PROCEEDINGS OF SCIENCE

The MEG II experiment & perspectives on lepton physics at PSI

Antoine Venturini[a,b,*]

[a] *Università di Pisa, Dipartimento di Fisica, Largo B. Pontecorvo 3, 56127 Pisa, Italy*

[b] *INFN Sezione di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy*

E-mail: antoine.venturini@pi.infn.it

The Paul Scherrer Institute is a leader laboratory in muon physics: its accelerator facility provides the most intense continuous muon beam in the world ($\mathcal{O}(10^8)$ μ^+/s), boosting fundamental research in the field of lepton flavor physics as well as precision physics. The goal of the High-Intensity Muon Beams project at PSI is to upgrade the facility to deliver muon beams with rates up to $\mathcal{O}(10^{10})$ μ^+/s, ensuring novel possibilities in the field of experimental muon physics. We review the present status and future prospects of cLFV experiments (MEG II, Mu3e and next generation $\mu \to e\gamma$ experiments) at PSI as well as the project for an experiment to measure the electric dipole moment of the muon (muEDM).

Workshop Italiano sulla Fisica ad Alta Intensità (WIFAI2024)
12-15 November 2024
Palazzo Hercolani, Bologna, Italy

*Speaker

https://pos.sissa.it/

PoS(WIFAI2024)029

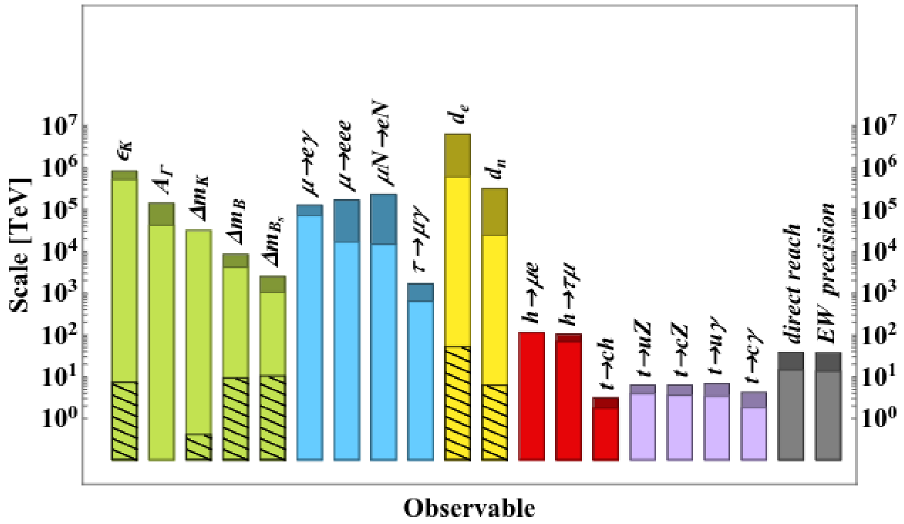


Figure 1: Reach in New Physics scale attained (light color) / attainable (darker color) by near-future experiments aiming at measuring these highlighted observables. From [2].

1. Introduction

The Paul Scherrer Institute produces the most intense continuous muon beam in the world, up to $\mathcal{O}(10^8)$ μ^+/s. This infrastructure is key to perform experiments at the intensity frontier in particle physics [1], such as searches for charged Lepton Flavor Violating (cLFV) processes like the $\mu \to e\gamma$, the $\mu \to eee$ decays or for the electric dipole moment of the muon d_μ. In Fig. 1 it is shown the energy scale of New Physics (in an Effective Field Theory formalism) that these experiments can probe, compared with expectations from other measurements.

cLFV processes, being highly-suppressed in the Standard Model (SM), are golden channels to probe the validity of the SM and to search for evidence of new physics beyond it. PSI has hosted many generations of cLFV experiments: in the past SINDRUM I, SINDRUM II and MEG I; today MEG II; and soon, Mu3e. Details on these experiments can be found in the review [3] and references therein. The topic of present and future cLFV experiments at PSI is treated in Sections 3, 4.

Similarly, the EDM of the muon is an observable much sensitive to Beyond Standard Model physics: the muEDM experiment is a novel project which will try to push the experimental sensitivity on the muon EDM down to $10^{-23} e\cdot$ cm, four orders of magnitude better than the present limit. Section 5 is dedicated to the muon EDM search.

Such ambitious physics programs call for an upgrade of the PSI muon facility: the High-Intensity Muon Beams project (HIMB) aims at a maximum muon rate of $\mathcal{O}(10^{10})$ μ^+/s, $\times 100$ the current achievable rate.

2. PSI HIMB upgrade

At PSI, the High-Intensity Proton Accelerator facility (HIPA) delivers a very intense proton beam of 1.4 MW which impinges on the two production targets. The high beam rates are possible

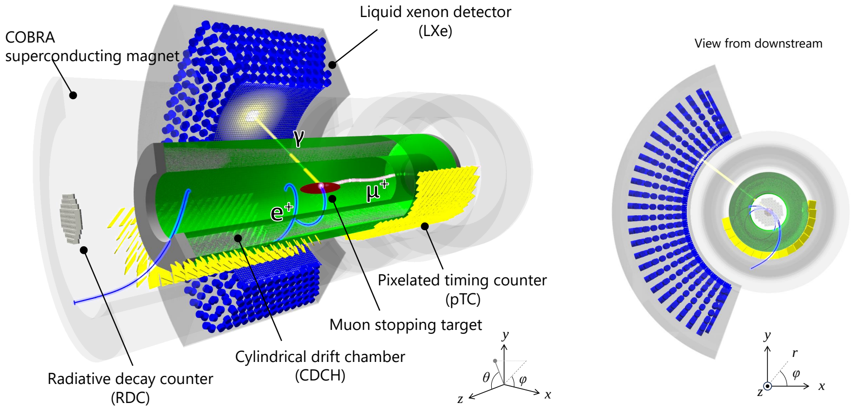


Figure 2: MEG II detector scheme with a simulated $\mu^+ \to e^+\gamma$ event [6].

exploiting *surface muons* [1]. The proposed HIMB upgrade (part of the IMPACT project [4]) focuses on:

- the optimization of the target stations where the HIPA proton beam impinges. At present, the targets are two polycrystalline graphite rotating wheels. One of them (target TgM) will be substituted with a new target suited for high-intensity production with a slanted geometry designed to increase the surface muon yield. The capture efficiency will also be increased using newly designed solenoidal magnets;
- the construction of two beamlines with higher transmission efficiency realized using nominal conducting solenoids as focusing elements instead of quadrupoles.

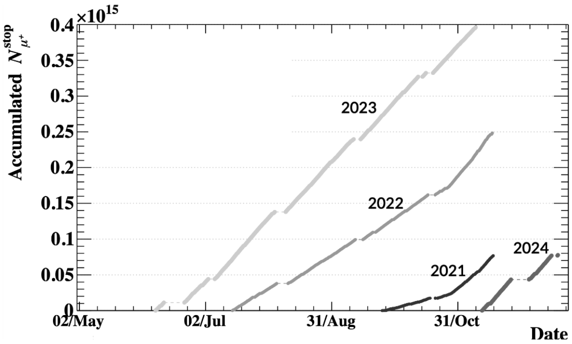
More details can be found in [5].

The HIMB upgrade is scheduled to start in 2027 and after $\sim$ 1.5 years of shut-down, in mid-2028, the first HIMB beam will be delivered.

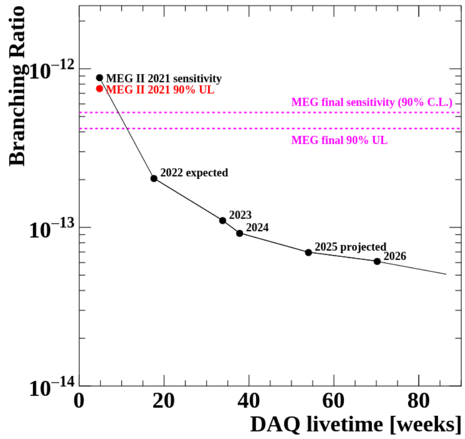
3. The status of the MEG II experiment

The MEG II experiment is located downstream the πE5 beam line at PSI delivering a continuous beam of positive muons with an average momentum of 28 MeV/c that can be stopped in a thin plastic target at the center of the apparatus. A signal from the $\mu^+ \to e^+\gamma$ decay has a clear signature in the center-of-mass frame: a positron (e^+) and a photon (γ) are emitted at the same time, in opposite directions and with almost the same energy ($E_{e^+} \approx E_\gamma \approx m_\mu c^2/2 \approx 52.83$ MeV). MEG II's detector system, which mainly consists of a magnetic spectrometer and a photon detector (Figure 2), has been optimized to improve the resolutions for e^+ and γ measurements, which is crucial to distinguish a signal event from background ones. The experimental background consists of two phenomena [7]: radiative muon decays (RMD) $\mu^+ \to e^+\gamma\nu\bar{\nu}$ and accidental coincidences (the dominant background) between high energy e^+ and γ. Detectors are constructed to achieve optimal performances in an extremely radiation-cluttered environment. A high muon rate $(2-5\times10^7\ \mu^+/\text{s})$

[1] Surface muons are μ^+ produced by the decay of π^+ at rest in the production target.



(a) Number of stopped muons on the MEG II target during 2021-24 data-taking periods.



(b) Experimental sensitivity to the $\mu \to e\gamma$ decay with MEG II apparatus and analysis scheme as a function of data-taking time.

Figure 3: The status of the MEG II experiment after four years of data-taking.

is indeed essential to acquire the necessary statistic to lower the sensitivity. More details about MEG II apparatus (including calibrations) can be found in [8].

The MEG II experiment ended the fourth year of physics data taking in 2024, successfully stopping at the center of the apparatus $\approx 7 \times 10^{14}$ μ^+ (Fig. 3 (a)). By 2026, MEG II should reach a sensitivity on $\mathcal{B}(\mu^+ \to e^+\gamma)$ of 6×10^{-14}, outperforming the sensitivity level of the previous MEG experiment by an order of magnitude [9]. We show in Fig. 3 (b) the MEG II sensitivity (present and expected), calculated from the detector calibration and data analysis on 2021 and 2022 data.

The MEG II Collaboration is finalizing the analysis for the unblinding of 2022 data and has started working on 2023 data as well. The 2021 dataset has been unblinded in 2023: no evidence for the $\mu^+ \to e^+\gamma$ decay was found, with the 90% CL upper limit of the branching ratio being set to:

$$\mathcal{B}(\mu^+ \to e^+\gamma) < 7.5 \times 10^{-13} \text{ (90\% C. L.)}$$

Combining these results with MEG ones we set the lowest limit on $\mathcal{B}(\mu^+ \to e^+\gamma)$ to date [10]:

$$\mathcal{B}(\mu^+ \to e^+\gamma) = 3.1 \times 10^{-13} \text{ (90\% C. L.)}$$

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

MEG II experiment operations will end in coincidence with the HIMB upgrade. The detectors' system is indeed not designed to fully exploit the capabilities of the future beamlines. Instead, the Mu3e experiment [12] will be commissioned in the πE5 area and will start its physics data taking campaign to search for the $\mu \to eee$ decay. Together with the Mu2e and COMET experiments (in search of the $\mu \to e$ conversion on nuclei), they will carry on the experimental efforts to search for cLFV in the muon sector in the next future. In the last years, a Study Group including also of scientists from the MEG II and Mu3e collaboration has been formed to investigate the feasibility of

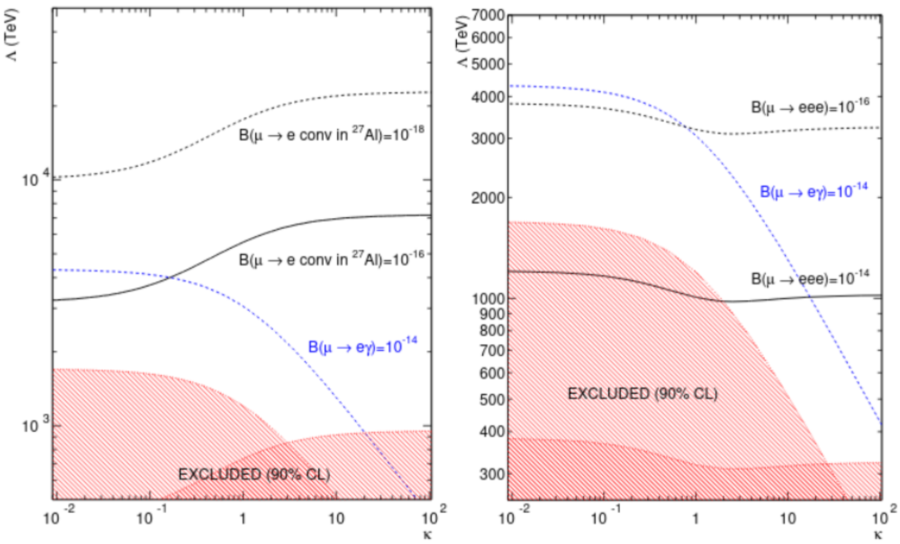


Figure 4: Comparison of achievable constraints on New Physics between $\mu \to e\gamma$ and $\mu \to e$ conversion (left) and between $\mu \to e\gamma$ and $\mu \to eee$ (right) experiments. The Beyond Standard Model operator of order 6 is parameterized in term of the energy scale Λ and the k parameter: for $k = 0$ it is a dipole operator, for $k \to \infty$ a four-fermion interaction. From [11].

a new $\mu \to e\gamma$ experiment, capable of overcoming present technical challenges to augment further the sensitivity to $\mathcal{B}(\mu \to e\gamma)$ down to the level of 10^{-15} [13]. It would be important to complement the future results from Mu3e, Mu2e and COMET, since the $\mu \to e\gamma$ decay is sensitive to different New Physics processes with respect to the $\mu \to eee$ and $\mu + N \to e + N'$ processes [3]. See Fig. 4 for the comparison of the sensitivity reach of these experiments over a Beyond Standard Model observable in an Effective Field Theory formalism.

Presently, the Study Group for future $\mu \to e\gamma$ experiments is conducting R&D works on:

- pixel detectors (*à la* Mu3e) to build an ultra-light e^+ tracker capable of sustaining the occupancy from a $\sim 10^{10}$ μ^+/s beam;
- a new photon detector concept based on the pair production $\gamma \to e^+e^-$. The photon would convert on thin, active converter layers made of LYSO bars coupled to SiPM, capable of measuring accurately the passing time ($\sigma_t \lesssim 40$ ps) and the energy loss in the material. Then, the e^+e^- pair would be reconstructed in a tracker, possibly a radial TPC.

Details on the ongoing research work on this experiment can be found in [14]. A scheme of the apparatus is shown in Fig. 5.

5. The muEDM experiment

The muEDM experiment at PSI plans to search for the electric dipole moment (EDM) of the muon, d_μ, employing the frozen-spin technique [15], pushing the sensitivity to this observable from $d_\mu \leq 1.8 \times 10^{-19}$ e·cm to $d_\mu \leq 6 \times 10^{-23}$ e·cm. The experiment will proceed in two phases:

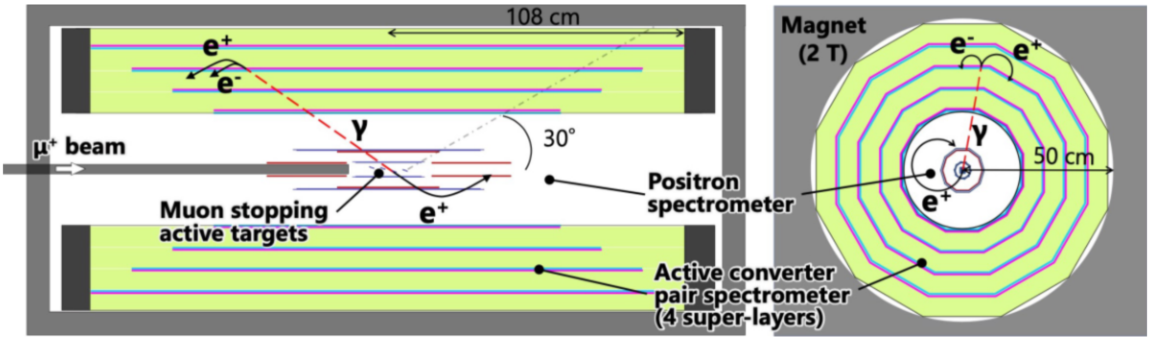


Figure 5: Concept design of a future $\mu \to e\gamma$ experiment at PSI.

- Phase I is planned to acquire physics data before 2027 (HIMB upgrade) to demonstrate the feasibility of the newly proposed techniques to measure d_μ. The goal sensitivity for this first stage is $d_\mu \lesssim 10^{-20}$. In the last years many elements of the apparatus have been successfully tested during beamtimes: these were important milestones toward the commissioning of the experiment by 2026;
- Phase II would eventually acquire data after the HIMB upgrade: the apparatus of Phase I would be redesigned to boost the sensitivity on d_μ.

A complete overview of the muEDM experiment, together with a detailed description of the apparatus for the Phase I measurement, can be found in [16]. In a few words:

Frozen-spin technique The spin precession relative to the momentum of a positive muon within a magnetic field $\vec{B}$ and an electric field $\vec{E}$ is given by the Thomas-BMT equation:

$$\vec{\Omega} = -\frac{e}{m}\left[a\vec{B} - \frac{a\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] - \frac{\eta e}{2mc}\left[c\vec{\beta}\times\vec{B} + \vec{E} - \frac{\gamma(\vec{\beta}\cdot\vec{E})\vec{\beta}}{\gamma+1}\right]$$

where $a \equiv \frac{g-2}{2}$, the anomalous magnetic moment of the muon. The precession is driven by the magnetic moment term $\vec{\mu} = \frac{ge}{2m}\vec{s}$ (first part of the equation) and by the electric dipole term $\vec{d} = \frac{\eta q}{2mc}\vec{s}$ (second part of the equation). If $\vec{B}$, $\vec{E}$ and β satisfy the following *frozen-spin conditions*

$$\begin{cases} \vec{B}\cdot\vec{E} = 0 \text{ and } \vec{B}\cdot\vec{\beta} = 0 \text{ and } \vec{\beta}\cdot\vec{E} = 0 \\ a\vec{B} = \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c} \end{cases} \tag{1}$$

then the precession contribution from the anomalous magnetic moment vanishes, while the EDM would cause a precession of the spin around $\vec{E}$.

muEDM apparatus for Phase I In the Phase I of the muEDM experiment, low momentum muons ($\approx$ 28 MeV/c) will be injected inside a 3T solenoid and stored at the center of the apparatus on a 3 cm orbit, using the combined action of a pulse coil to decrease the longitudinal component of the muon momentum and of a weakly-focusing field generated by a second coil providing the longitudinal confinement of the muons. The muon will then orbit inside a region with a radial electric field (satisfying the frozen-spin conditions): a voltage difference of $\approx$ 1.8 kV will be applied on two

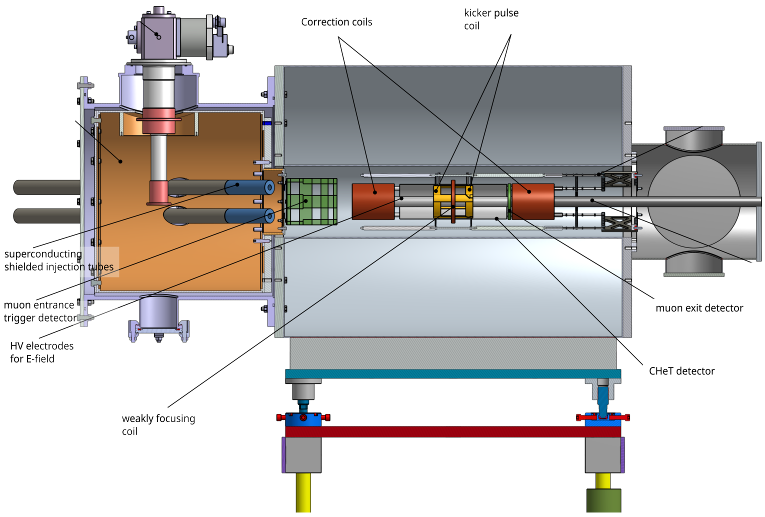


Figure 6: Overview of the muEDM experimental setup for Phase I. Modified from [16].

concentric cylindrical electrodes at radii 2.5 and 3.5 cm. In the experimental conditions of Phase I this is enough to ensure the spin of the muon is frozen.

The spin precession of the muon can be derived measuring the longitudinal asymmetry of the positrons emitted in the muon decay. A compact tracker with momentum resolution $O(1\ \text{MeV})$ and spatial resolution $O(1\ \text{mm})$ is needed to perform the EDM measurement with the goal sensitivity for Phase I. For this purpose a detector entirely made of scintillating fibers coupled to SiPMs (single-side readout) is being deployed, the Cylindrical Helix Tracker (CHeT).

The muEDM apparatus is composed of many elements crucial to the successful making of the experiment. Some of them are listed and displayed in the experimental setup scheme in Fig. 6.

INFN is directly involved in the realization of the CHeT detector and a small TPC designed to characterize the muon beam phase space during the commissioning phase of the experiment. The groups of researchers involved at the time of writing are from Pisa and Roma 1.

6. Conclusions

The MEG II experiment has successfully collected data between 2021 and 2024 in the pursuit of the charged lepton flavour violating decay $\mu^+ \to e^+\gamma$. The analysis of 2021 + 2022 dataset, which is being completed, will ameliorate the sensitivity on $\mathcal{B}(\mu^+ \to e^+\gamma)$, beyond the present best limit set with the combination of MEG II first results and MEG final ones of $\mathcal{B}(\mu^+ \to e^+\gamma) \leq 3.1\times10^{-13}$.

At PSI, in parallel, the Mu3e experiment is preparing to explore the $\mu \to eee$ decay with unprecedented sensitivity, with prospects significantly boosted by the forthcoming High Intensity Muon Beam (HIMB) upgrade, with an expected muon beam rate of $O(10^{10})\ \mu^+/\text{s}$. R&D on future $\mu \to e\gamma$ experiments at PSI in the era of HIMB is also continuing.

In the field of precision physics with muons, the development of the novel MuEDM experiment aims to probe the muon electric dipole moment with a sensitivity goal of 10^{-23}, $e \cdot \text{cm}$, offering a unique window into CP-violating physics beyond the Standard Model. The preparation and testing of the apparatus for Phase I is coming to an end, in view of a possible physics data-taking period by 2026.

Together, these complementary efforts underline the vitality of the field, reinforcing PSI's central role in the global program to search for physics beyond the Standard Model through precision muon experiments.

References

[1] A. Signer, K. Kirch, C. Hoffman, *Particle physics at PSI*, *SciPost Phys. Proc.* (2021) 001.

[2] H. Abramowicz, R. Forty, *Physics briefing book [input for the european strategy for particle physics update 2020]*, , Fermi National Accelerator Lab. (FNAL), Batavia, IL (United States) (10, 2019), DOI.

[3] L. Calibbi, G. Signorelli, *Charged lepton flavour violation: an experimental and theoretical introduction*, *Riv. Nuovo Cim.* **41** (2018) 71.

[4] R. Eichler et al., *IMPACT conceptual design report*, no. 22-01 in PSI Bericht (2022).

[5] G. Dal Maso et al., *Future facilities at PSI, the high-intensity muon beams (himb) project*, in *EPJ Web of Conferences*, vol. 282, p. 01012, EDP Sciences, .

[6] K. Afanaciev et al., *Operation and performance of MEG II detector*, 2310.11902.

[7] Y. Kuno, Y. Okada, *Muon decay and physics beyond the standard model*, *Rev. Mod. Phys.* **73** (2001) .

[8] K. Afanaciev et al., *Operation and performance of the MEG II detector*, *Eur. Phys. J. C* **84** (2024) 190.

[9] A. M. Baldini 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) .

[10] K. Afanaciev et al., *A search for $\mu + \to e + \gamma$ with the first dataset of the MEG II experiment*, *The European Physical Journal C* **84** (2024) 216.

[11] (Particle Data Group), *Review of particle physics*, *Phys. Rev. D* **110** (2024) 030001.

[12] K. Arndt et al., *Technical design of the phase I Mu3e experiment*, *NIMA* **1014** (2021) 165679.

[13] G. Cavoto et al., *The quest for $\mu \to e\gamma$ and its experimental limiting factors at future high intensity muon beams*, *Eur. Phys. J. C* **78** (2018) 1.

[14] (Study Group for Future $\mu \to e\gamma$ Searches), *Future $\mu \to e\gamma$ experiments*, *PoS* **Muon4Future2023** (2024) 025.

[15] A. Adelmann et al., *Compact storage ring to search for the muon electric dipole moment*, *Jour. Phis. G* **37** (2010) 085001.

[16] A. Adelmann et al., *A compact frozen-spin trap for the search for the electric dipole moment of the muon*, *arXiv preprint arXiv:2501.18979* (2025) .