NCCR Outline Proposal

Title of the NCCR	Muoniverse
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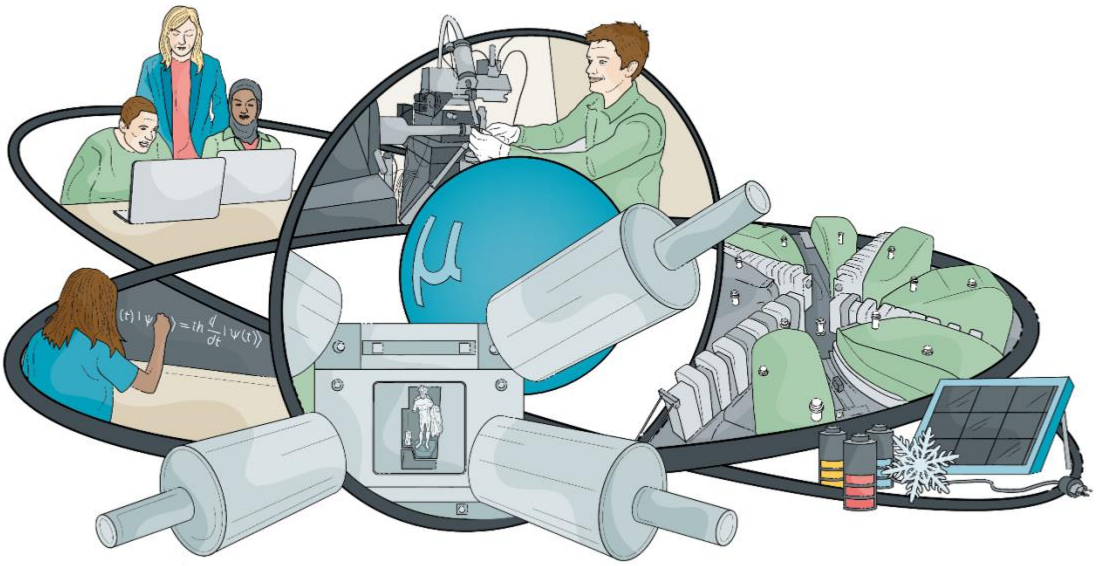

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1 Executive summary

Muon science is a vibrant field that explores and exploits the unique properties of muons, the ‘heavy siblings’ of electrons. The vision of NCCR Muoniverse is to inspire a pioneering community across the natural, engineering, and heritage sciences that directly benefits from muons as highly sensitive probes for fundamental physics, materials and devices, and cultural and archaeological artefacts — for the benefit of basic and applied science in Switzerland as well as of Swiss industry and society at large.

The muon is an elementary particle closely related to the electron, but of a different ‘flavour’ and about 207 times heavier. The unique properties of the muon stem from its relatively large mass, its magnetic moment, and the fact that it is unstable and decays with a lifetime on the order of microseconds, which is long compared to that of other unstable subatomic particles. Muons are established as prime probes for fundamental particle physics, for instance to study effects beyond the so-called Standard Model. They also form exotic atoms, the spectroscopy of which addresses questions regarding nuclear structure and quantum electrodynamics. In condensed-matter systems, muons are used in particular to investigate novel quantum materials such as exotic magnets or superconductors, where muons implanted into the material act as sensitive local magnetic probes. In the applied sciences, muons are being harnessed in a growing number of fields, including the characterization of semiconductor devices, radiography (‘muography’) of large natural and human-made structures, and non-destructive depth-resolved elemental analysis of materials and devices. These applications open up unique perspectives in fields ranging from environmental and energy research to archaeology and cultural heritage.

Switzerland already occupies a prominent place in the muon-science landscape, by operating a world-leading muon beam user facility at the Paul Scherrer Institute (PSI), which comprises the Swiss Muon Source (SμS) and the Swiss Research Infrastructure for Particle Physics (CHRISP). Both will be substantially upgraded in the coming years, and the overall objective of NCCR Muoniverse will be to provide the network to complement and leverage this unique infrastructure in ways that are impossible without a multidisciplinary and inter-institutional effort.

From the start of phase I, we will significantly extend the scientific use of muons by groups across Switzerland, by developing and transferring novel technologies, expanding experimental and methodological capabilities, and pushing the frontiers in applications that address some of the most pressing challenges in various disciplines, from quantum materials and spintronics to renewable-energy production and storage, and environmental monitoring. In parallel we will establish sustainable structures for education, industry collaboration, and public outreach that are unique in the world.

In this way, Muoniverse will enable an extraordinarily broad range of research groups based in Switzerland to establish strong collaborations across disciplinary boundaries and to inspire new links to industry and society. This will go hand in hand with promoting in particular early-career researchers and teams at Swiss universities, to pursue novel directions exploiting the full potential of muons. As such, the proposed NCCR will lay in its first phase solid foundations for two further four-year periods, to create a lasting ‘Muoniverse’ of talent and opportunities.

2 Overall goals and mid- and long-term vision

The overall mission of the proposed NCCR Muoniverse is to advance and broaden research driven by the study of the fundamental properties of the muon itself and the use of muons as highly sensitive probes for the samples with which they interact. Given the enormous breadth and depth of research questions to which muons can provide unique insights (see Fig. 1 and Sec. 3), we envision that Muoniverse will create a diverse and vibrant community in Switzerland — the most important legacy of the NCCR.

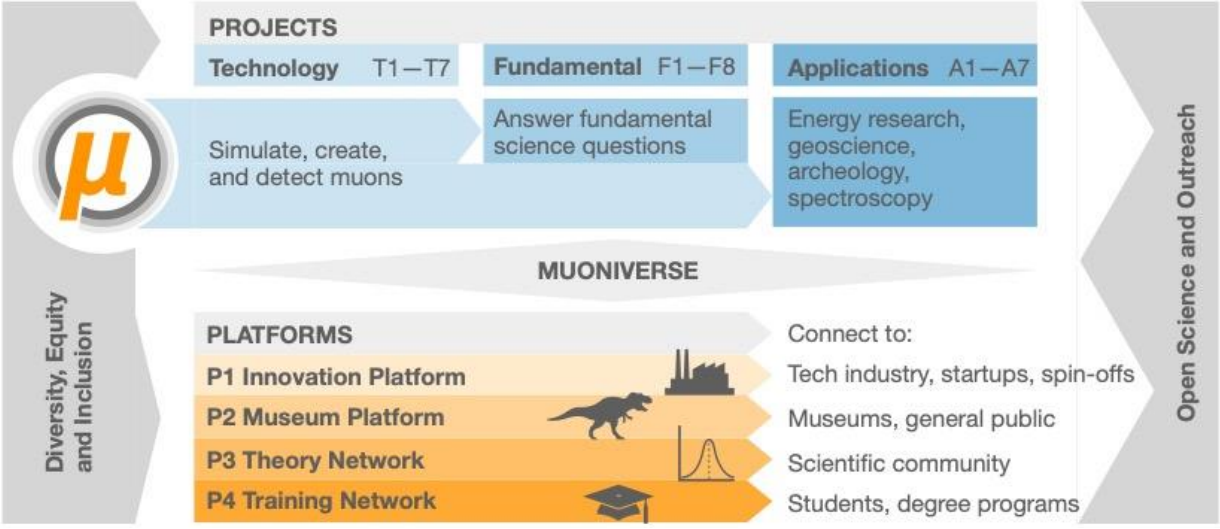

***Figure 1**: Elements of Muoniverse: Projects in fundamental research (F), applications (A), technology (T), platforms (P) and measures regarding Diversity, Equity and Inclusion (DEI), Communication and Outreach, and Open Science compose a forefront research programme, sustainable structural measures, and societal impact.*

Muoniverse will reach out to and connect with research fields that are not traditionally involved with muons, including chemistry, energy research, and archaeology. At the same time, it will enhance world-leading Swiss research in particle and condensed-matter physics and materials science. In Muoniverse, researchers from 11 Swiss universities and research institutes will work together beyond disciplinary boundaries, help develop, share, and distribute techniques and technologies, and enable novel research directions. Muoniverse aims to initiate around twenty research projects, each involving several PIs and bridging fields (see Sec. 3). These innovative projects will also provide unique opportunities for education. In addition, we will establish structures and platforms for attracting and coordinating communities across Switzerland that will establish a strong Swiss muon-science community and ensure impact through research that continues beyond the NCCR.

Main research questions and their significance

In Muoniverse, we will both expand the study of properties of the muon as a fundamental particle and explore how muons interact with nuclei, electrons, atoms, and molecules in a wide-ranging number of systems. Our science programme is designed on coordinated developments in three interconnected general areas: fundamental research, applications, and technology.

The questions addressed in **fundamental research** will span a wide range of fields of physics, chemistry, and material science. In particle, atomic, and nuclear physics, the main question concerns the range of validity of the Standard Model of particle physics, which is highly successful for describing the known basic building blocks of the Universe, but not all of its content. Frontier research with muons offers a considerable discovery potential for physics beyond the Standard Model [1]). This includes the question whether muons always emit neutrinos in their decays and if they always conserve family lepton number (Project **F5**, see Sec. 3); whether the theory of quantum electrodynamics (QED) withstands tests with precision spectroscopy of muonium and light muonic atoms (**F6**); whether nuclear theory can reliably predict muon-capture observables in medium to heavy nuclei that are important to neutrino physics (**F7**); and whether quantum chromodynamics (QCD) together with ab-initio nuclear theory describes the properties of the light nuclei from protons to neon, as they can accurately be determined by muonic atom spectroscopy (**F8**).

In condensed-matter research, materials science, and chemistry, muon spin spectroscopy (μSR) stands out as a powerful and versatile tool for studying quantum materials, offering unique insight into local magnetic and electronic properties, dynamic fluctuations, and the quantum behaviour of electrons and spins in general. Its unparalleled sensitivity and the ability to probe a virtually unlimited range of materials under various extreme experimental conditions makes it a key technique in the highly topical field of quantum-matter research. At SμS, Muoniverse researchers have access to worldwide leading capabilities in μSR, from which various areas of condensed-matter research will benefit, including studies of time-reversal symmetry breaking and chiral charge order in superconductors (**F1**), emergent magnetic semiconductors (**F2**), functional spintronics materials (**F3**) and hybrid interfaces of quantum materials (**F4**). Such advances will further underpin Switzerland's leading role in the discovery and investigation of new quantum materials for next-generation technologies, such as spintronics and quantum technologies.

In **applied muon research**, Muoniverse aims to further exploit the possibilities of muon spectroscopies and ultimately to create a multidisciplinary platform for research groups outside the traditional muon user communities. For instance, in energy research, μSR is rapidly emerging as a cutting-edge technique for studying defects at interfaces and microstructural properties in device structures. This capability provides unique insight into materials for advanced power electronics (**A1**) and solar cells (**A2**) and opens up new perspectives in understanding and optimizing such novel semiconductor materials. The control and characterization of defects in these materials is of utmost importance for optimizing device efficiencies, and muons can provide unprecedented resolution in determining depth profiles of these defects. A further focus in energy research will be tomographic in-situ investigations of lithium-ion, sodium-ion, and next-generation post-lithium-ion batteries using non-destructive negative muon spectroscopy (known as Muon-Induced X-ray Emission, MIXE [2]) to measure the distribution of lithium or sodium ions inside the batteries and to understand ageing mechanisms during charge–discharge cycles (**A3**). The same MIXE technique will be used and further developed in cultural-heritage studies to characterize rare archaeological artefacts from the late antique Roman site Augusta Raurica, and from a large collection of artefacts with close connection to Switzerland from the Swiss National

Museum (**A4**). We will also explore the use of cosmic muons to monitor large-scale natural (**A5**) and human-made structures (**A6**) such as snow layers or civic infrastructure. Finally, we will explore the use of laser technology developed for muonic atom spectroscopy in applications such as brain imaging and copper welding (**A7**).

Most of these advances require the combination of new developments in experimental and theoretical capabilities. Muoniverse offers a broad umbrella under which various **technology and methodology developments** will be coordinated, from equipment for attaining higher hydrostatic and uniaxial pressures (**T2**) and realizing muon microbeams (**T1**), to self-consistent density functional theory for muons (**T3**) and advanced detector technologies (**T4**, **T7**). In parallel we will aim to push technology far beyond what is currently possible with concept studies for the re-acceleration of muons produced from a microbeam (**T5**) and for muon microscopy (**T6**).

With this multi-disciplinary approach, Muoniverse motivates and enables research at the frontier of present fundamental knowledge and practical capability. The significance of this research for society is manifold. Our modern knowledge-based society is built on fundamental knowledge and generations of scientists pushing the boundaries of scientific progress, which led to both steady progress as well as unexpected and transformative discoveries. With its multi-pronged approach, Muoniverse is designed to deliver on both these counts: problem-driven research for short- and mid-term impact and curiosity-driven research that establish the basis for future research directions.

Present research landscape, mid- and long-term vision, and need for an NCCR

Switzerland operates a world-leading muon beam user facility at the High Intensity Proton Accelerator (HIPA) of PSI. As part of the structural goals of PSI and its core mission to provide national research infrastructure beyond the scale of single universities and to foster large user communities, several muon beamlines will be substantially upgraded in the coming years. The improvements pursued at PSI concern two key aspects, muon intensity and beam quality, realized through new proton-accelerator target stations and new beamlines.

These upgrades take place against the background of growing international competition, in particular from a few other leading large-scale facilities, including J-PARC [3] in Japan, ISIS [4] in the UK, TRIUMF [5] in Canada, FNAL [6] in the USA, and in the future at the CSNS-II [7] in China. The beams at PSI stand out by providing the highest continuous muon intensities by far, whereas the highest intensities elsewhere are obtained presently at J-PARC's pulsed source. Muoniverse projects are tailored to take full advantage of the continuous beams, allowing for precision timing of single muons and enabling coincidence techniques with strong background suppression as well as optimal event distribution for detectors and data acquisition.

Our vision is that NCCR Muoniverse will be the network to complement and leverage the unique Swiss muon infrastructure, to optimize its scientific exploitation by covering the full breadth of muon science beyond the well-established areas, with experiment and theory, and enable an extraordinarily broad range of research groups based in Switzerland to cooperate. The various connections between the proposed projects for phase I are highlighted in the project descriptions in Sec. 3. Beyond exploiting the available infrastructure, we will also develop highly novel technologies. For example, in phase I we will explore the concepts of re-accelerating cooled muon beams (**T5**) or of pixel detectors with unprecedented time resolution (**T4**). In phases II and III, the most promising concepts explored in phase I should be implemented and transformed into tools, for example depth-resolved non-destructive testing over a large range of implantation depths (**T1**) or, potentially, muon microscopy (**T6**).

This is why we designed Muoniverse for up to 12 years. Community building in areas where muons have not yet been applied or only very rarely will naturally take time. We are confident that in phase I Muoniverse will succeed not only in providing significant scientific and technological advances, but also in attracting highly talented researchers to postdoc fellowships, from which in phase II and III a number of young professors could establish themselves at Swiss universities. Muoniverse will also tackle developments of demanding new technology, part of which requiring a stepwise approach with the development of concepts and R&D stages with prototyping before novel instrumentation can be implemented. The development of instrumentation will go alongside with community building, as novel applications come in reach.

Currently, no structured cooperation or coordination of muon research exists in Switzerland or, to our knowledge, anywhere else in the world. This is in stark contrast to the significant interest in fundamental and applied muon science. There exists already a strong and growing national and international user community in particle physics and materials science around the PSI muon beam facilities. There is also growing interest in using both cosmic muons and muon beams for non-destructive analyses of a wide variety of objects. While the muon beams and detector technology are closely related to experimental physics, the range of applications is tremendously broad, including archaeology, civil construction, geology, chemistry, and materials science.

The potential of promoting and bringing together the technology development and techniques of the various fields is therefore huge. In the Swiss research funding landscape, an NCCR would offer a unique opportunity to boost the field of muon science and to create a strong Swiss muon-science community that makes optimal use of the world-leading and unique research infrastructure in Switzerland. The network of structures created by Muoniverse would strengthen Swiss muon science far beyond the funding periods. This is in particular true for the planned structural measures, which include the Museum, Open Data, and Innovation platforms and the Training Network (see Sec. 4). These will continue to ensure lasting impact. Establishing such measures would not be possible without the broadly based long-term funding provided to NCCRs.

3 Research programme for phase I

The research plan of Muoniverse is structured in individual projects in three interconnected areas: technology (T), fundamental research (F), and applications (A). The individual projects below are labelled accordingly, and the various connections to other projects of the NCCR are highlighted. They are mostly interdependent and require strong collaboration of several Muoniverse PIs, with diverse backgrounds and mostly from different institutions and fields. Each individual project is at the forefront of research with muons and will greatly benefit from the cooperation within Muoniverse. Often the research projects are embedded in a broader national and international context through further collaborations, which we indicate as well. International research groups are attracted by the excellence of the individual research groups and the unique facilities in Switzerland, and contribute additional know-how. In many respects, the state of the art of muon science is represented by Muoniverse science.

In addition to the individual projects, Muoniverse will implement overarching structural measures. They will be implemented holistically, in four Platforms (P1–P4, see Fig. 1). In particular, platform P3, the Theory Network, is designed to directly contribute to the research of Muoniverse projects also through international cooperation. It is, therefore, described here, while the others will be discussed in Sec. 4.

Legend: Lead PI, Further Muoniverse PI(s), Key collaborator(s)

Platform P3: Theory Network

***PIs**: P. Stoffer (UZH/PSI), N. Spaldin (ETHZ),*
T. Neupert (UZH), A. Signer (PSI/UZH)

***Connected projects**: F1–F8, A1–A3*

The goal of the Theory Network is to provide support to different projects of the NCCR that is not covered by the expertise of the theorists involved as PIs. The platform will allow us to host external experts as NCCR visitors. While targeted towards specific needs of the NCCR projects, the programme will also permit the visitors to be engaged in guest lectures at universities, thereby fostering education and training. Theory expertise that should be covered by the visitor programme includes for example simulations of magnetic and superconducting materials in **F1** and **F2**, the dynamics of light degrees of freedom beyond the Standard Model in **F5**, few-body theory, hyperfine splitting in muonic hydrogen, aspects of super-fluidity in **F6**, and the areas of nuclear matrix elements and QED for heavy elements in **F7** and **F8**.

Technology

Project T1: Muon microbeam with variable implantation energy

***PIs**: A. Antognini (PSI/ETHZ),*
K. Kirch (PSI/ETHZ), T. Prokscha (PSI)

***Connected projects**: T2, T4–T7, F3–F6,*
A1–A3, A7

Tunable, low-energy muon beams are used for example to investigate magnetic properties of thin films. The world-leading Low-Energy Muon (LEM) facility at PSI provides 25’000 μ^+/s at 1–30 keV in 5-mm beam spots [8–10]. This is still too large to investigate mm^2-sized novel quantum materials or devices. Improved beams would open up new research directions, vacuum muonium in tiny volumes, and enable re-acceleration to MeV energies with breakthrough applications (**T5**). A muon microbeam will be developed based on the muCool technique [11, 12]. A phased approach will ultimately deliver a beam tunable from 0.1 keV to 100 keV, 0.1-mm beam spot, and a rate of 100’000 μ^+/s, utilising the HIMB input beam [13]. This beam could be multiplexed to serve five small instruments simultaneously with rates around 20’000/s.

Project T2: Next-generation pressure cells for quantum-material research

***PIs**: H. Luetkens (PSI), M. Janoschek (PSI/UZH), R. Khassanov (PSI)*

***Connected projects**: T1, T3, T4, F1, F2*

μSR experiments under hydrostatic and uniaxial pressure provide unique insights into the local magnetic and electronic properties of quantum materials in a controlled manner, without introducing chemical or structural disorder [14–16]. Novel pressure equipment and methodology will significantly enhance the high-pressure capabilities for μSR and surpass PSI’s current world-leading pressure range [15, 17] by at least a factor of three, on dramatically smaller samples, allowing us to address topical questions of quantum-matter research not accessible today. This quantum leap will be made possible by the availability of high-intensity muon beams as part of the IMPACT project and the development of Si-pixel particle tracking detectors (**T4**).

Project T3: Self-consistent density functional theory for muons

***PIs**: N. Spaldin (ETHZ), T. Neupert (UZH)*

***Connected projects**: T2, F1–F4, A1–A3*

Predictive first-principles calculations are a backbone that enables research with muons interacting with matter. Currently employed computational frameworks do not solve the Schrödinger equation for the muon in matter self-consistently, making them unsuitable for quantitatively accurate modelling [18, 19]. We will develop a first-principles user-oriented library to fill this gap, employing machine learning to parametrize the effective potential. This will enable accurate calculations of muon–material interactions, muon spin dynamics and muon stopping sites. It constitutes a key methodological development ensuring all fundamental science and application projects within Muoniverse are based on the best possible theoretical predictions.

Project T4: Development of pixel detectors with precision-timing capabilities

***PIs**: L. Caminada (UZH/PSI), Z. Salman (PSI), P. Schmidt-Wellenburg (PSI), B. Kilminster (UZH), R. Wallny (ETHZ)*

***Connected projects**: T1, T2, T7, F5, F6, A4–A6*

Silicon pixel detectors are key components to provide high-precision measurements of the muon decay vertices in high-rate experiments [20, 21]. While current systems achieve excellent spatial resolution (<10 µm), their time resolution on the order of 10 ns is insufficient for many applications and requires additional instrumentation for timing information. We will use advanced monolithic pixel-detector technology [22] to develop an integrated system with timing resolution better than 100 ps. The availability of such detectors will not only enable fundamental particle-physics experiments, but also revolutionise the μSR technique (**T2**), enabling the measurement of sub-millimetre samples at high precession frequencies [13].

Project T5: Acceleration of an ultralow-emittance muon beam

***PIs**: T. Pieloni (EPFL), M. Seidel (PSI/EPFL)* | ***Connected projects**: T1, T6, T7, F5, F6*

A high-quality MeV μ^+ beam with 0.01% energy resolution and 0.1 mm beam spot would be a game changer for all of muon science. We will study the re-acceleration of muons produced from a microbeam of several 10 keV (**T1**) to energies of a few MeV and beyond. Several pathways are proposed or studied, for example at J-PARC with an RFQ followed by drift tube linacs [23] or with a muon cyclotron [24]. Detailed simulations and analyses will lead to an optimal conceptional design. Depending on the progress achieved, work towards a technical design will be pursued. Applications of such a beam of higher energies would be manifold, ranging from measurements of the electro-magnetic moments of the muon to non-destructive tomography of cultural-heritage artefacts and to microscopy (**T6**).

Project T6: Concept study for muon microscopy

***PIs**: F. Carbone (EPFL), A. Antognini (PSI/ETHZ)* | ***Connected projects**: T1, T5*

Transmission electron microscopy (EM) enabled breakthrough research and applications. However, even high-energy EM (e.g., [25–27]) suffers from low penetration depth. This greatly limits the feasibility of experiments in environmental conditions, the next frontier in biological imaging. Muons may pass through thicker environmental cells, possibly enabling new ways of looking at biological systems, catalysis, and other molecular dynamics under relevant conditions. Design and science-case studies for a muon microscope based on a microbeam (**T1**, **T5**) will be carried out. Important parameters will be the brightness of the beam, coherence, energy spread, damage ability, and penetration depth. We note a complementary development of a muon accelerator and microscope at J-PARC [24].

Project T7: Cryogenic detectors

***PIs**: A. Soter (ETHZ), A. Papa (PSI/Uni Pisa), L. Gastaldo (U. Heidelberg), A. Knecht (PSI)* | ***Connected projects**: T1, T4, T5, F5–F8, A3, A4, A7*

Precision experiments with muons are frequently carried out in cryogenic environments, at temperatures that can be below 50 mK. These measurements demand detectors with stringent requirements on spatial and energy resolution, single-photon sensitivity, and speed. Robustness against radiation or high magnetic-field tolerance can be additional constraints. Combining particle and condensed-matter physics expertise, we will develop detection technologies suited to such experiments, including cryogenic silicon photomultipliers and silicon tracking detectors [28], or inorganic crystal scintillators such as perovskite nanocrystals ($CsPbBr_3$) [29]. Metallic magnetic calorimeters [30], and superconducting nanowires [31] will be also optimised for high-resolution X-ray and low-threshold particle detection.

Fundamental research

Legend: Lead PI, Further Muoniverse PI(s), Key collaborator(s)

Project F1: Time-reversal symmetry breaking superconductors

***PIs**: F. von Rohr (UniGE), Z. Guguchia (PSI), F. Natterer (UZH), T. Neupert (UZH)* | ***Connected projects**: T2, T3, F2*

Superconductivity and magnetism typically oppose each other as collective quantum states. This, in turn, renders the appearance of spontaneous magnetic fields in superconductors remarkable. However, such magnetism is typically weak, appears at low temperatures, and is thus hard to detect experimentally. μSR is the only technique that sensitively probes both superconductivity and magnetism in a true bulk measurement, enabling the determination of volume fractions. We will use the technological developments within Muoniverse to probe (i) materials in which the superconducting order parameter also spontaneously breaks time-reversal symmetry [32–34] and (ii) so-called kagome metals in which superconductivity develops in a phase with chiral charge order [16, 35, 36]. These next-generation experiments will help determine these orders precisely and thereby contribute to identifying quantum materials for future technologies.

Project F2: Emergent magnetic semiconductors

PIs: *Z. Guguchia (PSI), T. Neupert (UZH)* | ***Connected projects***: *T2, T3, F1, F3, F4*

Identifying semiconductors that can be used to create magnetic thin-film heterostructures is a prerequisite for future spintronics technologies. A particularly versatile material family is transition metal dichalcogenides (TMDs) [37–39], but the currently known members do not exhibit magnetic order at high-enough temperatures for room-temperature applications [40]. Our objective is to employ μSR to investigate the unique properties of defect-induced magnetic phases in TMDs, explore the microscopic origin of their magnetism, and subsequently tune them to obtain the desired magnetic properties as ultrathin films. This constitutes an important stepping stone towards the development of integrated spintronics devices at industrial scales.

Project F3: 3D spin-polarization studies of functional (super)spintronics devices

PIs: *C. Bernhard (UniFR), Z. Salman (PSI),*
T. Prokscha (PSI) | ***Connected projects***: *T1, T3, F2, F4*

The availability of a muon microbeam with a diameter of 100 μm and a tunable energy from 1 to 30 keV opens up the intriguing prospect of 3D-resolved μSR studies in functional devices. μSR as a highly sensitive local magnetic probe enables the study of, for example, the spin propagation in spin-valve structures [41], the generation of spin-triplet supercurrents in superconductor/ferromagnet devices [42], or the spin accumulation due to the spin-Hall effect [43]. In the first phase of the NCCR, the experimental methodology will be developed based on the existing growth and microfabrication infrastructure in Fribourg and the low-energy-μSR facility at PSI. The ultimate goal is 3D-resolved studies of the induced spin-polarization in the active layers of various spintronics and/or super-spintronics devices.

Project F4: Hybrid interfaces of quantum materials — a route to novel applications

PIs: *Z. Salman (PSI), M. Kowalska (CERN/UniGE)* | ***Connected projects***: *T1, T3, F2, F3*

Multilayers of quantum materials present a new approach to designing systems with novel properties [44, 45]. The low cost of molecular magnetic materials (MMM), the tunability of their physical properties and long spin coherence times make them ideal for quantum computation and spintronics applications. Low-energy μSR is a unique technique to investigate interfaces between MMMs and other quantum materials such as superconductors and topological insulators. Our studies will be complemented by β-NMR at CERN/ISOLDE [46] to cover a wide range of spin-fluctuation rates (Hz up to GHz) and magnetic fields (10^{-6}–10 T). Our results will be of paramount importance to explore the interplay between the physical properties of quantum materials across interfaces and their prospects for spintronics applications.

Project F5: Hunting for rare muon observables

***PIs**: A. Papa (PSI/Uni Pisa), P. Stoffer (UZH/PSI), P. Schmidt-Wellenburg (PSI), A. Signer (PSI/UZH)* | ***Connected projects**: T1, T4, T5, T7, A6*

Muons are exquisite probes to search for answers to fundamental questions left open by the Standard Model (SM). A new generation of experiments, such as Mu3e [20] and muEDM [47], will search for muon decays forbidden in the SM, and measure fundamental properties of muons, such as the electric dipole moment. In both cases, the observation of a signal would point to the existence of yet unknown particles. To fully exploit the power of these high-precision experiments, the interplay with theory will be crucial, both to achieve a robust interpretation of the experimental results in the context of heavy new particles [48, 49], as well as to search for light ones, such as axion-like particles (ALPs).

Project F6: Muonium spectroscopy

***PIs**: A.Soter (ETHZ), A. Antognini (PSI/ETHZ), P. Crivelli (ETHZ)* | ***Connected projects**: T1, T4, T5, T7, A7*

As it was recently demonstrated by the Mu-MASS collaboration [50–52], with its intense μ^+ beam and the incoming developments [12, 13], PSI harbours tremendous opportunities for improving Muonium (M) spectroscopy experiments and the available statistics of experiments with M will increase by orders of magnitude [13], enabling accurate studies of systematic effects and the implementation of new measurement schemes, such as coherent pump–probe optical and microwave spectroscopy. This will provide stringent tests of bound-state QED [53, 54], improve the accuracy with which fundamental constants can be determined, and probe numerous scenarios beyond the Standard Model [55], including dark-sector particles and new muonic forces [56, 57], as well as testing Lorentz/CPT symmetries [58].

Project F7: Ordinary muon capture

***PIs**: L. Baudis (UZH), A. Knecht (PSI)* | ***Connected projects**: T7, F8, A3, A4*

Neutrinoless double beta ($0\nu\beta\beta$) decay addresses lepton-number violation and the mass and nature of neutrinos (Dirac vs Majorana). The relation of the $0\nu\beta\beta$ half-life and the effective Majorana mass involves a nuclear matrix element (NME) squared. The NMEs are difficult to calculate, with factors 2–3 between different nuclear models. Ordinary muon capture (OMC) provides an excellent tool to benchmark nuclear-physics models at similarly high momentum transfers as $0\nu\beta\beta$ [59, 60]. We aim to determine total and partial OMC rates for relevant isotopes, such as ^{136}Ba (daughter of ^{136}Xe), ^{76}Se (^{76}Ge), ^{48}Ti (^{48}Ca), ^{130}Xe (^{130}Te) from the spectroscopy of muonic atoms formed on enriched target material.

Project F8: Nuclear charge radii

***PIs**: K. Kirch (PSI/ETHZ), M. Kowalska (CERN/UniGE), L. Gastaldo (U. Heidelberg), A. Knecht (PSI)* | ***Connected projects**: T7, F7, A3, A4*

High-precision X-ray spectroscopy of light muonic atoms can deliver order-of-magnitude improved determinations of nuclear charge radii and other parameters, thus providing crucial benchmarks for nuclear theory and tests of quantum electrodynamics (QED). This is enabled by novel MMC (metallic magnetic calorimeter) detector technology [61] pioneered at the University of Heidelberg and recently demonstrated in first tests at PSI [62]. We will pursue and expand our efforts on charge-radius measurements of medium- and high-Z muonic atoms, thereby exploiting the synergies with the programmes ongoing at CERN/ISOLDE on hyperfine anomalies [63] and the preparation of pure, mass-separated targets by ion implantation.

Applications

Legend: Lead PI, Further Muoniverse PI(s), Key collaborator(s)

Project A1: Processing-induced defects, charge-state conversion, and dynamics of vacancy defects in advanced power semiconductor devices

***PIs**: U. Grossner (ETHZ), T. Prokscha (PSI)* | ***Connected projects**: T1, T3, A2, A3*

Semiconductor devices based on 4H-SiC are attracting increasing attention due to their low losses in advanced high-power applications, which are crucial for efficient power-conversion systems [64, 65]. However, a detailed understanding of the relation between processing-induced defects and observed limitations in device reliability and performance is still lacking [65, 66]. μSR has the unique ability to electrically probe and spatially resolve defects in the device [67, 68]. In combination with standard characterization techniques, a comprehensive picture of the defect generation during the fabrication process can be obtained. Our results will enable solving practical processing challenges and reliability issues in power semiconductor devices.

Project A2: Nanoscale behaviour of charge carriers and defects in perovskite solar cells

***PIs**: F. Fu (Empa), T. Prokscha (PSI)* | ***Connected projects**: T1, T3, A1, A3*

Perovskite solar cells (PSCs) have been established as photovoltaic devices with high power-conversion efficiency at low manufacturing cost [69, 70]. Further improvement of their device performance and operational stability is hampered, however, by an incomplete understanding of their microstructural properties, especially under operational conditions [71]. We will exploit the unique capabilities of μSR [72, 73] for studying nanoscale behaviour of charge carriers and defects in solar-cell devices to gain insight into how structural and chemical changes at the atomic level affect the overall efficiency and long-term reliability of PSCs. These research outcomes will contribute directly to the advancement of this promising renewable-energy technology.

Project A3: Muon spectroscopy for battery applications

***PIs**: A. Remhof (Empa), S. Trabesinger (PSI)* | ***Connected projects**: T1, T3, T7, F7, F8, A1, A2, A4*

Developing Li-ion and Na-ion batteries requires understanding chemical and electro-chemical processes within the bulk of battery materials and at their interfaces [74, 75]. Muon spectroscopy using both positive and negative muons (μSR and MIXE) provides unique depth-resolved insights, enabling operando studies of Li/Na distribution as a function of state of charge, formation of electrochemically inactive metal deposits, and interface stability [76–79]. Muon spectroscopy will be a cornerstone for understanding charge/discharge and aging mechanisms in Li/Na-ion and next-generation post-Li-ion batteries.

Project A4: Non-destructive elemental analysis of archaeological and cultural-heritage artefacts

PIs: *K. Schmidt-Ott (Swiss National Museum), K. Kirch (PSI/ETHZ), L. Raselli (Augusta Raurica)* | ***Connected projects***: *T4, T7, F7, F8, A3*

Non-destructive, position- and depth-resolved testing of the elemental or isotopic composition of objects is of great interest in many research fields and applications. However, corrosion layers for example can make the analysis of cultural-heritage objects very difficult or even impossible. Well-controlled negative muon beams and muonic X-ray spectroscopy offer a great opportunity to overcome such limitations. New instrumentation with an array of HPGe detectors has been implemented [78, 79] and proof-of-principle applications yielded novel insights on archaeological artefacts [80, 81]. This project will investigate and refine the reach of the method, for instance regarding the limits of measuring trace elements, and apply it to the most promising cases.

Project A5: Snow-coverage monitoring with cosmic muons

PIs: *M. Bavay (WSL), L. Caminada (UZH/PSI)* | ***Connected projects***: *T4, A6*

In mountainous areas, the evaluation of water resources has to take into account the water stored as snow, or snow water equivalent (SWE). This is critical for flood forecasting, hydropower production or irrigation management [82]. Moreover, SWE is an essential variable in monitoring climate change [83, 84]. Current SWE measuring techniques are not able to achieve continuous readout operation at a reasonable cost and accuracy [85, 86]. This project builds upon a proof-of-concept experiment successfully performed in 2023 and aims to use the pixel-detector technology developed in the context of particle-physics experiments in a novel SWE sensor for accurate, affordable and automated continuous measurement based on cosmic-ray muons. This would be a breakthrough for all regions where snow is a significant water resource.

Project A6: Methods for muography

PIs: *M. Weber (UniBE), L. Caminada (UZH/PSI)* | ***Connected projects***: *T4, F5, A5*

Cosmic muons reaching the Earth surface are a powerful tool for performing radiography of large-scale structures. A multitude of applications exist, including archaeology (voids in pyramids) [87], glaciology (erosion detection) [88], snow measurements (**A5**), and monitoring of civil structures (concrete-reinforcement corrosion, safeguarding of long-term nuclear-waste storage). In this project we carry out a concept study to apply the instrumentation and data-analysis methods developed to muon radiography systems with large-area coverage.

Project A7: Lasers from muonic atoms to applications

PIs: *A. Antognini (PSI/ETHZ), A. Soter (ETHZ), P. Crivelli (ETHZ)* | ***Connected projects***: *T1, T7, F6*

Laser spectroscopy of muonic atoms provides an ideal platform for measuring nuclear charge radii [89, 90]. Besides establishing benchmarks for nuclear physics [91, 92], they lead to the best bound-state QED tests in H, HD$^+$, H_2^+, He$^+$ and He. In this project, we aim to advance laser technology [93] currently under development to measure the ground-state hyperfine splitting of muonic hydrogen [94, 95] to search for temporal variations caused by beyond-Standard-Model physics [96] and to improve on the power of a laser system for muonium spectroscopy [97, 98]. We also plan to study the application of these laser systems, for example for photoacoustic imaging of the brain [99] and copper welding [100].

4 Organisation, management, and leadership of the NCCR

The highest instance of Muoniverse will be the PI Assembly. Its rules and a code of conduct will be signed by the PIs upon implementation of the NCCR.

The Executive Board (EB) of Muoniverse will be formed by the Director, Deputy-Director, and the Scientific Coordinator (SC). The Board of Muoniverse will have in addition a representative (plus deputy) of each of the three research categories (F, T, A) and the four platforms (P1–4; see below), as well as two representatives of the Early Career Researchers (ECRs). One of the ECRs will be a postdoc, the other a PhD student. An ECR Assembly will nominate their representatives, and the PI Assembly will elect the Board members. Table 1 shows an initial composition as discussed amongst the stakeholders.

Responsibility	Name	Affiliation	Name	Affiliation
Director	Klaus Kirch	PSI, ETHZ	Angela Papa	PSI, Uni Pisa
Scientific Coordinator	NN			
F: Fundamental	Anna Soter	ETHZ	Titus Neupert	UZH
T: Technology	Lea Caminada	UZH, PSI	Marc Janoschek	PSI, UZH
A: Applications	Ulrike Grossner	ETHZ	Arndt Remhof	Empa
P1: Innovation	Shaun West	HSLU	Fabian von Rohr	UniGE
P2: Museum	Katharina Schmidt-Ott	Swiss National Museum	Lilian Raselli	Augusta Raurica
P3: Theory	Peter Stoffer	UZH, PSI	Nicola Spaldin	ETHZ
P4: Training	Fabian Natterer	UZH	Christian Bernhard	UniFR
ECR	PhD NN		Postdoc NN	

***Table 1**: A possible initial composition of the Muoniverse Board.*

Muoniverse aims for a balanced composition of the Board regarding gender, age, and institutions. Decisions concerning everyday operation will be taken by the EB, while more far-reaching ones are the responsibility of the Board, and ultimately of the PI Assembly. The strategy of the NCCR is discussed and decided by the PI Assembly. All decisions are taken after broad consultation and an inclusive discussion culture will be fostered in the Board and in the PI Assembly.

Further PIs can be invited to join the NCCR at the proposal of the EB and approval by the Board and the PI Assembly. Members of the PIs' groups can be associated and become members of the NCCR. In addition to its various activities, the NCCR will hold plenary meetings at least once per year, PI Assemblies as well as ECR Assemblies at least twice per year, and Board meetings at least four times per year.

The SC will be the head of office of the NCCR, which in addition has an administrator, and two FTE covering the five structural areas (knowledge and technology transfer, education, equal opportunities, communication and outreach, open science) in a balanced way. The SC is, therefore, directly in touch with all measures regarding Diversity, Equity, and Inclusion (DEI), Communication and Outreach, and Open Science (see below), guaranteeing the appropriate attention by the EB and Board. Measures in these areas are deeply rooted in all NCCR activities and cut across all platforms and projects.

Regarding planned integral DEI measures we will work closely with experts on implementation and monitoring. We have established contacts with the Interdisciplinary Centre for Gender Studies (ICFG) [101] and will set up accompanying research to monitor the effects of our measures. The other structural measures, concerning knowledge and technology transfer as well as education and training, are represented in the Board via the platform coordinators of the Innovation Platform and the Training Network.

Muoniverse will attach great importance to open communication and transparency. Muoniverse PIs are committed to the highest scientific standards and to implementing the best-possible interpersonal interaction. We will treat each other respectfully and resolve differences in a constructive manner. In the event of major problems, for example of a personal nature, we will involve professional conflict management. In addition, we will pay particular attention to soft skills and transverse competences as part of our internal training and development programme (**P4**). Muoniverse will implement contacts to independent advisors to support the members of the NCCR when needed and considers installing an independent ombudsperson.

We plan that Muoniverse will in its various activities seek advice from external experts, as appropriate. It will consider installing advisory bodies such as a scientific advisory committee or committees for technology transfer and industrial contacts.

As part of the organisational structure, we will implement the following measures (see also Sec. 3 for a description of the Theory Network, **P3**):

Open Science and research data

Legend: Lead PI, Further Muoniverse PI(s), Key collaborator(s)

***PIs**: L. Caminada (UZH/PSI), C. Lange (PSI)*

We commit to the Open Science goals of the SNSF [102] and the DORA declaration [103]. The open-data platform of Muoniverse will be highly useful, also beyond the funding of the NCCR and in terms of communities that can be reached. We strive to follow the FAIR guiding principles [104] for scientific-data management and stewardship. Our ORD (open research data) exploration steps include a survey of existing services that would be expanded to accommodate the needs of our projects. We intend to establish a close relationship with ORD tool developers, specifically with SciCat [105] and the petabyte storage at the Swiss National Supercomputing Centre CSCS [106]. To find, access, and work with the open data, we will develop and implement an end-user friendly, web-based, graphical user interface.

P1: Innovation Platform

***PIs**: S. West (HSLU), F. von Rohr (UniGE), Ch. Hohmann (HSLU), P. Müller-Csernetzky (HSLU)*

Muoniverse will provide coordinated support to transfer core knowledge and technology into a broader field of application. From guided ideation processes and cross-disciplinary team collaboration additional opportunities, use cases, and business concepts can emerge. For instance, students and postdocs, while developing tools for their projects, often come across ideas that could directly benefit other applications in completely different areas — with the highly interdisciplinary environment of the Muoniverse network serving as a catalyst. We aim to unlock such future opportunities, crafting solutions that maximize value across all levels, and to transform inventions into innovation. Combining competence from all Muoniverse institutions, in particular from the Smart-up programme [107], we will develop activities within the NCCR, permitting connections via all institutions that go well beyond the NCCR. In addition, we will reach out to bench2biz [108] and work closely with established companies such as DECTRIS and anaxam (see their Letters of Support). The implementation and the effectiveness of the innovation measures will be closely monitored and researched with a dedicated project at HSLU.

P2: Museum Platform

***PIs**: K. Schmidt-Ott (Swiss National Museum), L. Raselli (Augusta Raurica)*

Muoniverse will establish a Museum Platform, starting with the participating institutions (Swiss National Museum and Augusta Raurica) as seeds and multipliers. It will operate in several directions. On the one hand, by helping researchers from related fields (such as archaeology, art history, geology, and arts) to coordinate their exchange and efforts to access analytical methods, in particular with muons (see **A4**). On the other hand, the museums will be an ideal place for education and outreach activities of the NCCR. As one example, we have established connections to the artists-in-labs programme [109] of the Zurich University of the Arts (ZHdK) and aim to exploit the opportunity for an enhanced multidisciplinary exchange using our laboratories and the museums.

P4: Training Network

***PIs**: F. Natterer (UZH), C. Bernhard (UniFR)*

The Training Network will coordinate all efforts of Muoniverse in the area of education and training, most of which can be sustainably maintained beyond the NCCR. On the one hand, these measures will benefit members of Muoniverse and students at the involved institutions, such as specialized courses on muon science taught at the universities or workshops on muon science, but also on communication in multi-disciplinary teams and on other transverse skills. This will be an important component for building a common 'language' across disciplines. As a successful example, we mention the EPT-hub [110] at ETHZ. Other activities will target, on the other hand, groups beyond the NCCR and the general public, with a special focus on diversity. We will systematically integrate high-school students into our programme, offering special projects and internships, and including, for instance, the cantonal high schools on the UZH campus [111].

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