ERC Consolidator Grant 2020
Research proposal [Part B1]

Search for the muon electric dipole moment using the frozen-spin technique

muEDM

Cover Page:

- Name of the Principal Investigator (PI) Philipp Schmidt-Wellenburg
- Name of the PI's host institution for the project Paul Scherrer Institute
- Proposal duration in months 60 months

The Standard Model (SM) of particle physics, as we know it, is on the brink of an extension to include the evidence of new physics indicating lepton flavor universality (FLU) violation. Electric dipole moments (EDM)s of fundamental particles violate time invariance and the combined symmetry of charge and parity (CP). The existence of a large muon EDM (muEDM), detectable in this proposal, is made plausible in semileptonic decays of heavy mesons at LHCb, BaBar, and Belle combined with the corroborated tension in the measurement of the muon's anomalous magnetic moment (AMM). The discovery of a muEDM would manifest CP and FLU violation, revealing physics beyond the SM (BSM).

Previous searches for a muEDM, with an upper limit of 1.8×10^{-19} ecm (CL 95%), used the high-precision data collected to measure the muon AMM to extract a signal.

In this application, I propose a dedicated search for the muEDM using for the first time the frozen-spin technique, improving the current sensitivity to better than 6×10^{-23} ecm. This novel technique uses the large relativistic electric field in the muon's rest frame moving in a strong, 3T, uniform magnetic field and increases the sensitivity by canceling the precession due to the AMM adjusting an electric field perpendicular accurately to the magnetic field and the muon's momentum.

In a precursor experiment, I will demonstrate for the first time the frozen-spin technique and improve the sensitivity to better than 3×10^{-21} ecm, probing uncharted and otherwise inaccessible territory in BSM theories. Further, the precursor serves as a perfect testbed to demonstrate the development of novel methods and techniques essential for the final high-precision measurement.

This project is the first step, within the muEDM initiative led by me, towards a final experiment at the Paul Scherrer Institute that significantly extends and ideally complements searches for EDMs in other systems and direct searches for new physics at high-energy particle colliders.

Section a: Extended Synopsis of the scientific proposal

Main Objectives and Impact

The project's primary goal is to measure the electric dipole moment (EDM) of the muon with a precision of better than 6×10^{-23}ecm using for the first time the frozen-spin technique applied in a compact storage ring [1]. This search for a non-zero muon EDM (muEDM) is a unique opportunity probing previously uncharted territory in theories beyond the standard model (BSM) and corresponds to:

- roughly three orders of magnitude improvement compared to the current experimental result of $d_\mu = (0 \pm 9) \times 10^{-20}$ecm [2];
- a model-independent and complementary search for new physics in the lepton sector;
- a unique test of lepton flavor universality (LFU);
- a first stringent limit on an otherwise poorly constraint Wilson coefficient.

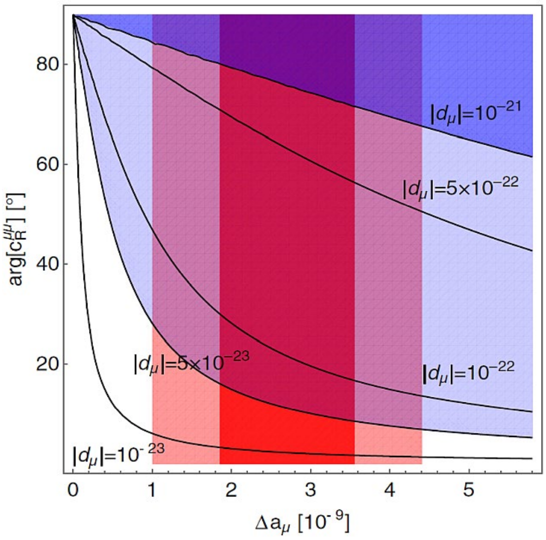

Figure 1: Exclusion contours of muEDM as function of the AMM of the muon, and imaginary phase of its associated Wilson coefficient.

The Standard Model (SM) of particle physics produces accurate predictions of nearly all fundamental properties and interactions observed in laboratories on earth. However, it is obvious that the model is incomplete, challenged by cosmological observations [3], requiring an extension to explain the origins of matter, dark matter, dark energy, neutrino masses. Notably, the observed matter-antimatter asymmetry of the Universe [4] hints at the existence of a complete theory at much higher energies beyond the SM, of which the SM is the low energy realization. Baryogenesis or leptogenesis, creating more matter than anti-matter, require an additional violation of the combination of charge conjugation and parity symmetry (CP) beyond the SM [5, 6]. Electric dipole moments violate time-reversal and parity symmetry, and by the virtue of the CPT theorem also CP. The same underlying interactions might link baryogenesis to laboratory measurements of EDMs.

Today, particle physics' principal focus is the discovery of BSM physics. While no BSM particles were found at the LHC yet [7, 8], high precision measurements have access to energies exceeding the reach of LHC by testing indirect effects [9]. Intriguingly, the most substantial evidence for BSM physics appears in measurements involving muons. Especially semileptonic decays of B-meson at LHCb, Belle, and BaBar [10, 11, 12] and the corroborated muon g-2 deviation from the SM [13, 14, 15] are evidence for lepton flavor universality violation (LFUV). These remarkable hints for new physics are incompatible with minimal flavor violation (MFV) in the lepton sector [16]. In model-independent effective-field theories, the imaginary part of the Wilson coefficient, see Figure 1, of which the real part gives rise to the g-2 of a lepton, gives rise to the EDM [17, 18]. This intrinsic connection of the muEDM to the g-2 and the tantalizing evidence for LFUV can be convincingly tested by searching for the muEDM.

In the past, a muEDM search seemed less attractive as the impressive limits on the electron EDM from measurements using atoms or molecules, e.g., thorium oxide molecules $d_e < 1.1 \times 10^{-29} e\mathrm{cm}$ (CL 90%) [19], were rescaled, by the ratio m_μ/m_e, assuming MFV. Naïve rescaling results in a limit $d_{\mu\leftarrow e} < 2.3 \times 10^{-27} e\mathrm{cm}$ (CL 90%), which is many orders of magnitude better than the direct limit $d_\mu < 1.5 \times 10^{-19} e\mathrm{cm}$ (CL 90%). However, MFV is a model-dependent assumption allowing a light particle spectrum in principle observable at the LHC, where this reduces the degree of fine-tuning in the Higgs sector while respecting at the same time flavor constraints.

Now is exactly the right time for a major step forward towards a dedicated muEDM experiment part of the broader muEDM initiative founded by me. With a team of outstanding post-doctoral researchers and PhD students, I will develop all features of a precursor experiment capitalizing on an existing solenoid at the Paul Scherrer Insitute (PSI) and demonstrate the frozen-spin technique for the first time. This will crosscheck results on the muEDM with a resolution of about $10^{-21}e\mathrm{cm}$ expected in the next five years by the FNAL(g-2) and the J-PARC(g-2)/muEDM collaborations [20, 21], probing unexplored territory. The outcome of this groundbreaking research will permit the construction of a new instrument, which will further increase the sensitivity to a muEDM to at least 6×10^{-23}ecm.

State-of-the-Art Measurements of the Muon EDM

In high energy physics, the EDM can be described as the form factor of the axial-vector coupling of the electromagnetic current to a photon of the electric field. At low energies, the EDM is equivalent to the coupling strength d of the spin, $\vec{s}$, to the electric field, $\vec{E}$, resulting in an electric precession frequency $\omega_e = -2d.E/\hbar$ of the spin in an electric field, E, similar to the Larmor precession $\omega_L = -2\mu.B/\hbar$ in the case of the magnetic dipole moment, μ, in a magnetic field, B.

The first dedicated search for an electric precession due to an electric dipole moment was performed on a beam of neutrons by the Nobel laureates E.M. Purcell and N.F. Ramsey and their student J.H. Smith [22]. As in most measurements that followed, the system under investigation was electrically neutral and could easily be exposed to large electric fields. If a charged particle is exposed to an electric field, the particle will accelerate and move to a region where the field is zero. A possible way to circumvent this problem is to use the motional electric field, $\vec{E}^* = \gamma\vec{v} \times \vec{B}$, generated in the rest frame of a charged particle moving with the velocity $\vec{v} = \vec{\beta}c$, where $\gamma = (1-\beta^2)^{-1/2}$ and c is the speed of light, in a magnetic field on a closed orbit. The motional electric field can be much larger than any practically applied field in a laboratory. In the here proposed scenario, muons with a momentum of $P = 125$ MeV/c, hence $\gamma = 1.57$ and $\beta = 0.77$ will be stored in a magnetic field of $B = 3$T which results in a field of $E^* \approx 1$GV/m.

The first measurement in 1958 already exploited this principle, which resulted in an upper limit of $2.9 \times 10^{-15}\ e\mathrm{cm}$ (C.L. 95%) [23]. Today's most sensitive results were extracted using data from muon (g − 2) storage ring experiments measuring the spin precession

$$\vec{\omega} = -\frac{q}{m}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \frac{q}{m}\frac{\eta}{2}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right], \qquad (1)$$

where q is the charge of the muon, $a = (g-2)/2$ with g from the definition of the magnetic dipole moment $\vec{\mu} = gq\vec{s}/(2m)$ and similarly, η is defined by the electric dipole moment $\vec{d}_\mu = \eta q\vec{s}/(2mc)$. The weak decay of muons is inherently parity-violating. Consequently, the highest-energy positrons are emitted along with the muon spin, and the precession can be measured by detecting decay positrons with a detector system inside the storage ring.

The first term of equation (1) is the anomalous precession frequency, ω_a. The second term is the electric precession ω_e due to an EDM, oriented perpendicular to B. In the presence of a muEDM, the observed frequency will be $\omega = \sqrt{\omega_a^2 + \omega_e^2}$, and a tilt in the precession plane by $\zeta = \mathrm{atan}(\eta\beta/(2a))$, will lead to a vertical oscillation.

Previous experiments were built and optimized to measure with the highest accuracy the anomalous magnetic moment $a_\mu = (g-2)/2$. The FNAL/BNL [2, 15, 24] experiment uses muons with $p = 3.1\mathrm{GeV}/c$, also known as "magic momentum", cancelling the electric term in ω_a in equation (1) and making the muon precession independent of electric fields. The sensitivity to a muon EDM is limited by resolving the vertical amplitude, proportional to ζ, of the oscillation in the tilted precession plane. The J-PARC E34 experiment [21] will use muons with a much lower momentum of $p = 300\mathrm{MeV}/c$ from a re-accelerated thermal muon beam with a thousand time lower horizontal emittance. This permits a storage ring design without an electric field, making all electric terms in equation (1) zero. An EDM will be deduced from the amplitude of the vertical precession. Both experiments aim for a sensitivity of about $10^{-21}e\text{cm}$ [20, 21].

Only by canceling the entire first term of equation (1), using an electric field, $E_f \cong aBc\beta\gamma^2$, perpendicular to the magnetic field and the muon momentum, it is possible to measure the electric precession in equation (3) alone, proportional to d_μ, increasing the sensitivity significantly. The seminal discussion of this frozen-spin technique by Farley et al. [1] proposed a storage ring with $r = 7\text{ m}$, using muons with $p = 500\text{ MeV}/c$ in a magnetic field of $B = 0.5\text{ T}$ resulting in an electric field of $E = 2\text{ MV/m}$, with a sensitivity of about $1.5 \times 10^{-16}\ e\text{cm}$ per muon.

Measurement of the muEDM Using the Frozen-Spin Technique in a Table-Top Storage Ring at PSI

At PSI, the highest intensity muon beams, suitable for the experiment, deliver up to $2 \times 10^8 \mu^+/s$ at a momentum of $p = 125\text{ MeV}/c$. Using the same electric field of $E = 2\text{MV/m}$ and a magnetic field of $B = 3\text{ T}$, this results in a table-top storage orbit of $r = 0.14\text{ cm}$ with a sensitivity of $0.5 \times 10^{-16}\ e\text{cm}$ per muon. The sensitivity scales with $\gamma/E_f\ = p^{-2}$, keeping the radius fixed.

Figure 2 shows a sketch of the experiment proposed by the muEDM initiative. Highly polarized muons, $P = 0.93\%$, with a momentum of $p = 125\text{ MeV}/c$ from backward decaying pions, enter the solenoid from the bottom through an injection channel, defining the lateral divergence. The muons move on a 3D helix to the center [21, 25]. a magnetic pulse twists the muons onto a stable orbit of radius $r = 0.14\text{ m}$ in the weakly-focusing field region. During storage, the spin precesses out of the

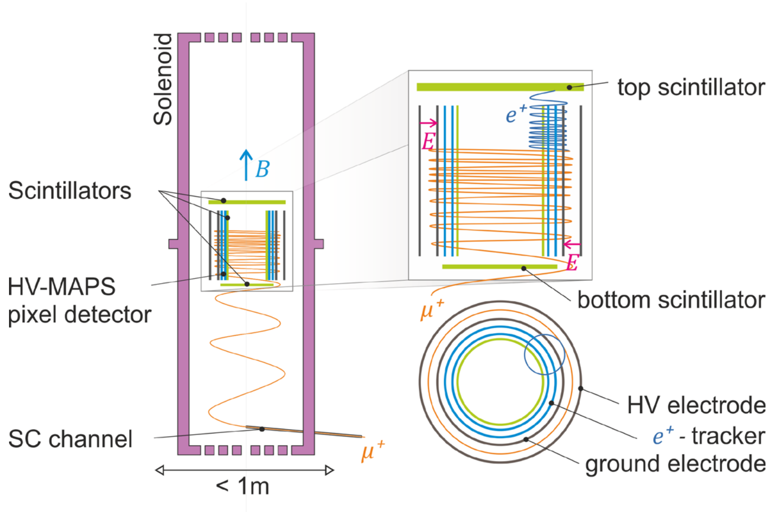

Figure 2: Sketch of compact storage solenoid to search for the muon EDM using the frozen spin technique. Muons are injected from the bottom through a superconducting channel and are kicked in the center of the solenoid onto a stable orbit. The decay muons are detected using a positron tracker made of HV-MAPS and scintillating fibers.The electric field is generated between two concentric cylinders, of which the inner is grounded.

horizontal orbital plane around the motional electric field until the muon decays after an average laboratory lifetime of $\gamma\tau = 3.4\mu\text{s}$ with an average decay asymmetry of $\alpha = 0.3$. A position sensitive detector records the track of the decay positrons to extract the vertical spin polarization with time $\Pi \approx P\alpha\omega_e t$. Combined with Poisson counting statistics this yields a measurement sensitivity of

$$\sigma(d_\mu) = \frac{\hbar\gamma^2 a}{2PE_f\sqrt{N}\gamma\tau\alpha}. \qquad (2)$$

First simulations of the injection combined with results from a characterization of a potential beamline, muE1, at PSI show that about $60000\,\mu^+/s$ could be stored. Assuming one year of measurements, effectively 200 days, and overall efficiency of 0.7, a statistical sensitivity of $\sigma(d_\mu) = 6 \times 10^{-23}e\text{cm}$ would be achieved. The spectrometer can be adapted to a lower or higher momentum by adjusting the electric and magnetic fields.

A lateral injection like in the FNAL storage ring, using a single horizontal kick generated by a pulsed magnetic field, becomes essentially impossible for a small diameter storage ring. Adelmann et al. [26] proposed circumventing this by using a multi-turn injection based on an approach used in a compact electron synchrotron radiation source [27, 28]. However, simulations showed that the injection channel's fringe field and the required multiple transitions of the muon through high voltage and ground electrode during injection lead to significant losses [29].

A vertical injection [25] will move the injection channel far away from the critical field region necessary for storage, and the muons can enter without passage through electrodes. Muons from backward decaying pions in the superconducting decay channel at PSI have a larger emittance, with $X', Y' \approx 90\,\mathrm{mrad}$, contrary to the proposed low emittance beam, with $X', Y' \leq 1\mathrm{mrad}$ at J-PARC. In order to accommodate better the large emittance of the existing PSI beam, a meticulous choice of the magnetic-field gradient between injection and detection region must be found. First results from Monte Carlo simulations using G4beamline and a relative magnetic-field gradient of 1\ calculated using a 2D FEM code, result in a 3×10^{-3} injection efficiency. In this concept, a pulsed magnetic quadrupole field, generated by two coils in anti-Helmholtz configuration, with $B_r^{\mathrm{pulse}} \approx 1\mathrm{mT}$, twists the vertical momentum component of the muon into the horizontal plane. Two cylindrical electrodes provide the electric field, $E_f \approx 2\,\mathrm{MV/m}$, for the frozen-spin technique. Inside the grounded inner electrode, a position-sensitive detector records the positron tracks from muon decay. Similar to the positron detection in the FNAL g-2 experiment, this will be used to measure the horizontal precession frequency ω, from equation (1), as a function of the electric field. Figure 3 shows the asymmetry of upwards n_u and downwards n_d tracks, $A(t) = (N_\uparrow(t) - N_\downarrow(t))/(N_\uparrow(t) + N_\downarrow(t))$, as a function of time from a simulation with a large artificial muEDM.

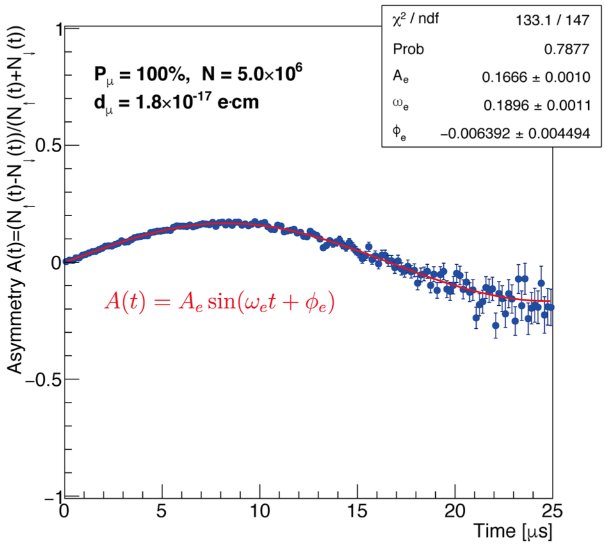

Figure 3: Up down asymmetry of simulated muon decay with an artificial $d_\mu = 1.8 \times 10^{-17} ecm$.

Pioneering Research and Development

Me and my group will spearhead investigations and develop methods and techniques required for the injection, storage, and application of the frozen-spin technique to search for the muEDM with unprecedented sensitivity. In a first measurement of the muEDM with a sensitivity of a $3 \times 10^{-21}\,e\mathrm{cm}$, using an existing solenoid magnet at PSI, we will prove these techniques' potential for a high precision measurement in the future and improve, in the case of a null result, the existing limit by more than a factor of thirty. My experience as technical coordinator of the neutron EDM measurement [30] and developing a UCN source with a ^{3}He cryostat [31] combined with my creativity in finding innovative solutions [32] will permit me to accomplish this ambitious goal. Two post-doctoral researchers will complete the team's expertise with skills in numerical modeling and accelerator physics. Several groundbreaking developments need to happen as part of the project:

- Magnetic quadrupole pulse with short $100\mathrm{ns}$ latency and short $100\mathrm{ns}$ pulse duration
- Nested electrode system made of ultrathin graphite sheets
- Development of a superconducting shield for the injection channel
- Design of magnetic-field correction coils and measurement device for precursor experiment
- Scintillator based detection system for precursor experiment

My team will investigate and optimize the injection of muons into the storage magnet. As the trajectories of muons are intrinsically linked to the magnetic and electric fields, we will set up a comprehensive finite element and Monte-Carlo model of the entire experiment. For this multivariate problem's multi-objective optimization, we will implement state-of-the-art generic algorithms combined with a surrogate model based on neural networks [33] to find an optimal configuration for the highest sensitivity.

A complex technological challenge is the counteracting effects between essential electrodes and the $100\mathrm{ns}$ magnetic pulse in the same region. The pulse will induce Eddy currents in the electrodes counteracting against the pulsed magnetic field. Thin and highlz resistive materials reduce damping of the pulse but increase the absorbed energy resulting in heat, difficult to remove in a vacuum. To find a good solution, we will test a series of different concepts in a dedicated setup. Colleagues from the PSI accelerator division will be consulted to design a suitable kicker power supply to deliver $1000\mathrm{A}$ at a repetition rate of $50\mathrm{kHz}$.

On top of the Eddy current issue, multiple scattering of positrons requires a minimal material budget for the electrodes. We will investigate design options by building a prototype made of high-performance plastics to mount and test graphite sheets and thin aluminum-coated Mylar or Kapton foils, minimizing the integral positron radiation length and take care that the damping of the magnetic pulse is acceptable. An alternative could be to use $20\mu\mathrm{m}$ diameter gold-plated tungsten wires closely spaced as electrodes. These tests will be accompanied by dedicated measurements of multiple scattering of positrons in sub-$100\ \mu\mathrm{m}$ substrates, using positrons at momenta below $100\ \mathrm{MeV}/c$.

In parallel, we will investigate and develop an efficient magnetic shield based on a superconducting tube made either of sheets of NbTi/Nb/Cu [34] or high-temperature superconductor (HTS) tapes/ribbons [35] to transport the muons from the outside of the magnet to the injection point. While the use of NbTi/Nb/Cu sheets was already demonstrated [36], previous tests with HTS failed, most probably due to soldering during fabrication. Using low-temperature solder and meticulous temperature control, we will produce a prototype tube with an HTS tape wound helically onto a copper tube. We will set up a cryostat for tests and demonstrate the shielding factor inside a high magnetic field of up to $5\mathrm{T}$.

We will produce various positron and muon detectors deploying scintillators read out by silicon photomultipliers for demonstration measurements. These will be tested with laboratory beta sources before mounted on the beamline.

A precision mapping device made of Hall sensors and NMR probes will be built to characterize the existing solenoid's magnetic field to design a correction coil system for the precursor experiment.

In test beam times on PSI's $\pi\mathrm{E}1$ muon beam, we will qualify each of these groundbreaking developments before combining them in the precursor experiment.

Expected Impact

The detection of a muon EDM would be a major discovery, comparable to the historical milestones by Wu, Lederman, Cronin, and Fitch, while a null result will serve as an important rail guard for models behind today's standard model. In any case, with a successful measurement, we will significantly contribute to a promising path to a substantially improved understanding of CP violation and lepton flavor universality.

In the course of this proposal, development of key components and their implementation in a first EDM measurement using a low muon momentum beam, the complexity of the project will be a constant driver of innovation in magnetic and electric field generation and control, muon and positron detection, and simulation techniques.

The know-how and experience gained in the project are also an important stepping stone towards a next-generation g-2 experiment that could use the planned high-intensity muon beam at PSI, crosschecking the final FNAL g-2 measurement.

An important extra impact will be the training and education of students and young researchers in a wide range of activities, simulations, hardware development, and data analysis. In addition, the relations of the new team at PSI with the newly founded muEDM initiative will be further developed and intensified to form the core of the future muEDM collaboration.

Section b: Curriculum vitae

PERSONAL INFORMATION

Family name, First name: Schmidt-Wellenburg, Philipp Anton
Researcher unique identifier(s): orcid.org/0000-0001-5474-672X
Date of birth: 19.09.1977
Nationality: German

- **EDUCATION**

2009 **Dr. rer. nat. Physik, "summa cum laude"**, *Technische Universität München, Germany*
"Production of ultracold neutrons in superfluid helium under pressure,"
PhD Advisor: Prof. Oliver Zimmer

2005 **Diploma in physics**, *Technische Universität München, Germany*
"Development and Tests of a Superthermal Helium-4 Source for the Production of Ultra Cold Neutrons"

- **CURRENT POSITION**

2015 – today **Staff Scientist,** *Laboratory for particle physics, Paul Scherrer Institute, Switzerland*
  - Leader of muEDM initiative (since 2019)
  - Co-Spokesperson of the neutron EDM at PSI (since 2018)

2009 – 2015 **Staff scientist on tenure track,** *Paul Scherrer Institute, Switzerland*
  - Technical coordinator of the neutron EDM at PSI (since 2011)
  - High voltage task manager (2009-2010)

- **PREVIOUS POSITION**

2006 – 2009 **Doctoral student,** *Institut Laue-Langevin, France*

- **SUPERVISION OF GRADUATE STUDENTS AND POST-DOCTORAL FELLOWS**

since 2009 **7 PhD students direct day-to-day supervision** (degree of co-supervision indicated if less than 100%, academic supervisor in parenthesis):

Mikio Sakurai (2018 -), muon EDM, (ETH Zürich, Prof. K. Kirch)
Pin-Jung Chiu (2017 -), Axion like particles, (ETH Zürich, Prof. K. Kirch)
Yoann Kermaidic (2014 – 2017) , neutron EDM, 30% co-supervision, (UJF Grenoble (2017), Prof. D. Rebreyend)
Elise Wursten (2013 -), neutron EDM, 50% co-supervision, (KU Leuven, Prof. N. Severijns)
Pataguppi Narasihma Murthy (2012 -), neutron EDM, 70% co-supervision, aborted (KU Leuven, Prof. N. Severijns)
Johannes Zenner (2009 - 2013), neutron EDM, (U. Mainz (2013), Prof. C. Plonka-Spehr)
Marlon Horras (2009-2012), ^{199}Hg magnetometer, 100%, (ETH Diss. Nr. 20558 , Prof. K. Kirch)

- **TEACHING ACTIVITIES (if applicable)**

2020 Lecturer – "How Neutron EDM-Experiments Really Work," HighRR lecture week, University of Heidelberg, Germany

2016 – today Lecturer – “Low energy particle physics,” ETHZ, Switzerland

2011 – 2011 Lecturer – Seminar “Epistomology – Physics of Light”, Zürcher Hochschule der Künste, Switzerland

- **ORGANISATION OF SCIENTIFIC MEETINGS**

2020 Organizer **“Kick-off workshop on the realization of a compact storage ring for the search of a muon EDM”** / Switzerland

2017 Member of International advisory committee, **“NOP – 2017”** / Japan

2014 Local organizer **"nEDM2014 – workshop"** / Switzerland

2010/14 Member of International advisory committee, **“GRANIT – 2010/14”** / France

- **SCIENTIFIC AND INSTITUTIONAL RESPONSIBILITIES**

since 2021 **Spokesperson** of the muon EDM initiative at PSI (founded 2021)

since 2018 **Spokesperson** of the neutron EDM collaboration at PSI

since 2014 **Leader** of the PSI based nEDM analysis

2010-2018 **Technical coordinator** nEDM experiment (2010-2018)

- **REVIEWING ACTIVITIES**

2018 Reviewer of the **TUCAN UCN** source project at **TRIUMF**

since 2017 Referee for the Austrian science fund (**FWF**)

since 2016 Referee for **J-PARC MLF**

2016 Reviewer of **SuperSUN** project for scientific council **ILL**

2014/19 Reviewer of **GRANIT** project for scientific council of **ILL** and **LPC**

Since 2009 Review for journal (last years: **PRL**, **PRC**, **PRA**, **OE**, **NIMA**, **EPJA**, **NJP**, **SciPost**)

- **MEMBERSHIPS OF SCIENTIFIC SOCIETIES**

since 2009 Member of CHIPP, Swiss Institute of Particle Physics

since 2009 Member of Swiss Physical Society

since 1998 Member of German Physical Society

- **MAJOR COLLABORATIONS**
    - ***Measurement of the muon Electric Dipole Moment*****,** since 2018**.** One publication
    Spokesperson of the muEDM@PSI initative
    - ***Measurement of the neutron Electric Dipole Moment*****,** since 2009. 33 publications.
    Member, technical responsible, and spokesperson of the nEDM@PSI collaboration
    - ***Time-of-flight Fourier spectrometry****,* period 2014-2016, Three publications.
    Member in the activity lead by A.I. Frank (JINR, Dubna, Russia)
    - ***Quantum mechanics of bouncing neutrons****,* period 2006-2009. Two publications.
    Member of the GRANIT collaboration led by V. Nesvizhevsky (ILL, Grenoble, France).
    - ***Production of ultracold neutrons in superfluid helium***, period 2004-2011, 13 publications. Member in the activity lead by O. Zimmer (ILL, Grenoble, France).

Appendix: Current research grants and any on-going applications related to the proposal of the PI (Funding ID)

Mandatory information

Current Grants

Project Title	*Funding source*	*Amount (Euros)*	*Period*	*Role of the PI*	*Relation to current ERC proposal*[1]
none					

On-going and submitted grant applications (Please indicate "None" when applicable):

Project Title	*Funding source*	*Amount (Euros)*	*Period*	*Role of the PI*	*Relation to current ERC proposal*[2]
Systematic Effects in Electric Dipole Searches at the Paul Scherrer Institute	SNF 204118	438229	01.10.21 to 31.09.25	Principal investigator	The request asks for 4 years PhD student in the neutron EDM, and **2 years** of **post-doctoral researcher** to investigate analytically and with MC methods systematic effects in the muon EDM. Complements task of post-doc in this proposal by taking account all sources of systematic effects.

[1] Describe clearly any scientific overlap between your ERC application and the current research grant or on-going grant application.

Section c: Early achievements track-record

My principal research interest focuses on applying spin precession physics to search for new physics beyond the standard model. The spins of the lightest unstable particles of their kind, the neutron (baryon) and the muon (lepton) are uniquely suited as probes. In particular, I am interested in measurements of an electric coupling to the spin, the electric dipole moment, or a pseudo magnetic coupling generated by Axions, which could be discovered in the next-generation experiments.

During my PhD, I acquired a broad experimental physics background by building, commissioning, and using a ^{3}He-cryostat to produce ultracold neutrons (UCN) in superfluid helium under high pressures. The following skills will contribute to the success of the proposed research:

- Cryogenic engineering and experimental techniques
- MC optimization and design of monochromator of neutron delivery beamline H172 of the GRANIT project
- Characterization of a UCN detector with spatial resolution, based on a ^{6}Li coated silicon pixel detector

At PSI, I am involved in all neutron EDM activities. As technical coordinator, analysis group leader, and co-spokesperson of the nEDM collaboration, I acquired a profound knowledge of the experiment, the underlying physics, and project management. I consider the following skills essential for the success of the proposed high-gain project off the beaten track:

- Expert in high electric fields
- Expert in magnetic field measurement and interpretation
- Creative thinking, developing new techniques like the UCN spin-echo measurement
- Development of an automatic data analysis on blinded data sets
- Integrative and participative management style, appreciating the different skillsets in large, diverse international teams

Since 2018, I lead the exploratory project for a muon EDM at PSI by characterizing possible muon beamlines and investigating concepts to identify the best experiment layout. I am the lead author of the successful letter of intent submitted to PSI's research advisory board. As the spokesperson of the muEDM initiative, I coordinate all research activities.

I have authored and co-authored 74 articles (60 without my Ph.D. supervisor) in peer-reviewed journals: 1 Phys. Rev. X, 3 Phys. Rev. Lett., 3 Phys. Rev. A., 5 Phys. Rev. C, 3 Phys. Rev. C, 6 Eur. Phys. J A and 32 others, with a total of 1148 citations. Seven papers have received more than 30 citations (the top one has 275 citations). My h-index is 18 (adsabs.havard.edu, Scopus). The nEDM collaboration board's publication policy imposed a strict alphabetic order of authors and decided against submission to Nature and Science in the past.

REPRESENTATIVE PUBLICATIONS

[Number of citations using adsabs.havard.edu, collaboration papers: three authors et al., full list of authors can be find in References at the end]

1. C. Abel, S. Afach, N.J. Ayres, *et al.* "Optically pumped Cs magnetometers enabling a high-sensitivity search for the neutron electric dipole moment," PRA 101, 2020, 053419, [cited by 8, without PhD advisor, supervisor of PhD on an adaptation of the variometer method to the nEDM experiment using scalar magnetometers [37]]
2. C. Abel, S. Afach, N.J. Ayres, *et al.* "Measurement of the Permanent Electric Dipole Moment of the Neutron," PRL 124, 2020, 081803, [cited by 90, without PhD advisor, lead and corresponding author, APS Focus and editor's suggestion [30]]
3. A. Crivellin, M. Hoferichter, P. Schmidt-Wellenburg, "Combined explanations of (g -2)μ,e and implications for a large muon EDM," PRD 98, 2018, 113002, [cited by 113, without PhD advisor, muEDM theory motivation and a description of the experiment]
4. C. Abel, S. Afach, G. Ban, *et al.* "*Search for Axion-like Dark Matter through Nuclear Spin Precession in Electric and Magnetic Fields*," PRX 7, **2017,** 041034, [cited by 23, the first

result on oscillating EDMs, technical coordination, demonstrating sensitivity to dark matter physics [38]]

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8. S. Afach, G, Ban, G. Bison, *et al.* "*Constraining interactions mediated by axion-like particles with ultracold neutrons*," PLB 745, **2015**, 58, [cited by 25, without PhD supervisor, coordination of measurement for the search of short-range spin-dependent force [40]]
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10. F.M. Piegsa, M. Fertl, S.N. Ivanov, M. Kreuz, K.K.H. Leung, P. Schmidt-Wellenburg, T. Soldner, and O. Zimmer, "New source for ultracold neutrons at the Institut Laue-Langevin," PRC 90, **2013,** 015501 [cited 30, with PhD supervisor, description of UCN source and beamline I developed during my PhD]

INVITED PRESENTATIONS

Since 2010 I have accepted 35 talk invitations at conferences (many plenary), workshops, colloquia, and seminars. Most relevant conferences and workshops:
744. WE-Heraeus-Seminar / Towards Storage Ring Electric Dipole Moment Measurements, Germany (online), 2021; **Snowmass EDM / MDM workshop,** USA (online), 2020, **APS April Meeting 2020** (plenary), USA (online), 2020, **Particle physics with neutrons at the ESS,** Sweden, 2018, **XIIth International Workshop on the Interconnection between Particle Physics and Cosmology** *, Switzerland, 2018,* **7th International Symposium on Symmetries in Subatomic Physics**, Germany, 2018, **Solvay workshop: "Beyond the Standard Model with Neutrinos and Nuclear Physics"**, Belgium, 2017, **XII Rencontres de Vietnam - High Sensitivity Experiments Beyond the Standard Model,** Vietnam, 2016, **6th International Symposium on Symmetries in Subatomic Physics**, Canada, 2015,", **5th International Symposium on LEPTON MOMENTS**, USA, 2014, **GRANIT 2014 - workshop,** France, 2014, **CP Violation in Elementary Particles and Composite Systems,** India, 2013, **EDM Searches at Storage Rings,** Italy, 2012, and **7th Patras Workshop on Axions, WIMPs and WISPs**, Greece, 2011.

Most relevant colloquia and seminars:
INFN Seminar, Roma (online), Italy, 2020, **HEP Seminar Californian Institute of Technology**, USA (online), 2020, "The latest episode in the quest for an electric dipole moment of the neutron," **University of Kentucky Department of Physics and Astronomy Colloquium Series**, Lexington (online), USA, 2020, **Forschungszentrum Jülich, Seminar on particle physics,** Germany, 2018, **TRIUMF Colloquium,** Canada, *"Search for static and oscillating neutron electric dipole moments at PSI,"* **Karlsruher Institut für Technologie – ITEP-Kolloquium,** Deutschland, 2017, **CENPA Seminar**, University of Washington, USA, 2015, **TUNL Seminar**, Duke University, USA, 2014, and **J-PARC**, Japan, 2014.

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