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# The search for lepton flavour violation with the MEG II experiment

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Lepton flavor violation in the charged lepton sector (cLFV) is expected to be unobservably small in the Standard Model (SM). On the other hand, many new physics theories predict rates of cLFV near the sensitivity of the current experiments. Hence, this is a very sensitive probe for physics beyond the SM, and the evidence for such new physics would be unambiguous if a positive observation is made. The MEG II experiment is searching for the cLFV decay $\mu \to e\gamma$ with a sensitivity below $10^{-13}$ on its branching ratio, a factor 10 better than the phase-1 MEG experiment. The construction and commissioning of MEG II have been completed and the first physics data have been collected in 2021. I will discuss the performance of the experiment, the status of the data analysis and the perspectives for the upcoming years.

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## 1. Introduction

Muon decays have been for many years and are still now an extremely powerful probe for investigating the foundations of particle physics [1]. The search for lepton flavor violation (LFV) in charged muon decays started already in the pioneering era of particle physics, with the work of Hincks and Pontecorvo [2], and accompanied the development of the Standard Model (SM), bringing over time to the introduction of the concept of lepton families and pointing toward the existence of three different neutrino species. More recently, the quest for LFV became one of the most promising tools to search for New Physics (NP) beyond the SM, thanks to the accidental nature of lepton flavor conservation in the SM. That symmetry is a mere consequence of the absence of right-handed neutrinos, it is not relied to the gauge structure of the theory, and it is consequently violated by most extensions of the SM. In particular, the introduction of additional fields in NP models at the multi-TeV scale typically generates lepton flavor violation rates high enough to be observed by state-of-the-art experiments. From a different point of view, the experiments searching for these processes strongly constrain already the development of most NP models.

Strictly speaking, LFV has been already observed in the form of neutrino oscillations. It indicates that the SM has to be modified, in the lepton sector, to accomodate such effects but, at the same time, the LFV rates for charged leptons directly induced by neutrino oscillations are prediceted to be unobservably low.

All these features make LFV muon transitions an extremely powerful and, at the same time, a very clean probe for NP. The most interesting processes are the $\mu \to e\gamma$ and $\mu \to eee$ decays and the $\mu \to e$ conversion in the Coulomb filed of a nucleus. At the lowest order in effective field theories, the latter two can be seen either as an extension of the former, where the photon is virtual, or independent processes produced by 4-fermion operators. In the first case, experiments searching for $\mu \to e\gamma$ gave so far the most stringent constraints. In the second case, the new operator can generate $\mu \to e\gamma$ only at loop level and experiments searching for $\mu \to eee$ and $\mu \to e$ conversion tend to be more sensitive. Going beyond this naive view, it becomes evident [3] that the relative sensitivity of the different experiments strongly depends on the flavor structure of the NP model. It makes the different efforts strongly complementary, and it is crucial to carry on all of them to increase the discovery potential and, if an observation is done, to discriminate among different models.

## 2. The search for $\mu \to e\gamma$

The $\mu \to e\gamma$ decay can be searched by looking for photon-positron pairs produced in the decay of positive muons stopped in a thin target. The kinematical constraints imposed by the two-body kinematics allow the signal to be separated from the large background coming from the accidental coincidence of a positron and a photon produced in two different muon decays. This is the dominant background when the experiment is performed at very high-intensity muon beams, as the ones available at the Paul Scherrer Institute (PSI, Villigen), where rates above $10^8 \mu$/s can be reached. For the same reason, continuous beam are preferred over pulsed beams, while positive muons are used to avoid their capture by the target nuclei, that would screw up the kinematics of the decay. Another source of background comes from the radiative muon decay (RMD )$\mu^+ \to e^+\overline{\nu}_\mu \nu_e \gamma$, whose contribution is anyway subleading at high beam intensities and can be also discriminated by kinematical requirements.

Based on the signal and background topologies, an experiment looking for the $\mu \to e\gamma$ decay should be able to reconstruct the direction and energy of positrons and photons, that are expected to be emitted back-to-back at 52.8 MeV, along with their relative time $T_{e\gamma}$, which allows accidental coincidences to be strongly suppressed.

The MEG experiment [4, 5] at PSI set the best limit on the branching ratio (BR) of $\mu \to e\gamma$, $BR(\mu \to e\gamma) < 4.2 \times 10^{-13}$ at 90% confidence level. It is worth noticing that, due to its accidental origin, the dominant background scales as the square of the beam intensity. As a consequence, if the experiment is expected to observe a significant background yield over its lifetime, the sensitivity of the experiment (scaling in this case as $S/\sqrt{B}$, being $S$ and $B$ the signal and background yields) is independent of the beam rate. Consequently, it is convenient to not exceed a beam rate producing an almost zero-background condition. Given the efficiencies and resolutions of the MEG experiment, the muon stopping rate was set to $3.3 \times 10^7$ $\mu$/s.

## 3. The MEG II experiment

The MEG detector underwent an upgrade of all subdetectors and their readout electronics, and further detectors were added to reduce specific sources of backgrounds and systematic uncertainties. The MEG II experiment [6] is composed of a liquid Xenon calorimeter (XEC) for the detection of the photon, a magnetic spectrometer with a cylindrical drift chamber (CDCH) for positron tracking and a set of scintillator tiles (Timing Counter, TC) for positron timing. A forward detector (Radiative Decay Counter, RDC) was added to detect low-energy positrons produced in coincidence with high-energy photons reconstructed in the calorimeter, indicating that the latter come from a RMD and not from $\mu \to e\gamma$. The experiment is sketched in Fig. 1.

The CDCH is a drift chamber with 9 layers of 20 $\mu$m gold-plated tungsten anodes and 40/50 $\mu$m silver-plated aluminum cathodes [7]. A full-stereo geometry was deployed, with cells in two consecutive layers oriented with an opposite angle (going from 6 to 8.5 degrees, from the inner to the outer layers) with respect to each other. The square cells have a minimum side length of about 7 mm in the central part of the innermost layer. The small size of the cells, which is necessary to keep acceptable occupancy and aging rate, combined with the requirement of an extremely low material budget to track low-momentum positrons, drove the choice of the very thin aluminum wires, that were reveled to be extremely sensitive to corrosion and consequently very fragile when kept under stretching in environments with normal air humidity conditions [8]. A careful control of humidity during the CDCH wiring, overstretching the chamber for a few hours to induce a breaking of the most fragile wires, and keeping the chamber under dry gas flow when fully wired allowed the construction of the chamber to be completed and its operations to be conducted without any wire breaking in 2021 and 2022.

The chamber is placed inside a superconducting solenoid producing a graded magnetic field, going from 1.3 T at the center of the magnet to 1 T at 1 m from the center. This configuration was adopted to allow positrons emitted almost orthogonally to the beam axis to be expelled from the spectrometer after only a few turns inside him. Thanks to a single-hit resolution below150 $\mu$m [9], the drift chamber provides a momentum resolution better than 100 keV for 52.8 MeV positrons.

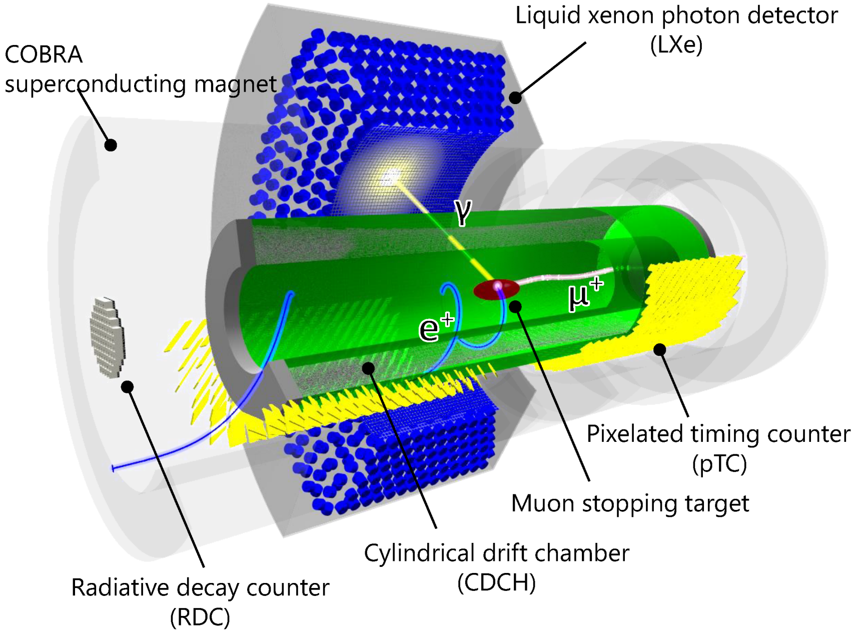


**Figure 1:** A schematic view of the MEG II experiment

The resolution on the muon decay vertex, defined as the intersection between the positron track and the target plane, is expected to be 1.6 and 0.7 mm along the beam axis and vertical direction ($z_e$ and $y_e$), respectively. The direction of the positron is expected to be determined with a resolution of 6.7 and 3.7 mrad in the $\theta_e$ and $\phi_e$ polar angles, respectively.

The positron reconstruction is completed by the TC, a detector composed of 512 BC-422 scintillator tiles with dimensions of $L \times W \times T = 120 \times (40 \text{ or } 50) \times 5 \text{ mm}^3$ [10]. Each tile is readout by 6 parallel-connected silicon photomultipliers (SiPM) at each end. The synchronization of the counters is performed by means of laser pulses distributed through the detector by a system of optical fibres [11]. The TC was tested with positrons from muons on target since 2019 and already reached the design resolution of 35 ns.

Photons are reconstructed in the XEC, a 800-liter liquid Xenon detector with excellent energy, time and conversion point reconstruction performance. The scintillation light is collected by PMTs in the lateral and back faces of the detector and silicon photon detectors (MPPC) in the front face. The MPPCs replaced the PMTs of the MEG's XEC detector, providing better coverage and hence better energy and position resolutions for photons converting at a small depth inside the detector, and a higher granularity to better separate multiple photons entering the detector at the same time. An energy resolution of 1.7% is expected at 52.8 MeV, with a position resolution of 2.4 and 5 mm in the direction parallel and orthogonal to the inner surface, respectively, and a time resolution of about 63 ps.

The analog signals coming from all the detectors are digitized with the WaveDREAM [12], a DAQ board instrumented with the DRS4 chip, a high-speed, 12-bit resolution waveform digitizer, also providing trigger capabilities and biasing for silicon photodetectors. The system allows a fully digital FPGA-based trigger [13] and the acquisition of digitized waveforms for offline analysis to be integrated into a single, compact system, in order to cope with the higher number of readout channels of the upgraded detector.

The design performance would allow to reach an upper limit of $\sim 6 \times 10^{-14}$ in a three-year run of the experiment.

## 4. Current status

The first physics data for the MEG II experiment were taken for less than two months in 2021 with all detectors installed and fully operational, collecting a statistics corresponding to about $0.8 \times 10^{14}$ stopped muons. The data taking was resumed in July 2022 and run until mid-November, collecting additional $2.5 \times 10^{14}$ stopped muons.

A decrease of the photon detection efficiency (PDE) of the XEC MPPCs was observed after running the detector on the muon beam. This deterioration, induced by the large amount of UV light from the LXe, is not expected to affect significantly the photon reconstruction performance, as far as the PDE stays above 4%. Anyway, staying above this threshold requires a periodic reconditioning of the sensors, that can be achieved by warming them well above the room temperature for several hours. It is obtained by Joule effect, letting them draw a large current when constantly illuminated by LEDs. The procedure to anneal all MPPCs requires several weeks, if the time necessary to warm up the XEC cryostat and cool it down again is included. For this reason, it can be performed only once per year, during the winter shutdown of the PSI proton accelerator complex, and the muon beam rate during the run has to be limited to keep a PDE larger than 4% till the end of the run. According to our current understanding of the processes, beam rates up to $5 \times 10^5$ $\mu$/s would allow to run the experiment for 120 days per year without a significative deterioration of the performance.

The CDCH have been operated without significant issues in 2021 and 2022, with a gas mixture of helium and isobutane in 90:10 relative volume concentration, and the addition of 1.5% isopropyl alcohol and 0.5% oxygen. These additives were necessary to suppress some high currents observed in the 2020 run and preventing a safe operation of the chamber, and no significant deterioration of the performance is observed with respect to the pure helium/isobutane mixture.

Data were collected in 2021 and 2022 at different beam intensities, from $3 \times 10^7$ $\mu$/s to $5 \times 10^7$ $\mu$/s, in order to study the detector response under different conditions. The analysis of the data is currently ongoing. Table 1 shows a summary of the resolutions that have been already achieved when running at $3 \times 10^7$ $\mu$/s. The $T_{e\gamma}$ resolution is extracted from the width of the $T_{e\gamma}$ peak produced by RMDs (107 ps), scaled down to take into account that signal positrons produce on average a larger number of TC hits, which implies a better time determination. Improvements are still possible with updated calibrations and reconstruction algorithms. Preliminary sensitivity projections based on simulated pseudo-experiments indicate that an upper limit of $2.1 \times 10^{-13}$ is expected, on average, for the branching ratio of the $\mu \to e\gamma$ decay. At the end of the foreseen 3-year data taking, an upper limit sensitivity of about $6 \times 10^{-14}$ will be reached.

| $E_e$ [keV] | $\theta_e$ [mrad] | $\phi_e$ [mrad] | $y_e$ [mm] | $z_e$ [mm] | $E_\gamma$ [%] | $T_{e\gamma}$ [ps] |
|---|---|---|---|---|---|---|
| 94 | 7.4 | 5.3 | 0.7 | 1.9 | 1.8 | 78 |

**Table 1:** Core gaussian resolutions from a preliminary estimate based on 2021 data at $3 \times 10^7$ $\mu$/s.

## 5. Conclusions

The MEG II experiment, based on a complete upgrade of the MEG detector, is currently taking data at PSI, searching for the LFV decay $\mu \to e\gamma$. The first two runs of data taking have been performed in 2021 and 2022, with beam intensities between $3 \times 10^7$ $\mu$/s and $5 \times 10^7$ $\mu$/s. The analysis of the data already collected is ongoing, and the experiment is targeting a final upper limit sensitivity of $6 \times 10^{-14}$. MEG II is the first running experiment in the current generation of muon LFV searches, and options for the next generation are already under study [14].

## References

[1] F. Renga, Rev. Phys. **4** (2019), 100029.

[2] E. P. Hincks and B. Pontecorvo, Phys. Rev. **73** (1948), 257-258.

[3] A. Crivellin, S. Davidson, G. M. Pruna and A. Signer, JHEP **05** (2017), 117.

[4] A. M. Baldini *et al.* [MEG], Eur. Phys. J. C **76** (2016) no.8, 434.

[5] J. Adam *et al.*, Eur. Phys. J. C **73** (2013) no.4, 2365.

[6] A. M. Baldini *et al.* [MEG II], Eur. Phys. J. C **78** (2018) no.5, 380.

[7] A. M. Baldini *et al.*, Nucl. Instrum. Meth. A **958** (2020), 162152.

[8] A. M. Baldini *et al.* JINST **16** (2021) no.12, T12003.

[9] A. M. Baldini *et al.* JINST **11** (2016), P07011 doi:10.1088/1748-0221/11/07/P07011 [arXiv:1605.07970 [physics.ins-det]].

[10] P. W. Cattaneo *et al.*, IEEE Trans. Nucl. Sci. **61** (2014) no.5, 2657-2666.

[11] G. Boca *et al.*, Nucl. Instr. Meth. A **947** (2019) 162672.

[12] M. Francesconi *et al.*, Nucl. Instrum. Meth. A **1045** (2023), 167542.

[13] M. Francesconi *et al.*, Nucl. Instrum. Meth. A **1046** (2023), 167736.

[14] G. Cavoto, A. Papa, F. Renga, E. Ripiccini and C. Voena, Eur. Phys. J. C **78** (2018) no.1, 37.

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