PROCEEDINGS OF SCIENCE

Electric Dipole Moment (EDM) searches for leptons and hadrons

Jörg Pretz[a,b,*]

[a] *RWTH Aachen University,*
Physikzentrum 26C 212, D-52074 Aachen, Germany

[b] *Forschungszentrum Jülich,*
Wilhelm-Johnen-Straße, D-52425 Jülich, Germany

E-mail: pretz@physik.rwth-aachen.de

This article gives an overview of current and future of activities on measuring electric dipole moments (EDMs) of fundamental particles. Implications for the search of dark matter particle candidates are also discussed.

16th International Conference on Heavy Quarks and Leptons (HQL2023)
28 November-2 December 2023
TIFR, Mumbai, Maharashtra, India

[*] Speaker

PoS(HQL2023)010

1. Introduction

Although the Standard Model of particle physics is very successful in describing fundamental interactions and particles, it does not provide an answer to very fundamental questions like:

- What is the origin of the matter anti-matter asymmetry in our universe?
- Why is $\mathcal{CP}$-violation not present in the strong sector, although in principle allowed?
- What is the origin of dark matter?

Measurements of electric dipole moments (EDM) will provide answers to these questions. These proceedings give an overview of the current status and future plans of EDM measurements. The document is organized as follows. First an introduction to EDMs is given. In section 3 various experimental methods used to search for EDMs will be discussed. Results and future plans will be presented in section 4.

2. Electric Dipole Moments (EDMs)

In a classical system an EDM is present if the center of gravity of positive and negative charges are different. Formally, for N point-like charges it is defined as

$$\vec{d} = \sum_{i=1}^{N} q_i \vec{r}_i \, , \tag{1}$$

where q_i denotes the electric charge and $\vec{r}_i$ the position vector of the point-like charge.

Interpreted as an operator in quantum mechanics, $\vec{d}$ has zero expectation value for states of a given parity, because the operator itself is odd under a parity transformation $\mathcal{P}$:

$$\vec{d} = -\mathcal{P}^{\dagger} \vec{d} \mathcal{P} \, . \tag{2}$$

As a consequence

$$\left\langle a \middle| \vec{d} \middle| a \right\rangle = - \left\langle a \middle| \vec{d} \middle| a \right\rangle = 0 \tag{3}$$

if $|a\rangle$ is a state of definite parity, i.e. $\mathcal{P}\,|a\rangle = \pm\,|a\rangle$. Molecules, such as water can acquire large EDMs because the ground state is a mixture of (almost) degenerate states of opposite parity.

Elementary particles (including hadrons) have a definite parity and thus should not possess an EDM. If however parity (and, as we will see below, also time reversal) violating interactions are present they can contribute to an EDM. In this case the particle ground state does not have a definite parity anymore. There is a small admixture of the opposite parity state:

$$|a\rangle = |+\rangle + \eta\,|-\rangle \ ,$$

where the parameter $\eta \ll 1$ describes the symmetry violating contribution. Now one finds in general

$$\left\langle a \middle| \vec{d} \middle| a \right\rangle = \eta \left\langle + \middle| \vec{d} \middle| - \right\rangle + \text{c.c.} \neq 0 \, .$$

PoS(HQL2023)010

Since the spin defines the only direction in the particle, the EDM, as its counter part the magnetic dipole moment (MDM), have to be aligned with the expectation value of the spin vector. This seems to be counter intuitive since the spin $\vec{S}$ is an axial vector but the electric dipole moment $\vec{d}$ is a polar vector. A rigorous proof that

$$\left\langle a \middle| \vec{d} \middle| a \right\rangle \propto \left\langle a \middle| \vec{S} \middle| a \right\rangle$$

in the absence of an electric field is given in Ref. [1] and invokes the Wigner-Eckart-theorem.

The Hamiltonian for a particle at rest in electric and magnetic fields reads:

$$H = -\vec{d} \cdot \vec{E} - \vec{\mu} \cdot \vec{B} \,. \tag{4}$$

In this form the parity and time reversal violation of the EDM term is explicitly seen. The EDM $\vec{d}$, the MDM $\vec{\mu}$, both linked to the spin, and the magnetic field $\vec{B}$ are axial vectors which transform even (odd) under parity $\mathcal{P}$ (time reversal $\mathcal{T}$) and the electric field $\vec{E}$ is a polar vector transforming odd (even) under $\mathcal{P}(\mathcal{T})$. This results in

$$\begin{aligned} \mathcal{P}(H) &= -\vec{d} \cdot (-\vec{E}) - \vec{\mu} \cdot \vec{B} & (5)\\ &= +\vec{d} \cdot \vec{E} - \vec{\mu} \cdot \vec{B} \,, \\ \mathcal{T}(H) &= -(-\vec{d}) \cdot (-\vec{E}) - (-\vec{\mu}) \cdot (-\vec{B}) & (6)\\ &= +\vec{d} \cdot \vec{E} - \vec{\mu} \cdot \vec{B} \,, \end{aligned}$$

explicitly showing that the EDM part is $\mathcal{T}$ and $\mathcal{P}$ violating, while the corresponding MDM term is not. Assuming the validity of the $C\mathcal{P}\mathcal{T}$ theorem, an EDM is also $C\mathcal{P}$ violating.

This means that finding a non-zero EDM for a fundamental particle is a clear indication for $C\mathcal{P}$ violation. The well established $C\mathcal{P}$ violation in the Standard Model leads to EDMs orders of magnitude below current experimental sensitivities (see figure 4). Many proposed extensions of the Standard Model allow for EDMs reachable with current sensitivities. A finite EDM of hadrons could for example be interpreted as a non-zero $\bar{\theta}_{\mathrm{QCD}}$ parameter [2]. If $\bar{\theta}_{\mathrm{QCD}}$ is different from zero, $C\mathcal{P}$ symmetry would also be violated in the strong sector. The experimental limit of the neutron EDM implies $\bar{\theta}_{\mathrm{QCD}} < 10^{-10}$. The fact that $\bar{\theta}_{\mathrm{QCD}}$ is so small, although as an angle it could have values of $O(1)$, is called the strong $C\mathcal{P}$ problem. A hadron EDM could also originate from other $C\mathcal{P}$ violating interactions. Therefore EDM measurements from many different particle species are needed in order to track down the fundamental interaction.

3. Experimental Methods

The observable in most of the experiments is the measurement of the spin precession. In general the spin precession angular frequency in a magnetic and electric field for a particle at rest is given by

$$\vec{\Omega} = \frac{-d\vec{E} - \mu\vec{B}}{|\vec{S}|} \,, \qquad \dot{\vec{S}} = \vec{\Omega} \times \vec{S} \,. \tag{7}$$

To get an idea of the complexity of corresponding experiments, it is instructive to look at the order of magnitude of the precession frequency Ω. A neutron in the earth's magnetic field has an angular frequency of $\Omega \approx 9000\,\mathrm{s}^{-1}$ due to its MDM. Assuming the neutron has an EDM of

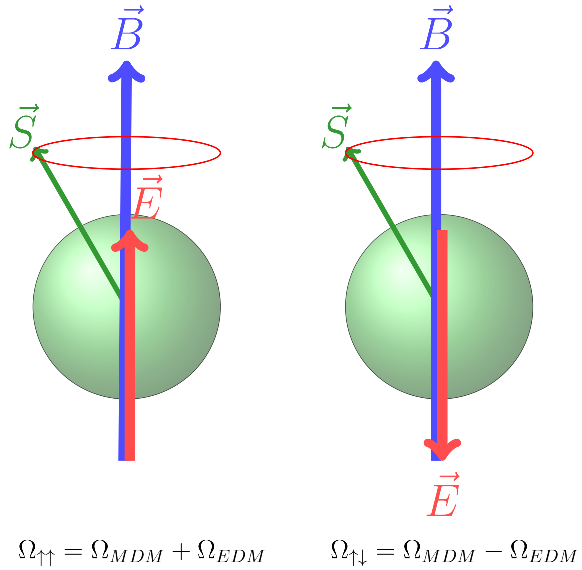


Figure 1: Spin precession for parallel and anti-parallel electric and magnetic fields.

$d_n = 1 \times 10^{-26}\,\mathrm{e \cdot cm}$, which corresponds roughly to the current experimental upper limit, in an electric field of $E = 10^7\,\mathrm{V/m}$, the precession frequency is 10 orders of magnitude smaller: $\Omega \approx 3 \times 10^{-6}\,\mathrm{s}^{-1}$.

To fight systematics most experiments observe the spin precession in a combination of electric and magnetic fields reversing their relative orientation. As indicated in figure 1 the difference in precession frequency is proportional to the EDM. The statistical uncertainty for a single measurement of duration T is generically given by

$$\sigma_{\mathrm{stat}} \propto \frac{\hbar}{P\sqrt{N}ET} . \tag{8}$$

Here P denotes the spin polarisation of the particle ensemble and N the number of detected particles. In order to increase the sensitivity, apart from maximizing N, P and T, another key ingredient is to provide a large electric field E. Depending on the experiment, this is done in different ways. The most obvious method is to use electric plates. For charged hadrons, storage rings using electric bends are proposed [3–5]. Placing atoms and molecules in an electric field, huge enhancement factors (order $100 - 10^6$) for fields inside the atom or molecules are obtained. This increases the sensitivity to the EDM signal [6, 7]. Bent crystals are considered to measure for example the EDM of baryons like Λ_c and Ξ [8]. For particles having a non zero velocity $\vec{v}$ in the laboratory system, a magnetic field leads to a motional electric field $\vec{v} \times \vec{B}$ in the particle rest frame. This method is employed for EDM measurements of charged particles in magnetic storage rings [9].

In order to measure the spin precession frequency again different methods are employed. Ranging from observing the shift of energy levels in atoms and molecules, analysing a scattering process for neutrons and protons to using the self analysing power of the decay for Λ or μ.

Given the variety of techniques, it is not surprising that many different experimental setups are used. Three examples are displayed in figure 2. It shows setups used for ^{199}Hg atoms, neutrons and a proposed storage ring for protons. From one example to the next the size of the experiments increases in size by two orders of magnitude. The Hg atoms are stored in two cells (MT, MB) with

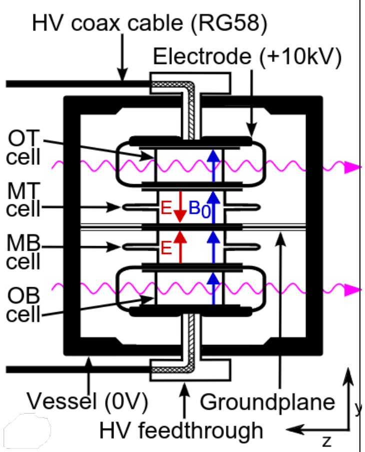
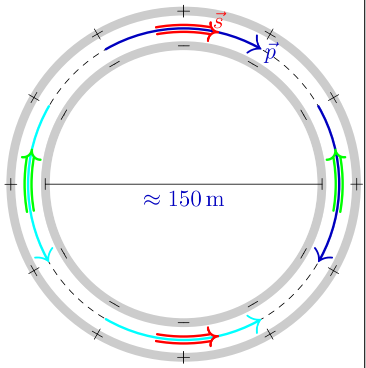
<table>
<tr><th>Hg atoms</th><th>neutrons</th><th>protons</th></tr>
<tr><td>
</td><td></td><td>
</td></tr>
<tr><td>≈1 cm</td><td>≈1 m</td><td>≈ 100 m</td></tr>
</table>

Figure 2: Three different setups to measure the EDM of various particles. Left: Cells to store Hg atoms in various field configurations at University of Washington, USA [10]. Middle: Chamber to store ultra cold neutrons at Paul Scherrer Institut in Switzerland [12]. Right: Proposed storage ring with electric bends to measure the EDMs of protons [5].

different relative orientation of electric and magnetic fields. Additional cells (OT, OB) only subject to a magnetic field are used for a further reduction of the systematic uncertainty. The size of the cells is of the order of one cm [10]. The difference in precession frequency is measured via the difference of energy levels in the Hg-atoms. As a diamagnetic atom, the Hg atom can be used to indirectly measure the EDM of protons and neutrons.

Ultra cold neutrons are stored in a cell (size about one meter). Between two consecutive runs the relative orientation of electric and magnetic field is reversed. The precession frequency is determined using the Ramsey method of oscillating fields [11]. The polarisation of the neutrons is finally measured via a spin dependent scattering process [12].

To measure the EDM of the proton, a storage ring (diameter $\approx$ 100 m) with electric bending fields of several Volt/meter is proposed [3, 4]. Here two proton beams can circulate simultaneously clockwise and counter clockwise to cancel systematic effects. Choosing a so called magic momentum of the proton of $p = 700.74\,\mathrm{MeV}/c$, the spin precession due to the magnetic moment is suppressed (frozen spin condition). An EDM would cause a build-up of a vertical polarisation for a beam initially polarized along the direction of the momentum vector. This vertical polarisation can be determined using elastic scattering of protons on a carbon target. The left-right counting rate asymmetry is proportional the vertical polarisation which is in turn proportional to the EDM.

4. Experiments and Results

4.1 Results on EDMs

Figure 3 gives an overview of running and planned EDM experiments around the world, grouped by particle species. Figure 4 shows current results for the electron, muon, tau leptons

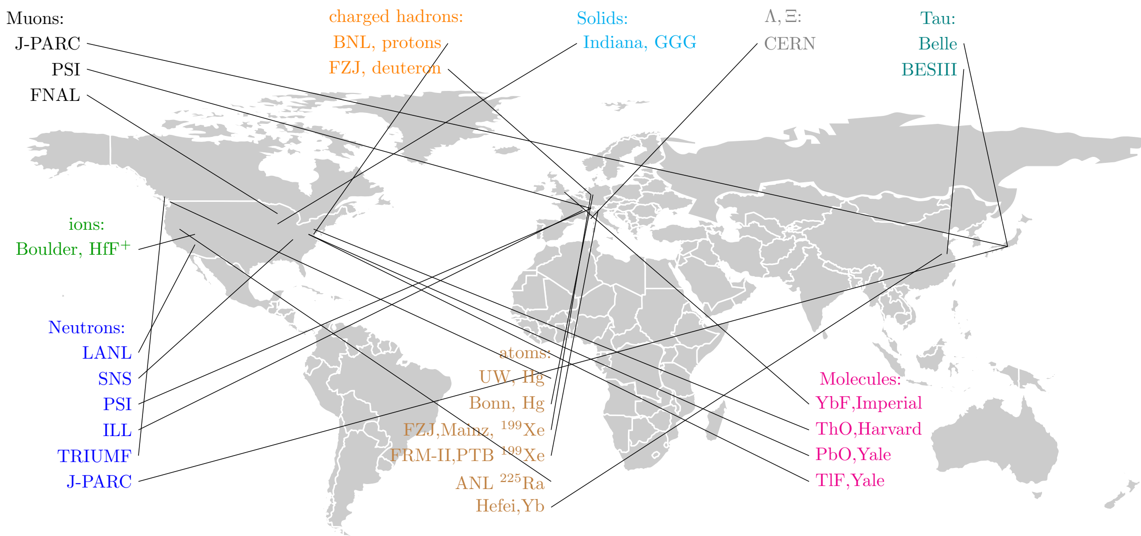


Figure 3: Current and proposed EDM experiments around the world.

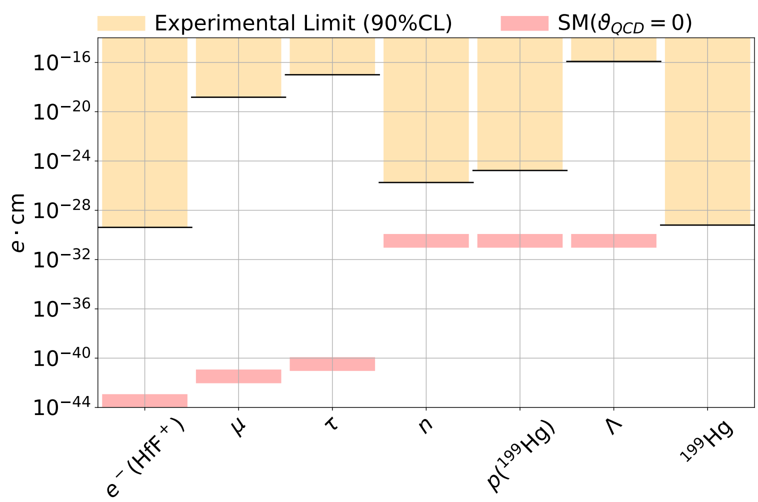


Figure 4: Upper Limits on EDMs and expectations form the Standard Model for various leptons, hadrons and the Hg atom.

as well for neutron, proton, Λ and ^{199}Hg. No finite EDM was found yet, but impressive limits were obtained. The red bands indicate expectations for EDMs from the Standard Model physics originating from the $\mathcal{CP}$-violation in the Standard Model (CKM matrix). Extensions of the SM, like super symmetry allow for much larger EDM values. Especially the electron EDM result derived from a measurement on HfF$^+$ ions exclude already some of the SUSY parameter space. Table 1 lists the results shown in figure 4 and gives also sensitivities goals of future experiments.

4.2 Connection to dark matter searches

Axion and axion like particles (ALPs) also influence the spin precession. One effect is an oscillating EDM:

$$d = d_{\mathrm{DC}} + d_{\mathrm{AC}} \cos(\omega_a + \varphi_a) \tag{9}$$

particle	current values	ref.	perspective sensitivity	ref.
e^-	$-1.3 \pm 2.0(stat) \pm 0.6(sys)\, 10^{-30}$e $\cdot$ cm	[13]	1×10^{-30} e $\cdot$ cm (ACME)	[14]
	$4.3 \pm 3.1(stat) \pm 2.6(sys)\, 10^{-30}$e $\cdot$ cm	[15]	5.8×10^{-30} e $\cdot$ cm (storage ring)	[16]
μ	$-0.1 \pm 0.6(stat) \pm 0.8(sys)\, 10^{-19}$e $\cdot$ cm (μ^+)	[17]	1.5×10^{-21} e $\cdot$ cm (J-PARC)	[18]
	$-0.1 \pm 0.3(stat) \pm 0.7(sys)\, 10^{-19}$e $\cdot$ cm (μ^-)		6×10^{-23} e $\cdot$ cm (PSI)	[19]
			1×10^{-20} e $\cdot$ cm(FNAL)	[20]
τ	$\mathrm{Re}(d_\tau) = -0.62 \pm 0.63 \cdot 10^{-27} e \cdot$ cm	[21]		
n	$0.0 \pm 1.1(stat) \pm 0.2(sys)\, 10^{-26}$e $\cdot$ cm	[12]	1×10^{-28} e $\cdot$ cm (n2EDM@PSI)	[22]
p	1.7×10^{-25} e $\cdot$ cm (90%CL)		1×10^{-29} e $\cdot$ cm (storage ring)	[5, 23]
	Hg: $2.20 \pm 2.75(stat) \pm 1.48(sys)\, 10^{-30}$e $\cdot$ cm (Hg)	[10, 24]		
Λ	$-3.0 \pm 7.4\, 10^{-17}$e $\cdot$ cm	[25]	1.3×10^{-18} e $\cdot$ cm (LHC)	[26]
Λ_c^+, Ξ_c^+			2.1×10^{-17} e $\cdot$ cm (LHC, bent crystalls)	[26]
deuteron			1×10^{-17} e $\cdot$ cm (COSY, magnetic ring)	[9]

Table 1: Current best EDM results and perspectives for improvement.

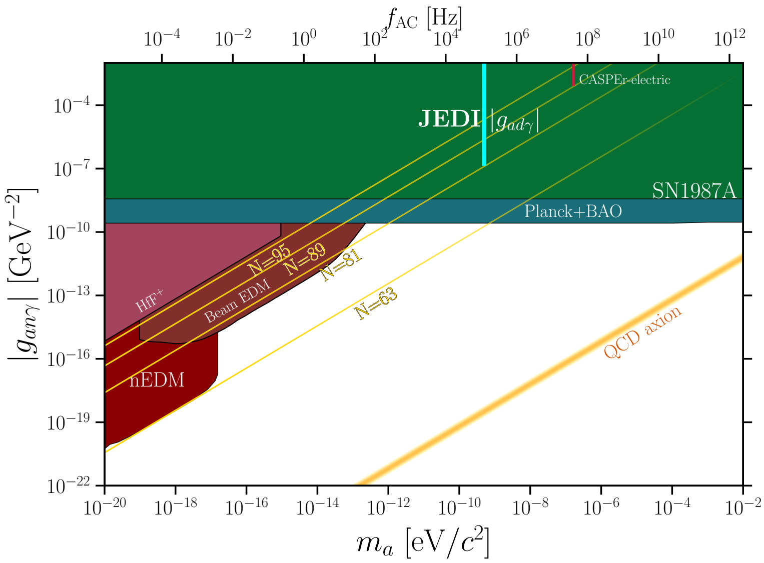


Figure 5: Limits on axion-EDM coupling from various EDM experiments [28].

caused by an axion/ALP background field [27]. The oscillation frequency ω_a is simply given by the axion/ALP mass: $m_a c^2 = \hbar\omega_a$. Many EDM experiments, in parallel to the analysis of the static EDM (d_{DC}) presented in section 4.1 also performed an analysis of the oscillating part, d_{AC}, which can be translated to an axion-EDM coupling constant. Results are shown in figure 5. EDMs experiment are dominating the limits. Note that the excluded area by SN1987A and Planck+BAO are strongly model dependent.

5. Summary & Conclusions

Measurements of electric dipole moments will contribute to answer fundamental questions of the Standard Model of particle physics and cosmology. Many experimental techniques are employed to search for EDMs of various particles. Up to now only impressive upper limits are obtained, excluding already some parameter space of proposed extensions of the Standard Model. EDMs are also sensitive to various axion/ALP couplings.

Acknowledgments

I would like to thank Achim Andres and Hans Ströher for carefully reading and commenting on the manuscript.

References

[1] Gordon Baym, D. H. Beck, *Elementary quantum mechanics of the neutron with an electric dipole moment*, *Proceedings of the National Academy of Sciences (PNAS)* **113** (2016) 7438.

[2] Particle Data Group collaboration, *Review of Particle Physics*, *PTEP* **2022, chapter 9** (2022) 083C01.

[3] V. Anastassopoulos et al., *A Storage Ring Experiment to Detect a Proton Electric Dipole Moment*, *Rev. Sci. Instrum.* **87** (2016) 115116.

[4] Hacıömeroğlu, S. and Semertzidis, Y. K., *Hybrid ring design in the storage-ring proton electric dipole moment experiment*, *Phys. Rev. Accel. Beams* **22** (2019) 034001.

[5] CPEDM Collaboration collaboration, Abusaif, F. et al, *Storage ring to search for electric dipole moments of charged particles: Feasibility study*, CERN Yellow Reports: Monographs, CERN, Geneva (2021), 10.23731/CYRM-2021-003.

[6] V.A. Dzuba and V.V. Flambaum, *Parity violation and electric dipole moments in atoms and molecules*, *Int. J. Mod. Phys. E* **21** (2012) 1230010.

[7] K. Jungmann, *Searching for electric dipole moments*, *Annalen Phys.* **525** (2013) 550.

[8] Baryshevsky, V. G., *Electromagnetic dipole moments and time reversal violating interactions for high energy charged baryons in bent crystals at LHC*, *Eur. Phys. J. C* **79** (2019) 350.

[9] J. Pretz, *Electric Dipole Moment Measurements at Storage Rings*, *JPS Conf. Proc.* **37** (2022) 011009.

[10] B. Graner, Y. Chen, E.G. Lindahl and B.R. Heckel, *Reduced limit on the permanent electric dipole moment of* ^{199}Hg, *Phys. Rev. Lett.* **116** (2016) 161601.

[11] N.F. Ramsey, *A molecular beam resonance method with separated oscillating fields*, *Phys. Rev.* **78** (1950) 695.

[12] C. Abel, S. Afach, N.J. Ayres, C.A. Baker, G. Ban, G. Bison et al., *Measurement of the permanent electric dipole moment of the neutron*, *Phys. Rev. Lett.* **124** (2020) 081803.

[13] T.S. Roussy, L. Caldwell, T. Wright, W.B. Cairncross, Y. Shagam, K.B. Ng et al., *An improved bound on the electron's electric dipole moment*, *Science* **381** (2023) 46.

[14] X Wu and Z Han and J Chow and D G Ang and C Meisenhelder and C D Panda and E P West and G Gabrielse and J M Doyle and D D eMille, *The metastable* $Q^3\Delta_2$ *state of ThO: a new resource for the ACME electron EDM search*, *New Journal of Physics* **22** (2020) 023013.

[15] 'ACME' collaboration, *Improved limit on the electric dipole moment of the electron*, *Nature* **562** (2018) 355.

[16] R. Suleiman, V.S. Morozov and Y.S. Derbenev, *High precision fundamental physics experiments using compact spin-transparent storage rings of low energy po larized electron beams*, *Physics Letters B* **843** (2023) 138058.

[17] Muon (g-2) collaboration, *An Improved Limit on the Muon Electric Dipole Moment*, *Phys. Rev.* **D80** (2009) 052008.

[18] Yutaro Sato, *J-PARC Muon g-2/EDM Experiment*, in *Proceedings of the 3rd J-PARC Symposium (J-PARC2019)* (2019), DOI.

[19] M. Sakurai, A. Adelmann, M. Backhaus, N. Berger, M. Daum, K.S. Khaw et al., *muedm: Towards a search for the muon electric dipole moment at psi using the frozen-spin technique*, in *Proceedings of the 24th International Spin Symposium (SPIN2021)*, Journal of the Physical Society of Japan, Dec., 2022, DOI.

[20] S. Foster, *Muon g-2 and EDM at Fermilab*, *PoS* **Muon4Future2023** (2023) 016.

[21] K. Inami, K. Hayasaka, I. Adachi, H. Aihara, S. Al Said, D.M. Asner et al., *An improved search for the electric dipole moment of the τ lepton*, *Journal of High Energy Physics* **2022** (2022) .

[22] N.J. Ayres, G. Ban, L. Bienstman, G. Bison, K. Bodek, V. Bondar et al., *The design of the n2edm experiment: nedm collaboration*, *The European Physical Journal C* **81** (2021) .

[23] J. Alexander et al., *The storage ring proton EDM experiment*, `arXiv:2205.00830`.

[24] B. Graner, Y. Chen, E.G. Lindahl and B.R. Heckel, *Erratum: Reduced Limit on the Permanent Electric Dipole Moment of* ^{199}Hg *[Phys. Rev. Lett. 116, 161601 (2016)]*, *Phys. Rev. Lett.* **119** (2017) 119901.

[25] L. Pondrom, R. Handler, M. Sheaff, P.T. Cox, J. Dworkin, O.E. Overseth et al., *New Limit on the Electric Dipole Moment of the Λ Hyperon*, *Phys. Rev. D* **23** (1981) 814.

[26] L. Henry, D. Marangotto, A. Merli, N. Neri, J. Ruiz and F. Martinez Vidal, *Search for new physics via baryon EDM at LHC*, `arXiv:2101.00928`.

[27] Particle Data Group collaboration, *Review of Particle Physics*, *PTEP* **2022, chapter 90** (2022) 083C01.

[28] S. Karanth, *New Method to Search for Axion-Like Particles Demonstrated with Polarized Beam at the COSY Storage Ring*, in *IPAC2021,Campinas, SP, Brazil*, 2021, https://doi.org/10.18429/JACoW-IPAC2021-WEPAB188.

PoS(HQL2023)010