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CHIPP Community Roadmap 2024

Update of Swiss Particle Physics Community Needs for Research Infrastructures 2029–2032 and beyond

CHIPP
Swiss Institute of Particle Physics

ABOUT THIS PUBLICATION

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Xavier Cortada • (with the participation of physicist Pete Markowitz), ‘In search of the Higgs boson: H → ZZ’, digital art, 2013

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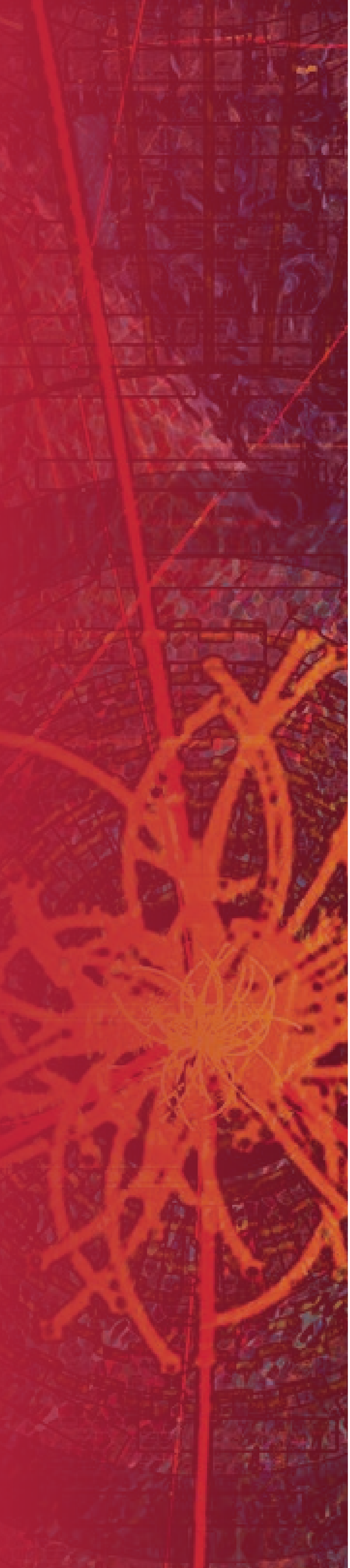
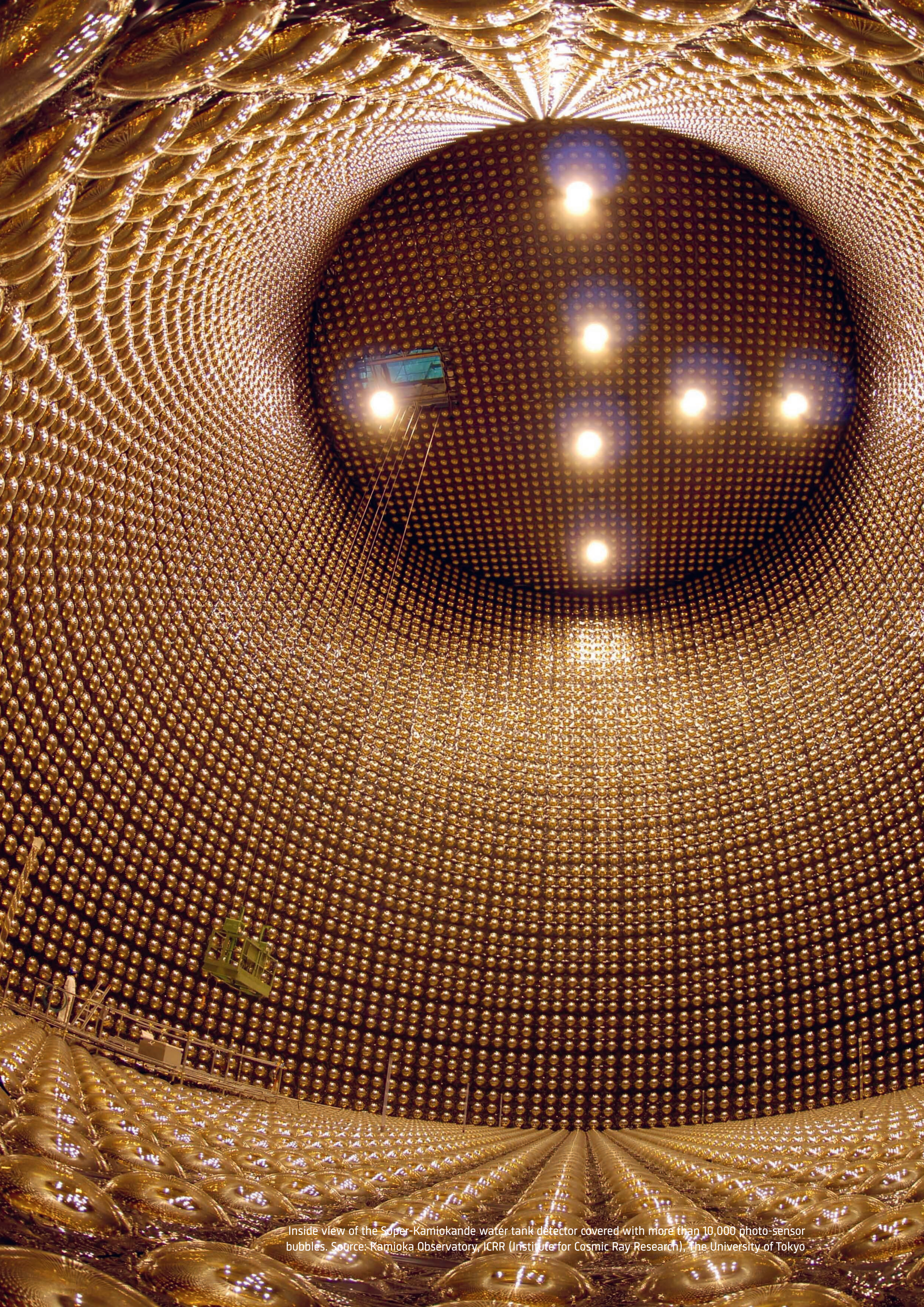


CHIPP Community Roadmap 2024

Update of Swiss Particle Physics Community Needs for Research Infrastructures 2029–2032 and beyond



Inside view of the Super-Kamiokande water tank detector covered with more than 10,000 photo-sensor bubbles. Source: Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

Content

The CMS experiment at CERN will be in operation until 2026, after which time, it will undergo an extensive 4-year upgrade to prepare for the High-Luminosity LHC. Source: CERN, Maximilien Brice

1 Foreword

This document is an update to the ‘CHIPP Roadmap for Research and Infrastructure 2025–2028 and beyond’ that was published in 2021, and which represented a comprehensive overview of particle physics, and its impact on education, society, and industry. The content of the previous roadmap can serve as a reference and provide detailed context for the updates within this document.

This document presents the needs of the Swiss particle and astroparticle physics community in terms of future national and international research infrastructures. Together with similar community roadmaps in other disciplines, it is an element of the four-year process leading to the development of the Swiss Roadmap for Research Infrastructures 2027 to be written by the State Secretariat for Education, Research and Innovation (SERI) in view of the ERI Dispatch 2029–2032 to Federal Council. The role for these ‘bottom-up’ inputs is to serve as an important basis for the strategic planning of the higher education institutions on new or major upgrades to national infrastructures and to inform and support SERI during its decision-making process on Swiss participation in international research infrastructure networks and organisations.

SERI has formally mandated the Swiss Academy of Sciences (SCNAT) to update the seven community roadmaps previously published in the disciplines of biology, chemistry, geosciences, astronomy, particle physics, photon science, and neutron science. SCNAT engaged its network of member societies and commissions to reach out to the scientists willing to get involved. It encouraged diversity of the participating scientists and provided the needed support for the collaborative writing, layout, publication and printing of this document.

To prepare this document, Board members began with a two-day roadmap workshop in January 2024. Each pillar of the CHIPP community met in parallel sessions to review detailed presentations of their experimental efforts and to discuss priorities. Following this, each pillar summarised their findings in a plenary meeting with the full community. Building on this, editors were chosen by each pillar to compile sections for this roadmap. The Editorial Board met several times to converge on a first draft. This draft was shared with the Board, which had several opportunities to provide comments. Finally, the document was unanimously approved in an October 2024 Board meeting.

The CHIPP Roadmap Editorial Board,

B. Kilminster (chair), P. Crivelli, G. Dissertori, T. Golling, G. Isidori, T. Montaruli, K. Müller, M. Seidel, D. Sgalaberna, M. Spira, M. Weber, A. Benelli (secretary)

November 2024

The ATLAS experiment at CERN has undergone an intense maintenance and consolidation in 2022 to meet the challenges of Run 3 of the LHC. Source: CERN, Maximilen Brice

2 Introduction

The Swiss Institute of Particle Physics (CHIPP) is the grassroots organisation of Swiss particle and astroparticle physics researchers in Switzerland as a legal entity of Swiss law. CHIPP oversees and coordinates Switzerland's national and international participation in particle and astroparticle physics and holds a number of important roles. A description of CHIPP as well as a description of its three main research pillars follows.

2.1 The Swiss Institute of Particle Physics (CHIPP)

The purpose of CHIPP is to coordinate the involvement of Swiss institutes in particle and astroparticle physics research and teaching. One of its important functions is to recommend priorities within the context of available resources. CHIPP consists of two bodies: the CHIPP Plenary and the CHIPP Board. Figure 1 shows a breakdown of CHIPP membership. The CHIPP Plenary consists of physicists with a postgraduate degree (PhD students, postdocs, senior scientists, and professors), who are active in the realm of particle and astroparticle physics, and who work for a Swiss institution; Swiss nationals with a PhD degree and who are employed by CERN are also included. The CHIPP Board is comprised of all professors from Uni. Basel, Uni. Zurich, Uni. Bern, Uni. Geneva, ETHZ, and EPFL with activities in experimental or theoretical particle and astroparticle physics, as well as the heads of the experimental and theoretical particle physics groups at the Paul Scherrer Institute (PSI), and additional members of the plenary with special functions. The CHIPP Board meets three times per year, and the CHIPP Plenary at least once. The CHIPP Board elects an Executive Board, consisting of a Chair and one to three Deputy Chairs, for periods of two years.

2.2 Pillar 1

Pillar 1 of CHIPP consists of Swiss activities at the high-energy, high-intensity, and precision frontiers of particle physics. This pillar focuses on precision measurements and tests of the Standard Model and searches for physics beyond the standard model in multi-purpose collider experiments, as well as targeted measurements in dedicated, accelerator-based experiments. Switzerland is in a unique position in terms of large-scale facilities for fundamental particle physics. It is a host country of CERN and it operates the Swiss Research InfraStructure for Particle physics (CHRISP) at the national laboratory, PSI. Particle physicists from all CHIPP institutions play leading roles in knowledge-frontier experiments running at CERN and at PSI. These roles comprise intellectual leadership, hardware R&D, design, construction, implementation, data taking, data analysis, and theory developments, as well as important managerial leadership roles. All of these activities significantly enhance the discovery potential of the experiments and considerably extend the boundaries of our current knowledge.

2.3 Pillar 2

The focus of CHIPP Pillar 2 is on unraveling the outstanding mysteries of neutrino physics. These include completing the measurement of all of the parameters of the neutrino PMNS matrix, including CP violation, identifying whether they are their own anti-particles, determining their mass ordering, and connecting to cosmology and leptogenesis. Swiss scientists strongly contribute to innovative and advanced detectors covering a large range of neutrino measurements, from very low to extremely high energies, and from the smallest to the highest rates of events. Neutrino physics has become a precision measurement field for which the Swiss institutions have great experience and an outstanding reputation. In the present landscape, multiple Swiss institutes have leading roles in the physics exploitation of running experiments, as well as the design and construction of future experiments.

2.4 Pillar 3

Pillar 3 of CHIPP relates to astroparticle physics, including searches for and measurements of particles from space. Experiments may be ground- or space-based, and include searches for dark matter, and measurements of multiple messengers that include gamma and X-ray radiation, cosmic rays, neutrinos, and gravitational waves. Swiss groups are engaged in large international research infrastructures such as gamma ray observatories, providing advanced detection technologies, and innovative analysis approaches. CHIPP groups are at the forefront of direct searches for dark matter, especially with liquid xenon, requiring cooperation with underground laboratories in Europe and the USA.

In support of the three primary experimental pillars, Swiss researchers are at the forefront of different aspects of theoretical research, whose ultimate goal is a deeper understanding of the underlying principles governing fundamental interactions. This common objective is pursued along different research lines, which span a wide range of topics from computing precise predictions for processes under experimental investigation to developing new models and new principles. Research groups in all institutes are also active in detector research and development, which often extend to applications in other scientific fields and industry.

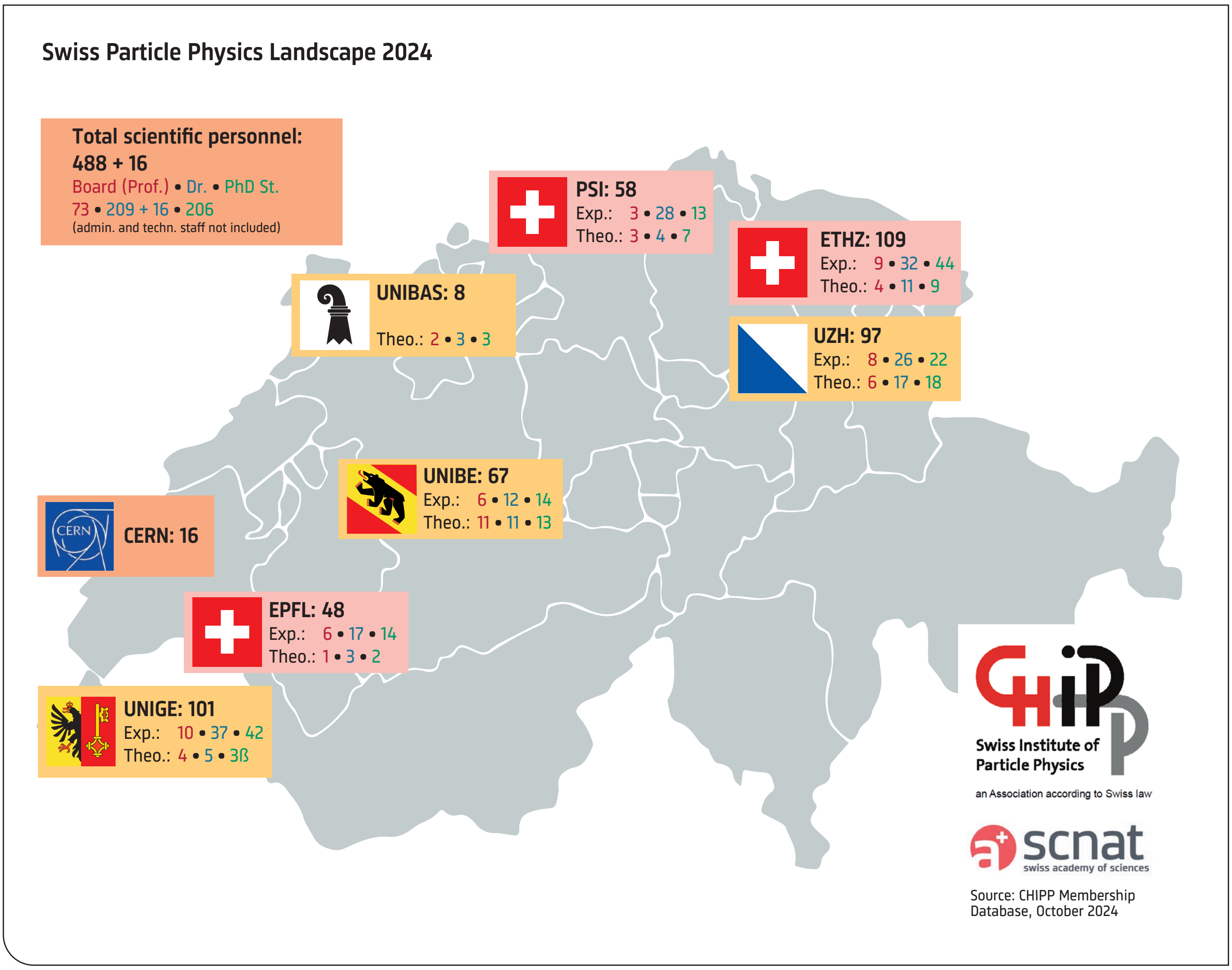


Figure 1: Map with the institutions involved in particle and astroparticle physics in Switzerland in 2024. Board members in experiment and theory are shown in red, postdocs and senior scientists in blue, and Phd students in green. Source: CHIPP

3 Findings and recommendations

Here we present the major findings and recommendations that build upon the detailed analysis that was presented in the CHIPP roadmap published in 2021.[1] Particle and astroparticle physics are both embedded in an international context, and CHIPP endorses the findings of the European Particle Physics Strategy Update[2] by CERN issued in 2020, the 'European Astroparticle physics strategy for 2017–2026' by the Astroparticle Physics European Consortium (APPEC),[3] and the 2024 Long Range Plan of the Nuclear Physics European Collaboration Committee (NuPECC) titled 'Perspectives for Nuclear Physics'.[4] Here, we provide further guidance on the implementation of the major findings and recommendations of those roadmaps in the Swiss context, and provide additional findings and recommendations specific to the CHIPP community.

Finding 1: The European particle physics community considers an electron-positron Higgs factory as the highest priority, together with the ambition to operate a proton-proton collider at the high-energy frontier of about or exceeding a centre-of-mass energy of 100 TeV. CHIPP points out that these ambitious goals will be best achieved through the Future Circular Collider (FCC) programme: an electron-positron *Z/W/H/t* factory (FCC-ee) as a first stage, starting operation around 2045, followed by a 100 TeV hadron collider (FCC-hh). Each of these stages serves distinct but complementary physics goals, and the motivations for doing the FCC-ee first and FCC-hh afterwards are rooted in maximizing scientific output via precision measurements and searches for new physics as well as technological feasibility. This would also have the benefit of securing the future of high-energy particle physics with CERN as a world-leading laboratory well beyond the 2080s. The timely start of the FCC-ee in 2045 is critical because it is commonly accepted that a greater delay will cause the community to dissipate. Additionally, the development of suitable high-field magnets for the FCC-hh is crucial for the continuation of the programme beyond the FCC-ee.

Recommendation 1a: CHIPP recommends that Switzerland strongly support CERN as the world-leading laboratory in particle physics. The research portfolio of CHIPP is well aligned with that of CERN such that CHIPP will continue to benefit greatly from, and lend strong support to, CERN for the foreseeable future.

Recommendation 1b: CHIPP recommends implementing a national strategy towards the participation in CERN's programme for an FCC, starting with FCC-ee, which encompasses detector development, computing, data analysis and simulation, and importantly theoretical research. CHIPP supports CERN's goal to incorporate sustainability considerations into the design of future colliders.

Recommendation 1c: CHIPP recommends that Switzerland maintain involvement in accelerator physics development, especially towards the FCC projects. In particular, CHIPP recommends the continuation of the successful Swiss Accelerator Research and Technology (CHART) programme, it being an excellent example of close collaboration between CERN, the national laboratory, PSI, national institutes, and universities.

Recommendation 1d: CHIPP recommends that Switzerland maintain strong involvement in generic detector research and development in close collaboration with the CERN DRD programme, which is essential for the future of particle physics, and which fosters synergies with other scientific fields.

Finding 2: The Large Hadron Collider (LHC), with its future high-luminosity running phase (HL-LHC) beginning in 2030, continues to be the flagship project at the high-energy frontier, until the end of its scheduled lifetime around 2041. Swiss research groups are actively advancing detector developments for various experiments associated with the HL-LHC. The HL-LHC will provide a plethora of new data that will allow for measurements of the properties of the Higgs boson, provide increased precision measurements of Standard Model (SM) parameters, and enable both further exploration of the flavour sector as well as searches for physics beyond the Standard Model (BSM). The long-term support to operate the LHC detectors, and to later provide performance and longevity upgrades, remains crucial during this period. Furthermore, the large volume of collected data will create challenges for data-analysis strategies and computing in the Worldwide LHC Computing Grid (WLCG) paradigm.

Recommendation 2a: CHIPP strongly supports the experimental HL-LHC programme and recommends that Switzerland continue to secure the operation and upgrades of the ATLAS, CMS, and LHCb detectors, to ensure full exploitation of previous and ongoing investments.

Recommendation 2b: For the full HL-LHC exploitation to be feasible, further computing infrastructure and R&D are required, possibly in collaboration with other fields facing similar computing challenges with large-scale computing and data handling strategies. CHIPP recommends that Switzerland engage in providing the necessary resources.

Finding 3: The quest for new physics at high energy is complemented by a diverse set of experimental activities at lower energies with precision obtained using high intensities. These activities are supported by the use of dedicated accelerators, either at the national laboratory (PSI), or at CERN by making use of the SPS and the AD facilities, running in parallel with the LHC. These experimental efforts are avenues towards exploring precision SM tests and intriguing BSM scenarios, and are therefore extremely important for CHIPP's multi-prong approach towards searching for BSM physics and putting the SM to the test.

Recommendation 3a: CHIPP supports the present and future exploitation of the High-Intensity Proton Accelerator (HIPA) complex at PSI. CHIPP recommends that a portfolio of dedicated experiments at the low-energy/high-intensity frontier should be pursued, and supports the High-Intensity Muon Beam (HIMB) programme at PSI.

Recommendation 3b: CHIPP supports the present and future exploitation of the CERN accelerator complex beyond the primary LHC experiments, in experiments that provide precision SM tests and searches for BSM physics using novel approaches. CHIPP recommends that Switzerland continue to play and expand its leading role in this experimental programme. Of these, priority should be given to the NA64 and FASER upgrades and to the construction of the SHiP experiment.

Finding 4: Long-baseline neutrino programmes at accelerators have been pursued with priority for many years, and CHIPP supports both operational experiments and approved future projects. T2K upgrades were completed and the mass production of the underwater electronic modules of the far-detector for Hyper-K has started, with support from the CERN Neutrino Platform. The SBN programme has finished construction and physics exploitation is now underway. The technical designs for the DUNE ND have successfully been demonstrated in prototype tests paving the way for detector construction.

Recommendation 4a: In light of the significant past contributions and Switzerland's highly visible commitments as well as the importance of these initiatives to the global community, CHIPP recommends advancing the construction and upgrades of the long-baseline facilities with continued priority to fulfill commitments of the Swiss groups.

Recommendation 4b: The Swiss participation in DUNE and Hyper-K should be supported with high priority to maximise the scientific reach.

Recommendation 4c: The operation of the ongoing experiments, T2K in Japan and SBL at FNAL, should be supported in order to benefit scientifically from previous investments, and in preparation for future long-baseline neutrino programmes.

Finding 5: The quest for the nature of neutrino and lepton number violation is a fundamental scientific goal in particle physics, requiring long-term involvement and a steady support of experiments. CHIPP contributes to the GERDA experiment, which searches for neutrinoless double beta decay of ^{76}Ge, achieving world-leading results. GERDA was successfully completed at the Gran Sasso Laboratory, and superceded by LEGEND-200. The next phase, LEGEND-1000, will also be constructed at Gran Sasso. The goal is to be sensitive to the full inverted neutrino mass ordering region. We note that the DARWIN/XLZD experiment will also search for neutrinoless double beta decay, and detect low-energy astrophysical neutrinos, which are also valuable to the neutrino pillar.

Recommendation 5: Swiss investment in the construction of the LEGEND-1000 experiment is recommended, in view of its unique physics potential.

Finding 6: The IceCube programme lasted about ten years, and has delivered many fundamental results of multi-messenger astrophysics with strong Swiss contributions, including the observation of the first cosmic neutrino source. In addition, IceCube is currently the most sensitive detector to neutrinos from supernova collapses up to the Large Magellanic Cloud, and it is expected to deliver results on tau neutrino oscillations and mass hierarchy in the next few years, complementary to accelerator neutrino experiments. Its future upgrade, IceCube-Gen2, is foreseen to have a factor of ten larger volume and is prioritised in the US in the P5 process.

Recommendation 6: IceCube is a relevant player in multi-messenger and neutrino oscillation physics, with a strong scientific case on neutrino oscillations (complementary to accelerator neutrinos) and on multi-messenger astrophysics (Pillar 3). While Swiss institutions do not plan to participate in the construction of its upgrade, its science programme remains of interest for scientists in Switzerland.

Figure 2: The ALPS super computer at CSCS. Source: Marco Abram

Finding 7: The Swiss Pillar 3 astroparticle physics community, involving a variety of ground and space-based experiments, recognises two priority lines of research: multi-messenger astrophysics and dark matter. Their scientific goals overlap with Pillar 1 and 2, and are of interest for astronomers, theorists in cosmology, and researchers in particle physics. With respect to the the 2021 Roadmap,[1] the community agreed on specific recommendations concerning the research infrastructures in construction and in planning reported in the three recommendations below.

Recommendation 7: CHIPP recommends that Switzerland undergoes a planification for the large research infrastructures of strongest interest for the astroparticle community involving particle physicists, cosmologists and astrononomers, in synergy with CHAPS. Plans to secure long-term data processing and storage infrastructure should also be considered.

Finding 8: The Cherenkov Telescope Array Observatory (CTAO) will explore the Universe at the highest energies based on the imaging air Cherenkov technique. CTAO will consist of two arrays of Cherenkov telescopes located in La Palma, Canary Islands, Spain and Paranal in Chile. Three types of telescopes are optimised for different fields of view and energy bands from 10 times to 300,000 times the proton rest mass. CTAO is driven by a consortium of about 1500 scientists from 25 countries, is a landmark of the European Strategy Forum on Research Infrastructures (ESFRI), and is in the Swiss SERI infrastructure roadmap.

Recommendation 8: The CTAO exploration of the gamma-ray sky with high precision enables a new era in multi-messenger astrophysics, opening unexplored paths to study cosmic particle accelerators and the origin of cosmic rays, dark matter, cosmic magnetic fields, and star formation in synergy with new messengers. CHIPP considers it a priority for Switzerland to become a member of the almost-finalised CTAO ERIC legal entity, in order to profit from the Swiss investments in the CTAO-CH Collaboration, widely spread between relevant Institutions in Switzerland, since 2005. Sustaining a strong community of scientists and a forefront data center at CSCS will secure the exploitation of CTAO for the next 30 years.

Finding 9: The Swiss astronomy and astroparticle physics communities, represented by CHIPP and CHAPS, consider, at present, the future Einstein Telescope (ET) as the most scientifically attractive new large facility in the preparatory phase of development. Following the recommendations from the 2021/2022 Roadmaps for Research Infrastructures, CHIPP and CHAPS have advanced towards a common strategy for participation in ET. A federated participation by Switzerland in this future large project, guaranteeing access to all researchers working at Swiss institutions, is of strategic importance. In order to fully leverage this large-scale Swiss participation, it is important to also take leading roles within ET in both instrument development and scientific exploration. To achieve this goal, it is essential to establish experience in the current generation of gravitational-wave observatories such as LIGO, Virgo, and KAGRA (LVK). This goal can be realised through active participation in the LVK Collaboration, with an outlook toward a flagship-level involvement in ET.

Recommendation 9: The CHIPP and CHAPS communities recognise the Einstein Telescope (ET) as a project of significant mutual interest. In order to take a leading role in instrumentation, the communities should actively participate in the LVK technical activities, in preparation for similar efforts for ET. We further endorse the continued, direct, and fruitful collaboration between CHIPP and CHAPS, leveraging common interests and tuning our strategy towards strong participation in ground-based, gravitational-wave observatories, in particular, ET.

Finding 10: The XENONnT and LUX-Zeplin (LZ) experiments are at the forefront of dark matter research, aiming to uncover this unknown matter that constitutes five times more of the universe than ordinary matter. These experiments not only serve as powerful tools for dark matter detection, but also provide valuable insights into nuclear physics, neutrino physics, and solar physics. Following in their footsteps, the DARWIN/XLZD experiment, a staged 80-tonne liquid xenon detector, will offer unparalleled sensitivity to dark matter across a wide mass range and probe other unexplored phenomena in neutrino and nuclear physics. In recent years, theoretical and experimental developments greatly increased interest in exploring dark matter in the mass range below the proton mass. Swiss scientists are leading the development of novel, low-mass dark-matter experiments with state-of-the-art quantum sensors, achieving leading low-energy thresholds to explore low-mass dark matter in experiments like TESSERACT and DAMIC-M. The combined efforts of these experiments ensure a leading and comprehensive physics programme by Swiss scientists, covering a wide range of dark matter mass ranges and contributing significantly to our understanding of the universe.

Recommendation 10: CHIPP considers the support of the ongoing and future direct dark matter searches a high priority of the Swiss programme. The ongoing operation and data analysis of the current generation XENONnT and LZ experiments are at the forefront of dark matter direct detection research. CHIPP advocates for continued Swiss leadership and instrumentation contributions to the future DARWIN/XLZD multi-tonne dark matter search facility. To explore low-mass dark matter and foster novel instrumentation, CHIPP also supports with lower priority smaller-scale cryogenic dark matter experiments employing quantum sensors, such as TESSERACT and DAMIC-M.

Finding 11: Theoretical physics is of pivotal importance to the development of fundamental physics, and is a research area in which Switzerland has an outstanding track record. It is a salient feature of particle physics that its theory provides an extremely powerful paradigm, namely the Standard Model, and consistent BSM extensions thereof. Unravelling the puzzles that the SM cannot answer will require renewed theoretical efforts on phenomenology, precision calculations, and model building. Now that the field seems to be leaving the realm of 'guaranteed' discoveries, such as theoretically predicted, but very rare phenomena like Higgs boson production or the detection of gravitational waves, theoretical guidance, even if 'only' of heuristic nature, is more important than ever. At the same time, concerted efforts towards improved theoretical predictions within the Standard Model are of key relevance for the interpretation of current and planned experiments at particle accelerators. The needed precision of theory predictions is driven by the ambitious current and future collider physics programme, as well as the high-intensity, low-energy experiments of Pillar 1, and requires a strengthening of the existing theory programme in Switzerland. This requires improved perturbative and non-perturbative calculations and their uncertainties. Similarly, theoretical physics plays a key role in the interpretation of astrophysical phenomena, the area from where we presently observe the strongest indications for BSM physics.

Recommendation 11: CHIPP recommends that Switzerland continue to strengthen its vigorous programme in theoretical particle and astroparticle physics as well as cosmology. Beyond the intrinsic goal to understand and adequately formulate the laws of nature, this effort is a necessary ingredient for the interpretation of current and planned experiments at accelerators, as well as astrophysical phenomena. Theoretical research is also of pivotal importance as a guide in planning long-term experimental efforts in particle and astroparticle physics. This requires also a long-term plan for maintaining and improving existing theoretical tools for future experiments to allow for their usability by future generations.

Finding 12: Swiss particle and astroparticle physicists have been, and continue to be, very successful in terms of transferring know-how from their specific research to other fields of science and to industry. In particular, close ties and collaborations exist with many Swiss and international companies, and an important number of start-up companies have been created, as described in more detail in the previous roadmap.[1] Because of their growing importance in recent times, fields of research such as artificial intelligence applied to all aspects of data analysis and simulation, or very fast inference and extremely low-latency, high data-rate applications, are particularly promising areas for future know-how transfer.

Recommendation 12: CHIPP encourages the academic and research institutions in Switzerland to pursue, and further strengthen, the support they give to researchers in terms of technology and know-how transfer.

Finding 13: In view of current and future large-scale experiments, the promotion of outreach and education is becoming increasingly important for particle and astroparticle physics. As it is basic research, whose benefits to society are often indirect, it is important to communicate the fascination, utility, and promise of particle and astroparticle physics to the wider public. Members of CHIPP are well-placed to give inspiring outreach talks, run visitor programmes for the general public at their universities, PSI or CERN, and convey the fascination of basic research to the next generation. In addition, the new CERN outreach flagship, the CERN Science Gateway, with thousands of visitors per week, strengthens the Swiss education and outreach activities.

The international outreach and education networks, such as the CERN Teachers Programme, the CERN Summer Schools and Camps for high school students, the International Particle Physics Outreach Group, and the European Particle Physics Communication Network strengthen the outreach efforts and provide support in the form of online platforms, tools and materials.

Recommendation 13: CHIPP encourages the academic and research institutions in Switzerland to pursue and further strengthen the support they give to researchers in terms of outreach and educational projects.

The new scintillating-fibre (SciFi) particle-tracking detector of the LHCb experiment being transported in November 2021 for installation, Source: Hertzog, Samuel Joseph, CERN

4 The present Swiss landscape and vision for the future

4.1 Energy frontier of particle physics

4.1.1 Experiments at CERN: current and planned

CERN's LHC delivers the highest-energy collisions ever achieved in any accelerator world-wide. These collisions are recorded by the ATLAS, CMS, and LHCb experiments, which serve the largest community of particle physicists within CHIPP. The CMS and ATLAS experiments are multi-purpose experiments, most notable for their discovery of the Higgs boson in 2012, and since then, providing precision measurements of its couplings and mass as well as exceeding expectations on the search for di-Higgs production, which will elucidate the structure of the Higgs potential. CMS and ATLAS have each published more than 1300 publications, covering a wide range of topics from measurements of the heaviest particle, the top quark, to searches for production of dark matter and many theorised BSM particles, to precision electroweak and QCD measurements, such as the precise measurement of the mass of the W boson, which has deep connections to new physics processes and the stability of our universe. A summary of some of these measurements is shown in Fig. 3, which highlights the agreement between theory and experiment over an impressive 14 orders of magnitude in production rates. The LHCb experiment focuses on studies of bottom and charm hadrons, providing insights into CP violation that help explain the matter-antimatter asymmetry in the universe, also by measuring their production and decay rates, testing the flavour physics of the standard model, and searching for violations of lepton flavour universality. The LHC experiments also study the quark-gluon plasma, providing insight into the phase transitions and correlations of particles in the early universe.

The CMS and ATLAS experiments are undergoing transformative upgrades to enable enhanced capabilities during the high-luminosity phase of the LHC (HL-LHC), which will deliver a factor of ten increase in luminosity. These upgrades improve the coverage and resolution of object measurements, incorporate precision timing measurements into particle identification algorithms, increase the allowed data rates, and make use of new algorithms for triggering on previously uncollected data. The upgrades, along with additional luminosity delivered by the HL-LHC, will enable more precise measurements of the

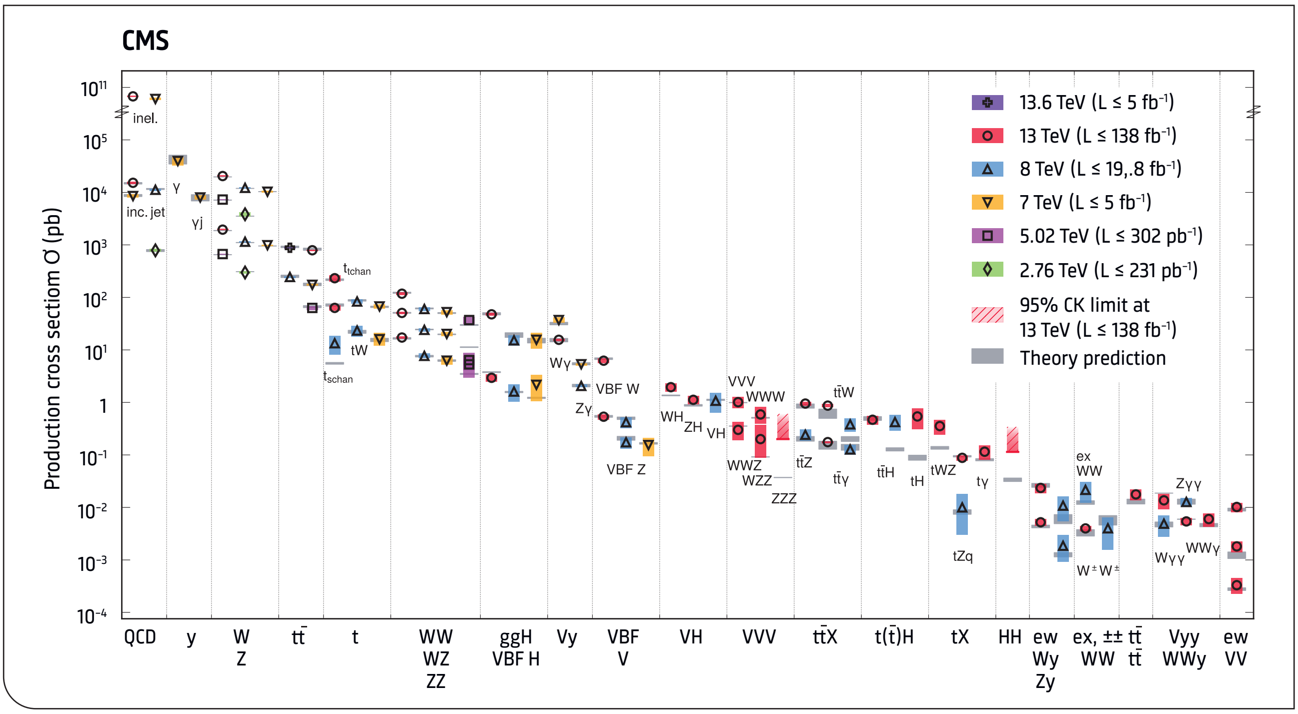


Figure 3: Cross sections of selected high-energy processes measured by the CMS experiment, from high-rate processes on the left to rare multi-particle production on the right, and at different center-of-mass energies.[5] What is notable is that the measurements in coloured bands cover over 14 orders of magnitude in cross-section, and that theory predictions in gray show excellent agreement. Similar plots by the ATLAS experiment are also available.[6]

Figure 4: The ELENA ring at CERN. Source: CERN

SM, the potential observation of di-Higgs production, and searches for new particles in phase space that was not previously accessible. The LHCb experiment is proposing a future upgrade with enhanced tracking capabilities and enhanced real-time data processing with a trigger-less readout so that it can significantly increase its luminosity in the HL-LHC phase. This increased data will allow for measurements of increasingly rare decays and refine the understanding of violations of CP and the universality of the electroweak interaction.

Swiss institutions play vital roles in the leadership of the CMS, ATLAS, and LHCb experiments, conduct a wide range of physics measurements and searches for new physics, and are making key contributions to the HL-LHC upgrades and operations of the experiments.

The FASER and SND experiments started operation in LHC Run 3 and recently reported the first observation of collider neutrinos. FASER is approved to run in Run 4, for which SND has also requested approval. The NA62 experiment at the CERN North Area is a leading kaon physics experiment, focusing on extremely rare processes that provide precision tests of the SM, and is very sensitive to a wide range of physics beyond the SM. Other CERN particle beams also provide unique opportunities, such as searches for light dark matter and dark sectors with NA64 at the CERN SPS or at the ELENA facility delivering antiprotons for precision measurements to the GBAR and BASE Experiments. CERN approved the construction of the high-power beam-dump facility in the ECN3 cavern where the SHiP Experiment, dedicated to dark sector searches, is foreseen to start operation in 2032. The Forward Physics Facility (FPF), targeting dark sector searches and collider neutrino explorations, and proposed in the context of Physics Beyond Colliders at CERN, will be evaluated for approval at a later stage.

4.1.2 Accelerator physics and technology

In Switzerland several large research infrastructures enable science in particle physics, but also in a number of fields like chemistry, life, and materials sciences. These facilities are driven by particle accelerators providing energetic and high-quality particle beams. For the development of new and existing facilities, accelerator science and technology are of paramount importance. After a long-term engagement in these areas, significant expertise on accelerators has been developed, both at PSI and at CERN.

Today PSI operates the High-Intensity Proton Accelerator (HIPA) for intense muon and neutron production, a state-of-the-art synchrotron light source, SLS2.0, that is undergoing an upgrade to be completed in 2025, and the

Swiss Free Electron Laser (SwissFEL). The IMPACT (Isotope and Muon Production using Advanced Cyclotron and Target) project will significantly extend and upgrade the infrastructure of HIPA with two target stations. The target station H, High-Intensity Muon Beam (HIMB), will increase the low-energy muon rate by two orders of magnitude to remain internationally competitive with muon sources in other countries undergoing similar upgrades. The second target station, TATTOOS (Targeted Alpha Tumor Therapy and Other Oncological Solutions), is an online isotope separation facility that will produce promising radio-nuclides in sufficient doses needed for research of cancer diagnosis and therapy in clinical studies.

The main parts of the project are expected to be completed between 2025 and 2028. In addition to the upgrade project, several renewal measures are planned for HIPA to ensure its operation for decades to come.

4.1.3 Experiments at PSI: current and planned

At PSI, the HIPA complex drives CHRISP beams, providing the highest intensities of low-momentum pions, muons, and ultracold neutrons. Among the most significant Swiss activities, the n2EDM experiment just entered its commissioning phase. With their new setup, the collaboration aims to improve the sensitivity to the neutron electric dipole moment (EDM) by an order of magnitude. Another experiment served with ultracold neutrons is a precision measurement of the neutron lifetime with τSPECT, aiming to catch up to the current best experiments and then to further improve precision. In addition, the intense cold and thermal beams provided at the Swiss Neutron Spallation Source SINQ at PSI are employed to perform various instrumentation developments and physics experiments. Some of these activities, e.g. the Beam EDM and QNeutron experiments, aim for a long-term perspective at a future dedicated fundamental neutron physics beam line at the European Spallation Source (ESS). A complementary approach to discovering fundamental EDMs involves using charged particles in storage rings. A new experiment at PSI is currently under development for measuring the muon EDM. Experiments at PSI continue to play a world-leading role in searches for charged-lepton, flavour-violating muon decays. The MEGII experiment is taking data to improve its current sensitivity in the $\mu \to e\gamma$ decay to reach branching ratios of 5×10^{-14}. On another front, Mu3e is being commissioned to search for neutrinoless $\mu \to eee$ decays with a sensitivity of 10^{-15} in its first phase. Achieving 10^{-16} in a subsequent phase will require the completion of the HIMB as part of the PSI IMPACT project, which will significantly boost the currently available muon beam intensities. A next-generation rare pion-decay experiment, PIONEER, has been approved at PSI and is currently in its design phase, with data-taking expected to begin in 2029. The goal is to improve the measurement of the charged-pion branching ratio to electrons vs. muons – $R_{e/\mu}$, which is one of the most sensitive tests of lepton flavour universality (LFU). PSI is a world reference facility for the study of muonic and pionic atoms. Swiss Institutes are playing major roles in various experiments (CREMA, MuMASS, PiHe, LEMING, QUARTET and muX) performing precision SM measurements, improving the determination of fundamental constants and searching for exotic interactions. The realisation of the HIMB project will deliver two orders of magnitude increased intensities in slow muons, enabling many new experiments.

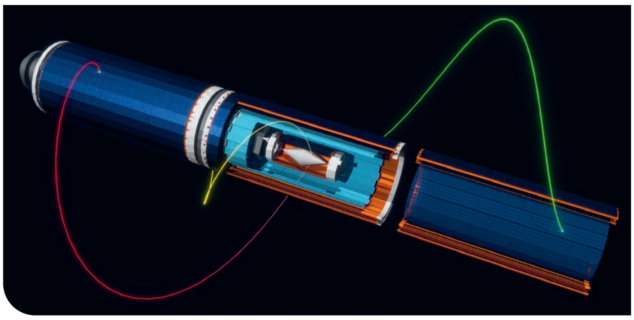


Figure 5: Rendering of the Mu3e detector showing the trajectory of three electrons produced by the decay of a muon. Source: Mu3e collaboration

An outlook of the approved projects in which Swiss researchers are engaged is given in Fig. 7.

4.1.4 The Future Circular Collider project

The Future Circular Collider (FCC) project is a major priority of the CHIPP community as well as the European strategy for particle physics. The first phase provides a 90 km tunnel with electron-positron collisions at various energies, allowing physicists to measure the properties of the electroweak bosons and their interactions with both known and yet unknown particles with unprecedented precision. The second phase, the FCC-hh, will collide hadrons to achieve center-of-mass energies of up to approximately 100 TeV, reaching an order of magnitude increase in the masses of potential new particles that could be discovered.[7]

CHIPP particle physicists are currently building up efforts to participate in the detector design, physics studies, computing tools and theoretical calculations needed in order to exploit the FCC programme to its potential. CHIPP is producing input to the 2025 European Strategy Update for Particle Physics, which will be presented by the European Strategy Group to the CERN council in 2026.

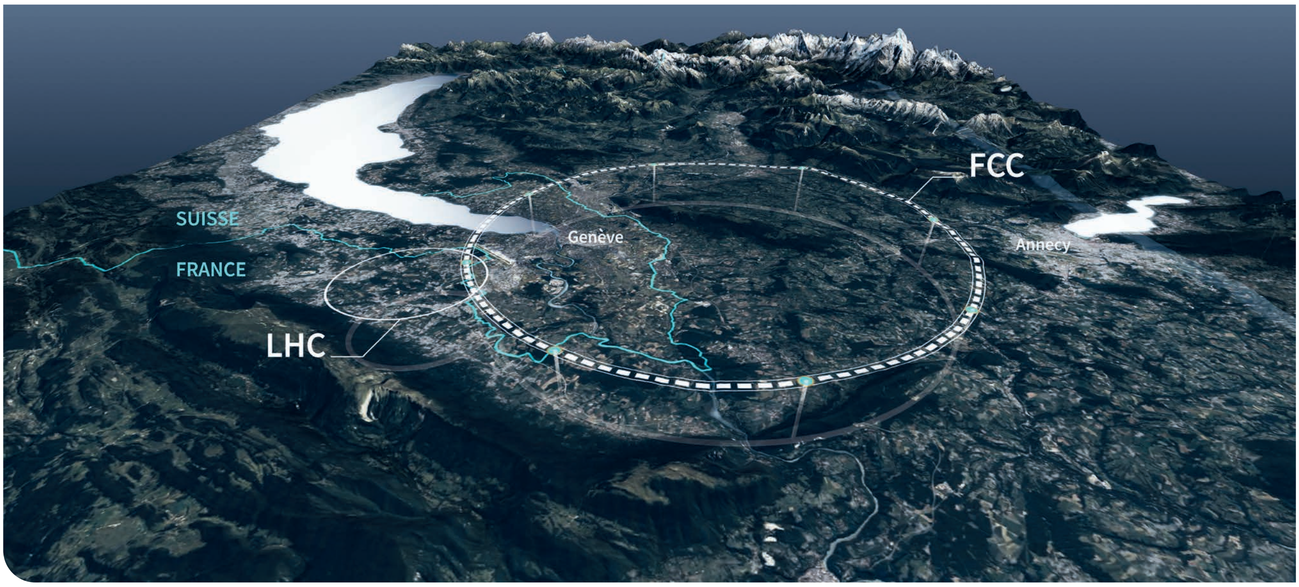


Figure 6: A schematic map showing a possible location for the Future Circular Collider around Geneva. Source: CERN

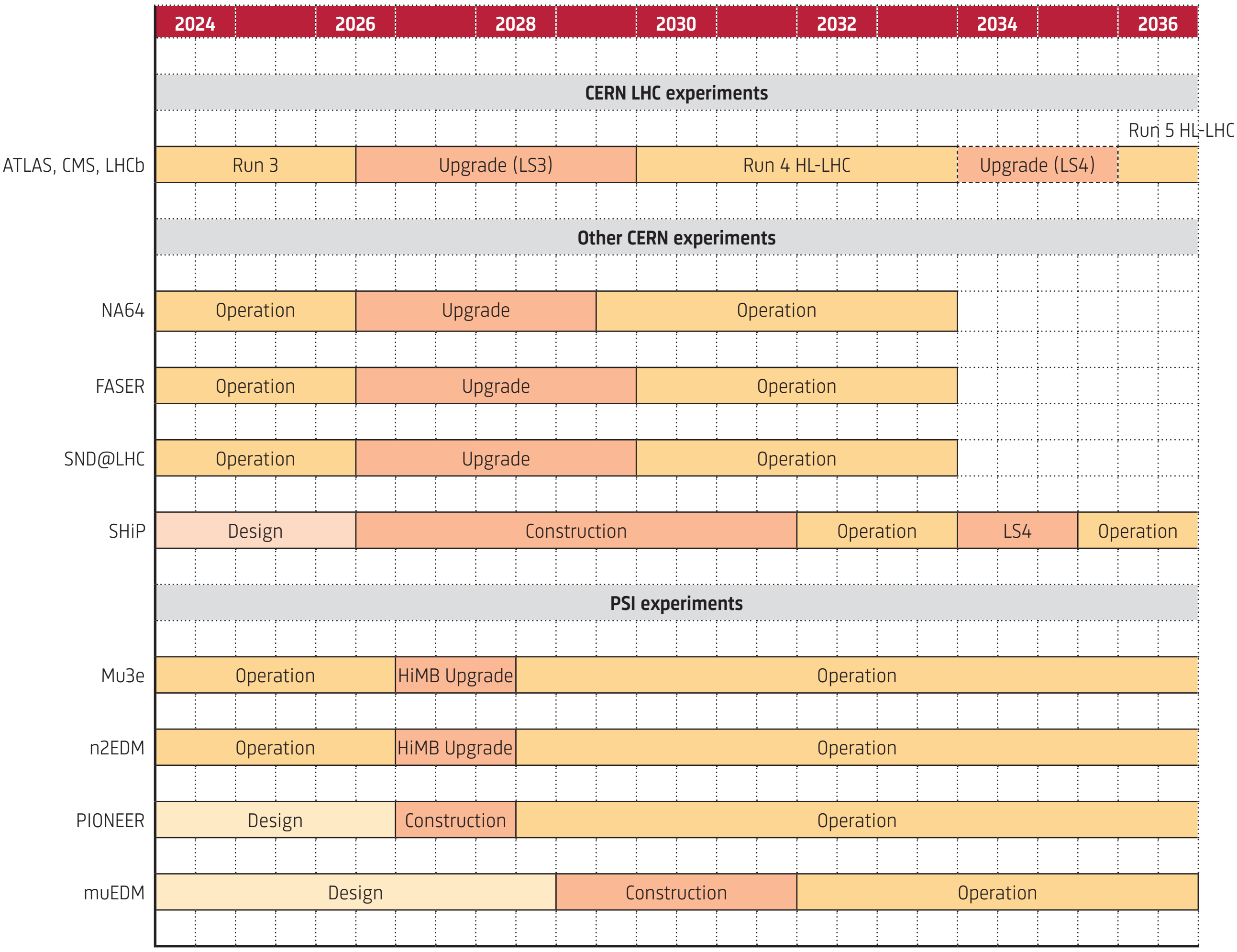


Figure 7: The timeline of the various representative ongoing approved projects where Swiss researchers are involved, at CERN and PSI. This timeline demonstrates activities in recent years starting in 2024 and extending to 2036.

Table 1: A summary of Swiss involvement in approved accelerator-based particle physics experiments. The acronyms, subjects, and goals of each experiment are described at chipp.ch/en/id/rFZJz.

Institution	Main involvements
UNIBE	Experiments at CERN: ATLAS and FASER Experiments at PSI: n2EDM , Beam EDM, QNeutron Detector R&D: Tracking detectors, data acquisition
UNIGE	Experiments at CERN: ATLAS and FASER Experiments at PSI: Mu3e Detector R&D: Tracking detectors, trigger and data acquisition
UZH	Experiments at CERN: CMS, LHCb, SHIP Experiments at PSI: Mu3e Detector R&D: Tracking detectors, trigger
EPFL	Experiments at CERN: LHCb, SND@LHC, NA62, SHiP Detector R&D: Tracking detectors, trigger
ETHZ	Experiments at CERN: CMS, NA64, GBAR, BASE, FASER Experiments at PSI: Mu3e, n2EDM, CREMA, mu-Mass, muX, piHe Detector R&D: Calorimetry, tracking detectors
PSI	Experiments at CERN: CMS Experiments at PSI: Mu3e, MEG II, n2EDM, CREMA, mu-Mass, muX, piHe, muEDM, τSPECT Detector R&D: Tracking detectors

The CHART (Swiss Accelerator Research and Technology) project, a collaboration between CERN, UNIGE, EPFL, ETHZ, and PSI, is dedicated to developing the accelerator technologies necessary to realise the FCC project at CERN and to develop advanced accelerator concepts in Switzerland beyond the existing technology. With exceptional support from SERI, the ETH Board and the participating institutions, CHART contributes to accelerator-driven research developments highlighted in the European Strategy for particle physics. It contributes to both the FCC-ee and FCC-hh phases, as well as also beam dynamics for the FCC, and geodesy and geology studies for the underground tunnel. The injector complex for FCC-ee is important for the luminosity performance of the collider, and its design is covered by a prominent CHART project during the next four years. The project is a collaboration between IJCLab, INFN Frascati, CERN, and PSI. For the linear accelerator sections, all operated at room temperature,the plan is to use technology developed for the electron linac driving SwissFEL. A new type of positron source is being developed to deliver a high yield of positrons per electron of the drive beam. A conceptual test of the source is planned at PSI. The development of a superconducting capture solenoid for the positrons presents a synergy with the High-field superconducting magnet (HFM) programme of CHART.

HFM and high-temperature superconductors are necessary for achieving record center-of-mass energies at the FCC-hh. Research on innovative HFM concepts presents a key activity in CHART also in the coming years. Several magnet concepts are being considered, based on the well-known Nb3Sn conductor material, but also utilising high-temperature superconductors (HTS). While the comparably new HTS tape conductors exhibit promising advantages in view of field strength and better cryogenic efficiency, there is still significant R&D work to be done before HTS magnets can be used to build a particle collider. HFM research has strong synergies with PSI projects since superconducting magnets are of great interest for the production of bright, hard X-rays (used in SLS 2.0, compact sources for lithography, security and personalised medicine applications), and for future proton-therapy gantry designs as they promise lighter and cheaper gantries. Also, the development of cost-efficient fusion reactors may benefit from the CHART HFM programme in a synergistic way. More information on the CHART programme is available on the CHART website (chart.ch).

4.1.5 Vision for the future

A summary of the ongoing and future efforts of CHIPP in the energy and intensity frontier is as follows.

1. Short- and mid-term prospects at accelerator-based facilities

Over the coming decades, the priority will remain to exploit the discover potential of the LHC/HL-LHC programme, and to use it to deepen our understanding of the SM. At the same time, it is important to continue Switzerland's pioneering role in conceiving and developing novel dedicated smaller-scale experiments with unique discovery potential, such as FASER, SND, NA62, NA64 and the SHiP beam-dump facility at CERN. This may involve the proposed LHC FPF, currently under conceptual development. At the low-energy side of the high-precision frontier, Switzerland operates a unique word-leading hub in the form of the proton accelerator HIPA at PSI, which provides the highest intensities of low-momentum pions, muons, and ultracold neutrons. The upgrade of this facility via the HIMB planned to be implemented at HIPA from 2025 to 2028 is a high-priority project opening exciting new opportunities at the intensity and precision frontier.

2. Long -term prospects at the high-energy frontier

The FCC programme at CERN represents a unique multipurpose facility, which can maximise the potential for the discovery of new physics in its possible two stages (ee and hh). The FCC-ee is a Higgs, electroweak boson, and top quark factory, and the machine choice with the maximum possible luminosity. In addition to precision Higgs physics, the extraordinary 10^{13} Z bosons produced provides unique opportunities for new physics discovery by way of ppm precision measurements, and by searches for feebly coupled new particles such as right-hand-

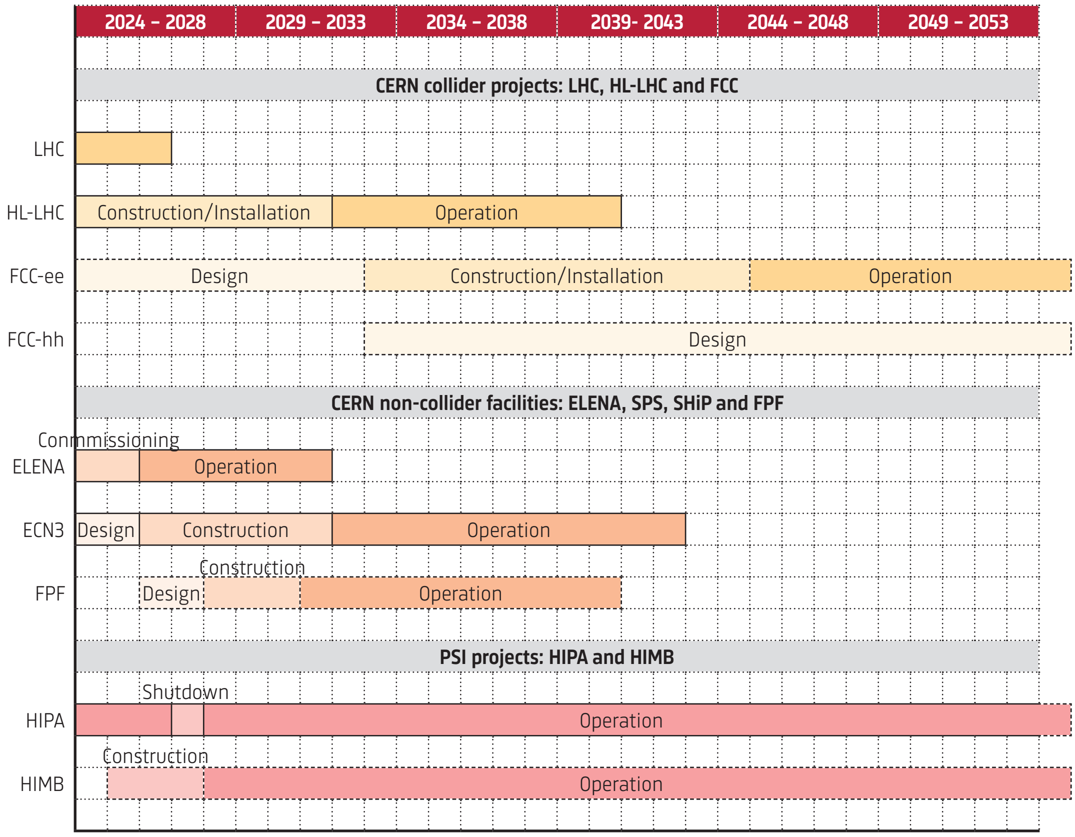


Figure 8: The timeline of major approved or prospective accelerator projects and facilities where Switzerland is already or plans to be engaged, at CERN and PSI. The intensity of a given colour type indicates the project phases: preparation and design, construction, and operation and exploitation of the machine. Dashed boxes indicate prospective projects that are not yet approved for construction.

ed neutrinos and Axion-like particles. It is also extremely challenging in terms of detector requirements, thus opening new avenues for detector technologies. The FCC-hh phase represents a unique high-intensity programme and an in-depth exploration of the high-energy frontier. The FCC-ee and FCC-hh phases provide synergy and complementarity, both for infrastructure and physics. Together, the facility would allow CERN to remain the global world leading laboratory of particle physics for the better part of the century.

Swiss particle physicists have played, and are continuing to play, a seminal role in the FCC accelerator concept, contributing greatly to the development of high-field magnets and working on key aspects of the FCC-ee accelerator design. At the end of 2018, when providing input to the ESPP update, the Swiss community clearly indicated the FCC programme as their main long-term priority. This input has been largely endorsed by the official ESPP update released in 2020. The CHIPP community has started engagement in detector design, physics studies, computing, and theoretical calculations for the FCC-ee.

4.2 Neutrino physics

Switzerland has a long history in neutrino physics with several institutes, (UNIBAS, UNIBE, UNIGE, UZH and ETHZ) actively involved in this research. Presently, the main open questions concern neutrino flavour oscillations, the search for $0\nu\beta\beta$ decay, and the origin of high-energy neutrinos from the cosmos. A detailed review can be found in the 'Whitepaper for neutrino physics (Pillar-2) in Switzerland for the period 2025–2032'.[8] The precise measurement of the neutrino oscillation probability at long-baseline accelerator-based experiments is the highest priority task of the neutrino pillar in Switzerland. The nature of the neutrino – the only electrically neutral elementary fermion that could very well be its own antiparticle – is also of utmost scientific relevance. Hence, the search for the $0\nu\beta\beta$ decay is also recommended. Research on extraterrestrial neutrinos shall continue beyond the successes achieved by IceCube and lead to IceCube-Gen2. Its complementarity with the long-baseline accelerator-based neutrino programme shall be exploited. Additional experiments, described in the energy frontier section (FASERnu and SND@LHC) and the astroparticle


Figure 9: Left: Image of the completed DUNE far detector cavern as of August 2024. Right: Image of the Hyper-K cavern during the excavation, near completion as of August 2024. Source: DUNE, Hyper-K experiments

physics section (XENONnT and DARWIN/XLZD), also perform neutrino physics measurements.

The development of novel technologies, crucial for the next generation of neutrino experiments, is being led by Swiss institutes. These developments include innovative detectors, the study of new particle-accelerator infrastructures, and technologies (notably at PSI), which have been strongly supported by CERN, host of the Neutrino Platform, an integral part of the global strategy. All of these Swiss-coordinated efforts led to maturity in the detector technologies required to perform precise measurements of the elusive neutrinos. These advances, together with those made in the analysis and interpretation of the data, will be key to the contribution of the theory group at UNIBAS leading to key advances in neutrino theory and phenomenology, and providing important guidance to the neutrino physics community. Switzerland is recognised world-wide as a key country for research in all different branches of neutrino physics.

Neutrino oscillation physics is a central priority of experimental particle physics in Switzerland, with major achievements starting with the K2K (Japan) and OPERA (CERN and Gran Sasso National Laboratory) experiments, and continuing today with the T2K (Japan) and MicroBooNE (USA) experiments.

Groups from UNIBE, UNIGE, and ETHZ have made considerable investments in the construction, operation, and scientific exploitation of the T2K Experiment; UNIGE and ETHZ are committed to the scientific exploitation of the experiment until the end-of-operation of T2K. More recently, UNIGE and ETHZ led the construction, in close collaboration with the CERN Neutrino Platform, of two key subsystems of the near-detector upgrade, and are now coordinating its scientific programme within the experimental collaboration. Swiss groups have made key contributions to the T2K upgrade and its near-detector infrastructure that will serve as the near detector of the Hyper-K experiment. The T2K experiment is critical for the development of analysis procedures to be used in Hyper-K, to which both UNIGE and ETHZ are fully committed. Their involvement is focused, in particular, on the design and the construction of the electronics system of the Hyper-K water-Cherenkov far detector.

UNIBE and ETHZ have also held key roles in the initiation of the LBNF/DUNE long-baseline programme in the USA, which originated from the merging of the LBNO project in Europe (led by ETHZ) and LBNE, an early project initiated in the USA for beams and detectors. This worldwide effort is based on the liquid-argon Time Projection Chamber (TPC) technology, the development of which was made possible due to leading contributions from Swiss researchers. The short-baseline programme at Fermilab, operating since 2015, serves as a pathway to the long-baseline LBNF/DUNE programme by using the same detector technology for neutrino detection. Swiss scientists from UNIBE have had leading roles in the construction of MicroBooNE, as well as coordinating the scientific programme of the collaboration. The strong Swiss engagement in DUNE led to the design concept proposed by the group at UNIBE for the near-site detector to be adopted by the collaboration as the main sub-system of the near detector complex. Its development has concluded with a demonstrator successfully built and tested in Bern and exposed to the NuMI neutrino beam at Fermilab.

UZH has made significant contributions to the search for $0\nu\beta\beta$ decay, starting with GERDA in 2007, which concluded in 2019. UZH now has crucial responsibilities in the

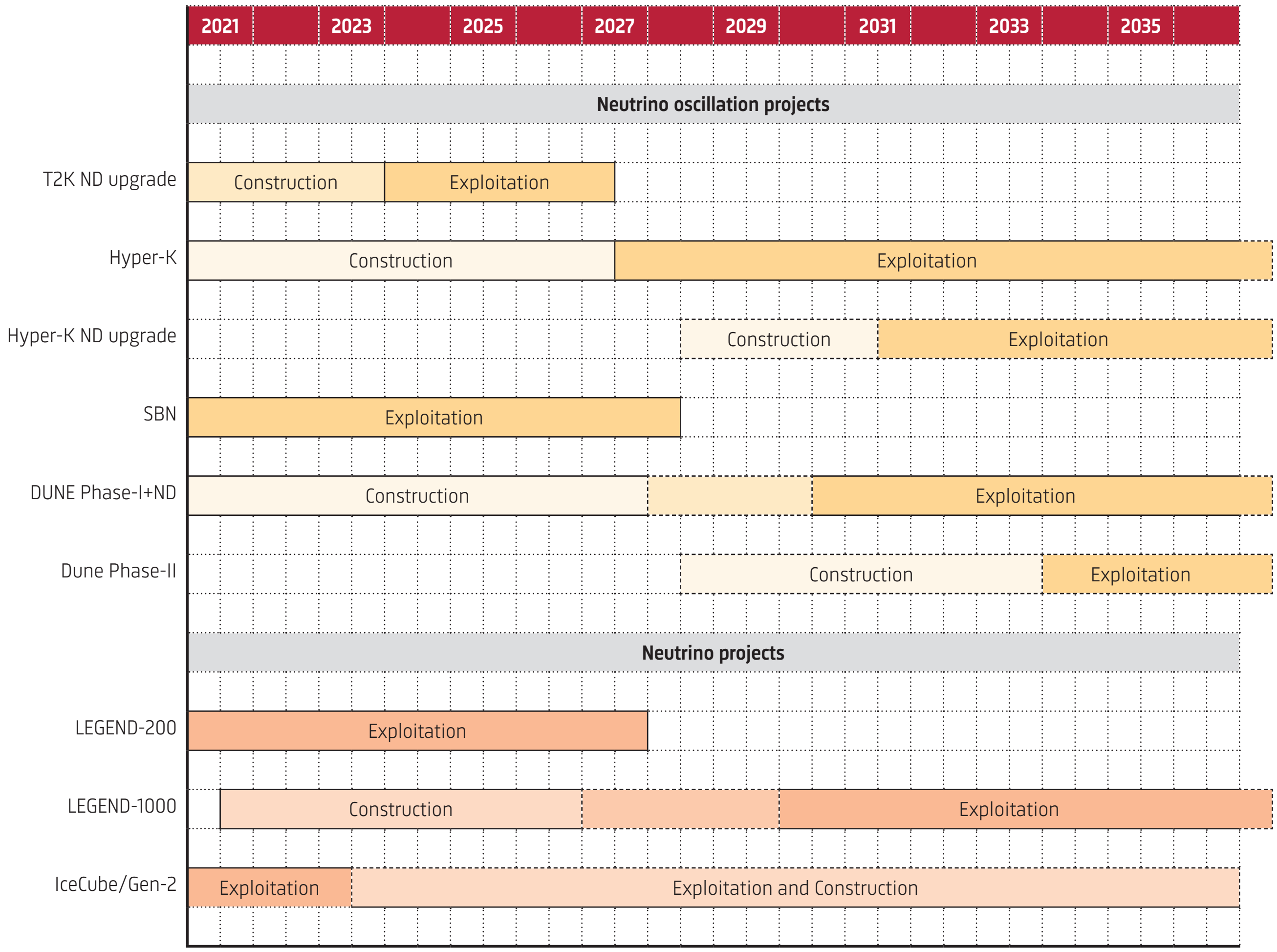


Figure 10: The timeline of major neutrino projects with strong Swiss engagement. The intensity of a given colour indicates the project phase, differentiating between construction (light colour) and exploitation of the machine (dark colour). Dashed boxes indicate prospective projects that are not yet approved for construction.

ongoing LEGEND-200 experiment. Involved in the construction and operation of the calibration systems, the production and characterisation of enriched germanium diodes, and in the development and production of the wavelength shifting system for the liquid-argon active veto. It is now also a leader in its physics exploitation. UZH is also leading the efforts towards the tonne-scale project LEGEND-1000, currently in the advanced design phase. Its unique sensitivity, achieved by increasing the mass of the germanium detector array to at least 1000 kg, with a total run time of around one decade, will make it among the world-leading experiments in the search for $0\nu\beta\beta$ decay in any isotope.

The multi-messenger astrophysics community in Switzerland is active across the borders of the astronomy and particle physics communities. UNIGE is involved in the IceCube Experiment and leads the multi-messenger astrophysical neutrino analysis.

The timeline of the major neutrino projects is shown in Fig. 10.

Table 2: A summary of Swiss involvement in experimental neutrino physics. The acronyms, subjects, and goals of each experiment are described at chipp.ch/en/id/rFZJz.

Institution	Main involvements
UNIBE	Long-baseline experiment: DUNE Short-baseline experiments: MicroBooNE, SBN
UNIGE	Long-baseline experiment: T2K/Hyper-K Ground-based astroparticle experiment: IceCube
UZH	Neutrinoless double-beta decay experiments: GERDA, LEGEND
ETHZ	Long-baseline experiment: T2K/Hyper-K

4.2.1 Vision for the future

Neutrino masses and their flavour oscillations are a tantalising sign for new physics beyond the SM, and thus a goal for long-baseline neutrino oscillation experiments is to measure the leptonic CP violating phase, to provide answers to fundamental questions such as what caused the matter-antimatter asymmetry in the universe, and to determine the neutrino mass hierarchy. This is addressed by the physics exploitation of the Hyper-K experiment in Japan and the DUNE experiment in the USA. A reduction of systematic uncertainties related to the neutrino-nucleus cross section will be crucial, in particular for the high-statistics phase of the experiments. Hence, data analyses at the ongoing T2K experiment and during the early phase of Hyper-K might point to the need of the final upgrade of the near detector complex. After an initial operation of the DUNE experiment, an enhanced near detector will be installed as part of Phase-II of the experiment, along with operation at a higher neutrino beam power and the installation of two additional far detector modules with improved liquid argon detectors. The complementary physics question related to the nature of neutrino masses is addressed by underground experiments, in which Swiss groups play a fundamental role. The LEGEND-200 and LEGEND-1000 experiments will achieve the lowest background levels and the best energy resolution in the field for a quasi-background-free search for $0\nu\beta\beta$ decay. The field of neutrino physics is entering a phase of unique precision, with high-statistics, long-baseline oscillation experiments, and sensitivities to beyond the inverted mass hierarchy in searches for $0\nu\beta\beta$ decay experiments. The future strategy will largely depend on the outcome of the experiments mentioned above. On the other hand, once the neutrino oscillation parameters have been precisely measured within the framework of three active neutrinos, it will be crucial to constrain the unitarity of the PMNS matrix at a level comparable to that of the CKM matrix of the quark sector, to either highlight or rule out the existence of additional leptonic states. Results on neutrino properties at a previously unprobed energy regime and possible discoveries from complementary experiments, like at the CERN collider experiments and the planned beam-dump facilities (e.g. SHiP, FASER, SND), will also provide inputs to the future strategy.

If long-baseline experiments determine that the mass hierarchy is normal, the field of $0\nu\beta\beta$ searches will require further advances in technology to combine high precision and extremely low levels of background in massive detectors.

The ultimate extension of IceCube Gen-2, focusing also on cosmic neutrinos, should become fully operational in 2033. Its exploitation provides an excellent programme complementary to accelerator neutrino physics that should be continued.

4.3 Astroparticle physics

With most of the universe composed of an unknown form of matter that is gravitationally bound and has seeded large-scale cosmological structure, direct and indirect searches for the particles that compose dark matter are of prime importance. In addition, multi-messenger astrophysics provides a complementary exploration of the inflation domain through the future generation of large-scale surveys and gravitational-wave observatories from space and ground. The Universe has been found to contain highly complex ‘cosmic accelerators’ observable in the electromagnetic spectrum, as well as gravitational waves and neutrinos. There has been enormous progress in these fields in the last few years.

Groups in Switzerland participate in large international experiments designed for detecting dark matter, γ-rays, neutrinos, cosmic rays and gravitational waves. γ-rays can be observed both from space and from the ground, albeit with very different technologies. Such γ-ray experiments are complementary to ground-based cosmic ray and neutrino observatories. A summary of the experiments with Swiss involvement can be found in Table 3. A detailed review can be found in the ‘Whitepaper for astroparticle physics in Switzerland for the period 2025–2032’.[9]

While some astroparticle physics experiments are still of limited size and duration, larger infrastructures are increasingly required, necessitating careful planning. The wide variety of experiments imply a wide range of technologies, that are increasingly producing larger amounts of data that require advanced processing and the use of artificial intelligence.

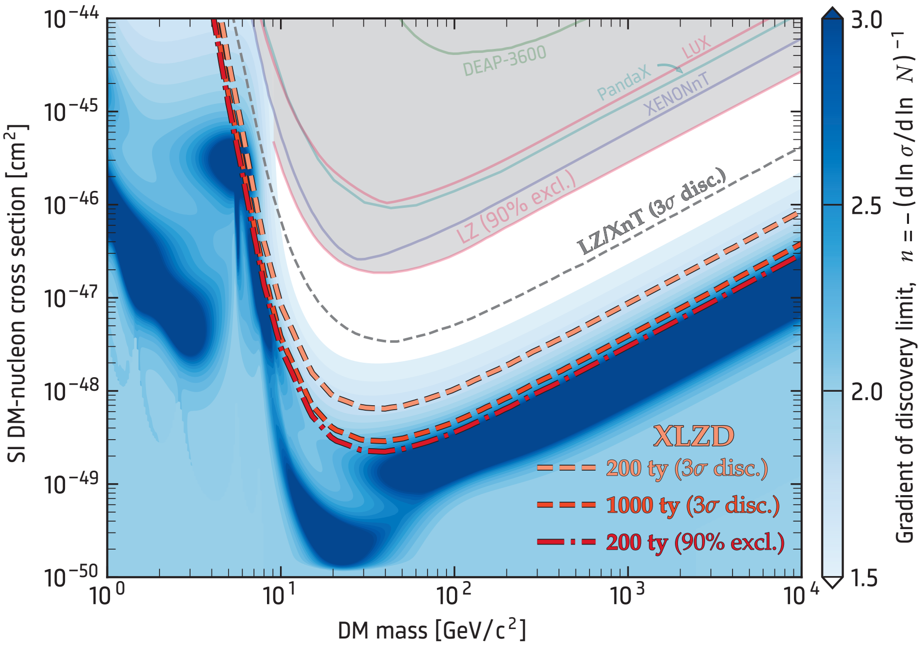


Figure 11: The 3σ WIMP discovery sensitivity of DARWIN/XLZD at a SI cross section of 3×10^{-49}cm² at 40 GeV/c² for two different exposures, 200 t y and 1000 t y, as well as the 90% exclusion sensitivity for an exposure of 200 t y. Also, shown is a comparison to observed results from XENONnT and LZ, and an expected future combination. The systematic limit imposed by coherent elastic neutrino nucleus scatters from solar and atmospheric neutrinos is also shown. At a given contour n, an increase in exposure by at least a factor of 10n is required to probe a 10 times lower cross section.[10]

Table 3: A summary of astroparticle experiments with Swiss involvement. The institutes presently participating in the experiments are indicated in parentheses. The acronyms, subjects, and goals of each experiment are described at chipp.ch/en/id/rFZJz. The timelines are detailed in Fig. 13.

X- and γ-rays, cosmic rays, and neutrinos	
From space	
AMS-02	(UNIGE)
DAMPE	(UNIGE, EPFL)
HERD	(UNIGE, EPFL)
NUSES	(UNIGE)
POLAR-2	(UNIGE)
From the ground	
CTAO	(EPFL, ETHZ, UNIGE, UNIBE)
MAGIC	(UNIGE, ETHZ)
IceCube	(UNIGE)
ET	(UNIGE, UZH)
LVK	(UNIGE, UZH)
Dark Matter	
DARWIN/XLZD	(UZH)
XENON1T	(UZH)
XENOnT	(UZH)
DAMIC-M	(UZH)
OSCURA	(UZH)

In the last decade, astrophysics and cosmology were revolutionised by multi-messenger probes, which require a large variety of techniques and experiments to be detected from ground and in space. Multi-messenger astrophysical processes bring together researchers in different observational domains using different forms of data, necessitating a common platform for analysis, early alert distribution, high data-reduction factors, and efficient processing in sustainable data centers in Switzerland, including the CSCS supercomputing center in Lugano, and other data centers distributed in institutes or elsewhere.

4.3.1 Vision for the future

1. **Gamma rays** provide a serendipitous view of acceleration processes in the most extreme high-energy relativity laboratories in the cosmos. Gamma rays are used to trace violent events in the Universe where a small fraction of the particles can undergo non-thermal acceleration processes. The main topics of interest of the scientific groups in Switzerland are to understand 1) the origin and feedback of cosmic rays, their acceleration in supernova remnants, starbursts, black hole jets, and other catastrophic phenomena such as galaxy mergers; 2) astrophysical systems such as pulsars, X/gamma-ray binaries, micro-quasars, magnetars, active galactic nuclei, gamma-ray bursts also via multi-messenger techniques; 3) the nature of matter in the universe and the sites where dark matter agglomerates; and 4) the cosmological evolution of early galaxies measuring the extragalactic background light and de-

termining magnetic fields in cosmic voids. The measurement of gamma rays from the ground will reach the precision era within this decade with the operation of the Cherenkov Telescope Array Observatory (CTAO). The establishment of the CTAO legal entity and the accession of Switzerland to it remains of high priority for the CTAO-CH Collaboration in Switzerland including CHIPP and CHAPS members. CHIPP researchers lead the instrumentation of CTAO with innovative cameras using silicon photomultipliers for gamma-ray astronomy that were introduced by Swiss scientists. In addition, it has been proposed to use the 4000 m^2 mirror area of the CTAO telescopes together with optical large telescopes to reach micro-arcsecond resolution in the optical to resolve accretion disks around galactic compact sources and quasars.

2. **Cosmic rays** are messengers of the most energetic shock processes in the universe. Direct measurement of cosmic ray spectra with the highest possible precision is crucial for understanding our Galaxy's dynamics, the synthesis of elements, the evolution of stars, and the composition of the interstellar medium. Cosmic rays also provide a window for indirect dark-matter detection through the detection of rare antimatter nuclei and observation of structures in antiparticle and electron cosmic ray spectra. With the tracker upgrade, AMS-02 experiment will collect sufficient data to extend measurements of rare nuclei fluxes to 3 TeV, positron flux to 2 TeV, and electron flux to 3 TeV. DAMPE and HERD will directly probe cosmic-nuclei spectra towards the PeV frontier, and electrons up to 100 TeV, and will perform gamma ray physics at a few GeV to 100 TeV energies.

3. **Gravitational Waves (GWs)** are a new messenger providing a complementary window to the Universe. GW signals represent distortions in space-time, thus opening up many exciting possibilities in studying differences between the visible Universe and the underlying medium through which light and other particles travel. All observed GW signals to date are believed to originate from some of the most energetic processes in the known Universe: the mergers of pairs of neutron stars and/or black holes into a single compact object. CHIPP and CHAPS members participate in the current generation of ground-based GW observatories, represented by the LIGO-Virgo-Kagra (LVK) Collaboration, which observed nearly 100 such signals by the end of the third observing run in 2020. Following an extended period of downtime for upgrades to the experimental apparatuses and subsequent commissioning, the fourth observing run began in mid-2023, and is planned to last until mid-2025. Subsequent upgrades and observing runs are planned for 2027–2030, and proposed for the early-mid 2030s, before reaching the limits of the current infrastructures.

   The Einstein Telescope (ET) is the proposed next-generation European GW observatory, representing a revolutionary step forward in sensitivity. While the LVK detector is only sensitive to merger events in the local Universe, ET would have sensitivity out to the era before star formation, thus it will see nearly every binary coalescence event that will take place in the Universe. This corresponds to an increase of the signal rate from roughly one per week with LVK to one signal per minute with ET, or an increase of four orders of magnitude. The ET project is now in the preparatory phase, following its approval as the largest-ever ESFRI project in 2021, and the subsequent formation of both the ET Scientific Collaboration and ET Organisation in 2022. If approved, construction of the ET observatory should begin in the mid-late 2020s, and data-taking should begin in the mid-late 2030s. Switzerland currently plays a leading role in defining the science case and in leading the ET Scientific Collaboration. The establishment of a strong experimental programme in preparation for ET is a high priority for the CHIPP and CHAPS communities.

   This update document acknowledges explicitly the interests of CHIPP members, with a strong theory component, and is in synergy with the vision presented by astrophysicists and cosmologists in CHAPS. The joint CHIPP and CHAPS objective is to play a leading role in ET, including defining the science case, the experimental apparatus, and the associated computing infrastructure. Increased participation in LVK is foreseen as a pathfinder toward ET, together with the participation in ET-dedicated activities such as mock-data challenges, and common LVK+ET developments. There are also important synergies with the space-based interferometer LISA, foreseen to be ready after 2035, which will provide access to the gravitational wave cosmic background and detect the signals of coalescing super-massive black holes, giving clues on their formation history.

4. **Neutrinos** also contribute to multi-messenger astronomy, and the IceCube experiment described in the previous section is active in collaborating with gravitational-wave observatories in the search for coincidental signals that can elucidate gravitational wave events.

5. **Dark Matter:** The identification of dark matter is one of the major quests in cosmology and particle physics, requiring multiple approaches. Direct detection probes the nature of dark matter and has explored a substantial fraction of the weakly interacting massive

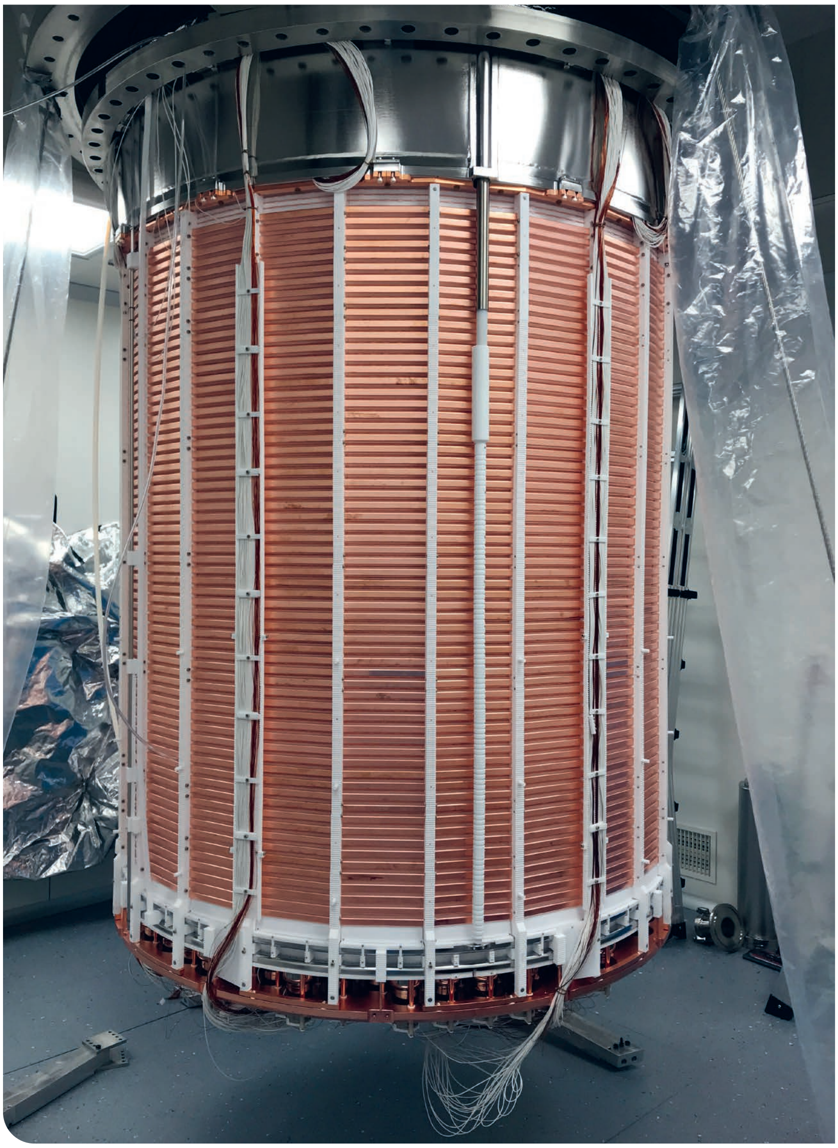


Figure 12: The XENONnT Time Projection Chamber in the clean room. Source: XENON Collaboration

particle (WIMP) parameter space of masses around 100 GeV/c^2 with the most stringent constraints coming from the currently operating XENONnT and LZ multi-tonne liquid xenon experiments. The next generation detector, DARWIN/XLZD, will be constructed by the new XENON-LZ-DARWIN (XLZD) collaboration. It will probe the WIMP paradigm down to the so-called neutrino fog and will also explore other, light dark matter candidates at the MeV and keV mass scale, as well as second-order, weak nuclear decays. Further, such a multi-ten-tonne liquid xenon observatory will also detect astrophysical neutrinos, and thus enter the multi-messenger domain. CHIPP groups are at the forefront of direct searches, especially with liquid xenon. The dark matter community in Switzerland strongly confirms with this update the common goal of establishing DARWIN/XLZD as a next-generation experiment (G3), while keeping technological innovation and exploration active.

It is also important to search for other candidates for dark matter. Hidden-sector dark matter, which interacts electromagnetically with standard-model (SM) particles via the mixing of the hidden photon with the SM photon, and causing very low-energy electromagnetic signals, is a leading candidate. Currently operating is the DAMIC experiment, which has an extremely low ionisation energy threshold, and which has placed the most stringent constraints on such DM in the 1–1000 MeV/c^2 mass range. DAMIC-M, an upgraded version of DAMIC, is under construction and will be installed and collect data from 2025. The next generation of DAMIC-M, OSCURA, seeks to achieve factor of ten improvements in detector mass and background rates. Tesseract is a cryogenic experiment utilising superconducting readout to achieve ultra-low energy thresholds. Tesseract aims to explore entirely new phase space for low-mass DM candidates, and is expected to begin operations by 2026.

Besides direct detection of dark matter, GW future experiments (ET and LISA) probe gravitational effects and with large scale surveys (e.g. DES, DESI, LSST, involving also scientists in Switzerland) have the potential to probe cosmological signatures of dark matter and dark energy. Indirect detection of dark matter is also conducted by space-based detectors of cosmic rays and gamma-ray and neutrino ground-based large observatories, which seek signatures of dark matter annhilation into standard-model particles, and can potentially locate dense regions of dark matter in the cosmos.

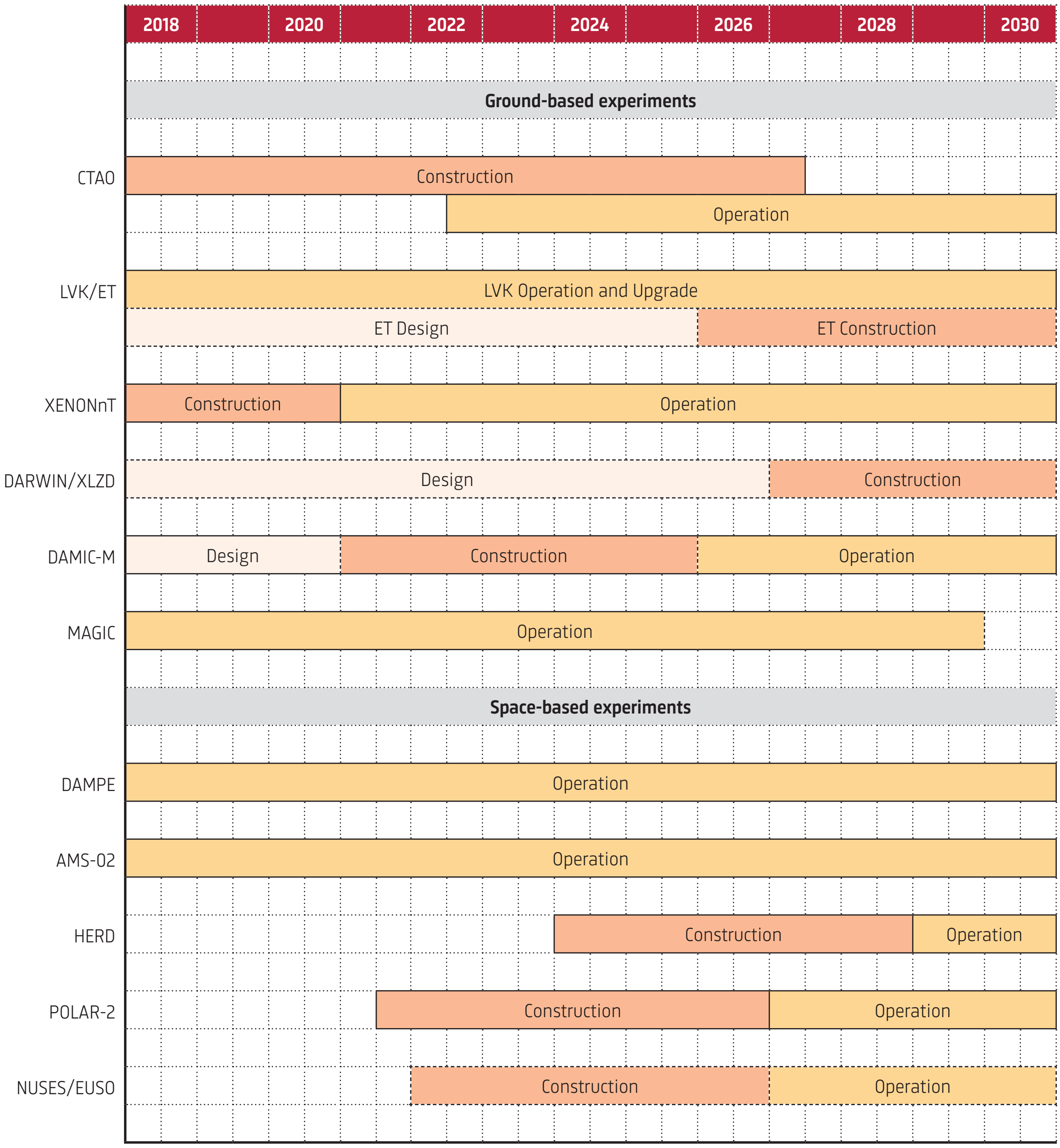


Figure 13: Foreseen schedule of astroparticle experiments of interest for scientists in Switzerland. Dashed boxes indicate prospective projects that are not yet approved for construction.

4.4 Theory

Swiss researchers are at the forefront of different aspects of theoretical research, whose ultimate goal is a deeper understanding of the underlying principles governing fundamental interactions. This common objective is pursued along different research lines, which span a wide range of topics from computing precise predictions for processes under experimental investigation to developing new models and new principles. We can roughly divide the research directions in this field into four main categories, as defined in the previous roadmap:[1] I) precise SM physics; II) model-building and BSM phenomenology; III) cosmology, astroparticle, and gravitational physics; IV) and progress in Quantum Fields and String Theory. Swiss researchers are actively involved in all four of these lines of research, with complementary expertise at different universities and research institutes, as summarised in Table 4. The research is of very high quality in all these areas: Swiss scientists are among the world-leading groups for precision calculations in the SM, including high-energy collider physics at the LHC and low-energy experiments at PSI; they are at the forefront of developing new theories and models, linking them to the present and future collider searches; they have significantly contributed to recent developments in cosmology, gravitational-wave theory, and string theory. The interplay between theory and experiments in all these areas, is of pivotal importance for the future of the field.

Table 4: Overview of the research activities in theoretical particle physics in Switzerland. The Roman numerals refer to the four main research lines discussed in the previous roadmap.[1]

Institution	Main research areas
UNIBAS	(II) Neutrino physics, high-energy BSM phenomenology (III) Cosmology, astroparticle physics
UNIBE	(I) Precision low-energy physics, lattice QCD, collider phenomenology (III) Cosmology, astroparticle physics (IV) String theory and formal aspects of QFT
UNIGE	(II) High-energy BSM phenomenology, model-building (III) Cosmology, astroparticle physics, physics of GWs (IV) String theory and formal aspects of QFT
UZH	(I) High-precision perturbative QCD, simulation tools for colliders, precision flavour physics (II) BSM phenomenology at low- and high-energies, model-building (III) Cosmology, physics of Gravitational Waves (GW)
EPFL	(II) High-energy BSM phenomenology, model-building (III) Cosmology, astroparticle physics, hidden sectors (IV) Formal aspects of QFT
ETHZ	(I) Precision perturbative QCD, collider phenomenology (IV) String theory and formal aspects of QFT
PSI	(I) Precision low-energy physics, collider phenomenology, simulation tools for colliders (II) BSM phenomenology at low- and high-energies, model building

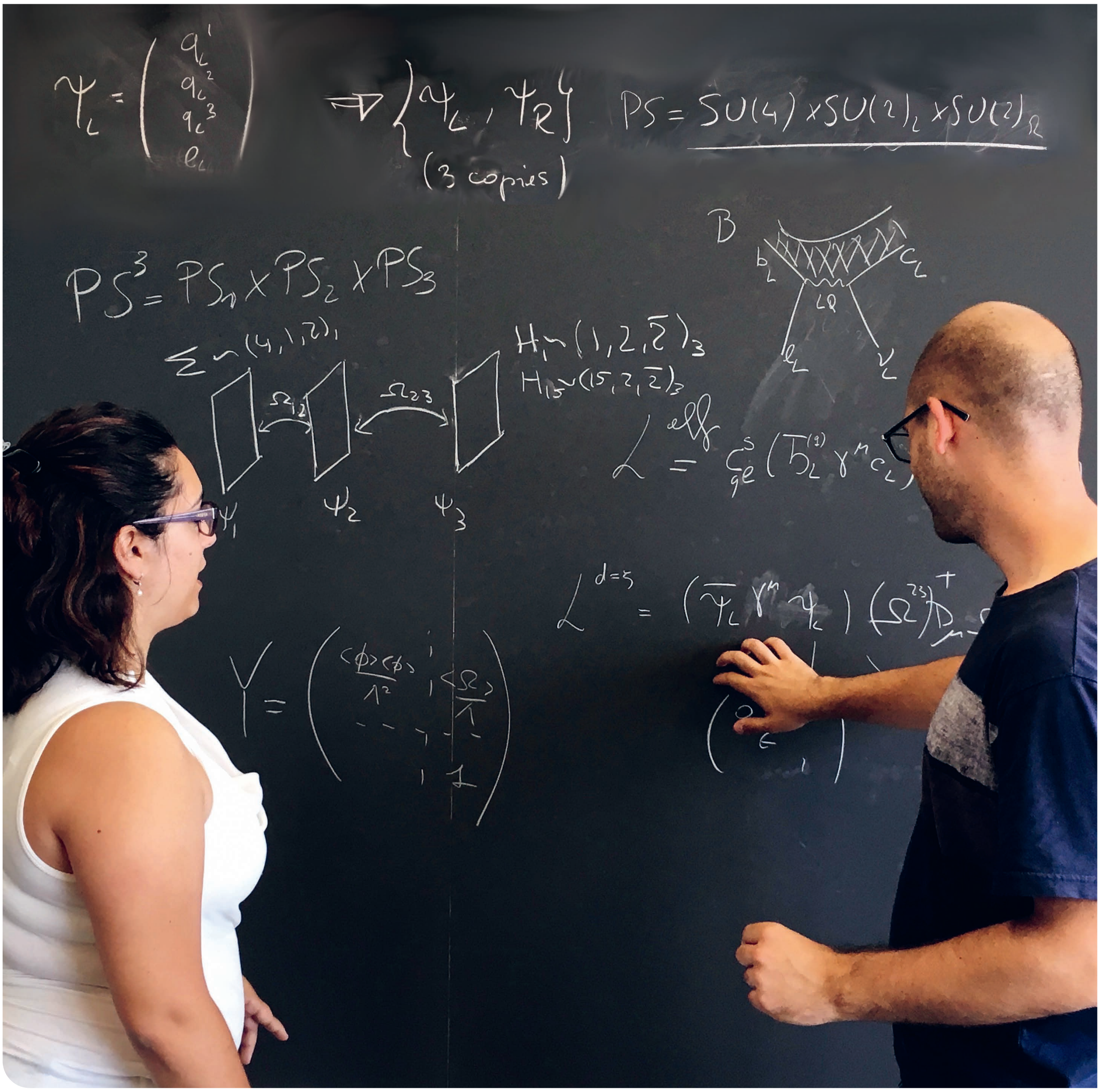


Figure 14: Theorists at work at UZH. Source: G. Isidori

LST-1 at night during commissioning with the Milky Way in the background.
Source: M. Huetten/CTA Collaboration

5 Conclusions

Particle physics addresses some of the most fundamental questions about Nature: what is matter made of, and how do the constituents of matter interact with each other. These basic questions are pursued by a vibrant community of particle and astroparticle physicists in Switzerland, federated in the Swiss Institute of Particle Physics (CHIPP). The Swiss particle and astroparticle physics community has enjoyed great support from the Swiss funding agencies and Swiss universities, and has made major and internationally acclaimed contributions to the field. Particle physics in Switzerland has greatly benefited from the proximity of CERN as a world-leading laboratory, as well as from the national laboratory, PSI. The exploitation of the Large Hadron Collider programme in its high-luminosity running phase, complemented by smaller experiments pursuing novel approaches at CERN, PSI, and elsewhere, will dominate accelerator-based particle physics for at least the next decade. In order to continue this success story in the decades to come, future accelerator infrastructures must play a key role; this is most notable for the FCC programme at CERN, which crucially hinges on advances in accelerator physics, where Swiss researchers are making important and highly visible contributions. Progress will depend on sustained support by Swiss funding agencies, thereby continuing the CHART programme and invigorating this research, which is on a critical path. Similarly, the upkeep and upgrade of accelerator infrastructure at PSI will be important to continue its compelling and diverse particle physics research programme. Swiss researchers are now building up an experimental and theoretical effort for participating in FCC experiments.

In the past years, Swiss institutes have made leading contributions to the design, construction, and operation of detector hardware and software, and will continue to contribute with their expertise and technical knowledge to both new experiments and the upgrades of the LHC experiments. This capability crucially hinges both on the support of the national funding agencies, as well as the support of the local research institutions engaged in particle physics and astroparticle research. Securing and continuing this capability into the future will be of utmost importance for the field.

Switzerland has a long history in neutrino physics, with several institutes holding key hardware, physics and management roles in the leading experiments worldwide. In the next decade, the long-baseline neutrino experiments in Japan and the USA will definitively measure the matter-antimatter asymmetry in neutrino oscillations, also thanks to the support of the CERN Neutrino Platform. These efforts will result in a crucial input to the particle physics community for a more profound understanding of the universe.

Swiss researchers are well invested in international projects in particle and astroparticle physics, and their success depends on securing access to international research infrastructures. Besides CERN, access to future long-baseline neutrino accelerators, as well as future astroparticle observatories, such as CTA and ET, will be very important. Particle physics has intriguing connections to astrophysics and cosmology, with astroparticle physics building an important bridge. Multi-messenger techniques combining both astroparticle and astrophysics results will lead to more insights into the universe and the cosmic accelerators therein. Front and center for astrophysics, cosmology, and particle physics is the quest to elucidate the nature of dark matter, a particle phenomenon that does not fit into the Standard Model of particle physics and yet appears to be five times more abundant than ordinary matter. The concerted and combined effort of all these disciplines is required to illuminate this mystery, which will hopefully be resolved in the next few decades.

Long-term support by national funding agencies to ensure that Swiss scientists exploit the scientific tools they develop, is vital to maximise the return on the Swiss investment in the CHIPP research program.

6 References

1 Swiss Particle Physics Community (CHIPP) (2021) **CHIPP Roadmap for Research and Infrastructure 2025–2028 and beyond**.

2 European Strategy Group (2020) **2020 Update of the European Strategy for Particle Physics**. Geneva: CERN Council.

3 APPEC (2017) **European Astroparticle Physics Strategy 2017–2026.** https://www.appec.org/wp-content/uploads/Documents/Current-docs/APPEC-Strategy-Book-Proof-19-Feb-2018.pdf.

4 NuPECC (2024) **NuPECC Long Range Plan 2024 Perspectives.** https://indico.ph.tum.de/event/7751.

5 CMS collaboration (2024) **Stairway to discovery: a report on the CMS programme of cross section measurements from millibarns to femtobarns.** Tech. Rep. CERN, Geneva. Submitted to Physics Reports. All figures and tables can be found at http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-23-004 (CMS Public Pages).

6 ATLAS collaboration (2024) **Standard Model Summary Plots June 2024.** Tech. Rep. CERN, Geneva. All figures including auxiliary figures are available at https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2024-011.

7 Benedikt M, Blondel A, Brunner AO, Capeans Garrido M, Cerutti F, Gutleber J, Janot P, Jimenez JM, Mertens V, Milanese A, Oide K, Osborne JA, Otto T, Papaphilippou Y, Poole J, Tavian LJ, Zimmermann F (2018) **FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2. Future Circular Collider.** Tech. Rep. CERN-ACC-2018-0057. 2, CERN, Geneva.

8 CHIPP Pillar-2 community (2024) **White paper for neutrino physics (pillar 2) in Switzerland for the period 2025–2032.** https://chipp.ch/en/id/rFZJz.

9 CHIPP Pillar-3 community (2024) **White paper for astroparticle physics in Switzerland for the period 2025–2032.** https://chipp.ch/en/id/rFZJz.

10 Baudis L (2024) **DARWIN/XLZD: A future xenon observatory for dark matter and other rare interactions.** Nuclear Physics B, vol. 1003, p. 116473. Special Issue of Nobel Symposium 182 on Dark Matter.

Please refer to
https://chipp.ch/en/meetings_documentation/strategic_workshops
for the list of experiments and of acronyms.

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Swiss Institute of Particle Physics (CHIPP)

CHIPP is an association uniting researchers active in particle, astroparticle and nuclear physics in Switzerland. It strengthens the Swiss participation in international projects and committees, coordinates research and teaching activities in Switzerland, and promotes public awareness of the field.