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Experimental limiting factors for the next generation of $\mu \to e\gamma$ searches

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The search for the Lepton Flavor Violating decay $\mu^+ \to e^+\gamma$ will reach an unprecedented level of sensitivity within the next five years thanks to the MEG-II experiment. This experiment will take data at the Paul Scherrer Institut where continuous muon beams are delivered at a rate of about 10^8 muons per second. On the same time scale, accelerator upgrades are expected in various facilities, making feasible to reach an intensity of 10^9 or even 10^{10} muons per second. We investigate the experimental limiting factors which will define the ultimate performances, and hence the sensitivity, in the search for $\mu^+ \to e^+\gamma$ with these extremely high beam rates. We then consider some conceptual detector designs and evaluate the corresponding sensitivity as a function of the beam intensity.

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1. Introduction

Flavor conservation in the charged lepton sector is an accidental symmetry of the Standard Model (SM), not related to the gauge structure of the theory but only due to the specific particle content of the model. Indeed, neutrino oscillations are expected to produce charged Lepton Flavor Violation (cLFV) processes, but the expected rates are far from being observable. On the other side, cLFV is expected at some extent in most of the New Physics (NP) extensions of the SM, and in most cases effects within the experimental reach of present or next future's experiments are predicted. The search for cLFV processes is then proficient because it allows to strongly constrain the NP models if limits are set, and it gives an unambiguous evidence of new physics if an observation is made.

In the last decade the MEG experiment [1] at PSI set the most stringent limit on the $\mu^+ \to e^+\gamma$ decay, $BR(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$, and the experiment currently undergoes an upgrade process which should improve its sensitivity by one order of magnitude [2]. In the meanwhile, efforts are on going [3, 4, 5] to deliver continuous muon beams with higher intensity for this kind of searches. We present here a study of the experimental factors which will limit the sensitivity of future searches for $\mu^+ \to e^+\gamma$ with such high muon beam reates.

2. Basics of the $\mu^+ \to e^+\gamma$ search

The $\mu^+ \to e^+\gamma$ decay is searched for by exploiting the decay at rest of muons form a high intensity beam stopped in a thin target. It allows to exploit the two-body decay kinematics for rejecting the background, coming from the radiative muon decay (RMD) $\mu^+ \to e^+\nu_e\overline{\nu}_\mu\gamma$ and from the accidental coincidence of a positron and a photon from two different muon decays. In particular, the positron energy E_e, the photon energy E_γ and the relative angle $\Theta_{e\gamma}$ are used to reject both backgrounds, while the relative time $T_{e\gamma}$ allows to further suppress the accidental background, which already gives the dominant contribution at the high muon rates presently available.

Hence, an experiment for the $\mu^+ \to e^+\gamma$ search should include positron detectors with tracking and timing capabilities, and a photon detector with good energy, position and time resolutions. It is important to notice that the accidental background rate is expected to scale with the resolutions according to [6]:

$$B_{\text{acc}} \propto \Gamma_\mu^2 \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot \delta T_{e\gamma} \cdot (\delta\Theta_{e\gamma})^2 \tag{2.1}$$

where Γ_μ is the muon stopping rate. The scaling with Γ_μ^2 implies that, if a significative number of background is expected over the experiment life, a further increase of the beam rate is useless, because the $S/\sqrt{B}$ ratio would remain constant. The beam rates used in the MEG experiment (3×10^7 μ/s) and its upgrade (7×10^7 μ/s) are optimized accordingly. The use of higher beam rates would require a significative improvement of the experimental resolutions.

Here we come to the choice of the detector technology to be used. On the positron side, a magnetic spectrometer with fast detectors at the end of the particle's trajectory allow to measure the kinematical variables with the best resolution with very high efficiency. Conversely, on the photon side, two alternative solutions can be considered: the calorimetric approach gives high efficiency and good resolutions; the conversion of the photon into an e^+e^- pair, tracked within a spectrometer, gives the best resolutions but is limited by a very low efficiency. In a low muon rate scenario, where

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the accidental background yield can be kept $<< 1$, the high efficiency of the calorimetric approach gives the best sensitivity. If the muon rate increases and the accidental background yield starts to be significative, it can be proficient to improve the resolutions with a photon conversion approach, even if it implies a large loss of efficiency.

Schematic views of typical detectors for the $\mu^+ \to e^+\gamma$ search with a calorimetric or photon conversion approach are shown in Fig. 1.

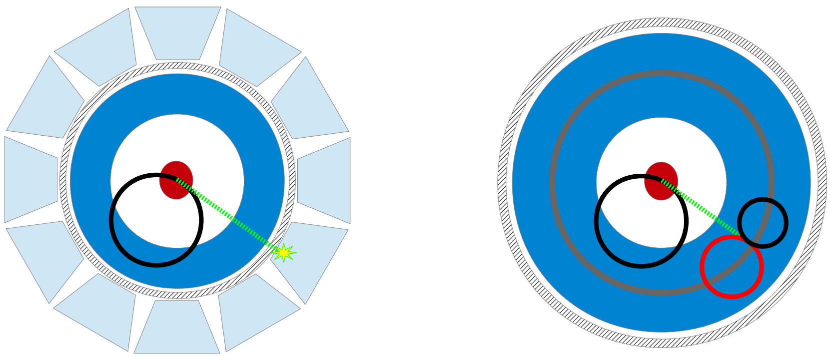

Figure 1: Conceptual detector designs exploiting the calorimetric (left) or conversion (right) technique for the photon detection, and a tracking approach in a magnetic field for the positron reconstruction. Muons are stopped in a target (dark red ellipse) at the center of the magnet. Positron tracks from the muon decays (in black) are reconstructed in a tracking detector (dark blue), photons (in green) either produce a shower in a calorimeter (light blue) or are converted by a thin layer of high-Z material (in gray) into an electron-positron pair (in red and black, respectively) which is then reconstructed by an outer tracking detector. The magnet coils (hatched area) surround the tracking detectors.

3. The next generation of high intensity muon beams

Efforts are on going around the world to deliver muon beams with an intensity of 10^9 to 10^{10} muons per second, which is one to two order of magitude larger than what will be used in the MEG upgrade.

Muon beams are produced by the decay of pions in a production target exposed to a high intensity proton beam.

At PSI, Switzerland, the High-intensity Muon Beam (HiMB) project [3] will exploit a higher muon capture efficiency at the muon production target and a higher transmission efficiency from the production target to the experiment, thanks to a new design of the muon capture magnets and beam optics. The goal is to reach a beam rate of 10^{10} muons per second.

At RCNP, in Japan, the MuSIC project [4] will use a thick muon production target surrounded by a pion and muon capture solenoid to maximally exploit the power of the incoming proton beam. Preliminary tests showed that 4×10^8 muons per second can be produced starting from a 400 W proton beam (to be compared with the 1000 kW of the PSI cyclotron).

Within the PIP-II project [5] at FNAL, the possibility of having a high intensity continuous muon beam has been also explored, and the facility could be competitive with HiMB.

4. Experimental limiting factors

The possible availability of muon beams with an intensity up to 10^{10} muons per second makes interesting the investigation of the experimental factors which will limit the sensitivity reach of an experiment for the search of $\mu^+ \to e^+\gamma$.

For what concerns the photon reconstruction, the two options discussed above (calorimetry and photon conversion) need to be considered.

1. In a calorimetric approach, an efficiency of 60% can be easily reached, like in MEG and MEG-II. It would be limited by the amount of material in front of the calorimeter (mainly the magnet of the positron spectrometer), where the photon can convert before reaching the detector. Among the different scintillating materials available on the market, $LaBr_3$(Ce) seems to be a promising candidate for future $\mu^+ \to e^+\gamma$ searches, thanks to the high light yield and the excellent time resolution. According to our simulations, cross checked against the result of a test with a small crystal, an energy resolution of about 800 keV and a time resolution of about 30 ps could be reached, both limited by the photon statistics. On the other hand, $LaBr_3$(Ce) crystals are very expensive and costs could limit the possibility of building a large-acceptance detector.

2. In a photon conversion approach, the performances will be limited by the interaction of the particles with the material of the converter (photon conversion probability, e^+ and e^- energy loss and multiple scattering). These effects are summarized in Fig. 2, where the conversion efficiency and the contribution to the resolution coming from the e^+e^- energy loss are shown, as a function of the thickness of a Lead converter. There is obviously no possibility of overcoming these limits with an improvement in the detector technologies. On the other hand, the reconstruction of the e^+e^- pair gives an information about the photon direction, which is not available in a calorimetric approach. It allows a rough determination of the photon production point on the target. So, the likelihood of the photon and positron to come from the same point can be exploited to suppress the accidental background. Our simulations show that $\sim 90\%$ of background events can be removed with a signal efficiency of about 50%.

On the positron side, the reconstruction in a magnetic spectrometer will be ultimately limited by the multiple Coulomb scattering in the detector. It makes gaseous detector the best candidate in terms of resolutions, while silicon detectors can be considered as a good option if gaseous detector would be found to be unusable at very high beam rates, due to aging effects and pattern recognition difficulties.

A dedicated discussion of photon and positron timing is also necessary. Timing plays a crucial role due to the necessity of suppressing the accidental background. In the MEG upgrade a time resolution of 80 ps is expected. A $LaBr_3$(Ce) calorimeter, combined with positron scintillating counters like in MEG would allow to replicate this kind of resolutions. For the photon conversion technique, it is necessary to include fast detectors on the trajectory of the e^+e^- pair. We considered the use of fast silicon detectors, like the ones developed for the TT-PET project [7]. Their small thickness (100 μm silicon on a 50 μm Kapton substrate) and their performances ($\sim$ 100 ps

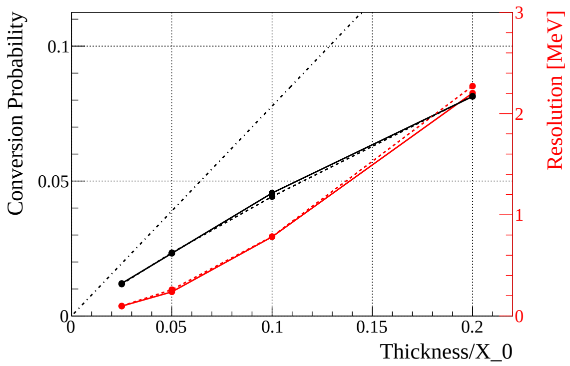

Figure 2: The conversion efficiency (black, left axis) and the contribution to the energy resolution from the energy loss in the converter (red, right axis), for Lead (full lines) and Tungsten (dashed lines), as a function of the converter thickness (in units of radiation length). The dash-dotted line shows the asymptotic conversion probability, $7/9$ times the thickness in units of radiation lengths.

resolution for a single detector layer) would give the required resolution and allow to stack several conversion layers with a small deterioration of the e^+e^- reconstruction.

5. Sensitivity Reach

We consider here a few scenarios where reasonable detector performances, from incremental technological progresses with respect to the present situation, are summed to the limiting factors described in Sec. 4. We consider either a calorimetric or photon conversion approach (with one or more conversion layers) for the photon reconstruction, while a magnetic spectrometer with gaseous detectors is considered for the positron tracking. We also investigate the advantages of having a small TPC as a positron vertex detector, in order to improve the angular resolutions. In an optimistic

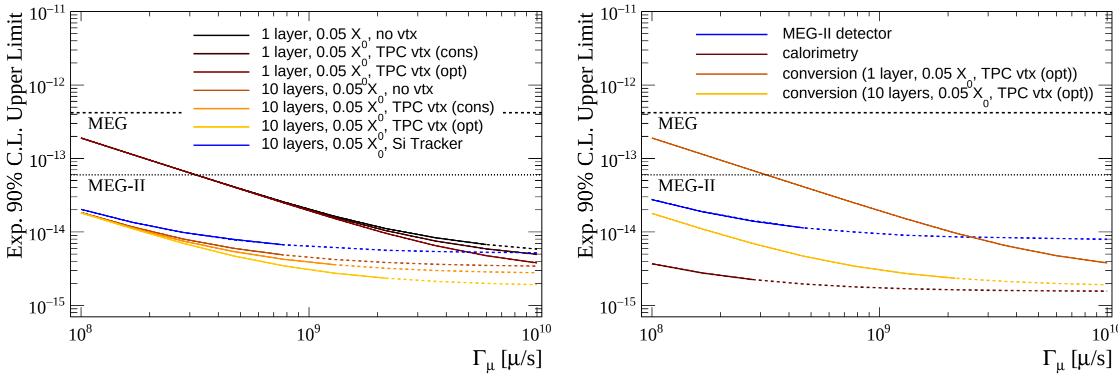

Figure 3: Expected 90% C.L. upper limit on the Branching Ratio of $\mu^+ \to e^+\gamma$ in different scenarios for a 3-year run. Left: a few different designs based on the photon conversion technique are compared, including the TPC vertex detector option in the conservative and optimistic hypotheses. Right: Calorimetry and the photon conversion technique are compared. The lines turn from continuous to dashed when the number of background events exceeds 10. The horizontal dashed and dotted lines show the current MEG limit and the expected MEG-II sensitivity, respectively.

scenario, this detector allows to eliminate the tracking contribution to the angular resolutions. In a conservative scenario, the only advantage comes from having the first measured point nearer to the muon decay point. In the best scenario, we also consider the use of a silicon tracker instead of gaseous detectors for tracking. Fig. 3 shows the expected sensitivity reach as a function of muon beam rate, for a 3-year data taking period.

With 10^9 muons per second, a sensitivity of a few 10^{-15} could be reached, but there are poor perspectives of going below 10^{-15} even with 10^{10} muons per second. Below 5×10^8 muons per second, the calorimetric approach needs to be used in order to reach this target. If a muon beam rate exceeding 10^9 muons per second is available, the much cheaper photon conversion option would be recommended and would provide similar sensitivities.

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