PROCEEDINGS OF SCIENCE

Status of the MEG II experiment

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The MEG II experiment, which focuses on investigating Charged Lepton Flavour Violation in muon decays, completed the commissioning of all subdetectors in time for the 2021 run and it is currently collecting its third year of beam time at the Paul Scherrer Institut (CH).
The experimental apparatus has been specifically designed to search for $\mu^+ \to e^+\gamma$ decay, aiming at improving the limit on the branching ratio from the current 4.2×10^{-13} at 90% confidence level set by the former MEG experiment. This requires high-performance and lightweight detectors capable of handling the pileup effect from world most intense continuous μ^+ beam.
This contribution provides a brief overview of the experimental techniques employed and then focuses on the description of the collected datasets and analysis strategy. Although we accumulated only a few weeks of data in 2021, the experiment already has a sensitivity of 8.8×10^{-13} to the $\mu^+ \to e^+\gamma$ branching ratio, with analysis strongly limited by available statistics. In the months following the conference, that dataset was unblinded and the limit was set at 7.5×10^{-13}. The combination of this with the existing limit yields the current best exclusion of $\mu^+ \to e^+\gamma$ process with a limit in branching ratio of 3.1×10^{-13} at 90% confidence level.
Finally, MEG II data-taking is expected to continue until the end of 2026, to achieve its final sensitivity of 6×10^{-14}.

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1. Introduction

Charge Lepton Flavour Violating processes (CLFV) are considered [1] sensitive probes to look for effects beyond our current Standard Model of particle physics. Indeed such processes are strictly forbidden in the Standard Model and, if neutrino masses and mixing angles are included, their value is way below the experimental reach (with branching ratios $\approx 10^{-50}$), resulting therefore in a clean signature for any new physics. In particular, processes involving muons are of interest because high-intensity μ^+ beams can be created and delivered to a dedicated experiment, collecting large statistics in a reasonable amount of time.

Among the possible muon channels, the current best upper limit on $\mu^+ \to e^+\gamma$ branching ratio was set by the MEG experiment [2] to 4.2×10^{-13}, exploiting the full experiment dataset, which was collected between 2009 and 2013 [3].

The signature for $\mu^+ \to e^+\gamma$ is very clean: in the muon rest frame, the two particles are generated with equal and opposite momenta at a value of approximately 52.8 MeV/c. This separates the signal from the only irreducible background being the $\mu^+ \to e^+\nu\bar{\nu}\gamma$ muon decays in which the neutrinos carry away a small amount of energy, closing the angle and reducing the energy of the detectable particles. Considering the high muon rate required for CLFV experiments, a non-negligible fraction of background comes from the accidental coincidence of a positron and a photon from a separate decay. Indeed positrons at signal energy are produced abundantly in the main $\mu^+ \to e^+\nu\bar{\nu}$ decay and high energy photons can be generated from the previously mentioned radiative $\mu^+ \to e^+\nu\bar{\nu}\gamma$ decays or from the in-flight annihilation of an high-energy positron ($e^+e^- \to \gamma\gamma$) in the detector material.

The upgrade effort of the MEG collaboration, known as the *MEG II Experiment*, aims at improving the sensitivity by an order of magnitude and involves all the subdetectors, providing higher granularity and resolutions to cope with an increased muon rate [4]. The commissioning process was concluded in 2021 with the first Physics Run of the new experiment, following a series of Engineering Runs [5].

2. Description of the MEG II experiment

The detectors constituting the MEG II experiment keep the same experimental layout as the former MEG setup [6], having a beam of positive muons stopped into a thin plastic target where they decay at rest.

Photons originating from the target are detected by a $\sim 900\ell$ liquid Xenon scintillation detector (LXe) where the produced showers are used to reconstruct the energy, timing and conversion point of the photons. The LXe acceptance covers $\sim 11\%$ of the solid angle from the target perpendicular to the beam direction, defining the MEG II experiment acceptance. Around LXe active volume, an array of 668 UV-sensitive photomultiplier tubes have been complemented with 4092 Multi-Pixel Photon Counters (MPPCs), located on the entrance face, to collect the scintillation light [7]. An energy resolution of $1.8 \div 2.0$ %, dependent on the conversion depth, and a conversion point resolution of 2.5 mm were measured during dedicated calibration runs using the *Charge EXchange* (CEX) reaction $\pi^- p \to \pi^0 n (\pi^0 \to \gamma\gamma)$, in which a negative pion beam was stopped into a liquid-hydrogen target [8].

Positrons curl in a non-uniform magnetic field which is designed to quickly remove particles emitted perpendicular to the main solenoidal component. The particles are tracked by an ultra-light cylindrical drift chamber (CDCH) using a mix of He : C_4H_{10} : C_3H_8O : O_2 in 88.2% : 9.8% : 1.5% : 0.5% fractions and an open square cell structure with size from 6.6 to 9.9 mm [9]. This detector provides the positron momentum and its emission angle from the target with a 90 keV/c core resolution.

The timing of the track is accurately measured by the pixelated Timing Counter (pTC) with a resolution of 43 ps for signal-like positrons, by averaging the hit time from an average of ~ 9 plastic scintillator tiles [10]. On the other side of the track, the extrapolation to the target surface identifies the muon decay point and the opening angle of the candidate pair when combined with the photon conversion point inside the LXe detector. The stability of the target surface was one of the largest systematics of the previous experiment, therefore in MEG II, two commercial videocameras collect images of a dotted pattern printed on the target foil [11, 12]. This provides a continuous measurement of its position and a monitoring for any deformation.

Downstream of the target, the Radiative Decay Counter (RDC) detector collects low energy positrons, likely originating from the $\mu^+ \to e^+\nu\bar{\nu}\gamma$ decay, whose turning radius is not large enough to reach the CDCH. The RDC rejects forward-going high-energy positrons by observing the deposit on a LYSO crystal layer which sits behind a segmented plastic scintillator used for the timing.

In order not to spoil the timing resolution of the subdetectors, full-waveform digitization is required on all channels with a sampling speed of 1.4 GSPS. Such a high sample rate, paired with a higher channel number than the former MEG experiment, helps identify and disentangle pileup events and is enabled by the use of a novel integrated trigger and data acquisition system [13] based on the Domino Ring Sampler 4 (DRS4).

3. 2021 data set and first MEG II result

The very first MEG II data-taking in 2021 collected 1.04×10^{14} muon decays during an allocated time of 2.9×10^6 s. During that run, a few different beam intensities in the range of $2 \div 5\times10^7$ μ^+/s, were investigated.

A process of data suppression and waveform reduction was developed during the first part of the run to allow the data acquisition to operate with trigger thresholds relaxed. Indeed this proved to be a good choice because two different bugs were later identified in the 2021 trigger logic:

- time walk of the LXe time online estimator, where the slow rising edge of the MPPCs in the inner face caused a correlation between pulse amplitude and its arrival time from a leading-edge discriminator. This was fixed for the 2022 data-taking by moving the time extraction to the faster PMT signals.

- a sporadic wondering of the baseline of the online LXe energy reconstruction in the presence of a very high signal was then observed in 2022. It was fixed for the 2023 physics run by dynamically lowering the threshold for a short time window after a pulse.

The overall trigger efficiency [4, 14] for the 2021 dataset was therefore approximately 80%, with dependence on the different data-taking conditions. In particular, the efficiency decreased when the threshold had to be tightened to cope with the increase in muon rate.

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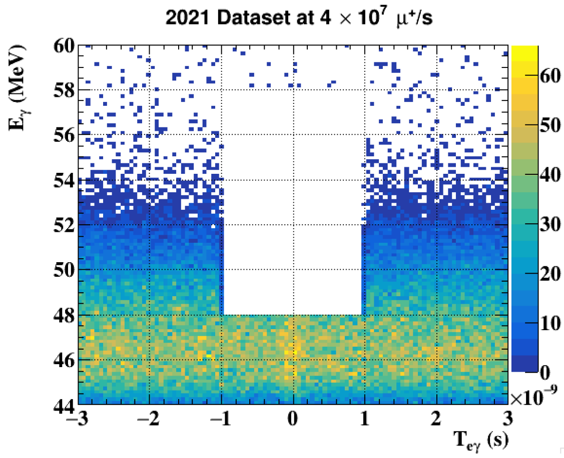

Figure 1: Fraction of the 2021 dataset at 4×10^7 μ^+/s

The MEG II data acquisition collects pieces of information using the UDP protocol which is intrinsically unreliable. If one of the packets could not be received the event had to be dropped, this was caused mainly by a CPU overload of the collecting server. Because of this, in 2021 we experienced a random data collection inefficiency up to 20%, which was solved in the following years by removing online data compression and moving to a faster CPU.

In addition to the previously mentioned efficiencies, for each MEG II detector, detection and reconstruction efficiencies play a major role. The two contributions combine to 62% and 67% respectively for the LXe and for the whole spectrometer (including both CDCH, pTC and their matching efficiency).

For each pair of candidates, the physics information is encoded in five variables: the energies E_e and E_γ, the relative time $\Delta t_{e\gamma}$, the pair opening angle in the two spherical intervals $\Delta\theta_{e\gamma}$ and $\Delta\phi_{e\gamma}$ [1]. In Figure 1 a fraction of the 2021 dataset is projected in the $E_\gamma - \Delta t_{e\gamma}$ plane and the blinded area of 48 MeV $< E_\gamma <$ 58 MeV and $|\Delta t_{e\gamma}| <$ 1ns is visible. The detector performances and the Probability Density Functions for the data fitting are obtained using events in the energy ($E_\gamma <$ 48 MeV, $\mu^+ \to e^+\nu\bar{\nu}\gamma$ enriched) and time sidebands (1ns $< |\Delta t_{e\gamma}| <$ 3ns, with only accidental coincidences). Additional inputs are provided from the yearly CEX calibration and very minor corrections are extracted from a Geant4-based Montecarlo simulation.

The upper limit extraction for the $\mu^+ \to e^+\gamma$ is based on a full frequentist approach following Feldman-Cousins prescriptions. In the likelihood maximization, the signal, $\mu^+ \to e^+\nu\bar{\nu}\gamma$ and accidental yields are fitted with an external gaussian constraint on the expected values from the sidebands. A sensitivity of 8.8×10^{-13} is obtained as the median upper limit of 100 background-only Toy Montecarlo experiments.

The blinding box was opened after the end of the conference, in the first days of September 2023. The fitted signal yield is compatible with zero, giving the first MEG II upper limit of 7.5×10^{-13} at 90% confidence level. All the details are described in the reference [15].

In the same reference, the upper limit was combined with the former one multiplying the likelihood curves of MEG I and MEG II experiments. The combined limit is 3.1×10^{-13} and it is

[1]The MEG coordinate system is defined such that the Z axis is aligned with muon beam and Y is the vertical direction

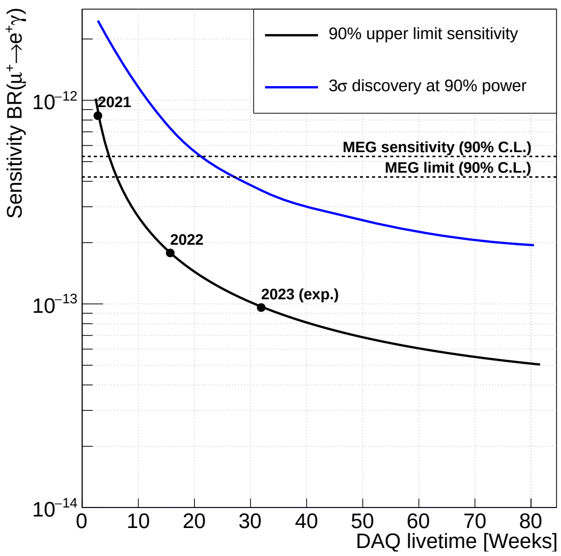

Figure 2: MEG II Sensitivity and 3σ discovery. For 2021 and 2022 datasets the amount of collected data is known. The 2023 point is the expected given the current data-taking

the world best limit on $\mu^+ \to e^+\gamma$.

4. Available datasets and long-term perspective

The MEG II collaboration already collected data for 7.76×10^6 s in 2022 and the 2023 run is currently ongoing with 8.32×10^6 s recorded at the moment of writing.

The two datasets combined are roughly 6 times as big as the 2021 one and profit of the experience gained in 2021, addressing all the observed issues. The figure 2 shows the evolution of the sensitivity and the 3σ discovery over time. The first two points correspond to the acquired datasets of 2021 ÷ 2022. The 2023 point is the expected value, given the current data acquisition rate. The MEG II experiment plans to take data until the major accelerator upgrade at Paul Scherrer Institut in 2026 [16], the final integrated beam time will depend on the beam usage allocated to the experiment.

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