutrino mass, while charged lepton flavor violation (CLFV) processes are allowed only at extremely low branching ratios (BR <10^{-55}). As a consequence, these processes are ideal, background free probes to explore NP effects, complementary to direct searches at LHC and HL-LHC. Indeed, many theoretical extensions of the SM allows for sizeable CLFV effects. A global experimental program of muon CLFV searches is underway in the US, Europe and Asia. By 2026 the MEG II experiment [1], now in the data-taking phase, will reach a sensitivity of few 10^{-14} on the BR of the CLFV decay $\mu^+ \to e^+\gamma$, improving by one order of magnitude the sensitivity of the previous MEG experiment, which set the present best world limit [2]. Impressive sensitivity gains up to four orders of magnitude improvements are expected in this decade in the $\mu^- N \to e^- N$ conversion and $\mu^+ \to e^+e^-e^+$ searches at the Mu2e [3], Comet [4], Mu3e [5] experiments. At the same time, the muon scientific community proposed an upgrade of the present facilities to get more intense muon sources, up to 10^{10}, 10^{11} muon/s [6, 7], about a factor 100 more than presently available sources, which will enable broad muon science with unprecedented sensitivity. To exploit this opportunity, new experiments have to be designed, since future higher particle-rate environments require reducing the occupancy by minimizing the detector granularity, while reduction of material budget and radiation hardness are also prerequisites. This paper focuses on future $\mu^+ \to e^+\gamma$ experiments. In order to organize efforts for the next generation of such experiments, and to identify synergies with other R&D efforts, a group has been setup, the Study Group for Future $\mu \to e\gamma$ Search Experiments, composed by about thirty people from the MEG II and Mu3e collaboration, and some R&D activity is already on-going.

2. Beam requirements

Positive muon beams are used for rare decay searches, to avoid deformation of energy spectrum due to nuclear capture of negative muons. Moreover, very intense muon beams are needed with a continuous time structure, which minimizes the accidental time coincidence of decay products from different muon decays. Muons must be stopped in a thin target, to avoid material effects that spoil momentum and angle resolution, so low energy muons are used. As an example, MEG II uses muons from pion decays at the proton target surface, with a momentum of 28.5 MeV/c^2. Muons are subsequently slowed down in a degrader and can be stopped in a thin target (hundred microns of plastic material) which fully contains the Bragg peak due to the small range straggling. As an alternative, it would be possible to stop only a fraction of the beam in the thin target, but that would introduce the complication of having the detector in vacuum, to avoid interactions of particles in the region surrounding the target itself.

3. Signal and backgrounds

In $\mu^+ \to e^+\gamma$ searches, the core of the design is the muon decaying at rest, so to have the clear experimental signature of a two body decay. The positron and the photon have an energy equal to half of the muon mass, are back-to-back and coincident in time. There are two sources of background events. One is the radiative muon decay $\mu^+ \to e^+\gamma\nu_e\bar{\nu}_\mu$, when the positron and the photon are emitted almost back-to-back. The other, which is dominant, is due to accidental coincidence, in the same acquisition window, of a positron from a muon decay and a photon from the radiative decay of another muon, annihilation in flight or the bremsstrahlung from a positron. Among the present CLFV experiments, the most critical with respect to accidental background is MEG II, since the photon reconstruction cannot provide the resolution necessary for an effective two-particle vertexing. To separate the signal from the background, four discriminating variables are used: the positron energy E_e, the photon energy E_γ, the relative angle $\Theta_{e\gamma}$ (often the two projections are used, $\phi_{e\gamma}$ e $\theta_{e\gamma}$) and the relative times between the two particles, $T_{e\gamma}$.

The number of accidental background events (B_{acc}) that falls in the signal window depends on the experimental resolutions on the above variables and on the beam intensity. An empirical formula is given by:

$$B_{acc} \propto R_\mu^2 \delta E_e \delta E_\gamma^2 \delta\Theta_{e\gamma}^2 \delta T_{e\gamma}, \tag{1}$$

where R_μ is the muon beam rate and δ indicates detector resolution on the different variables.

The dependence of B_{acc} on the beam rate is quadratic while the number of signal events (S) increases only linearly with it. As a consequence, the sensitivity of the search, i.e. the 90% Confidence Level limit that can be set on the $\mu^+ \to e^+\gamma$ branching ration by the experiment if no signal is found, becomes constant at high beam rates, at fixed detector performances (the sensitivity can be approximated as $\frac{S}{\sqrt{B_{acc}}}$). For a given detector, there is an optimal beam intensity which maximises the sensitivity and there is not further improvements in increasing it, unless if detector resolutions are improved. Increase of beam intensity by a factor 100, as expected at future facilities, requires thus an adequate improvement of detector performances, together with high rate capability.

4. Future $\mu \to e\gamma$ experiments

4.1 Positron detector

Magnetic spectrometers with tracking detectors are the optimal solution to detect the signal positron, which has a momentum of 52.8 MeV/c^2, providing very good energy and angle resolutions. In this momentum range the interactions with the material (multiple Coulomb scattering, energy loss) in the target region and in the detector can significantly spoil the measurement, so a light tracker must be used. Up to now, gaseous detectors have been used, e.g. MEG II uses a ultra-light cylindrical drift chamber [1]. In MEG II, now running at a beam intensity of $4{\times}10^7$ muon/s, the rate in this detector is up to 1 MHz per wire, already limiting its performances. Drift chambers, MultiWire Proportional Chambers (MWPCs) and Time Projection Chambers (TPCs) provide excellent hit resolution with low material budget but their use at very intense beam is problematic due to low granularity and being prone to ageing. New solutions are currently under investigation to obtain a new design that can simultaneously provide high resolution (at least the same as MEG II, about 100 keV in momentum, few mrad in angles), to minimize the accidental background, and high rate tolerance.

One direction of investigation is to consider alternative geometries for traditional detectors.

One proposal is to build a drift chamber with a transverse geometry. In this configuration wires are transverse to the beam direction and are shorter, so to reduce the hit rate per wire. The challenge here is that the supports for the wires should be light and no electronic can be placed in the tracking volume, so long transmission lines are needed for high voltage and signals.

Another possibility is a radial TPC. From the detector choice point of view, TPCs readout by multi pattern gaseous detectors are light detectors (only gas in the active volume) and have been proved to have high pile-up and rate capabilities. The intrinsically low ion feedback with this kind of readout allows operations without a triggered ion grid, while a high granularity is possible. In a traditional geometry at fixed target experiments or colliders, the detector is cylindrical, and electrons drift along the axis of the cylinder toward the readout electrodes placed at the endplates. On the other hand, in a radial geometry electrons drift in the radial direction, which allows to collect hits in a shorter time while the shorter ion drift times suppress space charge density. Moreover, the shorter distance traveled by the drifting electrons allows to keep diffusion small even in helium-based gas mixtures, thus preserving both good space resolution and very low material budget. Simulations are on-going and preliminary results show that sustainable rates are reached (1.2 MHz/pad), for a 2 m long radial TPC with pad readout (size equal to 5 x 3 mm^2), 30 cm radius with 10 cm radial extension, at a beam intensity of 10^9 muon/s. Challenges of this design are the front-end electronic integration and cooling in the outer surface of the cylinder, and field deformation corrections to preserve resolutions.

Other ideas circulating in the community are related to the use of transverse drift tube á *la* Mu2e, new material for drift chamber wires and new gas mixtures less prone to ageing.

In a different approach, a silicon detector á la Mu3e can be used with very high rate capability. In this case the material budget is a concern and momentum resolution can be slightly worse with respect to gaseous detectors, while the finite sensor thickness determines the positron angular resolution. Next generation of HV-MAPS, thinned down to 25 μm, will allow to fill the gap with gaseous detectors. Preliminary studies show that with an appropriate choice of the detector geometry and a strong magnetic field momentum resolution of less than 80 keV/c can be reached.

In all the above cases a faster detector should be added, to provide the required positron time resolution. MEG II uses a scintillating pixel detector [1], with a single counter resolution of about 40 ps.

4.2 Photon detector

Two different approaches have been used so far to detect the photon for $\mu^+ \to e^+\gamma$ searches: the calorimetric approach and the pair conversion approach.

Calorimeters have high efficiency and good resolution, but offer moderate rate capability. On the other hand, photon conversion spectrometers have low efficiency (order of few %) which is compensated by an extreme energy resolution. In addition, the resolution on the photon direction reconstruction allows the measurement of the positron-photon vertex, which provides additional background discrimination. It can be shown [8] that usually a calorimetric approach is more convenient at moderate beam rates, while pair conversion approach overwhelms the calorimetric at very high beam rates, where resolution is more important than efficiency.

The MEG II experiment uses a large liquid Xenon calorimeter with 10% geometrical acceptance, due to cost and complexity constraints, currently operating at the limit of its rate capability at a beam intensity of 4×10^7 muon/s.

For higher beam intensity, innovative fast crystals with high light yield look promising, even if also in this case cost and procurement can be an issue. The case of the LaBr3(Ce) has been studied [8] and it turned out that 800 keV resolution is within reach with an adequate time resolution (30 ps). Another promising crystal is LYSO, and simulations have been performed for a LYSO crystal matrix with front and back MPPC/SiPM readout. The expected performances in energy, time and position resolutions are 1.7%, 35 ps, 5-6 mm respectively. R&D phase is currently starting at PSI where the first large prototype is under construction.

In the photon conversion approach the photon is converted in a e^+/e^- pair in a converter layer and the e^+/e^- energy and time are measured in a tracking and a timing layer; multiple layers are usually stacked to optimize the performances. Target performances are about 0.4% and 30 ps, in energy and timing resolution, and in the last years a significant effort has been made to understand the potential performances. There are different possibilities for detectors to be used in the tracking layer as drift chambers, radial TPC and silicon detectors. In the case of a gaseous tracking layer the rate requirement is less stringent than for the signal positron, but drift chambers are difficult to fit in this design. The TPC case with strip readout is currently under investigation. Silicon pixel stations can be used as tracking detectors and a configuration with three Silicon layers has been proposed, where the first layer acts as active converter and the subsequent two as tracking layers, providing also timing information. An active converter can be used to measure the energy loss of the conversion pair, thus improving resolution. Scintillator materials can be used and simulations show that four layers of LYSO crystals (3 mm thick) provide about 10% efficiency, while the expected energy resolution for LYSO read-out by SiPM is 140 keV (considering only photoelectron statistics), without taking into account the effect of pile-up hits of the returning e^+/e^- in the crystal itself. Active converter can also measure time. A beam test has been performed at KEK laboratory in Japan with standard LYSO and fast-LYSO crystals (with size 3x5x50 mm^3) read out by SiPM on both sides. A 40-50 ps resolution has been obtained, using fast LYSO. The use of a multi-layer RPC has been proposed for the timing layer, exploiting the technology under study for the MEG II upstream radiative decay counter [1]. The diamond-like carbon technology has been developed and a time resolution of 110 ps has been obtained for a single layer RPC, with the possibility of further optimization with a thinned gap and many layers.

4.3 Sensitivity reach

As an example a possible layout of a $\mu^+ \to e^+\gamma$ experiment is shown in Fig.1, with a positron spectrometer á la Mu3e, a pair conversion spectrometer, multiple active targets [9]. In this configuration the angular acceptance is significantly improved over MEG II, allowing for measurement of angular distribution in case of discovery, thus providing insight of NP nature.

Sensitivity studies mostly based on simulations have been performed [8], and a sensitivity of 10^{-15} seems reachable with 3 years of data-taking, running at a beam intensity of 10^9 muons/s. Updated sensitivity estimates can be performed on the basis of the ongoing R&D studies.

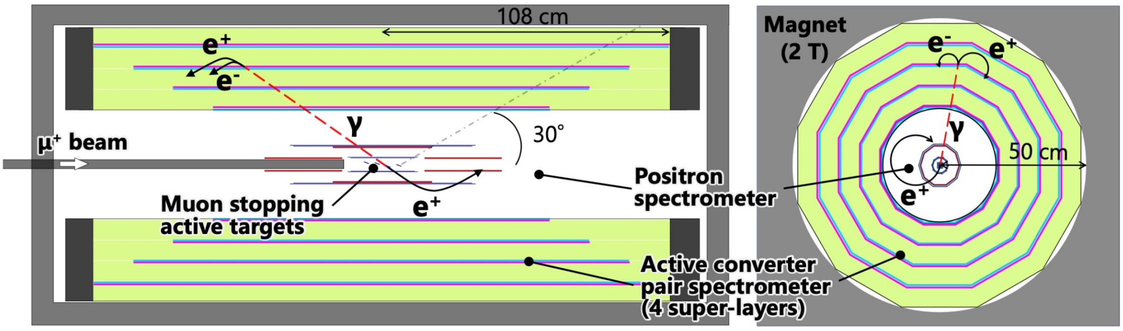

Figure 1: The possible layout of a $\mu^+ \to e^+\gamma$ experiment based on a silicon positron tracker and a photon conversion detector.

5. Conclusions

In conclusion, future facilities will make available intense muon beams, opening a window of opportunity for new $\mu^+ \to e^+\gamma$ experiments that will push the sensitivity or study the decay in case of discovery, thus providing insight into the nature of NP. A new experimental concept is needed to overcome the experimental challenges presented by such high intensity and an international study group has been constituted. Different R&D directions have been identified that will be investigated in the next years.

References

[1] Baldini A. et. al., The design of the MEG II experiment, Eur. Phys. J. C (2018) 78:380.

[2] Baldini A. et al., Search for the lepton flavour violating decay $\mu^+ \to e^+\gamma$ with the full dataset of the MEG experiment, Eur. Phys. J. C 76 (2016) 8:434.

[3] Abrams R.; et al., Mu2e Conceptual Design Report. arXiv 2012, arXiv:1211.7019.

[4] Abramishvili R. et al., COMET Phase-I Technical Design Report. Prog. Theor. Exp. Phys. 2020, 2020, 033C01.

[5] Arndt K et al., Technical design of the phase I Mu3e experiment. arXiv 2021, arXiv:2009.11690.

[6] Aoki M. et al., A new charged lepton violation program at Fermilab, arXiv: 2203.08278.

[7] Aiba M. et al., Science Case for the new High-Intensity Muon Beams HIMB at PSI, arXiv:2111.05788.

[8] Cavoto G. et al., The quest for $\mu \to e\gamma$ and its experimental limiting factors at future high intensity muon beams, Eur. Phys. J C (2018) 78:37.

[9] Corrodi S. et al , Workshop on a future muon program at FNAL, arXiv 2309.05933.