Vol. 16, No. 6, 2021

scnat
swiss academy of sciences

swiss academies
reports

swiss-academies.ch

CHIPP Roadmap

for Research and Infrastructure 2025–2028 and beyond by the Swiss Particle Physics Community

Swiss Institute of
Particle Physics

IMPRINT

PUBLISHER

Swiss Academy of Sciences (SCNAT) • Platform Mathematics, Astronomy and Physics (MAP)
House of Academies • Laupenstrasse 7 • P.O. Box • 3001 Bern • Switzerland
+41 31 306 93 25 • info@scnat.ch • map.scnat.ch 🐦 @scnatCH

CONTACT

Swiss Institute of Particle Physics (CHIPP)
ETH Zürich • IPA • HPK E 26 • Otto-Stern-Weg 5 • 8093 Zürich
Prof. Dr. Rainer Wallny • rwallny@phys.ethz.ch • +41 44 633 40 09 • chipp.ch 🐦 @CHIPP_news

RECOMMENDED FORM OF CITATION

Wallny R, Dissertori G, Durrer R, Isidori G, Müller K, Rivkin L, Seidel M, Sfyrla A, Weber M, Benelli A (2021)
CHIPP Roadmap for Research and Infrastructure 2025–2028 and beyond by the Swiss Particle Physics Community
Swiss Academies Reports 16 (6)

SCNAT ROADMAPS COORDINATION

Hans-Rudolf Ott (ETH Zürich) • Marc Türler (SCNAT)

CHIPP ROADMAP EDITORIAL BOARD

A. Benelli (secretary) • G. Dissertori[b] • R. Durrer[d] • G. Isidori[c] • K. Müller[c] • L. Rivkin[a, g] • M. Seidel[a, g] • A. Sfyrla[d]
R. Wallny[b] (Chair) • M. Weber[f]

CONTRIBUTING AUTHORS

A. Antognini[a, b] • L. Baudis[c] • HP. Beck[f] • G. Bison[a] • A. Blondel[d] • C. Botta[c] • S. Braccini[f] • A. Bravar[d] • L. Caminada[a, c]
F. Canelli[c] • G. Colangelo[f] • P. Crivelli[b] • A. De Cosa[b] • G. Dissertori[b], M. Donega[b] • R. Durrer[d] • M. Gaberdiel[b] • T. Gehrmann[c]
T. Golling[d], C. Grab[b] • M. Grazzini[c] • M. Hildebrandt[a] • M. Hoferichter[f] • B. Kilminster[a] • K. Kirch[a, b] • A. Knecht[a] • I. Kreslo[f]
B. Krusche[e] • G. Iacobucci[d] • G. Isidori[c] • M. Laine[e] • B. Lauss[a], M. Maggiore[d] • F. Meier[a] • T. Montaruli[d] • K. Müller[c]
A. Neronov[d, 1] • A. Papa[a, 2] • F. M. Piegsa[f] • A. Riotto[d] • S. Ritt[a], F. Riva[d] • L. Rivkin[a, g] • F. Sanchez Nieto[d] • O. Schneider[g]
M. Seidel[a, g] • N. Serra[c] • A. Sfyrla[d] • D. Sgalaberna[b] • M. Shaposhnikov[g] • L. Shchutska[g] • P. Schmidt-Wellenburg[a]
A. Signer[a, c] • M. Spira[a] • A. Tykhonov[d] • D. della Volpe[d] • R. Wallny[b] • R. Walter[d] • M. Weber[f] • X. Wu[d]

YOUNG SCIENTIST GROUP FOR THE ROADMAP INPUT

S. Bordoni[d] • A. Calandri[b] • X. Chen[b] • G. Cusin[d] • A. Fehr[f] • L. Franconi[f] • M. Galloway[c] • A. Greljo[f, h] • F. Lucarelli[d] • T. Pieloni[g]
F.L. Redi[g] • A. Soter[b]

CHAPS MEMBERS IN THE CHIPP/CHAPS WORKING GROUP

P. Jetzer[c] • M. Maggiore[d] • S. Paltani[d] • A. Refregier[b]

READERS

A. Clark[d] • M. Bourquin[d] • K. Kirch[a, b] • T. Nakada[g] • O. Schneider[g]

TECHNICAL AND TYPESETTING SUPPORT

B. Ristic[b]

LANGUAGE EDITING

S. Schramm[d] • D. Gordy (IFAGE, Genève)

[a] Paul Scherrer Institute
[b] ETH Zürich
[c] Universität Zürich
[d] Université de Genève
[e] Universität Basel
[f] Universität Bern
[g] EPFL
[h] CERN
[1] APC, Université Paris VII, Paris
[2] presently at University of Pisa

LAYOUT

Sandra Schwab, Bern

COVER PHOTO

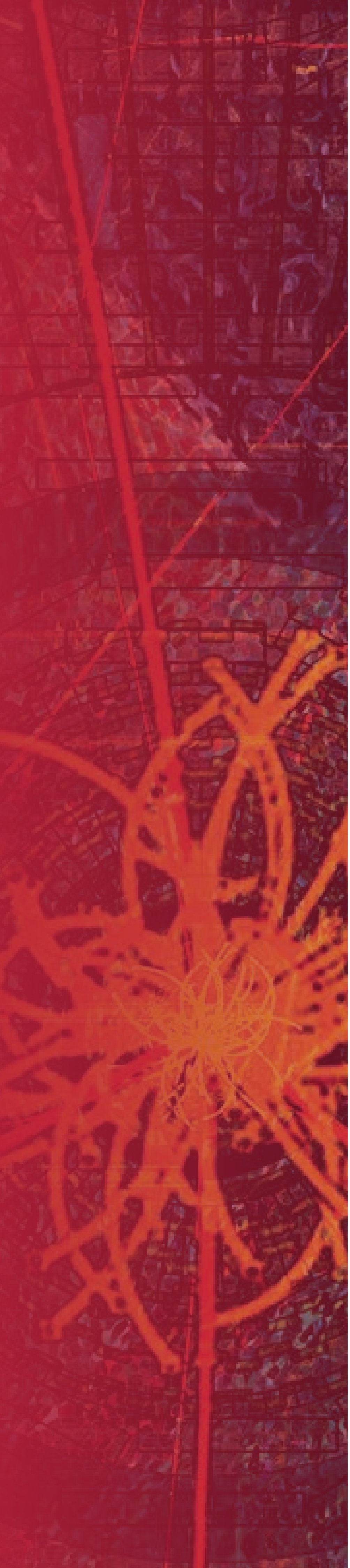
Xavier Cortada • (with the participation of physicist Pete Markowitz), ‘In search of the Higgs boson: H → ZZ’, digital art, 2013

ISSN (print) 2297–1793 • ISSN (online) 2297–1807

DOI: doi.org/10.5281/zenodo.4637623

Cradle to Cradle™-certified and climate-neutral
report printed by Vögeli AG in Langnau.

CERTIFIED cradletocradle GOLD



CHIPP Roadmap

for Research and Infrastructure 2025–2028 and beyond
by the Swiss Particle Physics Community

Content

1 Foreword

The 'Roadmap for Research and Infrastructure 2025–2028 and beyond' presents the view of the Swiss scientific community in the field of particle and astroparticle physics and their visions for future research in their respective fields; it also formulates the needs of these fields in terms of research infrastructure in the years 2025–2028. Particle and astroparticle physics research involves the pursuit of scientific goals that are long term in nature and rely upon long-lifetime research infrastructures that often take decades to build and that can take additional decades to exploit scientifically. It is therefore important for the national and international community to agree regularly on priorities and future needs in order to pool resources in the best possible way.

The Swiss Institute of Particle Physics (CHIPP) issued its first roadmap in February 2004 with a vision and recommendations for the future development of the field for the following 10–15 years.[1] An intermediate implementation document[2] was issued in July 2011 which reported on the progress of the implementation of the recommendations, has adjusted some of the initial recommendations and has added new ones. Following the release of the Long Range Plan 2017 of the Nuclear Physics European Collaboration Committee (NuPECC),[3] the European Astroparticle Physics Strategy 2017–2026 by the Astroparticle Physics European Consortium (APPEC),[4] and more recently with the Update of the European Strategy of Particle Physics 2020 by the European Organisation for Nuclear Research (CERN) Council,[5] it is now time for the Swiss scientific community in the field of particle and astroparticle physics to take stock of the accomplishments of the field with a fresh look.[1] The community can then build on the previous vision to develop new perspectives of the future of the field for the next decades, both in general and in terms of national and international research infrastructures, with particular emphasis on the funding period of 2025–2028.

For the latter purpose, this roadmap serves as a formal element of the process to elaborate the 'Swiss Roadmap for Research Infrastructures 2023' according to Swiss law (art. 41 Federal Act on the promotion of research and innovation; art. 55 of the corresponding Ordinance). In this capacity, it shall serve as an additional basis for the decision-making process on new or major upgrades of national research infrastructures and/or major participations in international research network infrastructures and user facilities. The responsibility for the elaboration of the 'Swiss Roadmap for Research Infrastructures 2023' rests with the State Secretariat for Education, Research and Innovation (SERI). It has thus launched a process that includes (phase 1) the selection of infrastructures by the ETH Board and swissuniversities, (phase 2) the evaluation by the Swiss National Science Foundation (SNSF), and (phase 3) the assessment of the feasibility again by the ETH Board and swissuniversities. The result will be submitted to the Federal Council for consideration and decision in the context of the Dispatch on Education, Research and Innovation 2025–2028. This whole process is complemented by a preparatory phase to establish the needs of the various scientific communities. SERI has formally mandated the Swiss Academy of Sciences (SCNAT) with the elaboration of these discipline-specific community roadmaps to which this document belongs.

SCNAT initiated the work to elaborate such discipline-specific community roadmaps in the fields of biology, geosciences, chemistry, and in sub-fields of physics in the last quarter of 2018. The board of SCNAT has determined a procedure that has defined the strategic goals of the roadmap process, interfacing with community-specific sub-projects that were led by acknowledged researchers in their respective fields. The whole process was modelled in analogy to the long-standing experience of SCNAT in the fields of astronomy and physics, where roadmaps for research infrastructures had been prepared in earlier years by the various communities, and which were assembled for that purpose around a so-called 'Round Table'. Accordingly, starting in 2019, such Round Tables were also established in biology, chemistry and geosciences. In the past two years, hundreds of researchers were invited to take part in this process and dozens of them actively participated in each of the various Round Tables. Whereas this effort was run under the overall responsibility and guidance of SCNAT, including the provision of considerable scientific, editorial and administrative personpower by its office, the final result must be considered as a genuine bottom-up contribution by the various scientific communities.

The roadmap at hand was established under the auspices of CHIPP.[6] CHIPP conducted a series of strategic workshops,[2] starting in 2014, including dedicated roadmap-planning workshops in 2018 and 2020. During its session of February 2020, the CHIPP board endorsed the

---

[1] As will be explained in the Introduction, part of CHIPP's particle physics activities are formally located under the international long term planning efforts of nuclear physics.

[2] https://chipp.ch/en/meetings_documentation/strategic_workshops

scope of this roadmap and confirmed an editorial board of representatives from different pillars and scientific activities to oversee the writing process. Members of the CHIPP board were invited to contribute to the roadmap, culminating in a dedicated roadmap workshop that was held in Kandersteg in August 2020. The text of the roadmap was further elaborated by the editorial board and was sent to the CHIPP board for comments in December 2020. This roadmap was formally endorsed by the CHIPP board during its meeting on 11 February 2021.

The CHIPP Roadmap Editorial Board,

A. Benelli (secretary), G. Dissertori, R. Durrer,
G. Isidori, K. Müller, L. Rivkin, M. Seidel,
A. Sfyrla, R. Wallny (Chair), M. Weber

March 2021

2 Introduction

Research in particle physics involves studying the constituents of matter and their interactions at the most fundamental level. Thanks to the great success of Quantum Field Theory (QFT), the Standard Model (SM) of particle physics describes three of the four known interactions: electromagnetic, strong, and weak nuclear forces, in a very successful way. Only gravity, the feeblest of them all, defies a predictive and consistent QFT description; the gravitational interaction is weak enough that it can be neglected when studying the other forces, but understanding its nature is still a fundamental part of understanding the Universe as a whole. With the discovery of the Higgs boson, the SM is now a self-consistent theory with the ability to predict many experimental observables to an astonishing degree of precision. Yet, many open questions in particle physics remain unanswered within the SM (see box).

Some of the questions left unanswered by the Standard Model

- What is dark matter? What is dark energy?
- What is the origin of the matter-antimatter asymmetry in the Universe?
- Why are there three families of quarks and leptons?
- What is the origin of the different quark and lepton masses?
- Is there a further substructure of fundamental particles?
- Are there more fundamental forces at the microscopic level?
- Is there a deeper unification of forces and/or matter constituents?
- What is the nature of the Higgs boson?
- Are the properties of the Higgs boson those predicted by the Standard Model?
- What is the nature of neutrinos?
- What is the origin of the tiny neutrino masses ?
- What is the behaviour of gravity at the quantum level?
- Do we need to go beyond the paradigm of Quantum Field Theory?

These open questions clearly indicate the necessity to go beyond the successful, but inevitably limited, SM paradigm. These are some of the most important questions pursued by CHIPP. CHIPP is the bottom-up organisation of Swiss particle and astroparticle physics researchers in Switzerland as a legal entity of Swiss law. Some of the activities of CHIPP researchers (such as hadron physics or double-beta decay) may technically fall under the auspices of 'nuclear physics' in an international context, but for simplicity, we subsume these particle physics research activities under 'particle physics' in this document.

CHIPP is tasked with coordinating the national efforts in the realm of particle and astroparticle physics and holds a number of important roles (see following box). Some of the aforementioned research questions, such as the particle nature of dark matter, the lack of a quantum description of gravity, or the particle physics mechanisms at work during the development of the early Universe, often connect particle physics to cosmology, astronomy and astrophysics; these disciplines are the remit of our neighbouring science community, the College of Helvetic Astronomy Professors (CHAPS). While the observation of intriguing phenomena such as dark energy and gravitational waves clearly falls into the CHAPS realm, where the experimental methodology is often distinct from that which is used in particle physics, synergies between CHIPP and CHAPS experimental research do exist e.g. in the exploitation of technology. Also, theoretical research pursued in CHIPP and CHAPS is interwoven and often transcends community boundaries due to its fundamental nature. Furthermore, we also observe 'natural' particle physics accelerators in the Universe that send particles to Earth at energies higher than can ever be achieved in human-made particle accelerators. Astroparticle physics, another research field of CHIPP, aims to study those sources and acceleration mechanisms, connecting them with what we experience at lower energies but in more controllable conditions on Earth.

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. 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 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). The CHIPP Board meets at least twice 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.

This roadmap represents the view of the Swiss scientific community in the field of particle and astroparticle physics. It addresses our political and financial stakeholders; the interested broader public, another important stakeholder of our field; and last but not least, the CHIPP community itself, especially the younger generation. This roadmap presents an overview of the state of the field at an important junction, pointing out future challenges and opportunities and offering a detailed vision of the future.

In order to support our heterogeneous audience, we offer the reader some advice on how to approach this document. In the various sections, boxed content will either offer additional information or provide a summary of the most pertinent information extracted from the respective chapter. For the reader interested in getting a fast overview on the future infrastructural needs and plans, this introduction together with the *Executive summary, findings and recommendations* (Chapter 3), *Purpose and scope* (Chapter 4), the *Vision for the future* (Chapter 11), the *Development of national infrastructures* (Chapter 12), and *Swiss participation in international organisations* (Chapter 13) should provide a reasonable overview when supplemented by the individual summary boxes within the other chapters. The multi-faceted aspect of our field, and its role within science as well as society can be best appreciated by taking into account its *Synergies with other scientific fields* (Chapter 8), with the close ties to astrophysics already noted, its strong *Relationship to industry* (Chapter 9) and its *Impact on education and society* (Chapter 10). Last but not least, much of our planning rests on the present *Swiss landscape* (Chapter 5) and is based on *Major successes 2017–2020* (Chapter 6); these two chapters are more technical in nature. Please note that the Appendix features a list of experiments, acronyms, and web links.

Research projects in particle and astroparticle physics are international endeavours by their very nature; the questions addressed require a long term commitment by the research community and crucially hinge on the availability of highly sophisticated research infrastructures, such as particle accelerators and detectors, telescopes, and satellites. Switzerland is well connected with international organisations in Europe and around the world such as CERN, the European Southern Observatory (ESO), and the European Space Agency (ESA). Switzerland also champions Paul Scherrer Institute (PSI) as the national laboratory that affords access to unique particle physics facilities that should be maintained and upgraded. The CHIPP community relies heavily on having access to these facilities and Switzerland should continue to guarantee access to these national and international research infrastructures as a reliable partner and provide its share in building the next-generation instruments needed, including, but not limited to, the ambitious Future Circular Collider (FCC) project at CERN, long-baseline neutrino experiments, the High-Intensity Muon Beam (HIMB) at PSI, and the Cherenkov Telescope Array (CTA). An equally important aspect for our community is the need to uphold our capabilities to develop highly sophisticated instrumentation and accelerator technology, also providing an exciting training ground for our engineers, postdocs and students, who may later pursue a career in industry. In order to uphold these capabilities, access to adequate public funding sources is needed to support the academic and technical personnel as well as the hardware needs; this funding is mostly provided nationally by SNSF projects and Funding LArge international REsearch (FLARE) grants in Division II, as well as internationally via European Research Council (ERC) grants.

Switzerland’s traditionally strong role in particle and astroparticle physics relies on highly qualified and inventive research groups with excellent engineering and technical support teams. In order to maintain Switzerland’s strong and vibrant research portfolio in particle and astroparticle physics, these highly qualified personnel based at universities and research laboratories must be retained. With the continued strong support from our funding agencies and stakeholders, the CHIPP community looks forward to the challenges and opportunities that our research field has in stock for us. We wish you an interesting read!

Fig. 1: LST-1 during commissioning with the Galactic centre in the background
(Image: M. Huetten/CTA Collaboration)

3 Executive summary, findings and recommendations

Here we present the major findings and recommendations which summarise the detailed analysis presented in the following chapters. Particle and astroparticle physics are both embedded in an international context, and the Swiss Institute of Particle Physics (CHIPP) endorses the findings of the European Particle Physics Strategy Update[5] by CERN issued in 2020, the findings of the Astroparticle Physics European Consortium (APPEC) Roadmap[4] issued in 2018, and the Nuclear Physics European Collaboration Committee (NuPECC) Long Range Plan 2017 'Perspectives for Nuclear Physics'.[3] We will 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 Higgs factory (FCC-ee) as a first stage, followed by a hadron collider (FCC-hh) around 2045, would secure the future of high-energy particle physics with CERN as a world-leading laboratory well beyond the 2080s. One key ingredient in this ambitious programme is the development of suitable high-field magnets for FCC-hh that define the critical path.

Recommendation 1a: CHIPP recommends that Switzerland strongly support CERN as the world-leading laboratory in particle physics. CHIPP's research portfolio is well aligned with CERN's such that CHIPP will continue to benefit greatly from and lend strong support to CERN for the foreseeable future.
Recommendation 1b: CHIPP recommends the development of a national strategy towards the participation in CERN's programme for an FCC, starting with FCC-ee, which encompasses detector development, theoretical research, and data analysis and simulation. 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, a national laboratory, national institutes, and universities.
Recommendation 1d: CHIPP recommends that Switzerland maintain strong involvement in detector research and development, which is essential for the future of particle physics and which fosters synergies with other scientific fields.

Finding 2: In anticipation of the FCC, the Large Hadron Collider (LHC) continues to be the flagship project at the high-energy frontier until the end of its scheduled lifetime in the mid-to-late 2030s. The LHC, with its future high-luminosity running phase (HL-LHC), will provide a plethora of new data which 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 eventually provide performance and longevity upgrades remains crucial during this period. Furthermore, the large volume of collected data will create challenges for 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 the investments so far.
Recommendation 2b: For the full HL-LHC exploitation to be feasible, further computing infrastructure is required, possibly in collaboration with other fields facing similar computing challenges with highly performant computing and data handling strategies. CHIPP recommends that Switzerland engage in providing the necessary resources.

Finding 3: The quest for new physics, through either direct searches or indirect searches via precision measurements of SM particles including the Higgs boson, is complemented by and shared with a diverse set of experimental activities at the low-energy/high-intensity frontier. These activities are supported by the use of dedicated accelerators, either at the national laboratory (Paul Scherrer Institute, PSI) or elsewhere, or by running in parallel with existing high-energy accelerators. These experimental efforts are avenues towards exploring intriguing BSM scenarios, and are therefore extremely important for CHIPP's multi-prong approach towards searching for BSM physics and putting the Standard Model to the test.

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

Recommendation 3b: CHIPP strongly supports the present and future exploitation of the CERN accelerator complex beyond the large LHC experiments, in experiments that search for new physics using novel approaches. It encourages the attempts to establish a high-power beam dump facility at CERN or elsewhere. CHIPP recommends that Switzerland engage in these diverse experiments.

Finding 4: Neutrinos continue to provide intriguing puzzles to the Standard Model. The elucidation of their nature (Dirac or Majorana) and properties (violation of charge conjugation parity symmetry, mass hierarchy) continue to be a vibrant sector of particle physics. Progress in neutrino physics depends largely on the next-generation long-baseline programmes as envisioned in the USA (DUNE) and Japan (Hyper-K). Other facilities and experiments such as LEGEND, searching for neutrinoless double-beta decays, are necessary to test the nature of neutrinos.

Recommendation 4a: CHIPP recommends that Switzerland strongly support the long-baseline neutrino programmes in both Japan and the USA in order to maximise the scientific reach.

Recommendation 4b: Experiments targeting the detection of neutrinoless double-beta decays continue to be vital to explore the nature of neutrinos. CHIPP recommends a continuous and adequate support to such experiments.

Finding 5: Dark matter is one of the biggest open questions in particle physics and beyond. Astronomical observations reveal its large abundance in the Universe and underline its pivotal role in cosmic structure formation. The elucidation of the particle nature of dark matter continues to be one of the most important quests in contemporary particle and astroparticle physics. As experimental results begin to stress the paradigm for the Weakly Interacting Massive Particles (WIMPs) interpretation, alternative scenarios for dark matter (axions, an entire dark sector, etc.) come increasingly into focus. Direct dark matter detection experiments (such as DARWIN and DAMIC), searches for dark matter production at accelerators (in particular at the LHC), as well as indirect searches for dark matter via astrophysical observations continue to be the multi-prong approach that needs to be pursued in order to solve this puzzle.

Recommendation 5: CHIPP recommends the direct search for dark matter as an effort that needs to be upheld. In addition, complementary approaches targeting dark matter scenarios outside of the WIMP paradigm and indirect detection via multi-messenger astronomical observations are encouraged and should complement the future search portfolio.

Finding 6: Astroparticle physics in Switzerland provides a diverse portfolio of experimental efforts, both ground-based and in space. Often, these facilities are of interest to researchers both in particle and astroparticle physics, as well as astrophysics and astronomy. A prime example is the Cherenkov Telescope Array (CTA), a scientific instrument that enables the pursuit of astronomical, as well as astroparticle physics research. The CTA science community in Switzerland is growing at the interface of CHIPP and CHAPS. Future big science endeavours, including research into the detection of gravitational waves, either in their own right or as part of a multi-messenger science programme using future ground-based or space-based facilities, will further excite scientific interest in both research communities and tie them closer together scientifically. To expedite this process, a CHIPP-CHAPS working group was recently established to explore common interest in both communities concerning future gravitational waves research. It is expected that significant investments are needed in this future research domain. While both CHIPP and CHAPS communities have strong scientific focal points that are otherwise very distinct, they share some similarities in their mode of operation, such as being dependent on large-scale instrumentation, which often takes decades to build in the context of large international organisations. CHIPP and CHAPS receive major instrumentation and operations support from the SNSF FLARE funding instrument for ground-based research activities. As project cost and duration tend to rise, an understanding in priorities of research instrumentation across both communities needs to be fostered. Both communities may also face challenges from dealing with large data volumes and hence, could profit from a closer collaboration.

Recommendation 6: CHIPP recommends a further strengthening of ties with the CHAPS community, both scientifically and technically. As an instrument of common interest for both communities, Switzerland should secure access to CTA at a level that is appropriate for the size of the Swiss researcher community interested in CTA. Both CHIPP and CHAPS should explore common interests in and develop a common strategy towards future gravitational waves experiments.

Finding 7: 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 us with an extremely powerful paradigm, namely the Standard Model. 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, i.e. theoretically predicted, but very rare phenomena such as the Higgs boson discovery or the detection of gravitational waves, theoretical guidance, even if 'only' of heuristic nature, is more important than ever. At the same time, efforts towards improved theoretical predictions within the Standard Model are of key relevance for the interpretation of current and planned experiments at particle accelerators. 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 7: CHIPP recommends that Switzerland continue to strengthen its vigorous programme in theoretical particle and astroparticle physics, and cosmology. Besides its 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.

Finding 8: Swiss particle and astroparticle physicists have been 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 in recent years.

Recommendation 8: CHIPP encourages the academic and research institutions in Switzerland to pursue and further strengthen the support they give to researchers in terms of technology transfer and know-how.

Finding 9: Fostering outreach and education becomes ever more important for particle and astroparticle physics. As basic research, whose benefit to society is very tangible but often indirect, CHIPP recommends that efforts be strengthened to communicate the fascination, benefit, and promise of particle physics and astrophysics to the greater public. The field also depends on attracting new talent to join the ranks of our research teams which is one of the most important assets that we have. The international networks in outreach and education, such as the CERN teachers programme, the International Particle Physics Outreach Group, and the European Particle Physics Communication Network strengthen the outreach efforts and provide and provide support in the form of online platforms, tools, and material.

Recommendation 9: CHIPP recommends a continuous pro-active communication and outreach strategy in order to remain engaged and further strengthen the dialogue with the public. Members of CHIPP are well poised to give inspiring outreach talks, lead visitor programmes at their universities, PSI, or CERN, and to convey the fascination of fundamental research to the next generation with events targeting high-school students; CHIPP strongly encourages such activities.

Finding 10: Particle physics is a very attractive field for bright young students who wish to get involved at the forefront of fundamental research and technological innovation. Their continuous education and training is of special importance for a sustainable development of the field. Special care should be taken to increase the recognition of individuals working in all areas of experimental work, particularly in large collaborations. Female researchers continue to be underrepresented in all areas of particle and astroparticle physics. CHIPP recognises the value of equality, diversity and inclusion, the importance of role models, and the need for continuous support to improve the gender balance within CHIPP.

Recommendation 10: CHIPP strongly encourages all institutes to develop strategies to support further the next generation of scientists, and continues to support early-career researchers by optimising their training in research and other areas and by providing a networking base for the mutual exchange of ideas and support. The CHIPP community remains committed to the principles of equality, diversity, and inclusion in all activities, and recommends the strengthening of efforts in these directions.

4 Purpose and scope

4.1 Particle physics, astroparticle physics and the Standard Model

Particle physics is the branch of physics that studies the elementary constituents of matter and the fundamental laws of nature. Our present understanding of the irreducible building blocks of matter and the principles that rule their microscopic behaviour is represented by the Standard Model (SM) of fundamental interactions. This theory, which was founded on experimental observations and developed over the last 50 years from the coherent marriage of quantum mechanics and special relativity, describes with success the three types of forces that are relevant at the microscopic level: the strong and weak nuclear forces, and the electromagnetic interactions. The SM also tells us that the fundamental constituents of matter consist of remarkably few elementary particles, as summarised in Fig. 2. The last ingredient in this theory is the so-called Higgs boson: a particle whose existence was postulated more than 50 years ago, since then long sought after, and finally discovered at CERN in 2012.

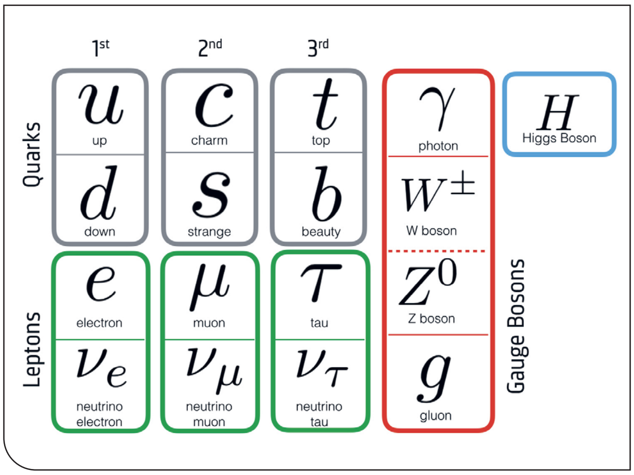


Figure 2: Table of the elementary particles according to the SM of fundamental interactions (Image: Physics Department, Uni Zürich)

The SM has been successfully tested over a huge range of energies: from a few electron volts (eV), comparable to the energy of atomic bonds, up to a few tera electron volts (TeV), reached in the proton-proton collisions occurring at the Large Hadron Collider (LHC) at CERN, i.e. at energies that are a trillion (10^{12}) times larger than those of atomic bonds. This wide range of energies corresponds to a variety of different physical phenomena: from the precise structure of atomic energy levels, to the fusion nuclear-reaction occurring inside the stars; from the magnetic moment of the muon, which is unambiguously predicted within the SM, to better than one part per million and is currently being measured with a similar level of precision to the particle-jet distributions generated in the high-energy collisions currently being analysed by the LHC experiments. Such a wide range of validity is remarkable and without precedent in the history of physics.

The Standard Model

The elementary particles present in the SM can be divided into three different categories: I) force carriers, II) matter constituents, and III) scalar particles. The force carriers (technically known as *gauge bosons*) are excitations of the fields responsible for a specific type of interaction; they are the *gluons* (g), mediating the strong interaction; the *photon* (γ), responsible for the electromagnetic interaction; and the Z and W bosons, mediating weak interactions. The number and properties of the force carriers are completely specified by the symmetry properties of the corresponding interaction. The matter constituents are 12 particles organised in three families, each containing a pair of *quarks* and a pair of *leptons*, as illustrated in Fig. 2. The pair of quarks in the first family are the up (u) and down (d) quarks, the elementary constituents of both neutrons and protons, which in turn form all of the atomic nuclei. The corresponding leptons are the electron (e) and electron neutrino (ν_e); the electrons combine with the atomic nuclei to form the whole series of chemical elements in the Periodic Table, while the feebly interacting electron neutrinos do not form bound states, yet they surround us as they are abundantly produced in the fusion-reaction processes which fuel the Sun. The charged particles of the other two families are heavier, unstable replicas of those appearing in the first family: they are produced in high-energy experiments in particle accelerators or in cosmic rays, and rapidly decay into the stable particles of the first family. Only the neutrinos are very light in all three families. The SM contains a single scalar particle: the Higgs boson. The corresponding Higgs field, interacting with the Z and W bosons, as well as with all quarks and charged leptons, is responsible for the non-vanishing masses of these elementary particles. Gluons and photons are massless.

However, compelling arguments from cosmological observations and theoretical considerations indicate that the SM cannot be the ultimate description of nature. For instance, the model does not provide a successful description of the phenomena of dark matter and dark energy, which are necessary ingredients for the model that currently best describes the Universe at large scales. A coherent merging of the SM with the classical theory of General Relativity, which successfully describes gravitational interactions, has not been found yet. Moreover, contrary to General Relativity, the SM contains a sizeable number of free parameters (coupling constants), whose peculiar values do not have an explanation in the model itself. Despite its success, the SM is thus viewed as an effective theory, i.e. a theory with a limited range of validity, especially at high energies, whose completion is still unknown. The search for a theory able to overcome the difficulties of the SM, extending its validity range and possibly predicting some of its free parameters, is the ultimate goal of the forefront of research in particle physics, on both the experimental and theoretical sides. Such a theory, generically denoted as *new physics*, should contain new degrees of freedom, which are expected to manifest as new particles or, more generally, to give rise to new microscopic interactions.

On the experimental side, the search for new physics is pursued by testing the SM throughout its domain of applicability, looking for phenomena not accounted for by the SM itself. This search is performed in several complementary directions using a series of very different tools. A natural strategy is the *direct search* for new particles at high-energy colliders, i.e. the direct exploration of the *high-energy frontier* of the theory. Thanks to the principles of quantum mechanics and relativity, analysing high-energy collisions of elementary particles corresponds to exploring the smallest accessible distances: particle accelerators can be viewed as the most powerful microscopes we have at our disposal. Historically, the direct search for new particles has led to major discoveries. Some of them were largely unexpected, such as the discovery of the J/ψ resonance in 1974 (which we now know is the bound state formed by two charm quarks); others were somehow anticipated, such as the discovery of the Higgs boson in 2012, whose existence was predicted by the consistency of the SM well before its observation. However, the direct search for new physics is limited by the maximal energy achievable at particle accelerators: this is a serious limitation given the technical and economic challenges posed by high-energy colliders.

A complementary approach in searching for new physics is that of the *indirect search* for new phenomena via precision measurements using intense beams of particles, not necessarily at the high-energy frontier, and detectors able to cope with a large amounts of data. This strategy has also played a major role historically in uncovering new physical laws, the most famous of which is probably the discovery of CP violation or the non-symmetric behaviour of matter and antimatter at the level of fundamental interactions. While this phenomenon has been observed in specific quark decays, the imbalance observed is too small to explain the baryon-antibaryon asymmetry observed in the Universe; such potential asymmetries are now also under study in the neutrino sector. The indirect search for new physics is the only viable option to uncover new degrees of freedom in the theory if either the mass scale of new physics is too high to be directly probed or if the coupling to known particles is so weak that it has escaped detection so far. Deviations of precision observables from the current theory predictions or the appearance of unexpected phenomena could both provide indirect, but unambiguous evidence for new physics. Of course, a golden scenario would show deviations in some precision observables and, simultaneously, direct production of new particles in high-energy collisions.

Furthermore, we know that *neutrinos* play a key role in the understanding of the fundamental laws of Nature. Due to their very low interaction rate, it is a challenge to obtain a high-statistics dataset of these particles, but important progress on this front has been made over the last decades opening up the *intensity frontier*. The discovery of neutrino oscillations is a clear indication that these particles have a non-vanishing mass: a property that goes beyond what is predicted by the SM (at least in its original formulation), and could therefore represent a unique window on physics beyond the SM. New measurements are essential to answer remaining open questions about neutrino properties, such as the absolute neutrino mass, the mass hierarchy, and the possibility of a matter-antimatter asymmetry in the neutrino sector. Neutrinos could also be Majorana-type particles (or particles coinciding with their corresponding antiparticles), a special property that would distinguish them from all the other matter constituents, possibly explaining the origin of their tiny mass. This property, which is still an open question, could be revealed experimentally via the observation of the elusive neutrinoless double-beta decay.

Besides the direct and indirect searches for new physics at colliders, a very important complementary way to explore physics beyond the SM is offered by indirect searches via astrophysical phenomena, taking advantage of series of ‘natural high-energy accelerators’ present in the cosmos. A variety of astrophysical observations forge models of cosmic accelerators. Sufficient precision and multiple messengers from photons in all energy bands to cosmic rays (charged leptons, antiprotons, and atomic nuclei), neutrinos, and gravitational waves are needed in order to draw solid conclusions on this *cosmic frontier* of particle physics, whose ultimate goal is to understand the origin and evolution of the Universe. To this cosmic frontier also belongs the direct search for dark matter, which is performed via large-volume detectors located in underground laboratories, where they are naturally screened against the large amount of (known) atmospheric radiation. In the last few years it has become clear that taking a multi-messenger approach to all forms of radiation coming from the cosmos could result in significant advances in many areas, from astrophysics to fundamental interactions. A recent showcase example is the binary neutron-star coalescence discovered first via gravitational waves (by LIGO/Virgo) and later seen by many electromagnetic counterparts in X-ray, optical, IR, UV, and radio regimes. These data have allowed us to address the long-standing question about the interior of neutron stars, while also providing a very stringent test of the equality between the speeds of propagation of gravitational and electromagnetic waves. This excludes entire classes of theories modifying General Relativity, which were proposed to explain the phenomenon of dark energy by modifying gravitational interactions on large, cosmological scales.

In each of these three frontiers (high-energy, high-intensity and cosmic), theoretical research plays a twofold essential role. On the one hand, theoretical models addressing the shortcomings of the SM are essential in guiding the experimental efforts toward the most promising research directions. On the other hand, a necessary ingredient relevant to all of the experiments is the development of precise predictions within the SM for the processes under study; without precise predictions to compare to, we cannot interpret the experimental results. While the SM is an apparently simple theory in abstract terms, making precise predictions for quantities observed in realistic experiments is often an extremely challenging goal, necessitating the use of sophisticated tools from both the analytical and numerical sides. This problem is further complicated for the cosmic frontier where the modelling of astrophysical objects and of the composition of the Universe play an important role.

4.2 The three pillars of CHIPP

Particle and astroparticle research, by its very nature, necessitates a strong collaborative environment, which enables, for example, mustering and coordinating the required resources, exploitation of synergies, and guaranteeing the long term pursuit of the envisioned scientific goals described above. In Switzerland, particle physicists are organised within CHIPP,[6] an association according to Swiss law and a member of SCNAT. CHIPP has played an important role in coordinating the Swiss activities in particle and astroparticle physics, including prioritising recommendations for the SERI-funded instrument FLARE[7] administered by SNSF.

In order to address the research presented above, the CHIPP experimental research activities can be grouped (non-exclusively and with considerable overlap) into three main pillars of experimental activity. Pillar 1 tackles the exploration of interactions between fundamental particles and the search for physics beyond the SM, using accelerators at the high-energy frontier (such as the LHC at CERN), as well as high-intensity, low-energy accelerators (such as the facilities available at PSI) at the precision/intensity frontier. Pillar 2 is dedicated to the exploration of the neutrino sector, with emphasis on the investigation of transitions between different neutrino types and, in particular, the consequences of non-zero neutrino masses. Pillar 3 focuses on the exploration of fundamental questions at the interface between observational cosmology and particle physics, such as the search for dark matter or multi-messenger astroparticle physics. While not federated per se in this pillar structure, accelerator physics as well as theory activities are tightly interwoven with the experimental activities in one or more of the experimental pillars, as described above.

CHIPP research topics have clear links to other disciplines, most notably astronomy, astrophysics, and cosmology, as well as computer science. Astroparticle physics is interdisciplinary by its very nature, connecting particle physics instrumentation and methodology to astronomical observation, but also relying on astrophysical input, such as in the search for dark matter. Particle and astroparticle physics also have strong bidirectional ties to various fields of engineering. Experimental accelerator particle physics involves sifting through enormous amounts of data, a task which requires sophisticated statistical and data-reduction tools, such as deep learning algorithms, distributed computing, and data handling. These techniques are typically the domain of computer science, but particle physics has also contributed new technologies in this realm, including the creation of the World Wide Web. In addition, particle physics detector requirements are a leading force in the development of more sophisticated hardware for medical imaging applications, such as scanners for Positron Emission Tomography (PET). Accelerator physics itself is a driver for innovation in magnet technology, with cross pollination to magnetic resonance imaging and high-field magnet applications, for example. More details on these various synergies are presented in Chapter 8 and Chapter 9. In 2020, a common working group was founded with members of the CHIPP Board and representatives from CHAPS, with the objective of developing closer research ties on existing and potential future projects of scientific interest to both communities.

4.3 Focus of this roadmap document

This roadmap document supersedes the first CHIPP Roadmap document[1] that was issued in May 2004 and its subsequent implementation document.[2] The objective of this document is to provide a comprehensive bird eye's view of recent CHIPP activities and the current state of the field in Switzerland, as well as to present a broad vision for the anticipated developments of the field in the next few decades in the context of the Update of the European Strategy of Particle Physics (ESPP) by CERN and the APPEC astroparticle roadmap, while also informing stakeholders in Switzerland about the national and international research infrastructure needs in the period 2025–2028. As the CHIPP community provides near-term, concrete prioritisation of those needs in the context of the FLARE calls (see above), the prioritisation in this roadmap is of a more general and long term nature, as commensurate with the long term nature of our research field.

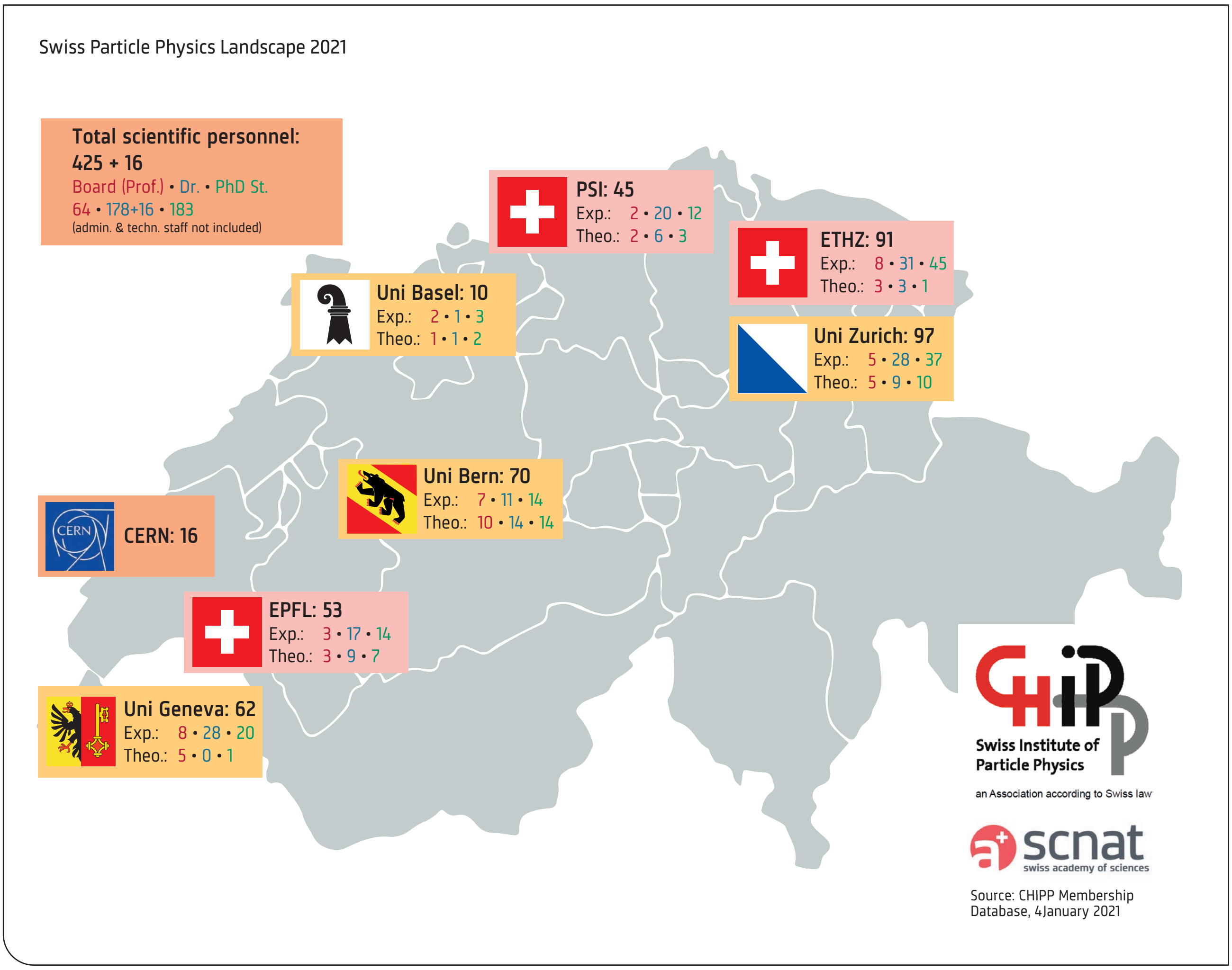
Figure 3: The CMS Experiment (Image: CMS Collaboration/CERN)

5 The present Swiss landscape

This section gives an overview of the major research areas in particle and astroparticle physics in Switzerland and the involved institutions. A map detailing Swiss participation is shown in Fig. 4. Overall, more than 400 people are actively involved. A large majority are PhD students (about 40%), showing the importance of educating talented young individuals in the field of physics and technology at the forefront of scientific research.

Switzerland is a host state of CERN, which is a strong motivation for the existence of a vigorous programme in particle physics at Swiss Universities (Uni Basel, Uni Bern, Uni Genève, Uni Zürich, EPFL, and ETH Zürich) and the national laboratory, PSI. Through CHIPP, a coherent programme is pursued along the three main pillars in a very collaborative way. At the same time, there are ample opportunities and support for involvement in a diverse set of both large and small projects.

This section is structured along the CHIPP pillars.



Source: CHIPP Membership Database, 4January 2021

Figure 4: Map with the institutions involved in particle and astroparticle physics in Switzerland (Image: CHIPP)

5.1 Energy frontier of particle physics

CHIPP Pillar 1 consists of Swiss activities at the high-energy, high-intensity, and precision frontiers of particle physics. 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 of all CHIPP institutions play leading roles in knowledge-frontier experiments run at CERN and at PSI (Appendix 15.1.1). These roles comprise intellectual leadership, hardware R&D, design, construction, implementation, data taking, data analysis, and theory developments, as well as important managerial lead roles. All of these activities significantly enhance the discovery potential of the experiments and considerably extend the boundaries of our current knowledge.

CERN's LHC drives the highest-energy proton-proton collisions in the world; these collisions are recorded by the ATLAS, CMS, and LHCb Experiments, which have used these data to consistently provide new insights and challenge our understanding of Higgs physics, SM parameters, flavour physics, and searches for new phenomena. These large experiments are all pursuing important upgrade activities, in particular, towards the HL-LHC phase. The new FASER Experiment is being installed downstream of ATLAS. Other CERN particle beams also provide unique opportunities, such as for rare event searches with NA64 and delivering antiprotons for precision measurements to the GBAR and BASE Experiments. Other R&D activities concern dedicated dark sector searches with SHiP at a possible future high-power beam dump facility.

CHRISP beams are driven by the HIPA complex at PSI. CHRISP provides the highest intensities of low momentum pions, muons, and ultracold neutrons. The most important Swiss activities concern the n2EDM and Mu3e Experiments and the laser spectroscopy of exotic atoms. They provide some of the most sensitive searches for CP and lepton flavour violation, as well as precision SM measurements and searches for exotic interactions. A new HIMB, with two orders of magnitude increased intensity and allowing for many new experiments, is currently under study.

An outlook of approved projects in which Swiss researchers are engaged is given in Fig. 5. Swiss researchers are also active in accelerator science and technology developments, which puts Switzerland in an excellent position for the future of particle physics, as detailed in Table 1.

5.1.1 High energy: LHC experiments

Swiss institutes are founding members and significant contributors to three of the four high-energy physics experiments at the Large Hadron Collider (LHC) at CERN: ATLAS (Uni Bern and Uni Genève), CMS (Uni Zürich, ETH Zürich, and PSI), and LHCb (Uni Zürich and EPFL). The activities of these Swiss scientists have spanned a very broad spectrum of physics pursuits: from precision measurements of the SM to explorations of new phenomena that could answer the open questions of our Universe. Since the discovery of the Higgs boson in 2012, a much deeper characterisation of this new particle has been achieved. After the long shutdown from 2013 to 2014, data were collected during Run 2 of the LHC, which took place from 2015 to 2018 at a centre-of-mass energy of 13 TeV. This dataset has allowed for a better understanding of the detectors, new sophisticated developments in reconstruction algorithms, and a reduction in the associated uncertainties. At the same time, a significant leap in the precision of the theoretical predictions has taken place. These are the basic ingredients that have made the LHC physics programme more compelling than ever before.

The Higgs boson, the physical manifestation of the Higgs field, provides mass to both fermions and bosons, and establishes the mechanism for how the high-energy electroweak interaction is broken into electromagnetism and the weak interaction at low energies. While the SM was constructed with the simplest Higgs mechanism with only one Higgs boson particle, many extensions to the SM predict a richer sector of particles with multiple Higgs bosons. The Higgs boson can currently only be studied by the ATLAS and CMS Experiments at the LHC. ATLAS and CMS have succeeded in measuring the overall production and decay rates of the new particle to within 20% at centre-of-mass energies of $\sqrt{s}$ = 7 and 8 TeV, and to within 10% at 13 TeV, finding results in all final states that are consistent with the expectations of the SM Higgs boson. The charge, spin, and parity have been established and the width and lifetime are also consistent with expectations. The Higgs boson is now, in a way, a necessary component of the SM of particle physics. Swiss physicists have made leading contributions towards the discovery and measurements of the Higgs boson, including various analyses and major hardware contributions essential for identification of the Higgs boson decay products.

Beyond the study of Higgs boson properties, precise measurements of SM parameters represent a pillar of the LHC physics programme. These parameters, such as the weak mixing angle and the mass of the W boson, are theoretically predicted by the SM and are measured to a high degree of precision at collider experiments. The comparison of predicted and measured values of these parameters

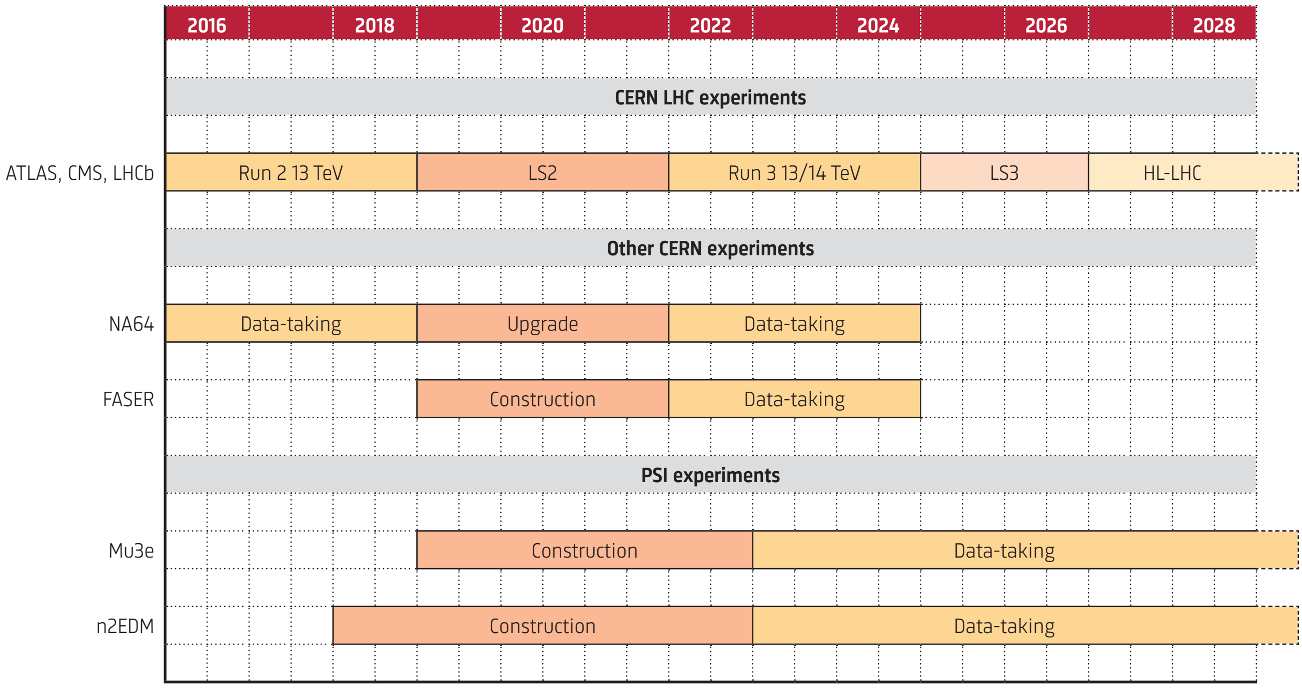


Figure 5: The timeline of the various representative ongoing approved projects where Swiss researchers are involved, at CERN and PSI. This timeline demonstrates activities in recent years, starting in 2016, and extending to 2028, one year after the HL-LHC project will have started.

constitute a crucial test of the SM and can uncover new phenomena. Swiss scientists are specifically engaged in the study of the top quark, the heaviest of the elementary particles and a natural probe of new physics. Production of SM processes with top quarks also represent some of the most significant background sources to searches for new physics. These Swiss groups have concentrated on improving the understanding of the top-quark production and decay mechanisms, as well as establishing the production of rare processes involving top quarks.

Direct searches for BSM physics have a high priority in the present Swiss landscape, with strong involvement by all Swiss LHC groups. This search programme is broad, covering and pushing beyond the existing landscape, while several centres of expertise guarantee that the Swiss contributions are of high importance and impact. Searches performed by Swiss physicists include ‘classical’ signatures, such as Supersymmetry (SUSY) or heavy resonances produced by new hypothetical particles. Given that there has been no sign of new phenomena so far, various theoretical models for new physics have been excluded, at least in their simplest formulations. Experimental search strategies are now being refined in order to test the scenarios that are still viable, where such remaining possibilities are typically characterised by a higher degree of complexity. The searches performed by Swiss physicists also extend into more unconventional signatures, including rare and forbidden decays from flavour physics phenomena, originating from more exotic yet theoretically viable and interesting models. This approach is a logical consequence in the increase of the LHC’s integrated luminosity and the confidence that has been gained while op-

Table 1: A summary of Swiss involvement in approved accelerator-based particle physics experiments. Research groups in all institutes are also active in detector research and development, which often extend to applications in other scientific fields and industry.

Institution	Main involvements
Uni Basel	Experiments at PSI: MUSE
Uni Bern	Experiments at CERN: ATLAS and FASER Experiments at PSI: n2EDM Detector R&D: Tracking detectors, data acquisition
Uni Genève	Experiments at CERN: ATLAS and FASER Experiments at PSI: Mu3e Detector R&D: Tracking detectors, trigger and data acquisition
Uni Zürich	Experiments at CERN: CMS and LHCb Experiments at PSI: Mu3e Detector R&D: Tracking detectors, trigger
EPFL	Experiments at CERN: LHCb Detector R&D: Tracking detectors, trigger
ETH Zürich	Experiments at CERN: CMS, NA64, GBAR, BASE 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 Detector R&D: Tracking detectors

erating the LHC detectors over many years. Rapid progress by Swiss groups in the search for BSM physics is made possible by innovation, both in covering new ground in the parameter space of experimental signatures and in designing new powerful tools in the areas of trigger, simulation, reconstruction, and data analysis. This combined approach allows for Swiss groups to exploit optimally the unique LHC dataset and to prepare a path towards future experiments. Among the most interesting examples is the use of advanced triggering methods to search in real-time for rare signatures in ways that are not feasible with conventional trigger strategies.

The LHCb Experiment, designed to exploit the enormous production rate of both bottom and charm hadrons at the LHC, has established itself as the leader in heavy flavour physics through important new results and measurements at the precision frontier. Some examples of achievements include the observation of very rare SM decays and measurements of phenomena violating the CP symmetry (see Fig. 6) between matter and antimatter in several different decays, which severely constrain BSM physics. In addition, LHCb has produced high-impact results, notably including the first robust observations of hadronic resonances consistent with tetraquark and pentaquark states, which are allowed by Quantum Chromodynamics.

Swiss groups have played leading roles in the LHCb Experiment and have carried out a variety of physics analyses. These analyses have mostly focused on flavour physics and CP violation, but have also covered other areas, such as direct searches for long-lived particles, thereby exploring a large territory where BSM physics may exist. In the last decade, they have pioneered important measurements, among which an angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays that has shown a yet-to-be-understood significant discrepancy with respect to the SM prediction. Together with other flavour physics results (from LHCb and the *B*-factory experiments Belle and BABAR), which also show hints of deviations from the SM, these results, dubbed the 'flavour anomalies', have raised the interest of the flavour community. LHCb has therefore expanded upon its original physics programme over the past few years, including measurements with electrons and tau leptons in order to test the lepton flavour symmetries of the SM, which are currently under question due to the flavour anomalies. These measurements also show intriguing deviations from the SM, with crucial updates being led by Swiss groups.

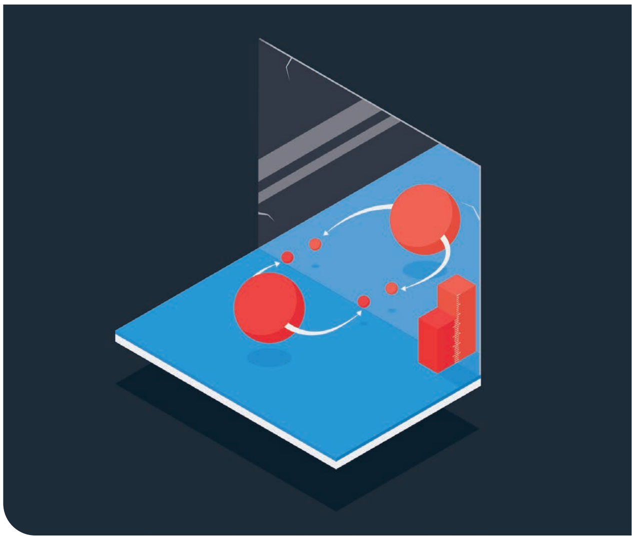


Figure 6: A CP-symmetry transformation swaps a particle with the mirror image of its antiparticle. This figure illustrates the decays of a D^0 meson (big sphere on the right) and its antimatter counterpart, the anti-D^0 (big sphere on the left), into other particles (smaller spheres). The number of decays in each case, which show an asymmetry, is displayed as vertical bars (Image: CERN)

These flavour anomalies, which at this point represent the only hint of BSM physics at the LHC, have generated a lot of excitement within and beyond the flavour physics community. Theorists are both revisiting their calculations of the SM predictions and building models that would explain all of the anomalies. ATLAS and CMS have also started to test lepton flavour symmetries in sectors other than flavour physics. LHCb is planning for a second upgrade to take place a decade from now, with a major emphasis on significantly increasing the precision of its measurements such that the anomalies can be turned into observations in case they are due to new physics. In this context, the CMS Collaboration has also opted to expand its *B*-physics programme by exploiting an unbiased dataset of 10^{10} beauty-quark pairs collected in 2018, just before the second long shutdown of the LHC.

The enormous amounts of data collected by the LHC experiments necessitate the ongoing transition to modern data analysis tools, such as machine learning (ML), which are being pioneered in Swiss groups. ML techniques are being employed at all levels of event processing, from triggering to reconstruction to data analysis; in this way, ML is enabling previously unattainable levels of precision in measurements, while also expanding the reach of analyses to new regions of parameter space and supporting model-agnostic searches through the use of anomaly detection techniques.

One of the major pursuits in collider high-energy physics is the design, construction, and commissioning of particle detectors. At the LHC, these tasks come with major challenges. The large number of proton-proton interactions per bunch crossing (pile-up) allows for large event rates, which is essential in the quest for rare phenomena. This leads to an enormous detector occupancy, high trigger rates, and severe radiation levels, which drive the

Figure 7: Opening of the LHCb detector in early December 2018 (Image: M. Brice/CERN)

requirements on detector granularity, fast electronics, and radiation hardness respectively.

Swiss groups have played key roles in the development of the detectors that were operated during Run 1 and Run 2. Swiss groups have also led upgrades of or additions to the existing detectors. These activities have been primarily focused on the tracking detectors (Uni Bern and Uni Genève for ATLAS; Uni Zürich, ETH Zürich, and PSI for CMS; Uni Zürich and EPFL for LHCb) and the calorimeters (ETH Zürich for CMS). Swiss groups have also been involved in the detector trigger and data acquisition systems (Uni Genève and Uni Bern for ATLAS). The LHCb Collaboration is currently installing a major detector upgrade (Fig. 7), driven by the need to readout the full detector at a rate of 40 MHz as input to a software-only trigger, thus supporting the operation of the detector at a five times higher instantaneous luminosity and with a much improved physics efficiency. For this upgrade, the Uni Zürich and EPFL groups have been involved in the design and construction of the tracking detectors. More specifically, EPFL has proposed and developed the scintillating fibre (SciFi) technology for the replacement of tracking stations downstream of the dipole magnet.

The upgraded HL-LHC is expected to start operations in 2027 and deliver about 250 fb^{-1} of proton-proton collision data per year until about 2038, which is approximately 10 times the current data size. The challenge associated with taking data under these conditions will be unprecedented and the experiments have developed plans to upgrade their detectors in order to cope with such extreme demands. ATLAS and CMS will proceed with the complete replacement of their inner and outer tracking detectors, including an extension of forward tracking acceptance to higher pseudorapidity with extended pixel detectors; the inner pixel detector specifications are at the forefront of radiation tolerance and rate capabilities for silicon detectors. Both experiments are also improving their track trigger capabilities, and CMS will implement a hardware-level track trigger. Both experiments are upgrading the electronics of their calorimeters for faster readout, while the CMS endcap calorimeters are being replaced with calorimeters based on high-granularity and radiation-hard silicon detectors. Detectors with timing information are being planned to reduce the effects of pile-up down to levels similar to current conditions.

Switzerland is playing a major role, both in ATLAS (Uni Bern and Uni Genève) and CMS (Uni Zürich, ETH Zürich, and PSI), in the design and construction of the inner tracking detector, including detector module and readout chip design, powering, qualification, detector system electronics, mechanics, and cooling. In CMS, the Swiss groups are also responsible for the barrel electromagnetic calorimeter electronics and will help to build the barrel timing layer. In the ATLAS and CMS Experiments, the Swiss groups are contributing to the trigger and data acquisition system and track trigger upgrades.

Swiss groups are equally active in sensor R&D. Two independent teams, one at the Uni Genève and another one joint between ETH Zürich and PSI, are developing very thin monolithic pixel prototypes with excellent resolution in terms of both position and time. These detectors are developed primarily for future particle physics experiments, although several other fields of basic research will also profit from them. The Uni Genève technology, which produced two patents and secured associated ERC funding, is presently proposed for the design and construction of a very-high-precision pre-shower detector for the FASER Experiment at CERN, as well as for medical-physics projects. The ETH Zürich and PSI detector will find a first application at the Mu3e Experiment at PSI. If these detectors are proven to be radiation hard, they promise to be excellent candidates for use in tracking detectors at future experiments.

Equally important to the detector construction is the computing infrastructure, without which the enormous amounts of data cannot be processed and analysed. The LHC computing challenge has been addressed at two scales in Switzerland. At a small scale, user-specific data analyses are performed independently by each institute, adopting whatever approach is more convenient for their needs and relying on local resources (Tier-3). On the large scale, Switzerland is a part of the Worldwide LHC Computing Grid (WLCG) project, which is a global collaboration of around 170 computing centres in more than 40 countries formed to fulfil the LHC computing requirements. The load on each participating country is regulated by annual pledges: each country is expected to contribute to the global effort by providing both the hardware and the personpower needed to operate it. The Swiss Institutes working at the LHC fulfil their pledges by providing Tier-2 resources in Bern and at the Swiss National Supercomputing Centre (CSCS) in Lugano.

Figure 8: Close up of the experimental setup of NA64 experiment hunting down dark photons, hypothetical dark matter particles, at the CERN Super Proton Synchrotron (SPS) (Image: NA64 Collaboration/CERN)

5.1.2 High energy: Other experiments at CERN

The lack of any direct discovery of new physics by LHC experiments has stimulated alternative research strategies and models of new physics. One possibility is to extend the SM by adding new light states with feeble couplings to SM particles, creating the so-called dark sector (DS), which is becoming an extremely fertile domain of exploration. Swiss researchers are pioneering DS searches in fixed-target beam experiments at CERN. ETH Zürich is among the original proponents and one of the main drivers of the NA64 Experiment searching for rare events at the Super Proton Synchrotron (SPS) at CERN, which uses a novel approach for a beam dump experiment: it operates a fully hermetic detector to gain access to missing energy techniques. NA64 was approved in 2016 and has been collecting data since then. Fig. 8 shows the close up of the experimental setup of NA64 experiment. Swiss groups in Uni Bern and Uni Genève are leaders in FASER (ForwArd Search ExpeRiment), a small experiment 480 metres downstream of the ATLAS detector, which will shed light in a complementary way on the DS. FASER, which was designed to capture decays of exotic particles produced in the very forward region, was approved in 2019 and is now being installed in its final location.

Beyond searching for new physics, the FASER Experiment will also, for the first time, provide the capability to measure properties of neutrinos at the highest human-made energies ever recorded, thanks to the FASERnu detector.

Furthermore, Swiss groups have been involved in future experiments that search for new weakly interacting particles. More specifically, they are founding members of the proposed Search for Hidden Particles (SHiP) Experiment, designed and optimised to search for very-weakly-interacting long-lived particles in the GeV regime, and have proposed a new Beam Dump Facility (BDF) at CERN where the experiment could be located. Proponents of the SHiP experiment, which include scientists from Uni Zürich and EPFL, have proposed that the detector technology envisaged for capturing the unprecedented number of ν_τ produced could be used in a smaller format to measure neutrinos produced at one of the LHC interaction points. This experiment, called Scattering and Neutrino

Figure 9: The ELENA ring at CERN (Image: CERN)

Detector at the LHC (SND@LHC), is similar to FASERnu, but explores a different pseudorapidity region.

5.1.3 Experiments with low-energy beams

Switzerland is in a unique position in terms of large-scale facilities for fundamental particle physics. It is both a host country of CERN and it operates its own large-scale research infrastructure at the PSI, in particular, the HIPA complex.

HIPA is home to the world's highest power (1.4 MW) proton cyclotron, delivering the highest intensities of low momentum pion and muon beams, as well as ultracold neutrons. A substantial fraction of the world-leading research with pions, muons, and ultracold neutrons is done at PSI. In order to cope with the requirements of the experiments and to continue to hold this leading position in the international context, design and feasibility studies are underway into how to further improve beam intensities and quality.

CERN houses the antiproton decelerator (AD) facility, the world-leading facility supporting research with low-energy antiprotons and antihydrogen. It is currently being upgraded with the addition of the Extra Low-ENergy Antiproton (ELENA, shown in Fig. 9) ring, which will be fully operational for all experiments making use of the AD after the restart of the LHC in 2021; Swiss research groups take part in these experiments and are thus set to benefit.

Beyond PSI and CERN, other facilities where Swiss researchers are involved include the neutron sources at the Institut Laue-Langevin (ILL) in Grenoble and the European Spallation Source (ESS) near Lund, especially for the Beam EDM experiment. Swiss researchers also use the positron laboratory at ETH Zürich.

All facilities serve an international community and provide the involved Swiss groups with excellent opportunities to initiate, pursue, and lead cutting-edge research. It is a considerable advantage of the Swiss groups to have some of the world's best research infrastructures within the immediate reach of their scientists, students, and technical workforce.

Most of the Swiss activities in low-energy particle physics make use of the unique facilities at PSI, which itself has three groups directly involved in the in-house physics programme. University groups from Uni Basel, Uni Bern, Uni Genève, Uni Zürich, and ETH Zürich are involved in various international collaborations at PSI. Many more groups from Swiss universities use PSI particle beams of protons, pions, muons, electrons, positrons and neutrons for R&D on detectors and electronics, and for irradiation studies. On the one hand, this largely increasing interest is due to the unique reach of low-energy precision experiments in the search for new physics; some of the tightest constraints on new physics come from this field. The global particle theory community is increasingly focusing on developing the necessary tools to evaluate quantitatively precision experiments and to allow comparisons with experimental constraints obtained from high-energy physics. Swiss particle theory is greatly contributing to and even driving the progress in this field. On the other hand, comparatively small collaborations and shorter time scales allow individuals to have an enormous impact on an experiment. PhD students can get a complete experimental physics education from conceptualising ideas to setting up measurements and producing results. PSI is the world-leading centre in the search for Charge-Parity (CP) violation with the neutron electric dipole moment, for charged lepton flavour violation experiments with muons, and for exotic atom spectroscopy with muons and pions.

The new experiment Mu3e, with strong Swiss participation (Uni Genève, Uni Zürich, ETH Zürich, and PSI), aims to search for one of the prominent charged-lepton flavour-violating reactions (cLFV), the decay $\mu \to eee$, by exploiting the presently highest-intensity muon beams at PSI. A sketch of the experiment is shown in Fig. 10. This new experiment is currently the most promising cLFV experiment worldwide; it aims to improve the existing limit of $B < 10^{-12}$, determined also at PSI over 30 years ago, by over 3 orders of magnitude. The complementary cLFV decay $\mu \to e\gamma$ is being searched for by the MEG Experiment, which also takes advantage of the high-intensity beamline at PSI. They expect to improve their own present limit of $B < 4 \times 10^{-13}$ by another order of magnitude.

5.1.4 Accelerator physics and technology

Accelerator science and technology developments in Switzerland are at the heart of several large research infrastructures used in particle physics, but also in a number of fields like chemistry, life, and materials sciences. Switzerland maintains a strong tradition of accelerator R&D, both at PSI and at CERN. Going back to the design and construction of high-intensity proton accelerators at PSI in the 1970s, with its world-highest-power proton beam, has resulted in state-of-the-art synchrotron light sources, such as the Swiss Light Source (SLS) and the Swiss Free Electron Laser (SwissFEL). The CHART programme, a collaboration between CERN, Uni Genève, EPFL, ETH Zürich, and PSI, continues to maintain this tradition. The mission of CHART is to support the future-oriented accelerator project of FCC at CERN, together with the development of accelerator concepts beyond currently existing technologies. With extraordinary support by SERI, the ETH Board, and participating institutions, CHART contributes to future accelerator-driven research infrastructures benefiting science and society.

5.2 Neutrino physics

Neutrino physics constitutes Pillar 2 of CHIPP, including activities in both theoretical work and experimental measurements. The development of novel detection techniques takes a prominent role in order to cover 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 design and construction of future general-purpose long-baseline experiments in the USA (DUNE) and Japan (Hyper-K): experiments aimed at determining the mass nature of neutrinos and experiments measuring neutrinos as part of their multi-messenger investigations. In parallel, the physics exploitation of running experiments is ongoing (SBN, T2K, GERDA, and IceCube).

Neutrino physics has a long history in Switzerland, including groundbreaking experimental and theoretical work. Currently Uni Basel, Uni Bern, Uni Genève, Uni Zürich, and ETH Zürich are actively involved in this research, which offers training for about 20 PhD students. The Swiss involvement in neutrino experiments is shown in Table 2 with the international experiments described in Appendix 15.1.2. Presently, the main challenges in neu-

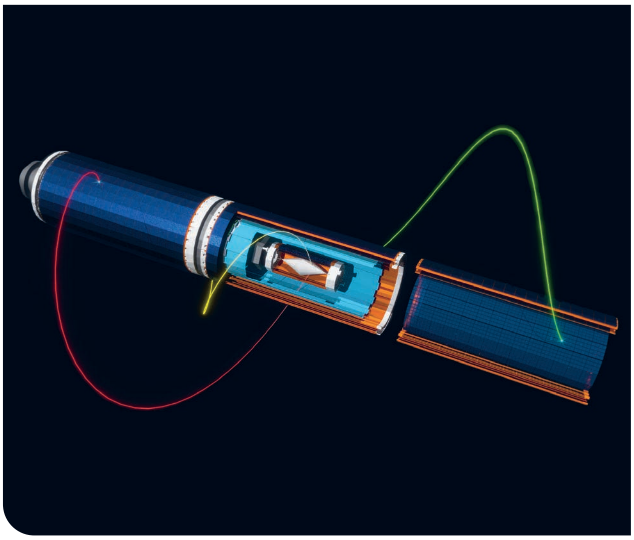


Figure 10: This CAD rendering shows the Mu3e detector with the trajectories of a decay $\mu \to eee$. Surface muons produced in a target station enter the experiment from the left inside the tube and stop on a target in the centre where the trajectories start. The detectors form full barrels, only a few of which are shown here for visibility. The experiment will be placed inside a solenoid with a 1 m diameter at 1 T (not shown) (Image: Mu3e Collaboration)

trino physics concern neutrino oscillations, the origin of high-energy neutrinos from the cosmos, and the search for neutrinoless double-beta decay. The measurement of neutrino properties at long-baseline beam experiments is the highest priority task of the neutrino pillar in Switzerland, and is considered to be a flagship of the overall experimental particle physics programme. There are also experiments described in the energy frontier section (FASERnu and SND@LHC) and the astroparticle physics section (DARWIN) which perform neutrino physics measurements.

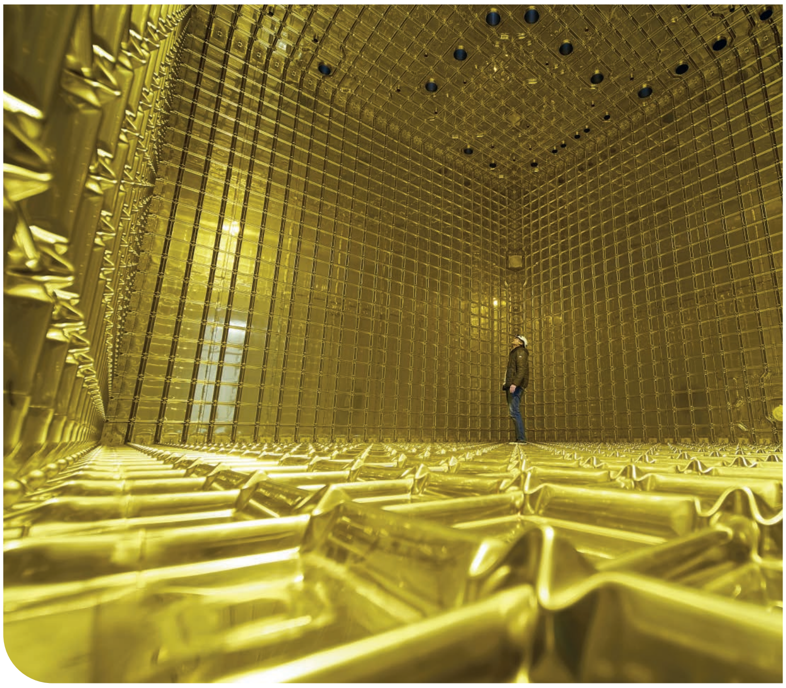


Figure 11: The ProtoDUNE detectors under assembly at CERN (Image: M. Brice/CERN)

All of these activities and experiments crucially depend on the development of innovative detectors, theoretical and phenomenological advances in neutrino physics, and the study of new particle accelerator infrastructures and technologies (notably at PSI). CERN is closely tied to the Swiss neutrino efforts and, as the host of the Neutrino Platform, is also an integral part of the global strategy. The Swiss groups have extensive experience in the development of the detector technologies required to perform measurements of the elusive neutrinos, as well as in the analysis and interpretation of the data. Equally relevant to the study of discovery prospects for new physics is the contribution of the theory group at the Uni Basel. Overall, the scientific impact and visibility of Switzerland is large and very well acknowledged internationally.

Neutrino oscillation physics is a central priority of experimental particle physics in Switzerland, with major achievements in the K2K (Japan), OPERA (CERN and Gran Sasso National Laboratory), T2K (Japan), and MicroBooNE (USA) experiments. Groups from Uni Bern, Uni Genève, and ETH Zürich have made considerable investments in the construction, operation, and scientific exploitation of the T2K Experiment; Uni Genève and ETH Zürich are committed to the scientific exploitation of the experiment until the end-of-operation of T2K. The Uni Genève and ETH Zürich are leading the R&D efforts towards the construction of two of the subsystems for the near detector upgrade in close collaboration with the CERN Neutrino Platform. The T2K upgrade, and the near detector infrastructure, to which Swiss groups have made key contributions, are considered to be the precursors of the neutrino observatory Hyper-K, as relates to both the hardware concept and the development of analysis procedures.

Uni Bern and ETH Zürich have also held key roles in the initiation of the LBNF/DUNE long-baseline programme in the USA (Fig. 11), which originates from the merging of the LBNO project in Europe (led by ETH Zürich) 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 Uni Bern have had leading roles in the construction of MicroBooNE, as well as coordinating the scientific programme of the collaboration. There is currently a strong Swiss engagement in DUNE; the design concept for the near-site detector now adopted by the collaboration was proposed by the group at Uni Bern based on past experience, while ETH Zürich pioneered the dual-phase approach for the far apparatus.

Table 2: A summary of Swiss involvement in experimental neutrino physics. The experiments are described in Appendix 15.1.2.

Institution	Main involvements
Uni Bern	Long-baseline experiment: DUNE Short-baseline experiments: MicroBooNE, SBN
Uni Genève	Long-baseline experiment: T2K/Hyper-K Ground-based astroparticle experiment: IceCube
Uni Zürich	Neutrinoless double-beta decay experiments: GERDA, LEGEND
Uni Zürich	Long-baseline experiment: T2K/Hyper-K

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

Significant contributions to the neutrinoless double-beta decay searches come from Uni Zürich, which has been involved in GERDA since 2007, and has crucial responsibilities in both GERDA and LEGEND in hardware, software, and data analysis, contributing to the design, 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.

5.3 Astroparticle physics

Pillar 3 of CHIPP relates to astroparticle physics; Swiss groups are actively working on different aspects of multi-messenger astroparticle physics, which is the most promising direction to follow, in order to understand the highly complex 'cosmic accelerators' observed in the Universe. These groups participate in large international experiments designed for γ-ray, X-ray, neutrino, and cosmic ray detection. While X-ray experiments must operate from space, 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. CHIPP groups are also at the forefront of direct dark matter searches, especially with liquid xenon. A summary of the experiments with Swiss involvement can be found in Table 3. A short description of each experiment can be found in Appendices 15.1.3 and 15.1.4.

In order to understand cosmic accelerators and other high-energy phenomena in the Universe from a multi-messenger approach, Swiss institutes are participating in various international experiments on γ-ray, X-ray, neutrino, and cosmic ray detection. Swiss groups are also strong contributors to theoretical cosmology, studying the problem of dark energy or modifications of General Relativity (see Sec. 5.4). [These groups are also involved in lower-energy observations (e.g. HIRAX, SKA, Planck, SPT, Euclid, and LSST), as discussed in the CHAPS roadmap.] In addition, Switzerland makes significant contributions to instrumental and theoretical activities associated with gravitational wave research in connection to LIGO/Virgo, LISA, and the future Einstein Telescope. These are discussed further in the theory subsection and in the CHAPS roadmap; see also Chapter 8 on 'Synergies with other scientific fields' for more details.

Table 3: A summary of astroparticle experiments with Swiss involvement. The institutes presently participating in the experiments are indicated in parentheses. The subjects and goals of each experiment are described in Appendices 15.1.3 and 15.1.4. The timelines are detailed in Fig. 32 of Chapter 11.

X- and γ-rays, cosmic rays, and neutrinos	
from space	
AMS-02 **DAMPE** **HERD** **EUSO** **POLAR-2** **eXTP**	(Uni Genève) (Uni Genève) (Uni Genève,EPFL) (Uni Genève) (Uni Genève) (Uni Genève)
from the ground	
IceCube **LHAASO** **CTA** **MAGIC** **FACT**	(Uni Genève) (Uni Genève) (Uni Genève, Uni Zürich, EPFL, ETH Zürich) (Uni Genève, ETH Zürich) (Uni Genève, ETH Zürich)
Dark Matter	
XENON1T **XENONnT** **DARWIN** **DAMIC-SNOLAB** **DAMIC-M** **OSCURA**	(Uni Zürich) (Uni Zürich) (Uni Zürich) (Uni Zürich) (Uni Zürich) (Uni Zürich)

5.3.1 X- and γ-rays, cosmic rays, and neutrinos

X- and γ-rays accompany the most energetic events in the Universe (such as the merger of a neutron star binary system, resulting in γ-ray bursts) and are one of the main ingredients that can be used to understand high-energy accelerators in the Universe. They are very often used in a multi-messenger approach, meaning that the same astrophysical source is studied with photons of different energy scales, neutrinos, and/or gravitational waves, thus presenting a combined picture of the phenomenon. X- and γ-rays are very useful in this context as they are detected with higher statistics than ultra-high-energy cosmic rays (UHECR), neutrinos, and gravitational waves; together with lower-energy photons detected by satellites or from the ground, they drive the searches for cosmic high-energy sources. Following the pioneering work on cosmic rays at Uni Bern, Switzerland has a long standing interest in high-energy γ-ray observations.

Groups at Uni Genève, Uni Zürich, EPFL, and ETH Zürich are currently involved in various aspects of CTA, including its construction, the definition of its scientific programme, and the preparation of software for the start of data-taking activities. The current leading γ-ray astrophysics observatories are the first Large-Size Telescope (LST) of CTA (Fig. 1), the two MAGIC telescopes, and the small FACT, all visible in (Fig. 12).

Figure 12: Visible in the photograph, from left to right: the first Large-Size Telescope (LST1) of CTA (24 m mirror-diameter), FACT (4 m) and the MAGIC telescopes (17 m) at Los Roches de Muchachos, La Palma. The LST1 was inaugurated in October 2019 (Image: CTA Collaboration)

Three more LSTs will be added in the coming five years, together with other Medium-Size Telescopes (MST) at the Northern CTA site; the preparation of the Southern site is also starting in Chile. In the coming year, the two small-size telescopes will start operation at the Ondreyov Observatory before joining the LHAASO Experiment. The technical skills on using silicon photosensors acquired with FACT and the small-size telescopes will also be used to build future cameras for additional LSTs. CTA will be an observatory operating for several decades and the science interest of the Swiss users will evolve with time. The main topics of interest of the current Swiss groups are 1) the physics of astrophysical jets, including the study of extragalactic background light, the Hubble constant, Axions, dark matter, UHECR, and cosmic magnetic fields; 2) galactic particle accelerators, including the question about the origin of PeV-scale cosmic-rays, propagation, and galactic feedback; and 3) fast transients (i.e. astronomical events of short duration), especially the prospect for multi-messenger observations of such phenomena. Uni Genève developed the Fibre Tracker for the HERD science mission that will start operation in 2025. Thanks to this tracking detector, HERD can be operated as a sub-GeV γ-ray observatory with unprecedented imaging resolution in the galactic plane and central regions. HERD and CTA, operating simultaneously, will provide a unique opportunity for multi-wavelength studies of variable sources and investigations of the structure of galactic shocks at different scales.

Swiss groups are also involved in the neutrino observatory IceCube at the South Pole and the Large High Altitude Air Shower Observatory (LHAASO), a new γ-ray telescope under Chinese leadership. A brief description of these experiments can be found in Appendix 15.1.4.

In addition to HERD, Uni Genève is involved in several space experiments studying high-energy astroparticle phenomena, the oldest of which, INTEGRAL, was launched in 2002. The cosmic ray detector Alpha Magnetic Spectrometer 2 (AMS-02) at the International Space Station (ISS) and the cosmic ray and γ-ray detector DArk Matter Particle Explorer (DAMPE) aboard the Chinese Space Station are both presently taking data. Future Uni Genève involvements in space include EUSO, Polar-2 and eXTP; a description of the capacities and the main science goals of these experiments can be found in Appendix 15.1.3.

All of these projects jointly contribute to the multi-messenger programme aimed at understanding cosmic accelerators and highly energetic cosmic phenomena.

5.3.2 Dark matter, direct detection

While there is ample evidence for the existence of dark matter (DM), as motivated by its gravitational interaction with luminous matter, the nature of DM at the microscopic level remains unknown. The objective of observing non-gravitational interactions of DM is a global effort, with Swiss scientists at the forefront of this search.

The Swiss group at Uni Zürich is a founding and leading member of the world's most sensitive direct DM detection programme based on Liquid Xenon (LXe) TPCs. The XENON1T Experiment, which used a total of 3.2 t of LXe, collected data at the Laboratori Nazionali del Gran Sasso (LNGS) of Istituto Nazionale di Fisica Nucleare (INFN) in Italy until December 2018. Its successor XENONnT, with a total of 8.4 t of LXe, is currently being commissioned at LNGS in preparation for the start of the first science run scheduled for later in 2021. This will then be followed by DARWIN, a 50-tonne LXe astroparticle physics observatory, with ultimate sensitivity to DM over a wide mass range and which also supports a rich programme in neutrino physics and other rare event searches.

The Uni Zürich group has played and continues to play a leading role at the XENON1T, XENONnT and DARWIN Experiments, with contributions to the hardware, the calibration and maintenance, and the analysis of the data. XENON1T's core detector, the TPC, was built with leading contributions from the Swiss group and is now back at Uni Zürich as part of a new science exhibition. The Swiss group has similarly played a leading role in XENONnT, which includes the design and construction of the TPC, the characterisation of the 3-inch photosensors in LXe (see Fig. 21), and the design and construction of the low-background voltage dividers. The group is responsible for the signal transfer between the TPC and the Data Acquisition (DAQ) on the xenon side, the amplification of these signals, the design and construction of the light calibration system, and for material screening using a dedicated high-purity germanium detector at LNGS. The TPC is designed to reconstruct the precise 3-dimensional position of the interaction. These positions can then be used to separate background events from signal candidates through the selection of an inner low-background region. Furthermore, the charge-to-light ratio differs between the backgrounds from electron recoils and the signal from nuclear recoils, providing complementary information. DARWIN is the ultimate LXe-based DM detector which will explore the full parameter space for WIMPs and will come into operation in 2026/27 at earliest. A Swiss PI (Prof. Laura Baudis) is the founder and spokesperson of DARWIN. Presently, the Swiss group is constructing a large prototype at Uni Zürich, hosting a 2.6-metre-tall LXe-TPC, with the support of funding from an ERC Advanced Grant.

The Uni Zürich group was a founding member of DAMIC, which established world-leading search results for weakly-interacting, low-mass DM, since its prototype phase at Fermilab in 2008. DAMIC operated at SNOLAB from 2015-2019 and used its low-energy threshold to produce the first direct-detection constraints on the absorption of hidden photon dark matter. DAMIC-M is the planned follow-up experiment, which should begin operation in 2024. The Swiss group plays a major role in low-background materials mechanics, electronics for the signal conversion, the detector control system, and more.

5.4 Theoretical physics

> 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.

The search for a theory able to overcome the difficulties of the SM, extending its validity range and possibly predicting some of its free parameters, is the ultimate goal of the frontier of research in theoretical particle physics. We can roughly divide the research directions in this field into four main categories as listed below. 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.

I. Precise SM physics

An essential ingredient for progress in the field is the development of precise predictions, within the SM, for particle physics experiments: without precise predictions to compare with, the experimental results cannot be interpreted. While the SM is an apparently simple theory in

Table 4: Overview of the research activities in theoretical particle physics in Switzerland. Roman numerals refer to the four main research lines discussed in Sect. 5.4

Institution	Main research areas
Uni Basel	(II) Neutrino physics, high-energy BSM phenomenology (III) Cosmology, astroparticle physics
Uni Bern	(I) Precision low-energy physics, lattice QCD, collider phenomenology (III) Cosmology, astroparticle physics (IV) String theory and formal aspects of QFT
Uni Genève	(II) High-energy BSM phenomenology, model-building (III) Cosmology, astroparticle physics, physics of GWs (IV) String theory and formal aspects of QFT
Uni Zürich	(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
ETH Zürich	(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

abstract terms, making precise predictions for quantities observed in realistic experiments is often an extremely challenging goal, requiring sophisticated tools both from the analytical and the numerical side.

Precision calculations for collider physics. Theoretical predictions based on the SM are a fundamental ingredient for the interpretation of collider data. The vast majority of experimental analyses make use of perturbative predictions at parton level or in combination with parton showers. Such predictions are relevant to test the SM, but they are also a crucial ingredient in the experimental measurements, both for the description of acceptance efficiencies and for the modelling of backgrounds in SM measurements and BSM searches. As a result of the continuously growing precision of the experimental data and in view of the expected improvements that will be achieved with the HL phase of the LHC, an increasing number of analyses are going to be limited by theoretical uncertainties.

Perturbative calculations are nowadays supported by automated tools in most cases, and their sys tematic application to hadron-collider studies is mandatory in order to reach a precision of $O(10\%)$. Several calculations reaching (or exceeding) this level of precision have been completed in recent years for relatively simple hadron-collider processes. However, the difficulty grows exponentially for more complex processes, such as those involving several particles in the final state. For these processes, the relevant computations pose formidable challenges: new analytical and numerical tools have to be developed. Several directions in which to face these challenges are presently being explored, in particular by the particle theory groups at the Uni Zürich and at ETH Zürich, which work at the forefront of this type of research. Related activities are also being carried out at the Uni Bern and at PSI.

Future efforts in this direction will be targeted towards key processes for the HL-LHC physics programme, as well as for future FCC scenarios. The conceptual frontiers to be addressed are high-multiplicity processes where novel approaches are being developed, such as multi-loop calculations, and multi-scale problems combing Quantum Chromodynamics (QCD) and electroweak effects or involving top quarks, with precise determination of the mass-dependent effects.

Precision low-energy physics. Precise SM predictions are also an essential ingredient for indirect searches for new physics in low-energy experiments. This task is particularly complicated by the phenomenon of quark confinement, which occurs at low energies. A further challenge arises from the extreme level of accuracy required by these experiments, which often involve very different energy scales (e.g. from the 100 GeV of weak interactions down to the 0.5 MeV of the electron mass). A series of effective theory tools have been developed to deal with these problems, as well as methods based on the combination of analytical calculations and experimental data.

Swiss researchers at Uni Bern, Uni Zürich, and PSI are particularly active in this line of research. Future efforts in this direction will be aimed at the new generations of experiments in this field, with special emphasis on planned experiments at PSI, the LHCb upgrades, and other low-energy experiments. A particularly interesting measurement concerns the anomalous magnetic moment of the muon, where there is currently a discrepancy between the SM prediction and past experiments; this discrepancy needs to be clarified. On the experimental side, this issue will be addressed by the ongoing Fermilab experiment and by a new experiment planned at the High-Energy Accelerator Research Organisation (KEK) in Japan, whereas on the theory side, there is a worldwide effort aimed at improving the theoretical predictions (the Muon $g-2$ Theory Initiative), which theorists in Bern are helping to coordinate.

A special role in this area is played by lattice QCD. The goal here is to overcome the problem of quark confinement through large-scale numerical simulations of strong interactions. Swiss theoreticians at the Uni Bern coordinate the Flavour Lattice Averaging Group (FLAG) report, which compiles and critically reviews the results from various lattice collaborations worldwide, and are members of the European Twisted Mass Collaboration (ETMC), one of the largest lattice QCD collaborations worldwide.

II. Model-building and BSM phenomenology

A core ingredient to theoretical research in particle physics is the development of new models of fundamental interactions, designed to address some of the shortcomings of the SM and to understand how these models could possibly be tested in present and future experiments. The theoretical efforts in this area can be conveniently organised into two distinct, yet largely complementary research directions, which address different aspects of BSM physics.

The first one deals with **the origin of the Fermi scale**. The SM Lagrangian contains a single mass parameter, namely the Fermi scale, or the vacuum expectation of the Higgs field. This scale (of the order of 250 GeV) controls the masses of all of the elementary particles, but it is highly unstable with respect to quantum corrections; it would naturally tend to be heavier in the presence of heavier degrees of freedom in the theory. Why this scale is much lighter than the fundamental mass scale associated with gravitational interactions (the Plank scale, of the order of 10^{19} GeV) is one of the big open issues of the SM. In the vast majority of proposed BSM extensions, this problem is solved by introducing new degrees of freedom around the TeV scale, whose main purpose is that of screening the Higgs field from its apparent large sensitivity to high energies. On general grounds, this implies new particles in the TeV range. This is why the direct exploration of the TeV energy domain remains a key priority of particle physics. Swiss theory groups at Uni Genève, Uni Zürich, EPFL, and PSI are very active on this front, developing explicit models of TeV-scale dynamics and, most importantly, working to understand how these models could be detected at present and future high-energy colliders.

The other line of research deals with the so-called **flavour puzzle**. Within the SM, the basic constituents of matter are the three families (or three flavours) of quarks and leptons. Each family contains four fermions (two quarks and two leptons) with different quantum numbers, which completely determine their properties under the strong, weak, and electromagnetic interactions. Ordinary matter consists almost entirely of particles of the first family, while the (unstable) quarks and leptons of the second and third families appear to be identical copies of those in the first family, except for having different (larger) masses. Why there are three almost identical replicas of quarks and leptons, and the origin of their different masses, are among the key open issues in the SM. The observed excess of baryons (over antibaryons) in the Universe, unexplained in the SM, is likely to be related to these questions. In many proposed BSM extensions, these questions are addressed by a series of new interactions whose elementary nature manifests itself only at very high energies. The mediators of such new interactions may be too heavy to be produced directly at high-energy colliders. Still, their presence could show up indirectly as deviations from the SM predictions in various rare low-energy processes, such as the decays of the heavy quarks and leptons under study at LHCb and at the PSI experiments. The theoretical investigation of these phenomena is carried out by the theory groups at Uni Zürich and PSI.

III. Cosmology, astroparticle, and gravitational physics

A growing aspect of theoretical particle physics concerns cosmology and, more generally, the connections between particle physics, astrophysics, and gravitational physics. The challenge here is understanding particle physics and fundamental interactions through predictions and observations of astrophysical phenomena, ranging from cosmic messengers to the large-scale structure of the Universe.

Dark sectors and neutrino masses. The SM could be extended not only by the presence of new heavy states, which have not yet been identified due to energy limitations of existing colliders, but also by new light states, which have not yet been identified because of their weak coupling to ordinary matter. This latter option, generically denoted as dark sectors, are natural candidates to explain the phenomena of dark matter and have received considerable attention in the last few years. While a large fraction of the parameter space of these models cannot be probed at accelerators, interesting regions of the parameter space give rise to long-lived particles which can be searched for by the existing experiments at hadron colliders, at dedicated fixed target experiments, and also with high-intensity particle beams including at low energies. A partly related issue is the origin of neutrino masses, whose small values naturally point toward the existence of new fundamental scales in the theory and/or new feebly interacting states (such as light quasi-sterile right-handed neutrinos). Moreover, CP violation in the neutrino sector could well be related to the observed matter antimatter asymmetry in the Universe. Swiss theory groups at Uni Basel and EPFL work on both of these aspects of BSM physics, building consistent models of neutrino masses, including possible new light exotic states, and analysing their implications for collider experiments taking into account astrophysical observations.

Cosmology and gravitational waves. There is an intimate connection between particle physics and cosmology; the aim is to build a link between the microscopic laws of physics and their manifestations in the macroscopic universe as a whole. Even though cosmological observations are usually made with standard astronomical methods and are part of the CHAPS roadmap, theoretical cosmology is part of the study of fundamental physical laws, especially gravitational interactions, which belong to the CHIPP topics. During the last few years, the link between fundamental physics and cosmology has been extended to gravitational-wave physics, which represents a powerful new probe of fundamental physics on cosmological scales. As an example of this connection, the precise mechanism that implements the electroweak symmetry breaking in the SM may have been connected to the inflationary phase of the early universe and may also have led to a first-order phase transition generating gravitational waves, which could be observable with the LISA gravitational wave observatory in the near future. Swiss theory groups at EPFL and at the universities of Basel, Bern, Genève, and Zürich are heavily involved in theoretical cosmology.

IV. Progress in Quantum Fields and String Theory

The SM is but one representative of the space of QFTs. Exploring all of the possibilities provided by QFTs is important to put the SM in perspective with respect to other ways in which Nature could have been conceived. Moreover, understanding QFTs at strong coupling, even in contexts substantially different from the SM (e.g. different particles or with a different number of space-time dimensions), could provide new tools to solve QCD eventually. Furthermore, the study of particle theories that incorporate gravity as a quantum theory, such as in String

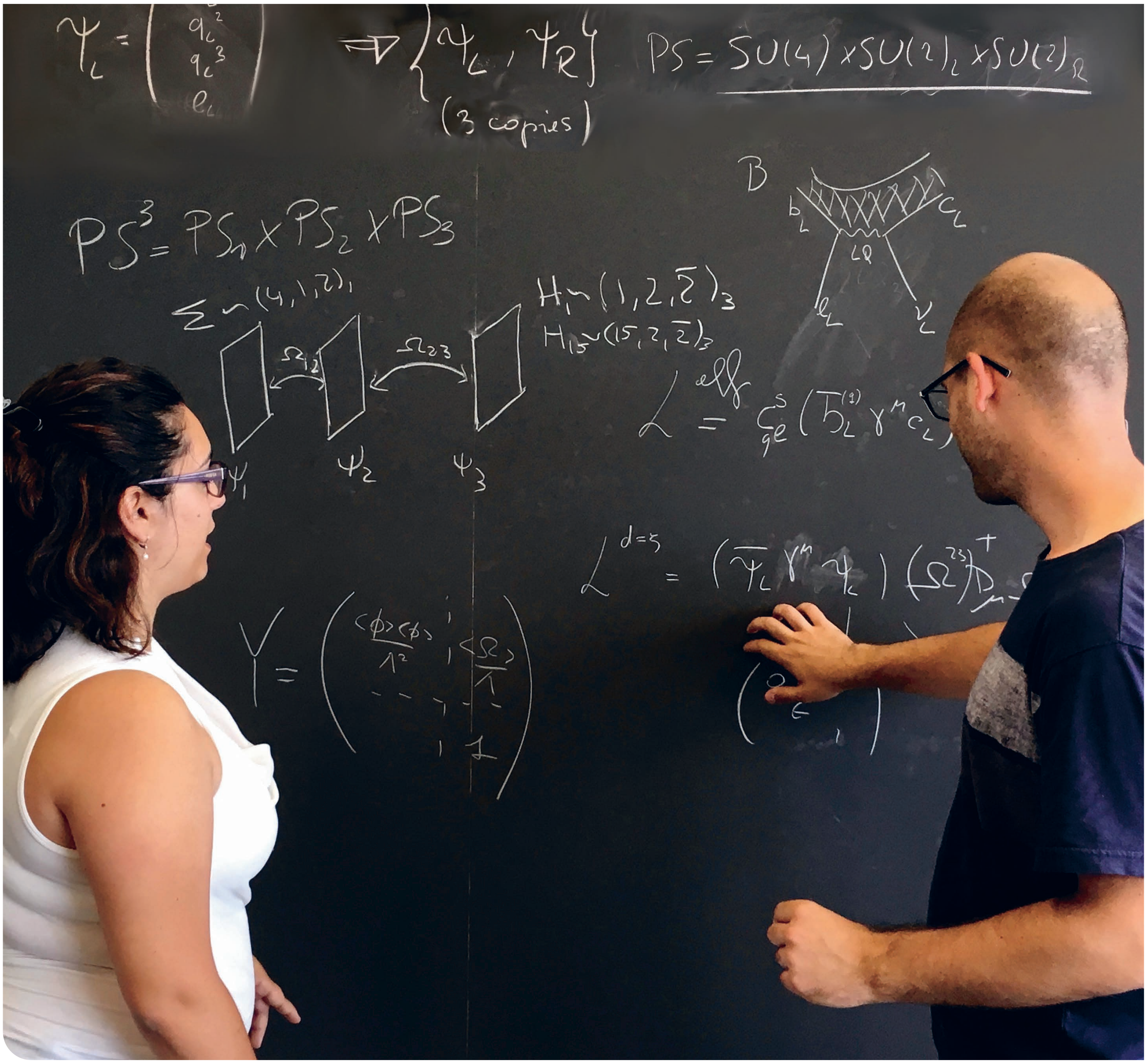


Figure 13: Theorists at work at Uni Zürich (Image: G. Isidori)

Theory, provides important candidates for the ultimate microscopic theory of Nature.

An important development in the understanding of strong coupling goes under the name of Bootstrap, and is based on the insight that one can characterise quantum field theory based on two intrinsic consistency conditions: the conservation of probability (quantum mechanics) and the condition that nothing can propagate faster than light (relativity). In its modern form, this idea was initiated at EPFL in the context of massless (conformal) theories, and has seen progress at the Uni Bern and EPFL, where an understanding of its implications for theories with large charge and with mass has recently been developed.

On a complementary front, the Anti-de Sitter space time/Conformal Field Theory (AdS/CFT) correspondence is a conjectured duality that relates strongly coupled (conformal) theories (CFT) with weakly coupled gravity ones (AdS). The latter can be computed with perturbative tools, thus providing a promising window into strongly coupled QFTs. At the same time, the duality may also give insights into the quantum behaviour of string theory, since the regime in which the AdS space is of string size (and difficult to compute) corresponds to a nearly free (and calculable) super Yang-Mills theory. Swiss theory groups at Uni Genève and ETH Zürich have significantly contributed to test and confirm this duality.

6 Major successes (2017–2020)

6.1 Energy frontier of particle physics

With the discovery of the Higgs boson in 2012, the SM is now complete. Present activities are concentrated on measuring the parameters of the SM particles with high precision, as well as on searching for BSM physics to answer the many questions that the SM leaves unanswered. The ATLAS and CMS Experiments have recently observed Higgs decay channels that were not previously accessible due to their small production rates, and have provided measurements of other SM properties with unprecedented precision. They have searched for BSM theories and models, often significantly constraining them by setting limits on the masses of associated new particles; in this route, they have also revealed interesting and challenging directions for further searches. The LHCb Experiment has established itself as the front-runner in heavy flavour physics. Recently, it has discovered CP violation in charm decays, as well as in baryon decays. It has intensified studies into the so-called flavour anomalies and improved our knowledge of various rare decays, both of which have strong implications on BSM physics.

All three experiments have explored, with Swiss contributions, dark sector particles in regions complementary to the exquisite exclusions by the NA64 Experiment. The newly approved FASER Experiment will complement such searches in a unique way and its construction is successfully proceeding on a fast track. For a future SHiP Experiment, many detailed technical studies have shown an unprecedented DS sensitivity. Swiss groups are responsible for various state-of-the-art tracking detectors used by the LHC experiments, which perform excellently and play a pivotal role in almost all analyses. They are equally engaged in the design and construction of upgraded detectors for the HL-LHC, as well as new detectors for other future experiments.

At PSI, Swiss groups lead experiments with muons and ultracold neutrons. The nEDM Experiment has pushed the limit on the neutron electric dipole moment. The MEG Collaboration has improved the limit on the lepton flavour violating decay of the muon to positron and photon, the best limit on any rare decay to date. Both are also pursuing DS searches and setting new limits. Precision spectroscopy of exotic atoms is undergoing a renaissance, with many activities and landmark results, probing SM parameters and searching for BSM physics.

Exciting results come from high-intensity muon beam physics: The MICE Experiment at RAL successfully demonstrated muon ionisation cooling with medium-energy muons, and the muCool Experiment at PSI demonstrated phase space compression for slow muons. In view of the HIMB project at PSI, aiming at two orders of magnitude higher muon intensities, a new configuration of the high-power production target was established.

6.1.1 High energy: LHC experiments

The ATLAS, CMS, and LHCb Experiments have achieved major advances in the understanding of the SM and the exploration of BSM phenomena. The collaborations have produced a large number of peer-reviewed and well-cited publications, which can be found in their respective publication list pages.[8, 9, 10]

In recent years, the highest priority in particle physics has been to measure the Higgs boson production and decay modes. Swiss physicists have helped to re-establish these at a higher centre-of-mass energy by determining precisely the Higgs boson cross-section and mass using $H \to \gamma\gamma$, and observing for the first time the $H \to \tau\bar{\tau}$ and $H \to b\bar{b}$ decays (Fig. 14), as well as $t\bar{t}H$ production, thereby definitively establishing the coupling of the Higgs boson to fermions. With the larger statistics available, Swiss physicists have measured the differential production of $H \to \gamma\gamma$, allowing for precise comparisons with both SM and BSM predictions.

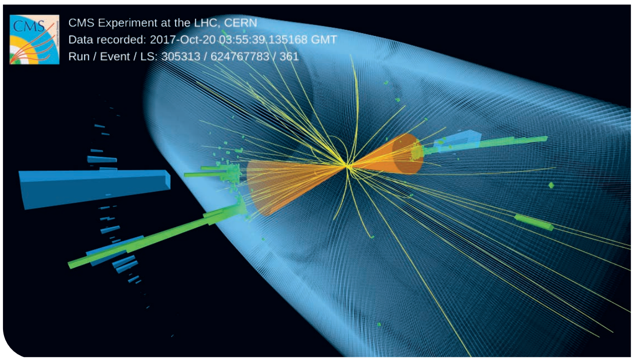


Figure 14: A display of an event as recorded by the CMS detector from an inclusive search for highly boosted Higgs bosons decaying to bottom quark-antiquark pairs (Image: CMS Collaboration/CERN)

Beyond the exploration of Higgs boson properties, many other previously poorly constrained SM properties, in particular those related to the top quark, are now being measured with unprecedented precision. During Run 2 of the LHC, new rare interactions such as the production of a

Higgs boson in association with a top-quark pair, $t\bar{t}H$ and the production of four top quarks, $t\bar{t}t\bar{t}$, were established. One of the main uncertainties in these measurements arises from the modelling of the production of a pair of top quarks in association with jets, a process that also constitutes a common background in many BSM searches. Swiss scientists have played a leading role in improving the understanding of $t\bar{t}$ production associated with jets. Identifying top-quark events has crucially pushed forward the development of algorithms for the identification of b-jets, as well as new reconstruction techniques, such as algorithms which can select boosted topologies. Swiss scientists have also led developments in these directions.

The higher centre-of-mass energy and the steady increase in luminosity in Run 2 is being fully exploited by a large repertoire of well-motivated BSM searches. On the SUSY side, this includes a plethora of searches targeting various production modes and final states, as well as exploring novel methodologies and powerful discriminating variables. These are complemented by searches for DM candidates and their mediator(s), as motivated by several exotic theoretical models. Open questions on the origin of neutrino masses and the matter-antimatter asymmetry are being studied by searches for heavy neutral leptons (HNLs) in prompt and displaced leptonic decays of W bosons. Recently, two ERC grants were awarded to young researchers associated with Swiss institutes for pursuing innovative searches within the LHC physics programme.

The LHCb Experiment has recently achieved a historic milestone in flavour physics: the discovery of CP violation in charm decays. This ultra-precise measurement represents a major breakthrough in flavour physics and opens up a new laboratory to study CP violation. For this, Prof. Tatsuya Nakada from EPFL was awarded the 2019 Enrico Fermi Prize.

While the energy frontier cannot be significantly increased in the near future, our knowledge of particle physics is constantly being challenged through precise measurements of very rare decays of heavy mesons. A well-known example and one of the 'standard candles' for such approaches is the very rare $B_s^0 \to \mu^+\mu^-$ decay. The LHCb Experiment has provided the most precise measurements of this process, including the first measurement of its lifetime. Recently a first LHC-wide combination of $B_s^0 \to \mu^+\mu^-$ measurements by the three collaborations (ATLAS, CMS, and LHCb) was performed, featuring a Swiss-led contribution from CMS.

Success in these physics pursuits would not have been possible without excellently operating detectors, a common success across all of the LHC experiments. More than 95% of the millions of channels the detectors are made of were operational at any given point in time during the LHC Run 2 data-taking period. This can be considered to be a major achievement for the Swiss groups when accounting for the fact that the number of channels in each experiment is dominated by the tracking detectors, whose design, construction, and operation were led by teams within Switzerland. Our understanding of the detectors has also been improved to the point of excellence, a fact that has led to novelties in triggering, reconstruction, and data analysis techniques. These efforts constitute the continuous focus of Swiss physicists and are documented in Chapter 5. These developments are staged and exploited in major measurements and searches as described above. The success of Swiss groups in detector R&D is remarkable, and has also been recognised with grants (including from the ERC) awarded in this direction. Looking to the future, Swiss groups are currently participating in HL-LHC detector upgrades and trigger & data acquisition projects that have been approved, and are steadily proceeding towards completion with significant efforts from all Swiss institutes.

On the computing side, all of the LHC experiments are in the process of developing the infrastructure to be able to exploit available resources, transparently and interchangeably, in an optimal way. One example of this process is the ongoing effort to transfer CPU-based reconstruction algorithms to equivalent parallelised versions that can be run on GPUs.

In support of open science, the LHC collaborations have unanimously endorsed a new open data policy for the release of scientific data collected by the LHC experiments. These data will allow scientific research related to particle physics to be more reproducible, accessible, and collaborative. Further information is provided in Chapter 10.

6.1.2 High energy: Other experiments at CERN

In the search for DS and possible DM candidates, NA64 has set the most stringent limit for light thermal DM below 0.1 GeV.[11, 12] It has also reported results that exclude part of the parameter space suggested by the so-called X17 anomaly. New experimental constraints have also been set on the mixing strength of photons with dark photons, as well as axion-like particles (ALPs), closing the gap in the ALP parameter space between previous fixed target and collider experiments.

In an effort to extend the pursuit of BSM phenomena beyond what can be done with the main LHC experiments, and in order to cover unexplored regions of parameter space which cannot be accessed by NA64, the FASER Experiment was proposed; a significant recent achievement

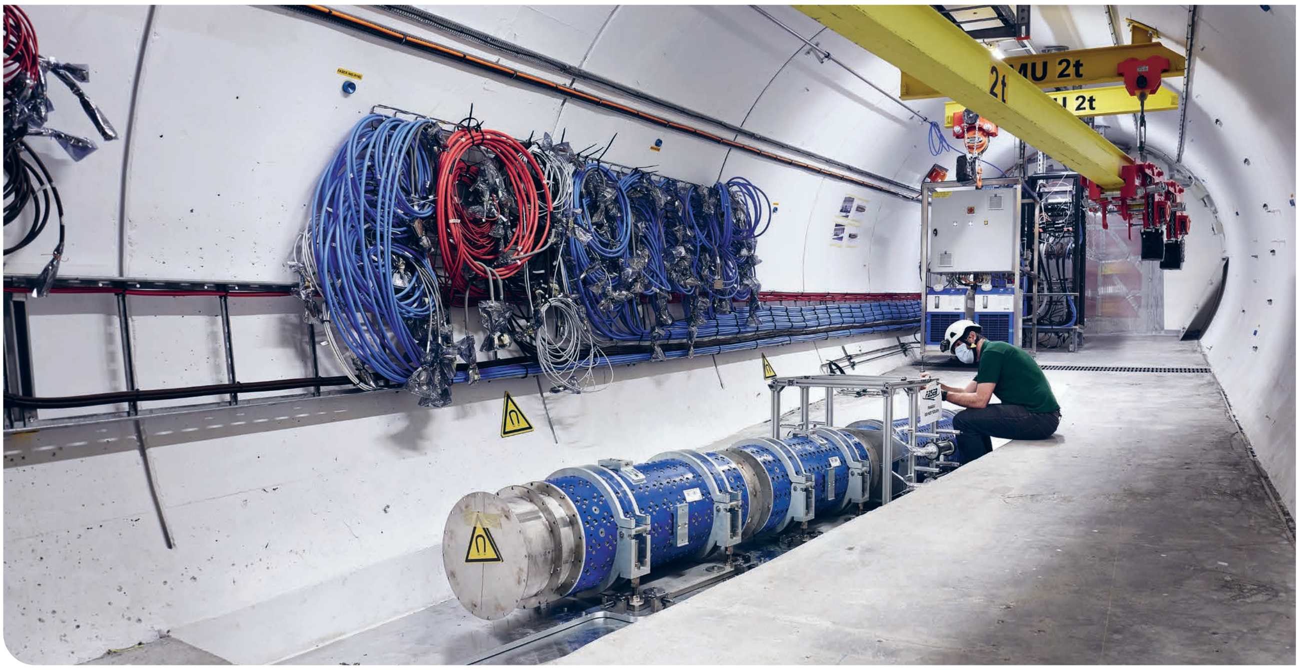


Figure 15: The FASER detector being installed in its final location (TI12 tunnel) (Image: FASER Collaboration/CERN)

was the approval of FASER by the CERN Research Board. The experiment has been primarily funded by the USA's Heising and Simons-Heising foundations and SNSF supports it with project funding. An ERC grant was recently awarded to a senior researcher associated with a Swiss institute. The construction of the experiment is progressing speedily (Fig. 15) and the experiment will collect data during Run 3 of the LHC.

The SHiP Experiment has attracted a large amount of attention in the particle physics community. Swiss groups have worked on SHiP from the experimental, phenomenological, and theoretical point of view. They have demonstrated that in addition to improving upon present and near-future constraints on hidden sector searches, the SHiP Experiment would enable precision measurements that can differentiate between different models. For instance, it is expected that if SHiP observes an HNL signal, it is possible to test the compatibility of these particles with different leptogenesis mechanisms.

6.1.3 Experiments with low-energy beams

Low-energy experiments have achieved major results with high-sensitivity searches for BSM physics as well as in high-precision measurements of SM benchmarks and fundamental constants. Three ERC grants were recently (2016-2018) granted to scientists in Swiss institutes: one in neutron Electric Dipole Moment (EDM) searches using a neutron beam and two in exotic atom laser spectroscopy with muons. This reflects the considerable progress and impact that these approaches have made over several years.

The nEDM Collaboration at PSI released in 2020 the most stringent limit on the permanent electric dipole moment of the neutron, $d_n < 1.8 \times 10^{-26}$ ecm (90% C.L.),[13] which has a direct impact on theories explaining the matter-antimatter asymmetry of the Universe. The nEDM data were also analysed for an oscillating neutron electric dipole moment, which could be induced by coupling of ultralight ALPs to gluons. Assuming that these ALPs would constitute the DM in the Universe, first laboratory limits on ALP-gluon coupling for ultralight ALP masses were established.

The MEG Collaboration at PSI has established the world-leading limit on the lepton flavour violating decay $\mu^+ \rightarrow e^+\gamma$, which is the most stringent upper limit on any branching ratio in physics, $B(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13}$.[14] From their dataset, MEG has recently provided the most stringent limits on hypothetical light, neutral particles X in the mass range between 20 and 40 MeV/c^2 for lifetimes of less than 40 ps and decaying to two photons $\mu^+ \rightarrow e^+X$, $X \rightarrow \gamma\gamma$.

After their successful measurements of the 2S-2P Lamb shift in muonic hydrogen and muonic deuterium (2010-16), the CREMA Collaboration at PSI has recently measured the 2S-2P Lamb shift in the muonic helium isotopes 3 and 4. Besides the extraction of benchmark charge radii in light and calculable systems, sensitive tests of QED and independent determinations of the Rydberg constant have become possible. To this aim, the mu-Mass Collaboration has demonstrated the creation of a muonium 2S metastable beam. The piHe Collaboration has succeeded in a first-ever laser spectroscopy of a pionic atom, further extending the reach of precision optical methods into the realm of particle physics. The muX Collaboration has demonstrated the ability to form heavy muonic atoms ^{248}Cm and ^{226}Ra using only microgram quantities of target material enabling, e.g., new symmetry tests in heavy nuclear systems with large enhancement effects.

In preparation for the development of a new HIMB first improvements to surface muon production were implemented with a new design of the production target, resulting in 40-50% improved muon yield for the same proton beam power, thus benefiting many muon experiments. The muCool project at PSI has succeeded in demonstrating transverse phase space cooling of a positive muon distribution. Taken together with the previously demonstrated longitudinal cooling, this confirms the promise of improved phase space quality by ten orders of magnitude, at the cost of only three orders of magnitude in muon intensity, translating into improved muon beam brightness by seven orders of magnitude with far-reaching consequences for experiments in fundamental particle physics and beyond.

Swiss scientists are among the founders and have a leading role in the Gravitational Behaviour of Antimatter at Rest (GBAR) Experiment, which started to be installed at CERN in 2017. GBAR (Fig. 16) is the only experiment that was connected to ELENA (the upgrade of the AD under commissioning) before Long Shutdown 2 (LS2). In 2018, the first antiprotons were delivered to and detected in GBAR with the trackers developed by ETH Zürich. This was a very important milestone for the experiment, which will resume after LS2.

A table-top experiment at ETH Zürich is using positronium to search for the specific case of massless dark photons which cannot be probed in fixed-target or accelerator experiments. Recently, this experiment has reached a sensitivity level comparable with cosmological bounds.

6.1.4 Accelerator physics and technology

As a consequence of the financial support provided by SERI and the matching funds in the form of personpower and hardware from the participating institutes, the projects of the CHART programme have achieved remarkable results. The activities of CHART have concentrated on three research directions: high-field superconducting magnet developments for FCC, FCC beam dynamic studies, and novel methods of laser acceleration. Exceptional operational conditions have also been achieved at the PSI HIPA facility.

CHART Phase-1 has engaged in superconducting-magnet R&D at various collaborating Swiss institutes. The results include the design of an optimised 16 T dipole magnet as an option for the FCC hadron collider main magnet; the development (design and prototype) of a high-field dipole magnet, which will be tested before the end of 2021 (see Fig. 17); and the development of splicing techniques for Nb_3Sn-based accelerator magnets.

The beam dynamics studies that have been conducted have concentrated on optimising the operational scenarios that maximise luminosity in future hadron colliders, with a focus on beam stability. The electron cloud and other collective effects have also been studied. Proposed scenarios have been accepted as baselines in the Conceptual Design Report of the FCC as a hadron collider (FCC-hh). Studies have covered several aspects of the design and,

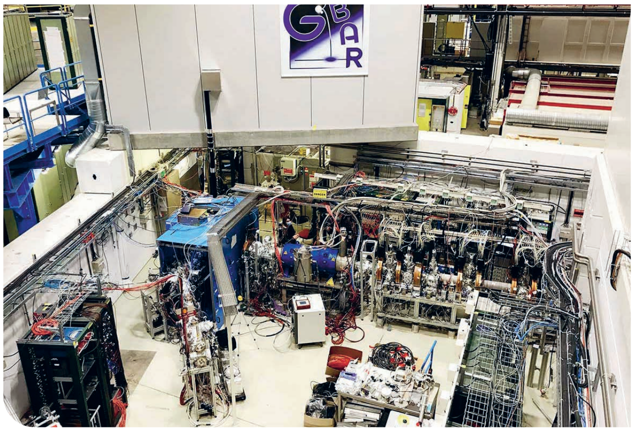


Figure 16: The experimental setup of the Gravitational Behaviour of Antihydrogen at Rest (GBAR) Experiment studying free-falling antihydrogen atoms at CERN (Image: GBAR Collaboration)

Figure 17: The superconducting technology-demonstrator dipole CD1 and the project team that built the magnet within the framework of CHART. The magnet was subsequently shipped to the partner lab LBNL in Berkeley, USA, and has undergone a first successful testing cycle. Additional tests are due in 2021 (Image: B. Auchmann/PSI)

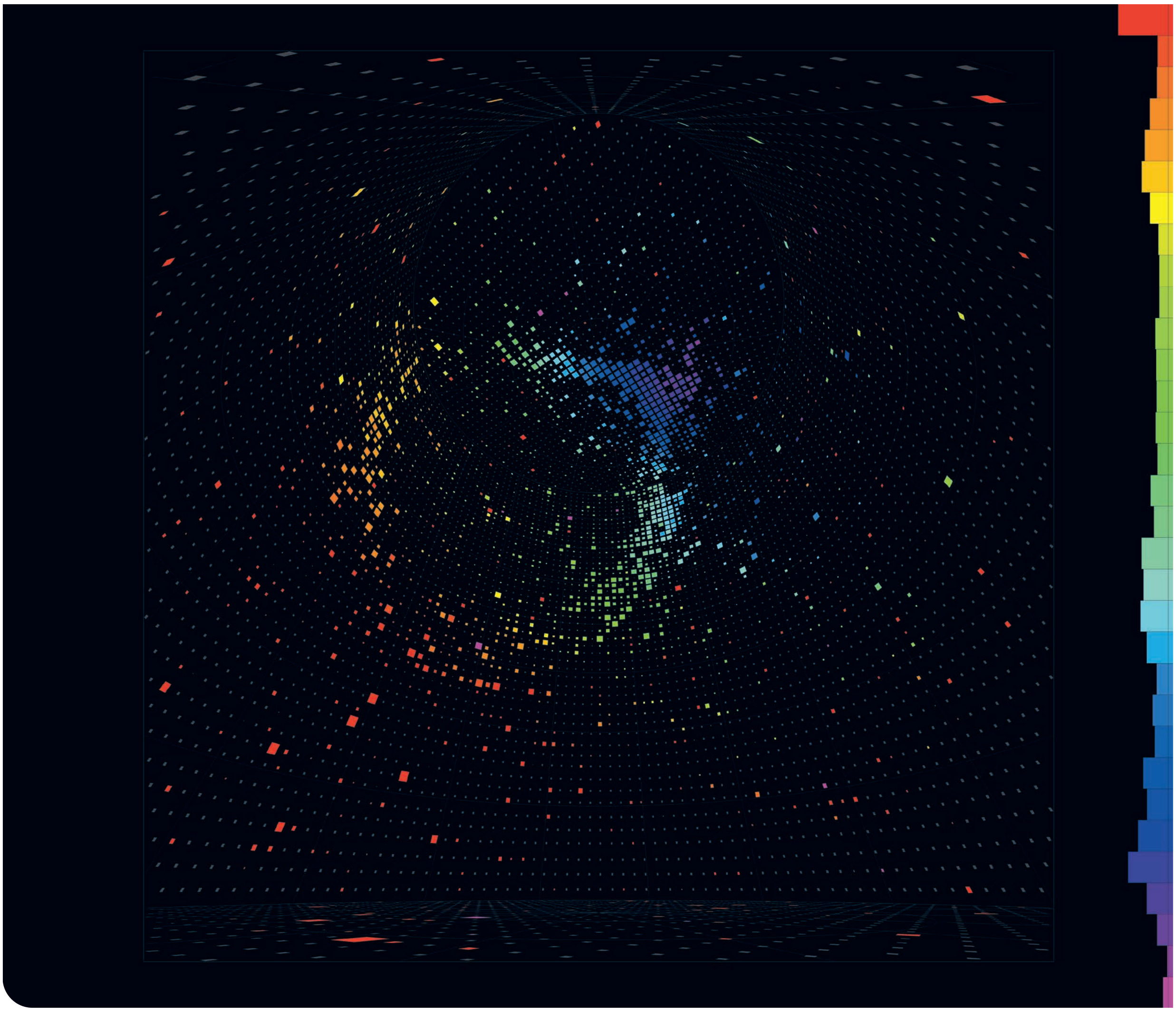


Figure 18: An anti-ν_e candidate detected in Super-K from the reversed T2K horn current beam. The picture shows the typical ring shape of the Cherenkov photons emitted by the positron created in the anti-ν_e interaction. Each pixel corresponds to a photo-detector while the colour scale represents the relative time of arrival of the light at the sensor (Image: T2K and Super-K Collaborations)

where possible, were supported by experimental benchmarking at the LHC. The studies performed range from single-beam stability to two-beam dynamics, which include beam-beam interaction effects and long term stability. The collider performance optimisation included studies into machine learning techniques. All of the results have been documented in the FCC Conceptual Design Report.

Since 2018, the SwissFEL has operated at PSI in regular-user mode. A key component of the facility is a high-brightness 6 GeV electron Linac that utilises innovative accelerator technology. This is achieved via unprecedentedly low machining tolerances and the high surface quality of the structures. Although the primary aim for developing this technology was the generation of bright, high-quality electron beams for an FEL, it can also be utilised as the injecting accelerator for the electron-positron version of a future circular collider (FCC-ee). A study on developing such an injector concept for FCC-ee has been launched within the CHART project.

The PSI HIPA facility generates a high-intensity proton beam, with a record beam power of up to 1.4 MW, for the production of high-intensity muon and neutron beams. The acceleration of such high average beam intensities is possible due to a reduction of the unwanted proton beam losses to a relative level of 10^{-4}. The energy efficiency of the facility for conversion of grid power to beam power is outstanding in comparison to other high-intensity accelerators, reaching a level of 18%.[15]

Muon storage rings have the potential to provide high-intensity, high-purity, calibrated neutrino beams, which would be suitable for precision experiments. Furthermore, muon colliders offer hope for the creation of affordable lepton colliders with centre-of-mass energies beyond a few TeV. The last two years have seen the completion of the International Muon Ionisation Cooling Experiment, MICE, with a demonstration of ionisation cooling as a means to reduce the size of a beam of muons of either sign, for a given intensity. The concept of the experiment was developed under Swiss leadership, which continued through to its successful implementation; both the construction and exploitation of the experiment occurred with major Swiss contributions.

6.2 Neutrino physics

Neutrino physics has seen important advances in the last few years, including fundamental science results and discoveries. Neutrino physics also plays an important role in cosmology and astroparticle physics. The measurement of the neutrino oscillation mixing angle (θ_{13}), the observation of muon-neutrino to tau-neutrino oscillations, and setting the most stringent limit on the germanium double-beta decay lifetime are major achievements in the field, all of which were performed with leading contributions by Swiss researchers.
Swiss groups have also achieved major milestones in detector design and construction (e.g. liquid argon TPCs), operation and physics exploitation of experiments, as well as in theoretical developments.

Significant knowledge has been gained in recent years on neutrino flavour oscillations, which are a sign that neutrinos have a non-zero mass and are described by a mixing between the flavour and the mass eigenstates, which can be parametrised as a 3x3 matrix, the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. A large number of experiments have contributed to measurements of the oscillation parameter. All but the CP violating phase (or phases) have been determined experimentally, with significant contribution from Swiss groups at Uni Bern, Uni Genève, and ETH Zürich.

The research of the scientists that established neutrino mixing was recognised by the prestigious Breakthrough Prize in Fundamental Physics in 2016 for the discovery and exploration of neutrino oscillations, and the related Nobel prize in 2015 to Art McDonald and Takaaki Kajita for solar and atmospheric neutrino oscillations, respectively.

The OPERA Experiment at the Gran Sasso laboratory has established the oscillation from muon neutrinos to tau neutrinos through the detection of the latter at Gran Sasso as originating from a muon neutrino beam generated at CERN. This has therefore established the three-neutrino paradigm which explains solar, reactor, atmospheric, and beam neutrino oscillations.

The T2K Experiment in Japan has provided the first indication that the θ_{13} angle of the PMNS matrix, the last mixing angle to be measured, is also non-zero. This was shortly followed by measurements from the Daya-Bay, Reno, and Double-Chooz Experiments which confirmed an uncontroversial effect. For these experiments, the θ_{13} angle and mass squared difference of the first and third mass eigenstate are the dominant source of oscillation behaviour. Given the small size of this angle ($\theta_{13} = 8.6 \pm 0.2$ degrees), its measurement is a major success, especially considering the precision reached in the combined fits of all available data in the last four years and the elusive nature of neutrino interactions. Fig. 18 shows an antineutrino electron candidate detected in Super-Kamiokande from the reversed T2K horn current beam.

There are experimental indications that more neutrino flavours may exist, as motivated by the measurement of neutrino oscillations which do not fit into the three-neutrino paradigm. These measurements come from beam neutrino experiments such as Liquid Scintillator Neutrino Detector (LSND) and MiniBooNE, but also from reactor-based experiments and setups with radioactive sources. MicroBooNE is the first experiment in the new Fermilab (USA) short-baseline programme which started taking data in 2015 using a liquid argon TPC. It was designed and built with major contributions from the Uni Bern, which also coordinates the scientific outcome. In the last four years, a set of 25 publications on reconstruction techniques and interaction cross-sections of neutrinos have been published, which constitutes a major success for the technology and science programme.

The search for neutrinoless double-beta decay *($0\nu\beta\beta$)*, a non-SM process, will shed light on the fundamental nature of the neutrinos and their masses. The GERDA Experiment at the LNGS laboratory is designed for rare event searches, using a very-low-background detector based on high-purity germanium. The leading sensitivity, expressed in terms of 0nubb half-life in germanium, was reached by GERDA with $T_{½} = 0.9 \times 10^{26}$ years. The Uni Zürich is a major contributor to and driver of this experiment.

The neutrino group of the Uni Genève is active in measurements of neutrinos from extra-terrestrial sources. Solar neutrinos first revealed the oscillation phenomenon in matter. The cubic-kilometre neutrino telescope, IceCube, recently proved the existence of > 100 TeV astrophysical neutrinos, which yields information on super-high-energy astrophysical sources in the Universe. These neutrinos are also probes of oscillations on extremely long baselines, PeV scale neutrino cross sections, and other possible exotic phenomena at energy scales which are inaccessible to terrestrial accelerators.

In view of future measurements, there have been important successes in the development of new detectors and the design of future programmes. The T2K near complex is being upgraded, and in particular its near detector (ND280) is being complemented with a super-high-granularity component developed at the Uni Genève. Switzerland pioneered the development of new liquid argon TPCs for the USA-based long-baseline programme (DUNE) with the groups from Uni Bern and ETH Zürich. These detector developments have proven to be major successes: large prototypes were successfully tested at CERN in preparation for use as detectors at the DUNE far site, and the ArgonCube design was chosen by the collaboration as the technology to be used for the near detector. The Uni Zürich has also accumulated a list of successes in the further development of extremely low-background cryogenic detectors for dark matter and neutrinoless double-beta decay searches in view of DARWIN and LEGEND.

6.3 Astroparticle physics

The Swiss astroparticle physics community has been engaged in numerous experiments, producing remarkable results. The Earth-based cosmic neutrino detector IceCube and the γ-ray telescope MAGIC, as well as the space-based FERMI-LAT, have discovered strong evidence for neutrinos and γ-rays from an active galaxy (the blazar TXS 0506+056) in a flaring state. A Swiss team was also involved in the installation of the the first CTA Large Scale Telescope (LST-1). In space, AMS-02, aboard the International Space Station made the most precise measurements of the cosmic flux of 'heavy' nuclei (He, Li, O, Si, Mg); DAMPE made the most precise measurements of the cosmic electron and proton fluxes; and POLAR measured the polarisation of five γ-ray bursts. Deep underground, the XENON1T Experiment has the world's best sensitivity to dark matter in the mass range from 85 MeV to 6 GeV, and has observed two-neutrino double electron capture events. The ultimate direct dark matter detector, DARWIN, has been invited to send the conceptual design report to the LNGS Scientific Committee. Last but not least, DAMIC has the world's best sensitivity to electronic scattering of dark matter and hidden-photon dark matter at low masses.

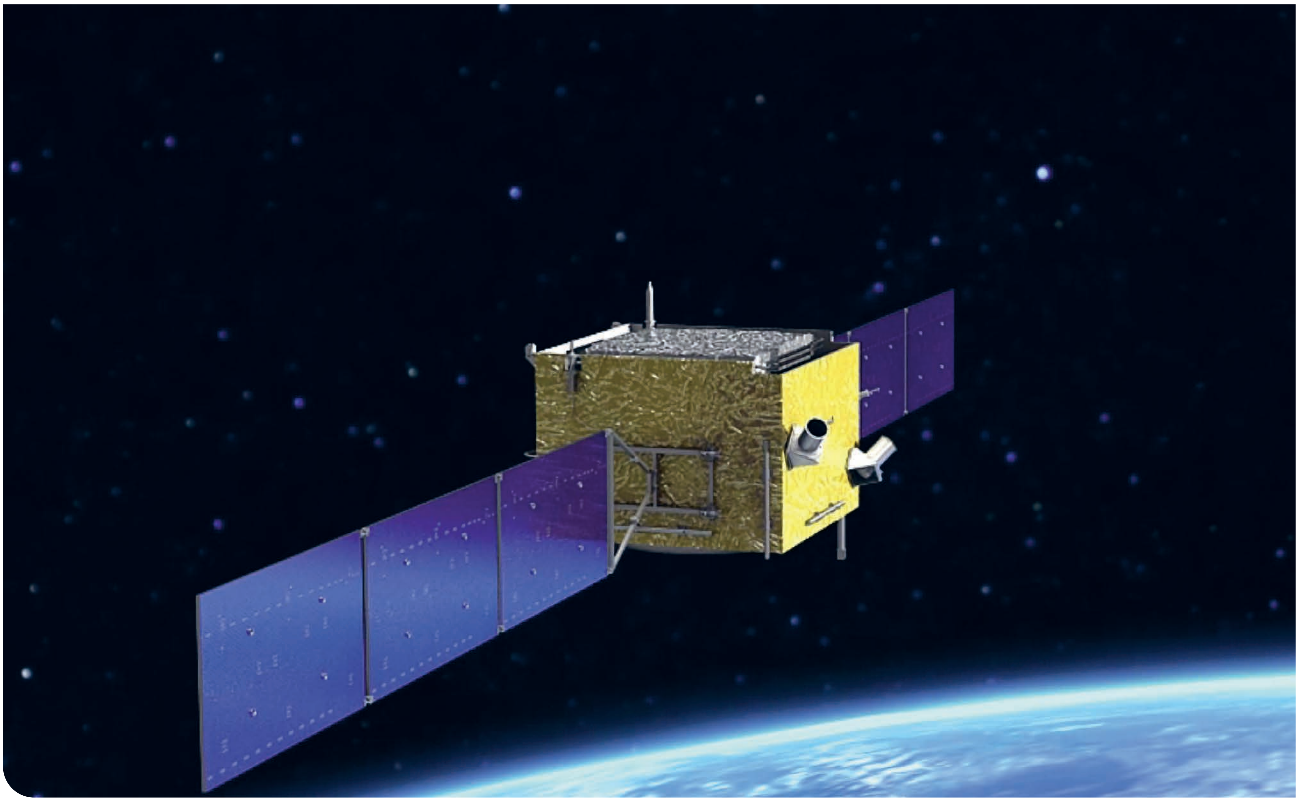


Figure 19: The DAMPE (DArk Matter Particle Explorer) space telescope launched by the Chinese Space Agency in 2015 (Image: DAMPE Collaboration)

X- and γ-rays, cosmic rays, and neutrinos

Despite the small size of the Swiss groups working on IceCube and MAGIC, some of the relevant scientific outcomes of these experiments would not have been possible without their contribution.

To date, about eight years of data have been analysed and published by IceCube. The significance of the cosmic neutrino flux has risen to more than five standard deviations.[16, 17] IceCube is well integrated into multi-messenger astronomy, giving rise to important event notifications. For example, it observed a PeV muon-neutrino event, which triggered an alert in the astronomy notification network, leading to a strong hint towards the discovery of the first cosmic high-energy neutrino source,[18] supported by MAGIC and VERITAS. The companion Science paper, which finds an older and longer neutrino flare, was the subject of a Swiss PhD thesis. A time-dependent search for coincident IceCube neutrino events with two extremely high-energy neutrino events, seen by the ANITA polar balloon flight, has recently been published and interpreted in many papers as a possible hint of new physics in the extreme energy domain. Swiss-led multi-messenger studies extend to the joint observation of events with ultra-high-energy cosmic rays (identified with the Pierre Auger observatory and CTA) and neutrinos (identified with ANTARES, KM3NeT and IceCube).[19]

The first installed large telescope of CTA (LST-1), which is still in the commissioning stage, has been successfully taking data from known γ-sources since October 2019. The first scientific verification results are being published. The Crab Nebula, which is the first TeV source ever discovered and also the 'standard candle' for γ-ray astronomy, has been detected at very high significance. It should be noted that pulsations beyond 100 GeV of the pulsars in the Nebula have also been seen. Another result on a probable neutrino source in a close-by starburst galaxy has recently been published. This discovery was awarded the Prix Wurth of the Physics Section of the Uni Genève for the best doctoral thesis in 2019.

Swiss scientists have led the development and construction of the AMS-02 Silicon Tracker, which is a key component enabling the unprecedented measurement precision of the AMS-02 mission launched in 2011. Swiss scientists have also made significant contributions to the AMS-02 data analysis. Using the expertise gained in building detectors to be used in space, Switzerland has equally led the proposal, design, and construction of the Silicon-Tungsten Tracker (STK) of the DAMPE mission (Fig. 19), launched in 2015. Contributions now extend to the DAMPE operation, data processing, and data analysis, also using modern sophisticated analysis methods. Swiss scientists have led the development and construction of POLAR, the first large dedicated γ-ray burst polarimeter launched in 2016; they have performed data processing and data analysis, and have measured the polarisation of five γ-ray bursts.

Dark matter, direct detection

XENON1T currently leads the world in sensitivity to light dark matter (LDM) in the mass ranges 3-6 GeV for DM-nucleon scattering, above 30 MeV for DM-electron scattering, and 0.2-1 keV for the absorption of dark photons and axion-like particles (ALPs). The experiment has improved sensitivity to LDM via electron recoil signals induced by the Migdal effect and Bremsstrahlung. It presently has the best sensitivity for DM masses between 85 MeV and 2 GeV. It has observed two-neutrino double electron capture events in ^{124}Xe, and has the lowest background ever reached in a direct detection experiment.[20] First results of XENON1T on the scalar WIMP-pion coupling have been published. Swiss scientists are playing leading roles in the XENON1T, XENONnT, and DARWIN Experiments; these activities have been awarded an ERC advanced grant.

DARWIN has performed a detailed study of its sensitivity to the neutrinoless double-beta decay of ^{136}Xe and has been found to be competitive with dedicated double-beta decay experiments without additional costs.

DAMIC at SNOLAB collected data from 2017 to 2019; the subsequent data analysis has led to the world's best sensitivity for electronic scattering of DM and hidden-photon DM in some mass ranges.

6.4 Theoretical physics

Swiss research in theoretical particle physics is of very high quality in all the four main directions outlined in the previous chapter. Swiss scientists are among the world-leading groups in theoretical calculations for collider physics, both at the LHC (high-energy) and the PSI experiments (low-energy). 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.

A representative figure of merit of the Swiss theoretical successes is the large number of grants awarded: in the last six years Swiss researchers have been awarded four ERC Advanced Grants and four ERC Consolidator Grants in the area of theoretical particle physics. This is a remarkably high figure given the relatively small community and the highly competitive nature of these grants. In the following paragraphs, we highlight some of the main achievements in the last five years.

Precision calculations for collider physics. Swiss particle theory groups at the Uni Zürich and at ETH Zürich are among the world-leading groups in QCD perturbation theory calculations for collider physics. In 2015-2016, they completed the first ever N^3LO calculation for a collider process, namely Higgs boson production via gluon fusion at the LHC. Other highlights of this research activity include the completion of fully differential next to next to leading order (NNLO) calculations for a wide class of processes, the development of a parton-level Monte Carlo generator for collider processes incorporating NNLO corrections, and the development of new techniques for analytical and numerical calculations of multi-loop amplitudes.

Other key results obtained by Swiss groups include the development of an effective field theory approach to perform all-order resummations of soft and collinear parton emissions, pioneered at Uni Bern, and the development of highly stable numerical integration methods for loop amplitudes at PSI.

Precision low-energy physics. Swiss groups are particularly active in this research line. Highlights of their recent results in this area include precise predictions for the anomalous magnetic moment of the muon, detailed estimates of signals and backgrounds for rare muon experiments at PSI, and precise predictions for experiments on rare B meson decays performed at the LHCb Experiment at CERN.

The origin of the Fermi scale. Swiss theory groups at Uni Genève, EPFL, Uni Zürich, and PSI are working on this front, developing explicit models of TeV-scale dynamics and, most importantly, trying to understand how these models could be detected at present and future high-energy colliders. Highlights of their recent research activity in this area include the development of general effective theories describing SM extensions where the Higgs is a composite particle, the development of experimental techniques to access suppressed BSM effects in high-energy collisions, and the development of new theoretical methods to deal with QFT theories in the strong-interaction regime.

The flavour puzzle. In the last few years, Swiss theory groups at the Uni Zürich and PSI have focused on understanding the interesting phenomenon of the so-called B-physics anomalies. Highlights of the recent research activity in this area include the development of consistent models able to describe these anomalies, and the detailed investigation of the implications of these models for future experiments, at both low and high energies. Key results have also been obtained in high-precision predictions of the dominant background processes for cLFV experiments at PSI, in particular $\mu \to e\gamma$ and $\mu \to eee$.

Dark sectors and neutrino masses. Swiss theory groups at Uni Basel, Uni Genève, and EPFL work on both of these aspects of BSM physics. Highlights of their recent research activities include the development of consistent models addressing both the origin of neutrino masses and the problem of dark matter, systematic analyses of the phenomenology of feebly interacting particles at existing and future high-intensity experiments, and systematic analyses of the impact of the DUNE Experiment in constraining unified models predicting neutrino masses.

Cosmology and gravitational waves. Swiss theory groups at Uni Basel, Uni Bern, Uni Genève, Uni Zürich, and EPFL are heavily involved in theoretical cosmology. Highlights of their recent research activities include important results in the study of Cosmic Microwave Background (CMB) anisotropies and cosmological large-scale structure (LSS), providing solid theoretical predictions for LSS observables, and actively contributing to the current experiments in the field, such as Planck and Euclid. More theoretical results include the possible explanation of the acceleration of the Universe and the phenomenon of dark matter as primordial black holes, and the corresponding analysis of gravitational wave (GW) signatures of interest for present and current GW observers. Other interesting theoretical results include the development of the so-called Higgs-inflation scenario, where the SM Higgs boson is the field responsible for inflation, and the detailed analysis of baryogenesis on motivated BSM frameworks.

Progress in Quantum Fields and String Theory The theory group at EPFL has provided a pioneering contribution to the modern formulation of the concept of Bootstrap, which is a key development in the understanding of strong coupling theories. Swiss theory groups at Uni Genève and ETH Zürich have significantly contributed towards testing and confirming the AdS/CFT correspondence. In particular, using techniques of integrability, ETH Zürich theorists have used these ideas to make predictions about the spectrum of a specific CFT ($N = 4$ super Yang-Mills) at all couplings, confirmed in certain limits by explicit computations. Moreover, they managed to prove that the complete spectrum agrees with the two descriptions when limited to a simple two-dimensional setup, an important step towards a complete proof of the duality in this setting.

7 The international context

Research in the domains of particle and astroparticle physics is carried out by international collaborations, which can be composed of thousands of members from all over the world. Switzerland, being one of the two host states of CERN and featuring an important number of very strong academic research groups, is a key player in this international environment and has strongly contributed to establishing the main strategic lines for the future evolution of the field, in particular in the context of the recent update of the European Strategy for Particle Physics.

Essentially all of the research in the domains of particle and astroparticle physics is carried out by international collaborations of varying sizes; the LHC experiments currently have the largest collaborations, with each one containing thousands of members from all over the world. Tackling the major open research questions typically requires very large and expensive research infrastructure (accelerators, particle detectors, telescopes, satellites, etc.), which explains why national and international laboratories such as PSI or CERN play a central role, and also why large collaborations are needed to join forces, thus pooling both technical knowledge and resources. It also naturally implies that strategies for future directions of the fields have to be developed at national, continental, and international level, not in isolation by single institutions. Importantly, the processes that lead to strategy developments and updates are bottom-up efforts, involving the entire community, whether that community be European, American, Asian, or representing the entire world. The two most prominent examples of such bottom-up efforts are the ESPP,[5] mentioned elsewhere in this document, and the Snowmass effort in the USA. Furthermore, structures and committees are put in place that, besides key institutions such as CERN, help in the coordination of such international efforts and initiatives. Examples of such committees are the European Committee for Future Accelerators (ECFA) and its international counterpart ICFA.

Switzerland, being one of the two host states of CERN and featuring an important number of very strong academic research groups, is a key player in this international environment.

7.1 Accelerator research

The Swiss accelerator community has strong international ties and is continuously seeking opportunities to strengthen collaborations with laboratories around the world, thus identifying and benefiting from synergies in related R&D efforts. In particular, the CHART FCC projects are carried out in close collaboration with both national and international research institutes. The high-field superconducting magnet programme, an effort within CHART, is based on a collaboration with groups at Fermilab near Chicago in the USA, and is using magnet testing infrastructure at Lawrence Berkeley National Laboratory (LBNL).

PSI is a prominent partner in the League of European Accelerator-based Photon Sources, a collaboration of 16 partners to foster R&D for light sources. EPFL and PSI are partners in an international programme called Accelerator on a Chip (ACHIP), which is co-funded by the Gordon and Betty Moore foundation. ACHIP aims to create laser-driven dielectric accelerator structures with microscopic dimensions and a broad range of potential applications. Several groups at PSI are involved in the EC-funded ARIES programme, aimed at developing new techniques and technologies for particle accelerators. In particular, these activities include R&D on low-emittance light sources and energy-efficient concepts and technologies. SESAME is a synchrotron light source project in Jordan, which was established with strong support from Europe and Switzerland, fostering collaborations and bringing scientists in the region of the Middle East together. SESAME has been in operation since 2018, and it presents a truly green facility, being fully powered by renewable energy sources.

Swiss accelerator physicists are also active in the Accelerator Group of the European Physical Society (EPS-AG) and assume roles of responsibility for the organisation of the International Particle Accelerator Conference (IPAC) series. This series was founded as a joint effort between Asia, the Americas, and Europe, combining three formerly separate conference series into the truly international IPAC. Over the years, a fundraising scheme for student grants has been established that allows 50 to 100 European students to participate in the conference with complete cost coverage.

7.2 Experiments at particle accelerators (energy and intensity frontiers)

The LHC experiments are composed of international collaborations. The ATLAS Collaboration has approximately 5000 members and about 3000 scientific authors affiliated with 182 institutions in 38 countries. CMS has over 4000 particle physicists, engineers, computer scientists, technicians and students from around 200 institutes and universities from more than 40 countries. The LHCb Collaboration consists of about 1500 members from 88 institutes in 18 countries (Fig. 20). The Swiss groups in the LHC collaborations work closely with researchers from abroad, both in the context of their physics analysis projects and the detector construction, commissioning, and operation. It is interesting to note that within these large collaborations, even computing infrastructure is being shared between institutes and countries; for example, Switzerland contributes to ATLAS with a standard computing cluster, located in Bern, and a High Performance Computer (HPC) at CSCS for ATLAS, CMS and LHCb.

As discussed in more detail elsewhere in this document, the LHC will remain the world's flagship project at the high-energy frontier for more than a decade to come, also thanks to its high-luminosity upgrade, which is expected to start operations after 2027. The type and location of its possible successor were the main focus of intense discussions during the recent ESPP update, with proposals for future colliders to be built at CERN in Europe (FCC, CLIC), in China (CEPC), and in Japan (ILC).

While the energy frontier is currently dominated by the CERN experiments, the intensity frontier in flavour physics is being vigorously pursued in Japan: the energy-asymmetric KEKB electron-positron collider provides beams to the Belle II Experiment, which is pursuing a physics programme complementary to the one of LHCb. Accelerator-based DM searches with dedicated experiments and associated international collaborations are another diverse area of research: in addition to NA64 and FASER, other experiments such as MATHUSLA and CODEX-B have been proposed at CERN.

Regarding the low-energy domain, CERN provides the only source of low-energy antiprotons and PSI provides the world's highest intensities of low-energy pions, muons, and ultracold neutrons (UCN). In Europe, other UCN sources are located at ILL Grenoble (France) and TRIGA Mainz (Germany). ILL provides the highest intensity beams of cold neutrons for fundamental physics. Cold neutrons are also available at FRM-2 in Munich (Germany), while the ESS in Lund (Sweden) is expected to build at least one fundamental physics beamline. In a global context, more sources for cold and ultracold neutrons with particle physics as part of their programme exist, including at LANL (USA), SNS (USA), NIST (USA), TRIUMF (Canada), and J-PARC (Japan).

Muon beams with different properties from those of PSI are produced at J-PARC (Japan) and Fermilab (USA). The PSI 'continuous wave' muon beams are preferred for coincidence experiments and when high instantaneous rates cause issues. Pulsed beams produced at J-PARC are well-suited for rare event searches with single particle detection, such as $\mu \to e$ conversion. Fermilab produces pulsed muons for dedicated purposes, such as the $g-2$ experiment. Muons are also available at TRIUMF (Canada) and at RAL (UK), mostly for muon spin spectroscopy and materials science, and at lower rates. Some new facilities are studying the implementation of a muon physics programme. The present beams of surface muons at PSI with rates exceeding 10^8/s currently lead the field; PSI aims to carry forward its leading position in muon beam intensities for the next few decades with new high-intensity muon beams (HIMB) which could transport on the order of 10^{10}/s low-energy positive muons to versatile experimental areas.

7.3 Long-baseline neutrino physics

At present, there are two major accelerator-based long-baseline neutrino facilities in the world: one is in the USA at the Fermi National Accelerator Laboratory (Fermilab) near Chicago, and the other is in Japan at the Japan Proton Accelerator Research Complex (J-PARC) in Tokai. They produce high-intensity neutrino beams that are probed both locally and at a detection site several hundred kilometres away. Swiss groups have been involved in both of these long-baseline neutrino experimental programmes for more than a decade.

The LBNF, together with the Deep Underground Neutrino Experiment (DUNE) in the USA, will be a world-class multi-purpose observatory for neutrinos, originating either from accelerator beams or astrophysical sources, as well as for matter instability searches. LBNF/DUNE is a global organisation, currently with 1100 scientists and engineers from 175 institutes in 31 countries, and the success of this endeavour is among the top priorities in both scientific and infrastructure roadmaps in Europe and the Americas. The detectors at the far and near site will be built by the DUNE Collaboration, and will be based on volumes of liquefied argon equipped with time-projection chambers, an advanced type of neutrino detector. Swiss researchers are among the world leaders in the development of this technology. The main excavation at the far site in South Dakota has started; the beginning of beam operation is planned for 2026 and it will last for at least 10 years.

Figure 20: Members of the LHCb Collaboration in the LHCb cavern, November 2008 (Image: LHCb Collaboration/CERN)

On the Japanese side, Hyper-K is an extension of the programme that started with the Kamiokande Experiment and continues with Super-K, which has yielded two Nobel prizes. Hyper-K will be a water Cherenkov detector centred on a huge underground tank containing 300,000 tonnes of water, with a sensitive volume about a factor of 10 larger than its predecessor Super-K. Like Super-K, Hyper-K will be located in Kamioka on the west coast of Japan directly in the path of a neutrino beam generated 295 km away at the J-PARC facility in Tokai, allowing it to make high-statistics measurements of neutrino oscillations. Together with a near-detector located close to J-PARC, Super-K has formed the T2K long-baseline neutrino programme. Hyper-K will be an order of magnitude more sensitive than Super-K, and will serve as the next far-detector for Tokai-to-Kamiokande Experiments, thus supporting a rich physics portfolio. The Hyper-K Collaboration was formally founded in 2020.

7.4 Non-accelerator-based particle and astroparticle physics

All the experiments in this domain have also been built and operated by international collaborations. The following is only a brief list of a few examples, without attempting to be comprehensive. Concerning direct dark matter searches, DARWIN extends the XENON Collaboration with additional groups from Europe and the USA; similarly, DAMIC-M has collaborators from these two regions. The future experiment, OSCURA, will unite two international collaborations that will search for DM with CCD detectors, DAMIC-M and SENSEI, bringing in additional North and South American institutions.

As another example, IceCube in the Antarctic is a collaboration of about 300 people from 52 institutions in 12 countries, with its full Phase 1 upgrade recently financed by the National Science Foundation (NSF) in the USA.

In the area of gamma astronomy, the MAGIC Collaboration encompasses about 150 scientists from 12 countries. While data belong to the collaboration and publications are signed by all collaboration members, proposals for observations can also be submitted by non-members. In addition, non-members can obtain access to data as associate scientists. The operation mode of MAGIC beyond 2025, when the CTA array at La Palma becomes operational, has not yet been decided. CTA is a consortium of about 1500 scientists from more than 200 institutes in 31 countries all over the world. Finally, the small FACT Collaboration, under the leadership of ETH Zürich, consists of scientists from Uni Genève, ETH Zürich, and the Universities of Dortmund and Würzburg (in close association with RWTH Aachen). Its fate beyond 2025 depends on final operation plans of the CTA Observatory.

One example of a space-based mission is DAMPE, which is a Chinese-European collaboration. The European contribution consists of 5 institutes, all from Switzerland and Italy, under the leadership of Uni Genève. Also under Uni Genève leadership is POLAR-2, an international collaboration with institutes from Switzerland, Germany, Poland and China. Uni Genève is further involved in the HERD and eXTP international consortia, which include major institutes from China, Europe, and other international partners.

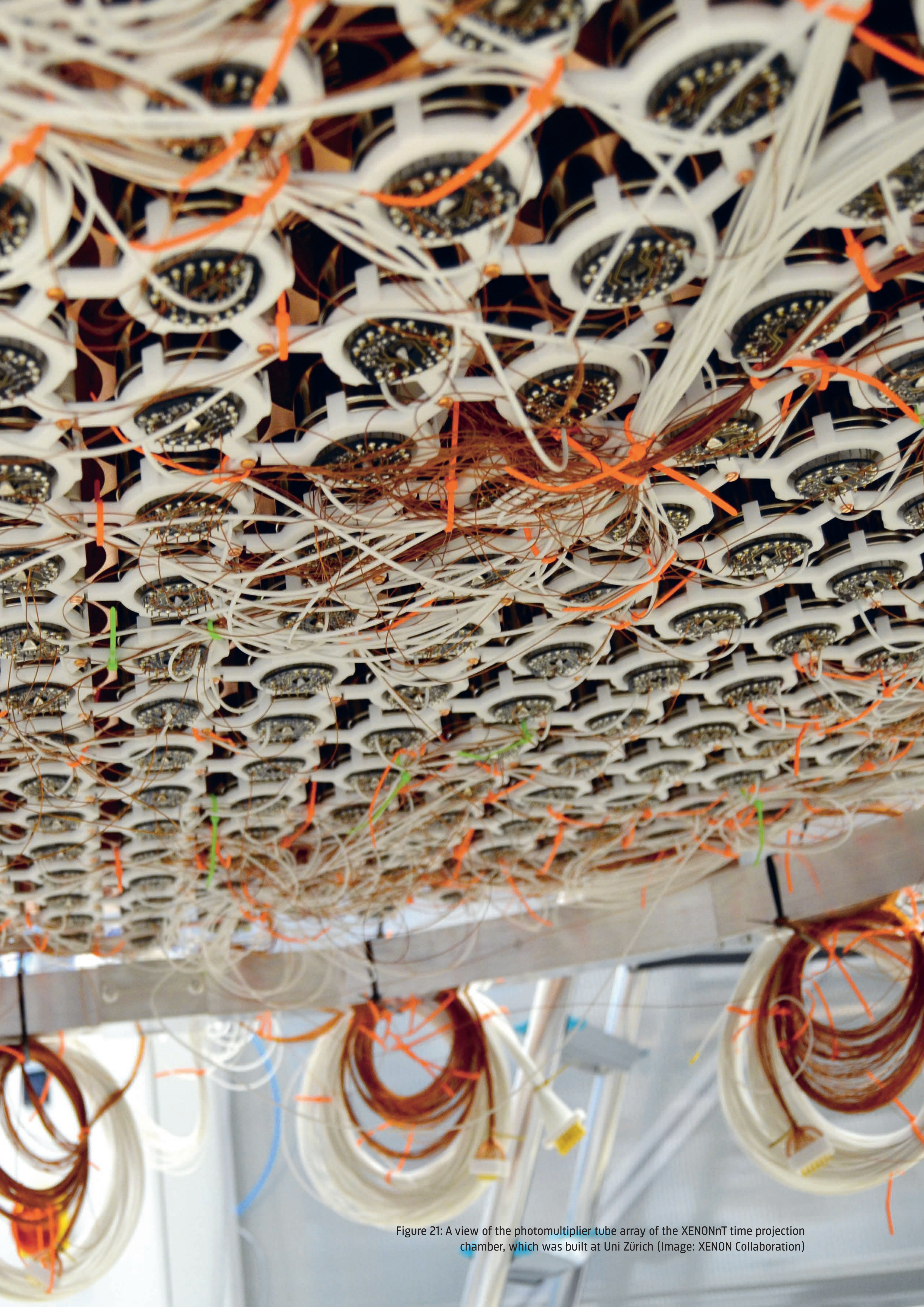


Figure 21: A view of the photomultiplier tube array of the XENONnT time projection chamber, which was built at Uni Zürich (Image: XENON Collaboration)

8 Synergies with other scientific fields

Developments in particle and astroparticle physics naturally provide a solid foundation for synergies with other fields. From instrumentation to large-scale equipment such as accelerators, and from (big) data analysis and computing techniques to theoretical and mathematical tools, particle and astroparticle physics developments find important uses elsewhere. Examples include synergies within the physical sciences, such as in the rapidly emerging field of gravitational waves, as well as in other fields of research, particularly including the medical and bio-medical sectors.

8.1 Interdisciplinary research

Mathematics As is well known, mathematics is the language of physics, and it is used to describe the laws of nature. This is the origin of the long and fruitful relationship between physics and mathematics. Physicists often need mathematical concepts that do not yet exist for their work, which helps to advance research in mathematics. On the other hand, using the adapted mathematical formalism to describe a physical law can make it clearer and render its consequences more transparent, thus mathematics also supports the understanding of physics.

8.1.1 Cosmology and gravitational waves

Astronomy As we have seen in the discussion of theoretical cosmology and astroparticle physics, there is an intimate relation between these physics topics and the more traditional domains of astrophysics and astronomy, which are discussed in the CHAPS roadmap. This link is so strong that several CHIPP members working in theoretical cosmology or astroparticle physics are also actually members of CHAPS, as they participate in the theory groups of some CHAPS experiments such as the Euclid Satellite, the SKA, and the Vera C. Rubin Observatory Large Synoptic Survey Telescope (LSST). In addition, all astroparticle physics experiments (one example of which is CTA) are related to and intertwined with astronomy research due to their usage in interpretations and their importance to multi-messenger studies, where astronomical observatories provide the complementary low-energy photons from radio to UV wavelengths.

Gravitational wave observations The field of gravitational waves (GWs) is emerging as one of the most promising areas of research for the next few decades, for both the CHIPP and CHAPS communities, and is a domain where future significant developments in Switzerland should be envisaged.

The first detection of GWs generated by the coalescence of a black hole (BH) binary system took place in September 2015, as observed by the LIGO/Virgo Collaboration,[21] and was a historic discovery recognised by the Nobel Prize in 2017. Another milestone occurred in 2017, where the coalescence of a neutron star (NS) binary system was detected together with the simultaneous observation of a gamma ray burst by the Fermi-GBM and INTEGRAL Collaborations. This astrophysical source was further studied for months, with observations made in all bands of the electromagnetic spectrum. At the current level of sensitivity, LIGO/Virgo detect approximately one binary black hole (BBH) coalescence per week. These discoveries mark the beginning of a new era for astrophysics, cosmology and fundamental physics, in which GWs are used as a tool to probe the Universe. Many remarkable results in astrophysics and in fundamental physics have already been obtained thanks to these first detections.[3]

Extraordinary as they are, these results are only the first step towards our exploration of the Universe with GWs, and third-generation (3G) detectors (after initial LIGO/Virgo and advanced LIGO/Virgo) are currently under study. In Europe, the Einstein Telescope (ET) is under development. The proposal is for a triangle-shaped GW interferometer, with arms that are 10 km long, to be located 200-300 metres underground in order to reduce seismic noise, and with many remarkable technological improvements. The project has recently been submitted to the European Strategy Forum on Research Infrastructures (ESFRI) Roadmap. In the USA, a 3G detector called Cosmic Explorer (CE) is under study. If approved, the ET and CE will start taking data in the mid 2030s. The ET is conceived as

---

[3] To mention only a few highlights: the observation of the NS-NS binary coalescence GW170817 solved the long-standing problem of the origin of (at least some) short gamma ray bursts; the multi-band observations of the associated kilonova revealed that NS-NS mergers are a site for the formation of some of the heaviest elements through r-process nucleosynthesis; observations of tens of BH-BH coalescences have revealed a previously unknown population of stellar-mass BHs, much heavier than those detected through the observation of X-ray binaries; the speed of GWs has been shown to be the same as the speed of light to about one part in 10^{15}; the first measurements of the Hubble constant with GWs have been obtained; the tail of the waveform of the first observed event, GW150914, showed oscillations consistent with the prediction from General Relativity for the quasi-normal modes of the final BH; and several possible deviations from General Relativity (graviton mass, post-Newtonian coefficients, modified dispersion relations, etc.) have been constrained.

an observatory whose research infrastructure will allow for continuous improvement, leading to an expected lifetime on the order of 50 years, during which it will have a leading position in the field; the ET would have a role comparable to the one the LHC has for particle physics.[4]

The space-based GW interferometer LISA (Laser Interferometer Space Antenna), which, with a planned launch date in 2034 and thus on a similar timescale to ET, will use GWs to explore the Universe in a different frequency band. Ground-based 3G detectors and LISA will be highly complementary as they will provide us with a multi-band picture of the Universe in GWs. LISA was preceded by the very successful LISA-Pathfinder mission, which tested necessary technologies such as drag-free control; following this successful prototype, the development of LISA is now underway, led by the ESA with important contributions from NASA. Similar to LIGO/Virgo and the proposed ET, LISA will also be based upon the use of laser interferometry; it will be built as a constellation of three spacecraft arranged to form an equilateral triangle with sides of 2.5 million km, flying along an Earth-like heliocentric orbit. This unique configuration will allow LISA to detect low-frequency GWs, thus opening up new possibilities for astrophysical studies, including sensitivity to supermassive black holes merging at cosmological distances. LISA is currently in the so-called study Phase A, which will last until the end of 2021, and will then be followed by a study Phase B, set to conclude around 2024, after which mission adoption is expected to occur. If successful, construction will begin and the launch is expected in the mid 2030s.

In Switzerland, several groups have significant experience in the domain of GWs and have made important contributions. Uni Zürich and ETH Zürich joined the LISA-Pathfinder project in 2013, with ETH Zürich, in particular, involved in the development of the Inertial Sensor Front End Electronics (IS FEE) in collaboration with industry, while Uni Zürich was involved in theoretical studies needed for the definition of the LISA mission. Presently, both groups are members of the LISA Collaboration, and Switzerland will further develop the IS FEE in collaboration with Swiss industry. These technical activities are financed by SSO through the Prodex programme, with an approved grant for Phase A. In addition to the technical work, Swiss groups are also involved in studies of future data analysis and scientific exploitation. Both the Uni Zürich and ETH Zürich groups are members of the LISA Board and have important roles in the collaboration. Uni Zürich is also active in several aspects of LISA science, in particular, regarding the formation of supermassive black holes and in the capacity of co-leading the Astrophysics Working Group. The Uni Zürich group is also a member of the LIGO Scientific Collaboration and is, among other activities, leading a working group on eccentric waveform modelling. Uni Genève is a member of the Steering Committee of ET in charge of coordinating the Science Case; Uni Genève theory groups are very well established and have been working in this domain for many years. Additionally, there are researchers in the Astronomy Department of Uni Genève who are members of the LISA Consortium, and who have interests in the Data Processing Group and the Astrophysics Working Group.

8.1.2 Detector technologies, data processing, and computing

Researchers in experimental particle physics have always been very interested in innovative materials, in particular for their usage in novel sensors, which have fostered strong links to the solid state physics and materials science communities. Furthermore, particle and future astroparticle experiments are true pathfinders of science involving big data; the very large datasets produced, processed, and analysed have required the development and implementation of such techniques. Additionally, the computational needs in terms of speed and data storage of these experiments are unparalleled, which have also contributed to the development and advancement of computer science in general. A few illustrative examples of such synergies are given below.

Technology Technology transfer of equipment and know-how as developed for particle physics in other applications is particularly prominent in the context of detector technology and electronics. At PSI, technologies for wire chambers, scintillators, and light read-out have found their way from particle physics to instrumentation used in muon spin rotation and neutron scattering, which are useful for solid state physics and materials science. Cutting-edge Si pixel detector technology for X-ray detectors in light sources and for medical applications has since been commercialised. Chip designs from PSI made for particle physics, originally coming from high-energy physics or photon science developments, have found many other applications both inside and outside of the field, and both on Earth and in space. The DRS chip (Fig. 22), in particular, originally developed for the MEG Experiment, now has a wide range of users and types of uses across the globe. Some software developed at PSI, such as the data acquisition system MIDAS and electronic logbook ELOG, have found a very large and versatile user base.

---

[4] The ET will detect BBH up to redshift $z \sim 20$, corresponding to a distance of about 80% of the radius of the visible Universe (by comparison, advanced LIGO/Virgo will reach about $z \simeq 1$), resulting in the detection of millions of BBH coalescences per year, and 10^5 binary NS coalescences per year, of which several tens/hundreds per year could have an observed electromagnetic counterpart.

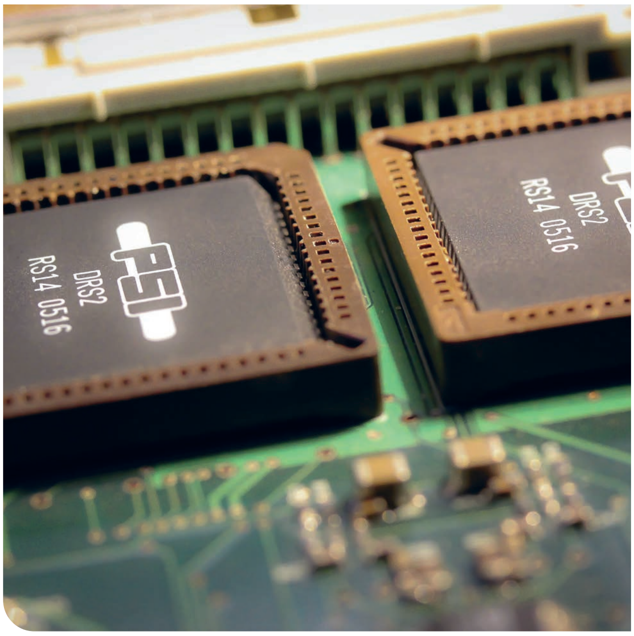


Figure 22: Image of the DRS chip developed at PSI (www.psi.ch/en/drs) (Image: S. Ritt/PSI)

Technology and methodology transfer also works in the other direction, with laser physics and radiochemistry as two examples of fields from which particle physics has benefited. New types of highpower laser systems, as needed for use in precision spectroscopy of exotic atoms, are being developed in close cooperation between particle physics and laser science; these new laser systems are also of interest for commercial applications. Radiochemistry overlaps with low-energy physics in a number of aspects related to nuclear physics, such as the provision of rare isotopes, preparation of radioactive targets, and measurements of the physical properties of certain isotopes. Precision low-energy particle physics experiments are performed at PSI by utilising intense muon beams generated at the HIPA facility. Muons and positrons are also useful for research in materials science, solid state physics, and chemistry. For example, the spins of positive muons can be tracked to give information on local magnetic fields; negative muons allow for non-destructive material analysis techniques with depth information, and the lifetime of positrons in materials can provide information about the electron densities. The use of these techniques generally relies upon the transfer of detection technology and knowledge from low-energy particle and nuclear physics, and thus are examples of where particle physics advances support other branches of research.

The search for DM is inherently multi-disciplinary: it relies on the complementarity of direct-detection, indirect-detection, and DM-production discovery strategies. These different approaches bring together underground laboratories, astrophysical observations, and colliders and beam-dump experiments, which have synergies with each other as well as with fields external to CHIPP such as solid state physics, fluid physics, and astrophysics. DAMIC-M, for example, combines solid state physics (device operation of semiconductors), nuclear physics (the major backgrounds are radioactive isotopes), and particle physics (the main field of research). XENON and its proposed successor DARWIN combine the physics of liquid noble gases with particle physics, nuclear and atomic physics, as well as materials science (particularly for the silicon photomultipliers).

Other fields of physics To understand galactic and extragalactic sources, multi-wavelength data are necessary, covering the full range from radio to optical to X-ray to TeV-level particles. CTA, which is primarily run by the astroparticle physics community, will be sensitive to the γ-ray part of the energy spectrum; this complements the work done by the astronomy and astrophysics communities, while benefiting in turn from their results, thus demonstrating the inherently multi-disciplinary nature of this endeavour. In the near future, multi-messenger astronomy will combine radio and optical observations with high-energy gamma rays, neutrinos, gravitational waves, and cosmic rays. This will enable an understanding of the most energetic astrophysical events/objects beyond their electromagnetic emissions. The interpretation of these data requires a combined modelling effort including most branches of theoretical physics, especially General Relativity, plasma physics, quantum field theory, and statistics.

Space technologies Members of CHIPP are also active in the development of new space technologies. For example, the detection of particles in the range of roughly 100 MeV/nucleon to a few GeV/nucleon in deep space is of critical interest for a broad range of applications in space activities, but such particles have not yet been measured precisely, nor have they been monitored on a long term basis in deep space. Currently Uni Genève is leading an international consortium, funded by the EU H2020 FET-OPEN programme, to develop a demonstrator (Mini.PAN) in three years (2020–2022). The PAN concept, based on a low-mass magnetic spectrometer with a high-precision silicon strip detector, has been presented to several deep space programmes. These include the NASA Artemis project (Lunar Orbiting Platform-Gateway), the ESA European Large Logistic Lander (EL3), and the ESA Voyage 2050 call for ideas (studies of Jupiter's radiation belts).

Computing and big data For the last several decades, modern High-Energy Physics (HEP) has successfully relied on human-engineered features, heuristics, and algorithms. With the LHC and its upcoming HL-LHC upgrade, HEP has entered the era of truly big data. Many improvements are needed in order to exploit fully the scientific potential of the LHC and especially the HL-LHC, including faster simulation of synthetic data, faster data reconstruction algorithms, and a move towards more real-time data analysis in order to alleviate the data storage bottleneck. Modern machine learning can offer solutions to these challenges, while also potentially providing a more efficient approach, with respect to both human and computing resources, in analysing the LHC data and inferring physics knowledge. Examples of places where machine learning techniques can contribute include the identification of physics objects, event classification, measurements of properties of interest through regression, and a more unified approach to searches for BSM physics through the use of anomaly detection techniques. In addition, the LHC's real-world science questions define realistic new benchmarks of relevance for the machine learning community as a whole. The increasing use of approaches from the big data and real-time data analysis communities to address HEP challenges are complemented by modern engineering commodity hardware, such as very fast FPGAs, System-on-Chip (SoC) devices, GPUs, and powerful computing farms.

HEP has very specific computing requirements due to its need to process large volumes of data, thus pushing the use of fast networks, fast processors, and large storage sites. Nonetheless, many synergies with other disciplines can be found in the development of flexible software that can be run on a globally distributed mixture of computing clusters, using different technologies and hardware, as required in HEP to run software on the WLCG.

CTA will be a pathfinder in Switzerland for big data experiments in astroparticle physics. Once in operation, it will produce roughly 20 PByte/year of data. Other astronomy experiments, such as the SKA (see the CHAPS Roadmap), will also enter the big data regime in terms of data processing needs and storage. While each of these experiments will independently result in very large amounts of data, the need to analyse the data from a multi-messenger perspective requires collective databases, where the data from many different experiments are available and can be readily combined, thus further increasing the challenge. The need to combine these datasets suggests the importance of defining a common format, which is a task that some groups are now working on, including EC CLOUD projects (like ASTERICS and now ESCAPE), as well as groups in Switzerland. This effort requires cooperation between astrophysics, cosmology, and astroparticle data centres for the different multi-messenger clients, as well as with the computer science community given the modern analysis tools that are required. For example, Machine Learning algorithms for shower identification and a prototype archive for CTA have been developed as a collaboration between Uni Genève and CSCS.

8.2 Medical applications

Technologies that are developed for particle physics experiments frequently find applications elsewhere, for example in medicine, where the applications of detector R&D are numerous; Positron Emission Tomography (PET) is one particular area where particle physics sensors play a key role. A team from ETH Zürich, in collaboration with scientists and medical doctors at Uni Zürich, the University Hospitals of Zürich and Lausanne, and PSI, is working on a new generation of pre-clinical and clinical PET scanners; these scanners use crystal detector technologies, which are based on developments made for the CMS calorimeter. Teams from Uni Bern and Uni Genève are developing fast silicon sensors to use as the building blocks of a high-granularity Time-Of-Flight PET scanner, based on technology studied for upgrades of the ATLAS detector. This work is being done in close collaboration with the University Hospital in Genève and will ultimately result in a device to be used in combined PET-MRI scanners. Similarly, the scintillating-fibre technology developed by EPFL for the LHCb Experiment is under study for use in beam profile monitoring in stereotactic radiotherapy, in collaboration with the University of Lyon. Groups working on all three LHC collaborations that Switzerland is involved with are therefore actively facilitating the transfer of detector technology to medical applications. Along this line, research on novel radioisotopes for medical diagnostics and therapy (theranostics) is currently being conducted at Uni Bern, PSI and CERN. In particular, a new generation of targets, beam monitoring detectors, and irradiation techniques are being developed to enhance the performance of medical cyclotrons.

Cancer treatment using particle beams from an accelerator is an established concept with strong advantages over X-ray treatments in many cases. PSI in Switzerland originally pioneered the technology of pencil-beam scanning

Figure 23: One of the treatment areas for tumour therapy with protons at PSI (Gantry 3) (Image: PSI)

for precision treatments of deep seated tumours since 1996. In spite of its obvious advantages, this technology is expensive; the treatment gantries with iron-pole electromagnets are large and heavy, leading to mechanics driving the associated costs. Superconducting accelerator magnet technology, which was developed for particle colliders, has the potential to reduce the weight of today's gantries by one order of magnitude (Fig. 23). In addition, a superconducting final bending section could be implemented as an achromatic lens with significant momentum bandwidth, thereby allowing for fast energy scans. The potential use of High-Temperature Superconductors (HTS) could further increase the simplicity and attractiveness of such solutions. Particle therapy will thus benefit from accelerator R&D as performed in the CHART programme, with significant potential for enhancements of the treatment quality, as well as the possibility for large improvements in the size and weight of the required facilities through the use of modern superconducting accelerator magnet technologies.

Many of the multi-messenger astrophysics projects in Switzerland use photosensors, which are of interest to the medical diagnostic community. A FET-OPEN exchange project, named SENSE, has recently been concluded; this effort defined a roadmap towards the creation of sensors optimal for low levels of photons.

The experience gained in constructing photosensors for CTA is also relevant for surgical practices, namely Radio-Guided Surgery (RGS). This practice is revolutionising the surgical management of many malignancies, including breast cancer, melanoma, and colorectal cancer, as well as the surgical management of parathyroid disease. Uni Genève has started a project under the ATTRACT framework, called POSICS, that provides very-high-definition images, thus supporting higher-precision identification of the edges of tumours. The POSICS project aims to prove the feasibility of a hand-held imaging device, which can work as a beta or gamma camera, targeting a large number of medical applications. The project is being carried out in collaboration with the Foundation Bruno Kessler (FBK), which is developing an innovative position-sensitive SiPM for the project.

A group of physicists, engineers, and technicians affiliated with CERN have developed a ventilator to address the needs of COVID-19 patients. The so-called High-Energy Ventilator (HEV) is a high-quality versatile ventilator design that can be produced at low cost. It was developed in full consultation with medical professionals at Hôpital de La Tour à Meyrin in Genève and from the Lausanne and Genève university hospitals. EPFL researchers are members of the HEV Collaboration.

8.3 Accelerator technology and sustainability

High-energy and high-luminosity collider facilities consume a significant amount of electrical energy, which can reach the order of TWh/y. With an increasing fraction of sustainable energy sources in the future European energy mix, such as wind and solar power, the production of energy will fluctuate significantly. One way to mitigate the impact of HEP facilities on the electrical grid is to actively manage their energy consumption; high loads could be avoided during low supply conditions, and excess energy could instead be preferentially used. The possibility of managing energy usage by dynamically operating facilities and utilising energy storage systems are topics of interest in and investigated for industrial applications; it may be possible to identify synergies between such applications and HEP research infrastructures. In addition to potential dynamic approaches, it is also necessary to invest R&D effort into improving the energy efficiency of HEP facilities through critical technologies. In certain areas, such R&D will have an immediate impact on research facilities being operated today, and the savings in energy consumption may be used to co-finance the investments. Certain improved technologies may also serve society or other applications. The R&D fields of interest include optimised magnet design, efficient RF power generation, cryogenics, SRF cavity technology, beam energy recovery, district heating using recovered heat, and energy storage. The use of permanent magnet material replacing electrical coils for accelerator magnets is a promising technology in this context. The ongoing design of SLS2.0 at PSI plans to make extensive use of permanent magnets; through the successful completion of this project, the technology will be refined, thus improving the potential for future applications. Another area of relevance is the development of efficient klystron-based RF sources by improving beam dynamics or through the use of HTS focusing coils.

Accelerator-Driven Subcritical (ADS) reactors can be used to reduce significantly the storage time of radioactive waste from nuclear power stations. In this approach, an accelerator is used to generate a fraction of the neutrons needed to induce the fission of high-level waste incorporated in the subcritical core; such reactors are thus passively safe, as the accelerator must be active to enable the fission process. This application of high-intensity proton accelerators could provide part of the solution to a major problem for public society in Switzerland. The cyclotron-based HIPA at PSI generates 1.4 MW of proton beam power and represents a prototype solution for a driver accelerator. In addition, PSI has performed the pioneering MEGAPIE experiment, in which a liquid metal target was operated with a megawatt class beam. Such target configurations are key elements for any ADS reactor.

9 Relationship to industry

The fields of experimental particle and astroparticle physics have a long-standing tradition of I) very close collaboration with (high-tech) industry and II) pushing technological frontiers, ultimately resulting in innovations that are successfully transferred to the private sector and industry. These frontiers are typically related to leading-edge nuclear and particle physics instrumentation, developed for and installed in small- and large-scale detectors, as well as particle accelerator technology. In all of these areas, Switzerland is particularly well placed, thanks to a) its hosting of a considerable number of national and international high-tech companies, b) the fertile grounds and resources available for founding spin-off companies, and c) the substantial support given by the Swiss academic institutions and its national lab (PSI) to those researchers who are interested in the technology transfer of their ideas, developments, and inventions.

The following list is non-comprehensive; rather it gives examples that are intended to provide a glimpse of the rich spectrum of technology transfer activities, spin-off companies, and other relations to industry that exist in the Swiss particle and astroparticle physics landscape.

9.1 Examples of spin-off companies

Spin-off companies founded by Swiss researchers in recent years typically have origins linked to novel particle detector techniques and their related data acquisition systems, such as silicon-based pixel detectors, scintillating crystals or other materials, photosensors (most notably, silicon photomultipliers in recent times), or dedicated Application-Specific Integrated Circuits (ASICs) as front-end readout elements of such detectors. In addition, familiarity with and knowledge of the usage and control of particle beams from accelerators turns out to be highly valuable in a number of applications. A particularly targeted sector is the 'med-tech' field, with a focus on biomedical imaging; the fields of (homeland) security and the handling of nuclear waste are also of relevance. A few examples of such spin-off companies are briefly described in the alphabetically ordered list below:

- *Advanced Accelerator Technologies AG (AAT)* is a joint venture of leading global industrial suppliers for research and high-tech enterprise equipment, and a commercialising and licensing partner to PSI. Its main mission is the commercialisation of PSI intellectual property in accelerator technologies and applications, with the objective of creating value beyond the shareholders' individual expertise. Examples of activities include accelerator component and system design and construction, proton therapy instrumentation and services, compact accelerators including synchrotron sources spanning various energies, neutron instrumentation, and services and consulting.

- *Arktis Radiation Detectors Ltd* (Fig. 24), which was co-founded by ETH Zürich Prof. A. Rubbia and former ETH Zürich PhD students R. Chandra and G. Davatz, was built on expertise related to the detection of neutrons and high-energy photons, and addresses the challenge of detecting radiological and nuclear materials that pose a threat to the customer's safety and security. Arktis develops next-generation systems that categorise, prevent, and intercept radiological and nuclear materials, in addition to contaminated cargo.

- *Dectris* was established by former students of Prof. R. Horisberger (PSI) in 2006, thanks to their expertise in silicon pixel detector technology, and has grown from an initial four people to a current total of approximately 130 employees. Its main products are 1D and 2D hybrid photon detectors for scientific, industrial, and medical applications. Products include the Pilatus pixel detector, the Mythen strip detectors, a new fast pixel detector with a 3kHz frame rate (Eiger), and a high-Z detector for higher-energy X-rays. While initially the company's main focus was related to X-ray imaging at synchrotron facilities, such as for protein crystallography, over time the product range has expanded to other imaging applications in the medical industry (notably Human CT and Mammography).

- *Positrigo AG* was co-founded by Prof. G. Dissertori and Dr. W. Lustermann (ETH Zürich), together with former ETH Zürich PhD students (Dr. M. Ahnen and Dr. J. Fischer) and colleagues from the University of Zürich (Prof. B. Weber) and the University Hospital Zürich (Prof. A. Buck). Building on their expertise in scintillating crystals and silicon photomultipliers, which are key components of PET scanners, and on previous experience with the development of a pre-clinical PET scanner, the company is working towards the development of a cost-effective and versatile brain PET scanner for the early diagnosis and treatment follow-up of Alzheimer's disease. In addition to an ETH pioneer fellowship and a donation through the ETH foundation, the initial setup of this effort was supported by a dedicated Innosuisse grant.

- *RADEC GmbH,* which was founded in 2017, performs tests on existing electronic components and materials to quantify their degree of radiation hardness; they use particles generated at accelerators located at PSI or other facilities in order to do this. The company also offers advice and assistance in the development and construction of radiation-hard components and systems. RADEC GmbH collaborates with companies involved in creating technologies for space (e.g. ARC POWER GmbH, Kramert GmbH, Teledyne (E2V)), as well as companies developing terrestrial technology, where potential failures due to radiation must be eliminated.

- *SENSIRION* is one of the most successful ETH Zürich spin-off companies, being the world's leading manufacturer of digital micro-sensors and -systems. The product range includes gas and liquid flow sensors, as well as differential pressure and environmental sensors, for the measurement of humidity, temperature, volatile organic compounds, carbon dioxide, and particulate matter. One of its founders (Dr. M. Lechner) was an ETH Zürich PhD student of Prof. R. Eichler, collaborating with Prof. R. Horisberger at PSI on the chip design of the silicon tracker for the H1 Experiment at DESY.

- *SE2S GmbH,* Space Environment Systems and Services was founded in 2020 by PSI researchers and based on over 30 years of experience in radiation qualification, particle detection, and data analysis. The company offers next-generation services and products in radiation effects and qualification (e.g. radiation modelling and assessment of radiation effects), detection of particles and radiation (e.g. novel detector technologies, equipment, and software), and space weather services (e.g. space weather and radiation modelling, analysis of space weather data, and impact assessment and risk prediction).

- *SWAN Isotopen AG* was founded in 2008 by the Bern University Hospital (Inselspital) and the University of Bern in order to establish a combined centre for commercial radioisotope production for nuclear medicine applications and multi-disciplinary academic research. This innovative facility is based on an 18 MeV medical cyclotron and a research beam line (Fig. 25). It has been operational since 2013, an achievement that was possible thanks to strong collaboration with the Laboratory for High-Energy Physics (LHEP) of the Uni Bern. SWAN Isotopen AG now has more than 20 employees and a portfolio of four PET radiotracers and one radiopharmaceutical drug for cancer therapy. It is presently collaborating with Prof. S. Braccini from LHEP in the search for new radiolabeled bio-molecules for theragnostics.

- *Transmutex SA* is a Swiss company founded in 2019 by a team of present and former scientists, mostly linked to CERN, with Prof. em. M. Bourquin (Uni Genève) as a

Figure 24: A Radiation Portal Monitor that screens passing pedestrians and their luggage for illicit radioactive sources, developed by Arktis Radiation Detectors Ltd, a spin-off from particle physics research at ETH Zürich. Swiss authorities use systems like this for spot checks at airports (www.arktis-detectors.com) (Image: R. Chandra/Arktis)

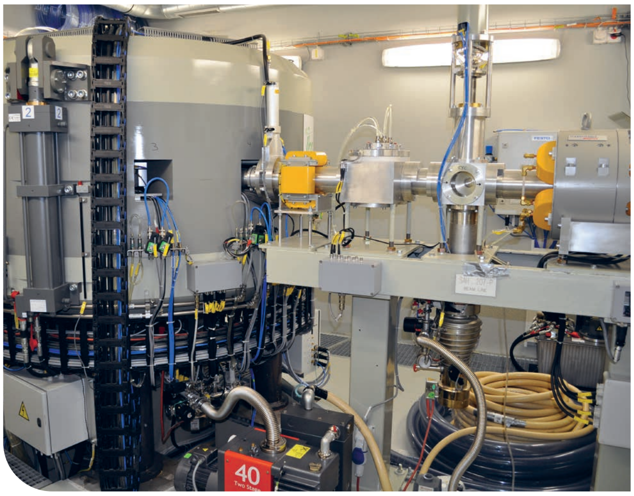


Figure 25: The medical cyclotron by SWAN Isotopen AG in operation at the Uni Bern hospital, Inselspital, with its unique beam transfer line for research, including medical applications of particle physics techniques (Image: S. Braccini/Uni Bern)

member of its Scientific Board. The company is developing the concept of Accelerator-Driven Systems (ADS), invented by Prof. C. Rubbia to solve the issue of long-lived nuclear waste, based on key experiments performed at CERN and at PSI, which have validated the idea. The recent substantial advances in particle accelerators (notably high-power cyclotron technology) and computing power (including simulation tools) have helped to build confidence in the ADS concept of being ready for industrial development. Interestingly, in the recent *Energiebericht*[5] of SERI, a report by Prof. Bourquin on thorium ADS has been included. As a consequence, SERI now recommends that Switzerland should engage in such research.

9.2 Contacts and collaborations with industry

Besides the obvious contacts of Swiss researchers with spin-off companies based on their own research and/or which they have co-founded, our field profits from a very extensive portfolio of contacts and collaborations with small-, medium- and large-scale national or international companies, typically working in the high-tech sector. The usual trigger for such collaborations arises from the need to push technology beyond its current boundaries, such as when new detectors or accelerator components are under development for specific research applications; the detectors of the CERN LHC experiments are prime examples, but are not the only ones. The scope of such collaborations is multi-faceted, ranging from simple orders of equipment based on the researcher's own in-house developments to joint prototyping and/or large-scale production efforts, as well as joint ventures towards transferring and/or licensing and future commercialisation of intellectual property by industry. A typical approach is the development of tooling and testing equipment by researchers in order to enable the companies to determine and improve their production tolerances. As an example, in the context of the CO_2 cooling system for the upgrade of the CMS pixel detector, researchers from Uni Zürich have worked with Swiss industry to develop tooling for aligning components to be welded. A Uni Zürich scientist has developed a testing setup for the company in order to pressure-test welded stainless steel pipes, thus enabling the company to reach the standards required by the experiment. By maintaining strong relationships with these companies, the scientists involved have been able to convince the companies to do further R&D work with titanium pipes to see if a reliable and lighter-weight system can be produced. As a consequence, the companies are now interested in exploring this R&D for other future contracts with industry, as well as other interested partners at CERN. This example is not an isolated occurrence, and it shows how industry not only profits commercially from orders received from our field, but more importantly, how the companies' internal expertise, quality management, and product portfolio can be enhanced, thanks to the close interactions with demanding customers, namely particle physicists. A few further examples of such collaborations are given in the non-exhaustive list below.

- *ESPROS photonics corporation – EPC:* Researchers at Uni Zürich, ETH Zürich, and PSI, who lead the initial construction and upgrade of the CMS pixel detector, collaborate with this high-tech company located in Sargans (SG). This medium-scale company with approximately 50 employees specialises in Integrated Circuits design and production. In particular, the Swiss researchers collaborate with EPC on the design of Monolithic Active Pixel Sensors (MAPS) for future applications, using the company's special CMOS technology.

- In the context of the aforementioned upgrade of the CMS pixel detector, especially related to the development and construction of the so-called supply tube and the cooling system, Uni Zürich scientists have collaborated with a long list of Swiss companies (a few examples of which are MEDELEC SA, Createch AG, Spalinger Präzisionsmechanik GmbH, and Bolleter Composites AG). These collaborations involve the production of thin-wall precision tubes made of stainless steel and titanium, the bending and precision cutting of such tubes and related laser welding, and the production of

---

[5] https://www.sbfi.admin.ch/sbfi/en/home/services/publications/data-base-publications/report-energy-research.html

carbon-fibre-based and foam-core-based support structures, as well as complex plastic parts.

- The Laboratory for High-Energy Physics (LHEP, Uni Bern) collaborates with the Canadian company D-Pace on the development of accelerator and detector technologies for medical applications. The Universal Beam Monitoring detector (UniBEaM) is a beam profiler based on doped optical fibres passed through the beam. Developed at LHEP, it was commercialised under license by D-Pace. More than ten UniBEaM detectors are now in use in research centres worldwide. Furthermore, LHEP and D-Pace are collaborating on the development of a compact active irradiation system for non-conventional medical radioisotope production.

- Researchers at PSI have developed the so-called DRS4 readout chip (Fig. 22) for the MEG Experiment, which they sell through PSI's technology transfer programme. So far, this has already resulted in more than 200 international companies and institutes as customers. As an example, the Italian company CAEN SpA (specialised in High/Low Voltage Power Supply systems and Front-End/Data Acquisition modules) has a product using the DRS4 chip. The PSI group is currently in discussion with a start-up company (RADEC) to outsource the chip distribution.

- CAEN SpA, mentioned above, is also a partner of choice for many other particle physics experiments. Swiss scientists have numerous commercial contacts and joint developments with this company.

- In the context of the aforementioned PET scanner developments at ETH Zürich, close contacts for the production of silicon photomultipliers (photosensors) have been established with the Japanese company Hamamatsu, and with the Chinese company Sichuan Tianle Photonics Co. for the delivery of scintillating crystals made of LYSO. Hamamatsu will also be the main supplier of silicon strip and pixel detector modules for the major upgrades of the ATLAS and CMS tracking detectors.

- During the first construction of the CMS Experiment, important collaborations and major industrial contracts were established with Swiss industry, in particular for the construction of the CMS superconducting magnet cables (Kabelwerke Brugg AG and Nexans) and the large-scale manufacturing of printed circuit boards (ASCOM Systec AG).

- A strong cooperation has been developed between the CTA project and the Swiss coating industry, namely with Thin Film Physics close to Zürich, in order to develop light-guides for sensors and the coated entrance window of cameras. These developments were also transferred to Chinese collaborators in the LHAASO project, who also procured materials from this Swiss company. The hardware development of the SST telescopes of CTA by Uni Genève and of the actuators by Uni Zürich led to cooperation with the mechanical and electronics industries. For example, Uni Genève worked with HABA on raw materials, mechanics, and cooling developments and with SURCOTEC on coating for electrical surface conductivity. The CTA project has also cooperated with the consulting company DAES on system engineering issues.

- In general, large accelerator-driven research facilities, such as PSI or CERN, give rise to a substantial number of close collaborations and joint ventures with industry, combined with technology transfer. Here, we mention only a few examples, related to a) the (co-)development of components (AMPEGON Power Electronics, Daetwyler Industries, Cosylab, SCS-Super Computing Systems, Ferrovac GmbH, VDL, etc.), b) imaging and analytics (Anaxam, ABB, Roche, GE-General Electric, Novartis, Nestlé, BASF, etc.), c) medical technology such as proton therapy and medical imaging (Varian), and d) business development (SwissNeutronics, InterAx, GratXRay, Eulitha, etc., plus Dectris and AAT as mentioned earlier).

9.3 Future opportunities

In addition to the aforementioned, existing spin-off companies and collaborations with industry, ongoing R&D in the fields of particle and astroparticle physics carries substantial potential for industrial applications. As an example from astroparticle physics, direct DM detection experiments rely on the development of many challenging materials and associated technologies. For example, liquid Noble gas detectors drive the development of materials with extremely low levels of radioactivity and low radon emission, as well as low-noise Vacuum UltraViolet (VUV)-sensitive silicon photomultipliers (and other photosensors) for operation in liquid xenon detectors. Direct DM experiments also drive the development of low-noise, low-radioactivity electronics that work at cryogenic temperatures. Similarly, extremely low-energy-threshold detectors may find a use commercially measuring extremely small interaction processes.

Besides the enabling support given by local technology transfer offices at Swiss Universities and PSI, it is worth mentioning that CERN has successfully proposed that the European Commission (EC) launch the ATTRACT (breAkThrough innovaTion pRogrAmme for a Pan-European detection and imaging eCosysTem) funding programme. This is an initiative bringing together Europe's fundamental research and industrial communities to lead the next generation of detection and imaging technologies. From a first call in 2019, 170 projects have been selected out of 1200 proposals, with 19 successful proposals involving CERN scientists. These proposals target applications in a diverse range of fields, from medical imaging and treatment to the aerospace sector. Others seek industrial applications, such as high-tech 3D printing of systems equipped with sensors, the inspection of operating cryostats, and applications in environmental monitoring.

The potential for a major breakthrough with significant industrial ramifications should not be discounted, especially given the history of such developments in the field. The recently announced *Quantum Technology Initiative* at CERN, which foresees close collaboration with national and international research groups and industrial partners, promises great potential for future breakthrough technologies. Significant efforts are currently being invested in the development of novel software and computing approaches, typically based on machine learning and novel processing unit architectures, in order to tackle the computing challenges of the HL-LHC operations; these activities could potentially lead to a breakthrough. The upcoming feasibility studies towards a future collider project at CERN, with a focus on accelerator technologies, may also lead to (potentially disruptive) innovations.

In conclusion, research in particle physics instrumentation and accelerators has proven to be a very fertile environment, and will continue to be so in the near and far future. This results in win-win collaborations between academia and industry, with Swiss companies playing a particularly relevant role.

10 Impact on education and society

Any new large-scale project in particle and astroparticle physics will require concerted efforts in global education, outreach, and communication; it is necessary to have a strong and committed dialogue with the public and stakeholders, as well as to adequately educate pupils and students of all ages. Scientific outreach fulfils important and necessary obligations to society. Outreach activities involve the direct participation of scientists active in current research in particle and astroparticle physics in order to improve public understanding of our field and appreciation of the benefits of fundamental research, to raise interest and enthusiasm among young people, and to strengthen the integration of science in society.

As the number of scientists engaged in outreach increases, so does the variety and ingenuity of their efforts, as reflected in the wide selection of activities. Research laboratories, experiments, universities, and institutes offer a wide selection of outreach activities, ranging from Public Lectures to YouTube videos, and lab tours to Science Nights. Travelling and standing exhibitions attract broad audiences, while specific communities are targeted by organising events at schools, universities, museums, and science cafes to raise interest and widen scientific understanding. Many universities and dedicated outreach centres offer projects primarily aimed at high-school students and teachers. Such activities range from training teachers in the field to helping high-school students create their own particle physics experiments, and giving high-school students the opportunity to visit real experiments during laboratory tours. Often, as a result of these efforts, young students become more inclined to choose STEM-related subjects for their future careers, and they may even go on to join the next generation of particle physicists. What is most important, however, is the fact that they will be more educated about and appreciative of the importance of research, and thus more suited to make informed decisions about science and scientific questions in their future.

The success of particle physics research in Switzerland is largely a result of the highly qualified and innovative scientific and technical teams within Swiss institutes. All institutes in Switzerland, therefore take great efforts to provide excellent education in particle and astroparticle physics at all levels.

10.1 Education

The purpose of this section is to discuss briefly the structure of particle physics education in Switzerland as offered by universities, with a focus on students studying physics as a major. Education provided in high schools and universities of applied sciences are briefly discussed.

The success of particle physics research in Switzerland largely results from the highly qualified and innovative scientific and technical teams within Swiss institutes. To maintain such a high level of excellence, the best and most highly motivated students must be attracted to the field; an education in particle physics is thus mandatory in all undergraduate physics curricula.

Table 5 summarises the number of students and postdocs in particle, astroparticle, and nuclear physics in Switzerland over past years, in comparison to the number of Bachelor students in Physics.

Table 5: The number of Bachelor students in physics programmes at Swiss universities, as well as the number of Master's and PhD students and Postdocs in particle, astroparticle, and nuclear physics.

Year	Bachelor	Master	PhD	PostDoc
2016	1445	28	167	95
2017	1540	44	172	92
2018	1505	41	180	103
2019	1608	43	166	91
2020	N/A	43	136	95

10.1.1 Bachelor and Master

At Swiss universities, general courses on nuclear and particle physics are commonly included in the final year of the Bachelor's programmes. Some of these modules are accompanied by advanced student experiments at PSI or laboratories at the respective institute.[6]

Most Swiss universities offer Master's programmes with a strong focus on particle or astroparticle physics. Some of these programmes are clearly structured and are targeted towards a specialisation in a chosen topic, while others

---

[6] There are a few specialised Bachelor's programmes in physics for which an option with strong emphasis on nanoscience and technology or an option with an extended minor can be chosen. These curricula include nuclear and particle physics only as an elective or core elective modules.

encourage breadth but allow specialisation if the student so wishes. ETH Zürich offers a unique and very attractive joint Master's degree in High-Energy Physics, together with the École Polytechnique (Institut Polytechnique de Paris – IP Paris), which prepares excellent students for a future research career in High-Energy Physics. The two-year Master's programme is set up symmetrically between the two universities: students spend one year in Zürich and one year in Paris. ETH Zürich and EPFL offer a joint Master's programme in nuclear engineering, where students spend the first semester at EPFL, the second semester at ETH Zürich, and the second year at PSI.

EPFL and ETH Zürich offer courses in accelerator physics. Due to close ties with PSI, CERN, and the complementarity of the activities at these institutions, research projects for Bachelor's, Master's, and PhD students cover a diverse range of topics and also take place at CERN and PSI.

10.1.2 PhD

The formation and guidance of PhD students in Switzerland is performed within the respective research groups, involving the continuous daily efforts of professors, postdocs, and senior researchers. The continuous exchange with national and international collaborators in the context of specific projects and working groups also plays an important role in the students' intellectual development. CHIPP has initiated a specialised education programme in particle physics, open to PhD students all over Switzerland, with the CHIPP Winter School and Zuoz Summer School, both of which are organised bi-annually. The purpose of these schools is to learn about recent advances in particle physics from a mixture of local and world-leading researchers; Swiss PhD students are expected to participate in at least one such school during their PhD studies. The programme includes lectures on accelerator and non-accelerator particle physics from an experimental and phenomenological perspective, based on the activities of the Swiss institutes involved in particle and astroparticle physics. Further education of the students is guaranteed and supported by their institutes through specialised schools regularly offered by CERN, Fermilab, DESY, and other institutions.

10.1.3 High school

Education in the field of particle and astroparticle physics at high schools helps students to understand the structure of matter, and allows for discussion of the fundamental concepts of quantum mechanics and special relativity along with their applications, such as the photo-electric effect, Compton scattering, X-rays, and CO_2 absorption spectra. Furthermore, with the SM of particle physics at hand, Big Bang cosmology can be discussed from a conceptual viewpoint.

Scientists of all institutes support teachers and educate students by going into classes or offering directed courses at their institutes as stand-alone events or in the framework of TecDays or technology and IT weeks as outlined below. Currently, particle physics is not part of the physics curriculum at high schools in Switzerland. We would strongly support the inclusion of basic concepts in the curriculum, namely the constituents of matter and the fundamental interactions, in order to foster interest in modern research and concepts in physics.

10.1.4 Universities of Applied Sciences

CHIPP members also offer continuous education in radiation protection at universities of applied sciences for Bachelor's and Master's students in medical technology.

10.2 Outreach activities in Switzerland

Current efforts in particle physics outreach in Switzerland raise awareness, appreciation, and understanding of the field and its current state of research. The different outreach activities address diverse audiences and different venues, ranging from traditional ones such as schools, science festivals, and museums to less traditional activities including YouTube videos, science slams, bars, and music festivals. Audiences include primary- and secondary-school pupils, teachers, journalists and communicators, key stakeholders and policy makers, as well as the general public. The outreach activities of all institutes and universities are aimed at fostering a broad and long term impact, and make use of current research in order to raise and maintain the interest of the audience. Furthermore, these activities emphasise the underlying nature of the scientific process, the strength of fundamental research, and the key role that scientific research plays in society.

It is important that outreach activities involve audiences beyond those that are already scientifically educated and supportive. The goal of such outreach to more distant audiences is to strengthen public trust in science and its method of evidence-based decision-making in order to offer future generations a meaningful base that generates supportive structure in their lives.

Outreach activities within CHIPP are intended to inform the political platform and the general public, but also to target specifically the next generation of potential physicists and high-school students. In the view of

Figure 26: An ATLAS detector construction hall, transformed into a detector component exhibition during CERN Open Days in 2019 (Image: S. Mehlhase/ATLAS Experiment)

the Swiss particle physics community, the primary aim of such outreach is to convey the importance, excitement, and fantasy of basic physics, together with recent developments in particle and astroparticle physics to young secondary-school students. In this process, the importance of having a sound mathematical background is conveyed, as physics is, by definition, a mathematical description of fundamental phenomena. By convincing the audience of the importance of fundamental research in general, and particle physics in particular, these outreach activities are of benefit to all STEM-related subjects and to fundamental research as a whole.

The following examples outline a few of the key outreach activities aimed at the general public and high-school students, which have been conducted over the past years.

– Visits to CERN: As the centre of high-energy research, CERN is an extremely attractive destination for visits, which are organised regularly by CHIPP members. In recent years, about 50 visits per year have been organised for university students in physics and other disciplines, high-school students, alumni, politicians, members of associations, media, and the general public at large. Swiss scientists were significantly engaged in the CERN Open Days event in 2019 (Fig. 26), which hosted about 70,000 visitors from Switzerland and abroad.

– Talks to industry, high schools, and the general public: Many CHIPP members, from all CHIPP institutes, actively participate in giving talks to the general public and other open audiences. These talks are typically given in addition to the regular public talks organised by their host institutes.

– Teacher education: The CHIPP community collaborates with secondary-school teachers in the development of innovative and interesting physics demonstrations, sometimes using particle physics data. Secondary-school teachers are supported and educated by providing teaching material, via the CERN Teacher programme, and by holding specific topical workshops, as well as open days for teachers at our institutes.

– YouTube video ‘How particle physics works: hopes and worries on the *B*-physics anomalies’: This short movie illustrates how experimental and theoretical physicists at Uni Zürich work together to understand recent puzzling results in *B*-physics that have been reported by the LHCb Experiment.

- UNSOLVeD, funded by Agora: This platform contains ten videos addressing open questions in physics, from quantum field theory to dark matter. These videos are used to create a dialogue with non-scientists, and are particularly targeted at high-school students.

- Swiss physicists in dialogue with society (Interactions/das verflixte Higgs funded by SCNAT, Agora and SERI): This project launched an interdisciplinary dialogue with representatives from other disciplines, such as sociology, theology, philosophy, writers, and politicians. This dialogue was supported through posting content on YouTube, in the form of portraits, interviews, short films, and discussions. Additionally, in-person dialogues took place in the form of articles in newspapers, events in schools, and discussions with the general public in a variety of places, such as museums, industrial centres, and at screenings of the film Particle Fever.

- Exhibits: A multidisciplinary Art & Science exhibition on the discovery of cosmic rays took place at the Espace Ballon in Château-d'Oex, featuring the Swiss physicist Albert Gockel from Fribourg, who established the first hints for such phenomena in his balloon flights over a century ago. Experiments carried out at high altitudes, in balloons, aeroplanes, and in high mountain stations, such as the Jungfraujoch and Gornergrat research stations, allowed researchers to detect radioactivity in the atmosphere and to conclude on the existence of cosmic radiation.

- Scientifica – the Zürich Science Days: This bi-annual event typically attracts more than 25,000 visitors. Particle and astroparticle physicists of Uni Zürich and ETH Zürich regularly contribute with topical talks and booths. In 2019 for example, the general topic of the Scientifica 'Science fiction – Science facts' was perfectly suited to the discussion of antimatter and dark matter with the general public. In 2017, the discovery of the Higgs boson was discussed in the overall context of 'What data reveal'. Similar bi-annual events took place at 'Nacht der Forschung' in Bern, with about 10,000 visitors, and 'Nuits de la Science' in Genève and EPFL, with about 30,000 visitors.

- Dark Matter Day: During the last few years, the world has celebrated the hunt for dark matter at the end of October. Swiss institutes regularly contribute by organising local events, during which they highlight the experiments that could deepen our understanding of the mystery of dark matter.

- Medical Application of particle physics: Uni Bern and PSI feature outreach projects on accelerator physics; they also offer courses on radiation protection for industry, which is one of the examples of synergies between industry and academia.

- CERN's Science Gateway project: This project foresees the construction of an education and outreach facility at CERN, featuring exhibitions and hands-on educational activities. It will enable people of all ages and backgrounds to engage in the science and technologies of CERN, thereby sharing the passion for knowledge and research.

Specialised school labs, together with lectures and workshops for school classes, play a key role in attracting young students to study STEM-related subjects. There are several dedicated laboratories at CHIPP institutes, which offer special courses in cosmology, as well as particle, astroparticle, and neutrino physics for school classes targeting young students of different age groups. With hands-on experiments, laboratory visits, and by meeting Bachelor's and Master's students, the school classes are put in contact with state-of-the-art research and passionate researchers. Examples include Physiscope at Uni Genève, Science Lab at Uni Zürich, and iLab at PSI.

10.2.1 International outreach networks

The International Particle Physics Outreach Group (IPPOG[7]) is tasked with the mission of maximising the impact of education and outreach efforts related to particle physics, and is an excellent example of how outreach can be done as a collaborative effort. Since 2016, IPPOG has been an international collaboration formed of scientists with experience in research, education, and outreach. The collaboration members represent 28 countries, six experiments, and two international laboratories. IPPOG provides a network of scientists, science educators, and communication specialists working across the globe, sharing knowledge and providing tools for outreach in particle physics and related fields, such as astroparticle physics, neutrino physics, radiation treatment, and gravitational waves. Prof. H.P. Beck (Uni Bern) served as IPPOG co-chair from 2013 to 2019, and was the driving force behind transforming the IPPOG into a scientific collaboration.

The European Particle Physics Communication Network (EPPCN[7]) was established by the CERN Council in 2005, following the approval of the European strategy for particle physics. It is a network of professional communication officers from each member and associated state with the

---

[7] Switzerland, via CHIPP, SCNAT, and SERI, is a member in these networks and pays associated fees.

mandate of supporting and strengthening communication between CERN and the member states.

APPEC is a consortium of 19 funding agencies, national government institutions, and institutes from 17 European countries, and is responsible for coordinating and funding national research efforts in astroparticle physics. In collaboration with IPPOG, APPEC encourages and supports outreach and education activities, particularly astroparticle physics summer schools and studentships.

The CHIPP community also benefits from material provided by and discussed with communities in other countries, such as ‘Netzwerk Teilchenwelt’, which is a network of researchers and communicators in particle physics, astroparticle physics, and hadron and nuclear physics in Germany; another example is e-Péron (Plateforme Educative sur les Rayons cosmiques et les muONs), a platform for education on cosmic rays in France.

Figure 27: Impression from the masterclass at EPFL during the video conference with CERN (Image: EPFL)

10.3 Support of young talents

Particle physics is a field that both fascinates and attracts high-school and university students; the research field is, therefore, very well suited to attract interested and talented high-school students to study physics, and later to motivate excellent students to continue into a career in research. Several activities for different ages are already in place, and others will be developed in the next few years.

The following presents a brief summary of the different activities currently used to attract young and talented students to our field of research:

- International Particle Physics Masterclass programme for high-school students: This international one-day programme targets high-school students who are very interested in physics and especially particle physics.[8] After an introduction to the concepts of the SM of particle physics, particle detection, and particle measurement techniques, the students learn how to perform a simple data analysis through hands-on experiments and interaction with physicists at CERN. In Switzerland, the various masterclass events typically attract about 200 students each year. Figure 27 gives an impression of students interacting with scientists at CERN, along with other high-school students from around the world during a masterclass event held at EPFL;
- High-School Student Internship Programme at CERN (HSSIP): This new programme, for which 2021 will be the first instance, provides a two-week internship at CERN for 24 high-school students from Switzerland. More than 60 excellent applications of extremely motivated students were received, which made the selection of the final candidates a challenging task;
- Individual coaching for high-school students, such as an internship or support with the matura thesis;
- Internships for students in physics or related fields within our research groups;
- CERN summer student programme: Students pursuing Bachelor’s or Master’s degrees in physics, computing, engineering, or mathematics are eligible to participate in this programme, where successful applicants attend lectures and perform their own research projects at CERN during eight to thirteen weeks. As this is an international project with more than 3,000 student applications for the 340 places available each year, competition is high and only well-prepared applications from extremely motivated students are successful;

---

[8] This programme is organised by IPPOG and is offered worldwide over a period of about eight weeks. The 2019 edition hosted 14,000 students from schools located in 54 countries.

- Mentoring of PhD students and Early Postdocs in the LHC collaborations (ALICE, ATLAS, CMS and LHCb): All of the LHC collaborations have created early-career offices that organise training sessions and activities for newcomers, in addition to providing help and advice in the early-career stages of young scientists. Senior scientists from the Swiss universities actively support these early-career efforts, including by acting as mentors.

CHIPP efforts in support of young talents will be further enhanced in the coming years in order to strongly motivate, support, and strengthen the next generation of young scientists that choose to engage in the particle physics community. This will be done by offering a platform within CHIPP, which will be designed to connect young scientists.

10.4 Service to society

Fundamental research in particle, astroparticle, and neutrino physics serves both the Swiss and global societies in various ways.

Since ancient times, human progress has been driven by curiosity; the search for meaning and understanding of the Universe, as well as the structures and phenomena on Earth, are timeless questions. This quest for answers pushes the development of new methods and technologies, as well as intellectual innovation, and is a driving force for humanity to develop science as a global endeavour. Therefore, basic research is a fundamental need of humanity; like music or arts in general, science is a part of our culture.

The international nature of particle physics research has led to democratic management structures in the large international collaborations, and fostered the culture of global collaboration that supports the sharing of innovative ideas with competing experiments. This competitive, yet collaborative, spirit is a shining example of how the global society can act together when facing urgent global threats like climate change, limited fresh water supplies, electricity production, non-proliferation of nuclear weapons, and more. By demonstrating that such an approach is both possible and productive, there is a realistic chance of creating a worldwide collaborative spirit when facing overarching needs and challenges.

Scientific achievements in particle, astroparticle, and neutrino physics push the frontiers of technology, which have a positive impact on global society. Although the core mission of the institutes involved is fundamental research, they also have a remit to train the next generation of scientists and to bring scientists and technicians together, across political and religious borders, to work in a collaborative spirit towards a common goal. Only about 10% of the PhD students educated in our institutes stay in academia; the other students bring their knowledge and skills, as well as the collaborative spirit that they have acquired during their education, to industry, politics, and non-governmental organisations.

Fundamental science further benefits society by training people in the knowledge-acquisition process: how do we acquire, test, and trust the knowledge that we have gained? It is important for a well-educated society to understand that fundamental research requires scrutinising findings and underlying models, both of which need to be tested at all relevant scales (often in terms of energy and intensity in the particle physics context) in order to gain knowledge.

Particle physics has traditionally been a driving force for new technical developments in medicine, such as PET or cancer therapy with particle beams; while these are two well-known examples, there are now many more medical applications making use of photons, electrons, protons, heavy ions, and even antiprotons. Additionally, detectors that were developed to measure charged particles in high-energy experiments are, nowadays, used for precise positioning in medical imaging applications. This cross-talk extends also into the realm of computing: many tools and software applications are, in fact, very similar in particle physics and medical applications. Detector R&D is continuously progressing within particle physics in order to continue to meet the ever-increasing demands for faster, more precise detectors, which also must be radiation hard both in terms of the hardware itself and the readout electronics. As this research continues and detector capabilities continue to increase, it is expected that these developments will continue to have a significant impact on other fields, such as medicine, materials science, and space science.

10.5 CERN open data policy

The four big LHC collaborations have recently endorsed a new open data policy for scientific experiments at the LHC. This policy commits each of the experiments to release scientific data they have collected to the public within approximately five years after the data have been collected. The data are released through the CERN Open Data Portal in a form suitable for most physics studies together with the software and documentation needed to use the data. This data release strategy will allow for high-quality analysis by scientists in physics and related fields such as scientific computing, in educational and outreach activities, and by the general public; it will also make scientific research more reproducible, accessible, and collaborative.

10.6 Input from young scientists on the roadmap document

Young particle physicists from Swiss institutes were also involved in this update of the CHIPP roadmap, with input collected in the weeks before the roadmap workshop through the use of questionnaires and interviews. This section describes the most important points raised in this process by young community members.

Young particle physicists were very interested in this roadmap update and desire a more regular collection of feedback. Having a 'Young People Vision' update roughly every two years could help, both to integrate the young researchers into the CHIPP community more effectively and to take their needs and viewpoints into account. In order to have concise and consistent input, the feedback collection process should be conducted in the same manner over all branches of particle physics research. Particle physics research in Switzerland covers a large variety of cutting-edge research topics; it is important to help young researchers become familiar with their academic neighbours and to cultivate an informative and advanced picture about the scope and future of the field. We suggest that each Swiss institute and university prepare an overview of their current status and future plans in the form of a brochure and/or integrated presentations to young researchers. Additionally, we suggest the organisation of topical meetings and discussions; these would be excellent opportunities for fruitful interactions and collaborations among projects in the same research field and cluster.

CHIPP is the ideal platform to share information about outreach events among young researchers, especially outside of their own affiliations, across Switzerland. More frequent participation in such events helps young researchers better recognise the positive impact particle physics has on society. Young PostDocs are likely to apply for Swiss or European grants during their career. Not all institutes are currently able to support the applicants with practical help and reviews of the required documents. This kind of support would be very beneficial in preparation for the series of grants aimed at early-career researchers as proposed by the Swiss National Science Foundation, and can also provide valuable management skills for the organisation of a research project over the timescale of a few years. We suggest that CHIPP help to put in place such a service at each institute, or to generalise it to all of Switzerland, thereby actively contributing to the career evolution of young researchers.

Beyond the different physics research experiments, there are important accelerator infrastructures to be built. The design of such facilities should take into account, not only the global cost, but also the sustainability of those infrastructures in terms of energy efficiency and the impact on the environment where the facilities will be located.

10.7 Partners

The Swiss Physical Society (SPS), the Swiss Academy of Sciences (SCNAT), and the European Physical Society (EPS) are strategic partners of CHIPP.

The Swiss Academy of Engineering Sciences (SATW) is a network of experts in engineering sciences in Switzerland, and is in contact with the Swiss bodies for science, politics, and industry. The network is comprised of selected individual members, member organisations, and experts.

IngCH covers a range of activities that raise the status of engineering studies as a solid and promising start to an interesting career in a huge range of industries and functions, and enhances the positive image of engineering as a career. IngCH gives the public, and young people in particular, an insight into the central significance of technology in our lives.

11 Vision for the future

11.1 Overall vision

The Higgs discovery has marked the beginning of a new era in particle physics. The underlying goals of research in the field of particle physics, namely trying to understand the microscopic laws of Nature, are unchanged. Nonetheless, a paradigm shift has occurred: having completed the set of particles required for the SM to be self-consistent, there are no more 'guaranteed' discoveries as there have been in the past. We have clear indications that the SM is not the ultimate microscopic theory of Nature, but we have no precise indications of where to find new particles or how to reveal the structure of new fundamental interactions. The pre-Higgs phase was somehow an exceptional period, where theoretical predictions based on the consistency of the model could precisely guide the experimental efforts in the field toward anticipated discoveries. Now we are back to a genuinely exploratory phase, where we cannot unambiguously predict when and how the next discovery will occur.

The field has entered into a more exciting, but also more challenging phase. The situation is conceptually similar to that of fundamental physics at the very end of the 19th century, where all electromagnetic phenomena found a beautiful and coherent explanation in terms of Maxwell's Theory, and gravitational interactions were perfectly described by Newton's Laws. Nobody could have anticipated the series of discoveries that started at the beginning of the 20th century, which led to the formulation of Quantum Mechanics, later on Quantum Field Theory, and finally the Standard Model; nor could anyone have predicted the development of General Relativity. Now we are back with two internally self-consistent, but apparently not fully compatible, theoretical pillars describing all known fundamental interactions. We furthermore know that some crucial ingredients are still missing, such as explanations for the phenomenon of dark matter or the origin of the matter-antimatter asymmetry in the Universe.

Theoretical physics still plays a key role in guiding experimental efforts, but the theoretical indications of where to look are less precise than they were in the past. What is clear is that we need a diversified effort to identify new building blocks of Nature. In particular, we definitely need to scrutinise the electroweak scale in more depth, as its dynamic structure has only been superficially analysed by the LHC experiments. More concretely, we have discovered the Higgs boson, but so far we know very little about its interactions. At the same time, we need to directly probe the highest accessible energy scales: the vast majority of proposed extensions to the SM predict new particles in the few TeV domain, which can be probed only with a new generation of accelerators able to produce collisions of elementary particles at substantially higher energies than those presently accessible at the LHC (the **high-energy frontier**). We also know that we can probe well-defined classes of extensions to the SM via their indirect imprint in low-energy observables, such as rare decays and other processes (EDMs, $g-2$, and similar) that are extremely sensitive to the fundamental symmetries of the underlying theory (the **high-precision frontier**).

A complementary and unique opportunity in the search for clues of physics beyond the SM is offered by neutrinos, whose non-vanishing tiny masses naturally point toward the existence of new degrees of freedom, which have yet to be revealed. A lot has been discovered about neutrino masses in the last two decades, but more is still to be understood: the precise pattern of mixing angles, the absolute neutrino mass scale, matter-antimatter asymmetry in the neutrino sector, the fundamental nature of neutrinos, and the possible existence of sterile neutrinos are all key questions that both need to be and can be addressed in the near future with dedicated facilities (**neutrino physics**). Last but not least, cosmological observations indicate that some form of dark matter and dark energy is needed, which are striking signals that the SM is not complete. The search for new phenomena via astrophysical observations (the **cosmic frontier**) is, therefore, an essential part of this global effort.

This general programme requires a series of complementary experiments, with different time and cost scales. These experiments are oriented along the three pillars of CHIPP and require corresponding investments in accelerator technologies and particle detectors and, more generally, in the facilities that will host these different type of experiments.

I. Significant progress on the high-energy frontier can only be achieved with the support of a large-scale facility, available in the long term. With this long term perspective in mind, the FCC programme at CERN stands out as a unique multi-purpose facility, that can maximise the discovery potential with a possible two-stage approach (ee and hh): it is the facility that would allow us to explore the high-energy frontier in more depth (in the FCC-hh phase), while also being the Higgs-factory with the maximal possible luminosity (in the FCC-ee phase), and it would also offer unique opportunities for more specific high-precision searches (again in the

FCC-ee phase). Thanks to the CHART initiative, Swiss particle physicists are playing 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. Swiss physicists have played pivotal roles in the management of the project since its infancy and in unveiling the physics opportunities that such a project would support. 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.

II. While preparing for this long term effort, in the short- and medium-term, it is essential to exploit the discovery potential of the existing facilities in the context of the high-precision frontier. In particular, one should make optimal use of the HL-LHC project at CERN. This new phase of the LHC complex increases the discovery potential of the LHC experiments and necessitates upgraded versions of the ATLAS, CMS, and LHCb detectors; some of these upgrades involve leading Swiss contributions. At the same time, it is important to conceive of and develop dedicated smaller-scale experiments with unique discovery potential; this may involve new initiatives in the context of a future beam-dump facility at CERN. 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 the HIPA accelerator, along with the pion and muon production targets, is a high-priority project. In particular, the HIMB that could be implemented at HIPA (2025-28) would boost the available muon intensity by up to two orders of magnitude, thereby extending the reach of many experiments, including high-impact searches for charged-lepton-flavour-violating muon decays.

III. Progress in neutrino physics requires a twofold path. One direction involves long-baseline experiments with high-intensity neutrino beams, which are required to answer key questions, such as the amount of matter-antimatter asymmetry in the neutrino sector and the neutrino mass hierarchy. This effort should be pursued via participation in the complementary long-baseline facilities under development in the USA and Japan, where the Swiss community is already significantly engaged in both efforts. The second direction relies on underground experiments that detect neutrinos either emitted from radioactive sources or originating from the sky, such as LEGEND, DARWIN, and IceCube, in which Swiss groups are leading participants. These passive experiments are the only way to address the overall scale of neutrino masses and to reveal the nature of neutrinos as being either Dirac or Majorana particles. As an interesting note, two of these experiments, DARWIN and IceCube, are multi-purpose experiments, which also play a key role in the cosmic frontier.

IV. The search for new physics at the cosmic frontier also requires a twofold path; the first approach involves the search for dark matter via direct detection at underground laboratories, which continues to represent a core CHIPP activity. This effort should continue along the main strategies pursued to date, at least until experiments reach the background represented by solar and atmospheric neutrinos (the so-called neutrino floor); this goal is within the reach of the DARWIN experiment, for which Switzerland is a leading participant. The second path focuses on observing the Universe with astronomical instruments in different wave bands and with different messengers. The diverse set of efforts that fall under the over-arching strategy of multi-messenger astronomy form a rapidly expanding field, and this field relies upon the use of various complementary experiments at the interface between CHIPP and CHAPS. Of special interest is also the emerging field of Gravitational Wave physics, where Switzerland currently has significant theoretical expertise but has made very little experimental impact so far. The opportunity to get involved also experimentally in the 3G GW observatory, the 'Einstein Telescope', is an exciting possibility.

The future strategy of CHIPP

I. Long term prospect at the high-energy frontier. The FCC programme at CERN represents a unique multi-purpose facility, which can maximise the potential for the discovery of new physics in its possible two stages (ee and hh): it is the facility that would allow for a more in-depth exploration of the high-energy frontier (in the FCC-hh phase) and it is the Higgs-factory with the maximal possible luminosity (in the FCC-ee phase); it would also offer unique opportunities for more specific high-precision searches (again in the FCC-ee phase). Swiss particle physicists are playing 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 has clearly indicated the FCC programme as their main long term priority. This input was largely endorsed by the official ESPP update released in 2020.

II. Short- and mid-term perspective at accelerator-based facilities. While anticipating a new large-scale facility, the priority is to exploit the discovery potential of existing facilities in the context of the precision frontier, starting from the HL-LHC project at CERN. At the same time, it is important to also conceive of and develop dedicated smaller-scale experiments with unique discovery potential; this may involve new initiatives in the context of a future beam-dump facility at CERN. 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 that could be implemented at HIPA from 2025 to 2028 is another high-priority project.

III. Neutrino physics. Long-baseline experiments with high-intensity neutrino beams are essential to answer key questions such as the amount of matter-antimatter asymmetry in the neutrino sector and the neutrino mass hierarchy. This effort should be pursued via participation in the complementary long-baseline facilities under development in the USA and Japan, where the Swiss community is already significantly engaged in both efforts. Underground experiments, in which Swiss groups are leading participants, also play a fundamental role in addressing key complementary physics questions such as the nature of neutrino masses.

IV. Cosmic frontier. The search for dark matter via direct detection at underground laboratories represents a core CHIPP activity; this effort should be continued with high priority, especially in the experiments where Swiss groups are leading participants. In parallel, it is important to strengthen and diversify efforts in the direction of multi-messenger astronomy; this rapidly expanding field relies upon the use of various complementary experiments at the interface between CHIPP and CHAPS, such as the CTA observatory. A future engagement in gravitational wave experiments is also an interesting possibility.

11.2 The Future Circular Collider project

The high-luminosity phase of the LHC is expected to come to an end around 2038; although this seems like a long time away, it is essential to plan already for the facility that will come afterwards at CERN. The 2020 Update of the ESPP proposes an ambitious long term vision based on a Higgs and Electroweak factory (FCC-ee), followed by a ≥100 TeV hadron collider (FCC-hh), with the option of also supporting electron-proton collisions (FCC-ep). The two proposed facilities would be run sequentially and located within the same infrastructure, namely a 100 km tunnel at CERN, Fig. 28. This proposal agrees very well with the views expressed by the Swiss particle physics community in its contribution to the ESPP process.

Overall plan and physics goals

The FCC-ee project plans to start operations by the end of HL-LHC programme, with a high-luminosity, high-precision electron-positron collider abundantly producing the four heaviest known particles (Z, W, and H bosons and the top quark). The FCC-ee will enable per-mille precision and model-independent measurements of the largest Higgs boson couplings; it will also allow for the determination of the Higgs boson coupling to the charm quark and possibly even to the electron. Furthermore, the FCC-ee project plans to perform a large number of advanced investigations of Higgs boson decays, including studying the potential for CP and lepton flavour violation, as well as further studies of the top quark. Moreover, the huge number of Z and W bosons produced at the FCC-ee will provide sensitivity to the existence of physics beyond the SM by means of a leap in precision in electroweak and flavour observables by one to two orders of magnitude. The search for dark sector (feebly coupled) particles is a particularly fertile analysis when performed at the Z pole.[22] Following the FCC-ee is the ultimate FCC goal: the 100 TeV FCC-hh, which could start operations around 2060. The physics programme of the FCC-hh features the production of more than 10^{10} Higgs bosons and precision measurements of rare Higgs boson decays as well as of the Higgs boson self-coupling. Beyond these specific goals, the FCC-hh is also a formidable exploratory tool for new, high-mass particles.

The current plan for the next steps of the FCC project foresees the delivery of a technical and financial feasibility study report for the next European strategy update, which will start in 2025/2026. This document should also provide an enhanced conceptual design report for the FCC-ee detectors, including the formation of proto-collaborations around detector concepts and R&D projects starting in 2023.

The high luminosity of the FCC-ee when running at the Z pole will lead to data rates of up to 100 kHz and to precision requirements on the associated systematic uncertainties as low as a few ppm. The experimental conditions will be very clean, but extremely challenging, while discovery opportunities will abound right from the start of operations. The Swiss community has a strong role to play in the experimental and theoretical programme, including in the preparatory stages. It can thus be expected that some of the groups in the High-Energy pillar will already begin to devote resources to the definition of detector requirements and design before 2023, and will invest significant R&D resources starting at about that date and lasting until at least 2029.

Accelerator technology for the FCC

Swiss particle physicists have played a seminal role in defining the accelerator concept for the FCC.[23] A strong

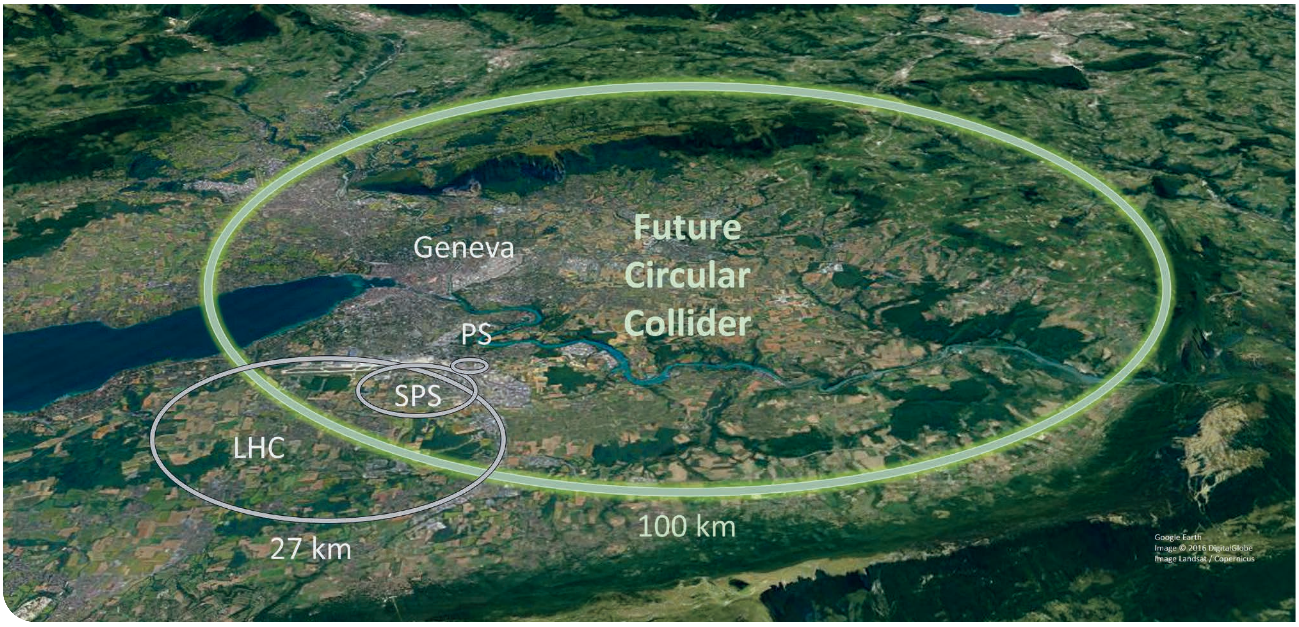


Figure 28: Layout of the Future Circular Collider (FCC) (Image: CERN)

programme of accelerator R&D since 2016 (CHART), with seed funding from the Swiss Confederation, has enabled and continues to support strong contributions in high-field magnet research. More recently, this programme has also contributed to other key R&D aspects of this ambitious project.

- The Geology Department of Uni Genève is currently working on a CHART project to understand fully the subsurface geology that will be crossed by the FCC tunnel and access shafts.

- The innovative linear accelerator technology designed for the SwissFEL can be advantageously used for the development of an FCC-ee injector concept. A CHART project is working to develop an injector concept including an efficient positron source. Well-established, low-tolerance manufacturing methods allow for a cost-effective mass production, in addition to good performance. As compared to an FEL, the collider facility requires significantly higher bunch charges for maximum luminosity and positron production by the linear accelerator beam. Controlling the collective effects triggered by the high-intensity beam is one of the challenges for this project. Another challenge is the creation of a positron source that delivers the desired beam intensity for a collider. In particular, the conversion efficiency from electrons to positrons must be maximised, while keeping the thermal and thermo-mechanical requirements for the conversion target realistic. A prototype of this newly developed positron source is planned to be tested in the SwissFEL facility at 6 GeV.

- Any future collider facility serving particle physics research will represent a large accelerator based research infrastructure, and will require a significant investment, come with large operating costs, and demand a large electrical power consumption. The latter point is not only a cost factor; for the implementation of such projects, sustainability aspects, such as energy efficiency and other factors impacting the environment, are becoming increasingly important. Proposals for competitive European research infrastructures must be optimised for many different aspects, foremost of which are the physics potential and associated costs, but sustainability must also be seriously considered. The particle and accelerator physics communities should work towards developing technological and conceptual advancements in multiple fields, which contribute to an overall optimisation of the concept to be proposed.

- The CHART programme focuses on important tasks in the field of accelerator R&D, such as the development of high-field superconducting magnets aimed at maximising the energy reach of a circular collider facility of a given size. CHART is addressing the most pressing problems in the design and construction of such superconducting accelerator magnets. These include, in particular, establishing a magnet laboratory at PSI capable of designing and constructing superconducting accelerator magnets in Nb3Sn and HTS (REBCO tape) technologies.

11.3 Short- and mid-term prospects for experiments at accelerator-based facilities

In the years to come, the Swiss particle physics community plans to be engaged in the accelerator-based facilities located at CERN and the PSI, which are summarised in Fig. 29. Swiss involvement at CERN includes leading roles in collider activities, naturally including the LHC and HL-LHC, with contributions to the ATLAS, CMS, and LHCb Experiments. In addition to the foreseen LHC and HL-LHC activities, Swiss groups also plan to contribute to prospective FCC studies, for which community activities are starting to ramp up. Swiss researchers are also involved in non-collider facilities located at CERN. They participate in experiments (GBAR and BASE) at the ELENA decelerator; they have been among the proponents of the proposed BDF, where the SHiP Experiment would be hosted; and they are participating in the Forward Physics Facility (FPF), where the upgraded FASER2 Experiment could be housed. Last but not least, Swiss researches are significantly engaged in experiments at the PSI accelerators, in particular Mu3e, MEG II, and n2EDM. This involvement includes experiments based at the operating HIPA and the prospective HIMB, which will open up new routes in particle physics exploration of precision-frontier physics with unprecedented beam intensities.

Physics pursuits with ATLAS and CMS at the HL-LHC

The central motivations for the HL-LHC physics programme are precision measurements of the least-known properties of the Higgs boson as well as an in-depth study of the weak scale, using a dataset approximately ten times larger than what will have been accumulated before the start of the HL-LHC. In order to fully exploit this dataset, upgraded detectors are required to mitigate the increased pile-up conditions (Fig. 30) that come with the higher, instantaneous luminosity; these detector upgrades will be installed from 2025 to 2027 in preparation for the HL-LHC programme, which will start thereafter and last until the mid-to-late 2030s. With this dataset, the improved ATLAS and CMS detectors, and improved theoretical uncertainties, the HL-LHC is expected to deliver measurements of Higgs couplings with uncertainties reduced by a factor of two. The study of differential (and double differential) cross-sections, which are currently statistically limited, will also provide more opportunities for the discovery of new physics.

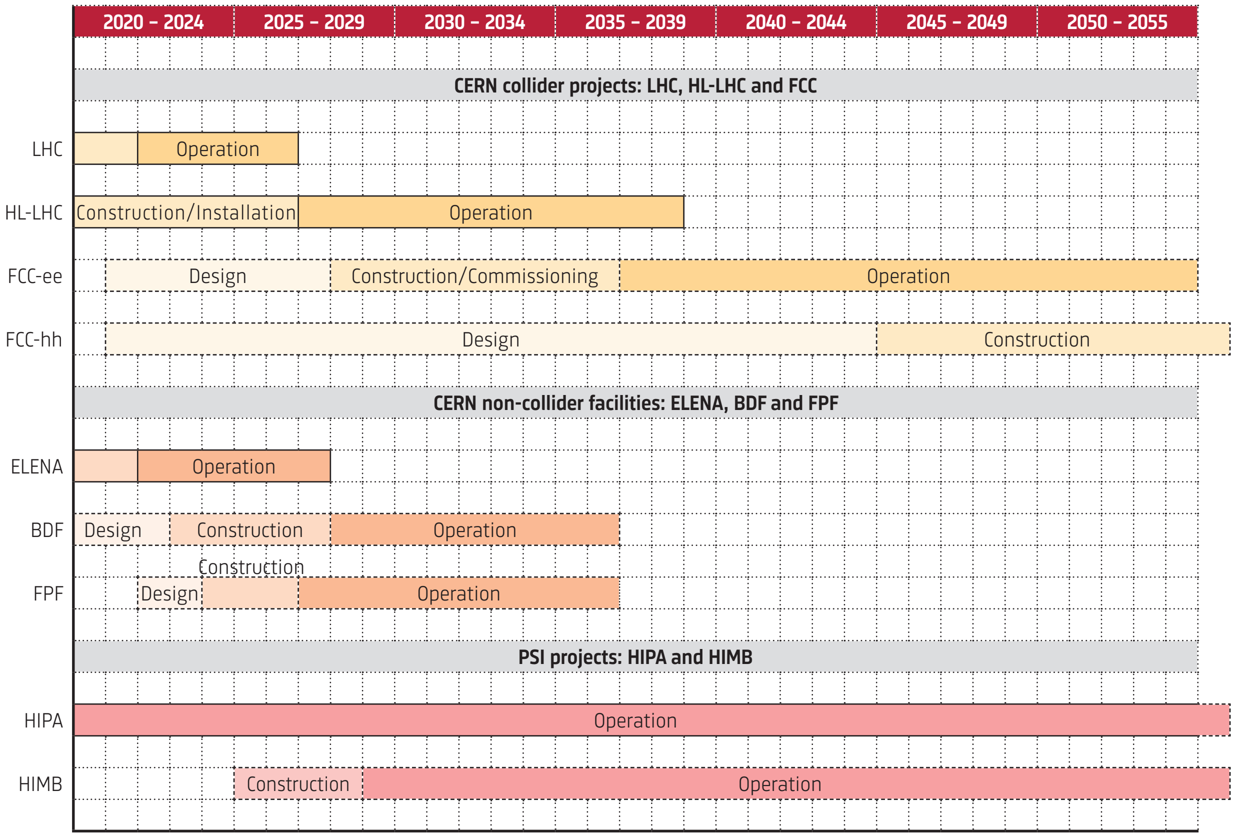


Figure 29: The timeline of major approved or prospective accelerator projects and facilities where Switzerland is already or plans to be engaged, at CERN and the PSI. The intensity of a given colour type indicates the project phases: preparation, construction, and operation and exploitation of the machine. Dashed boxes indicate prospective projects that are not yet approved for construction.

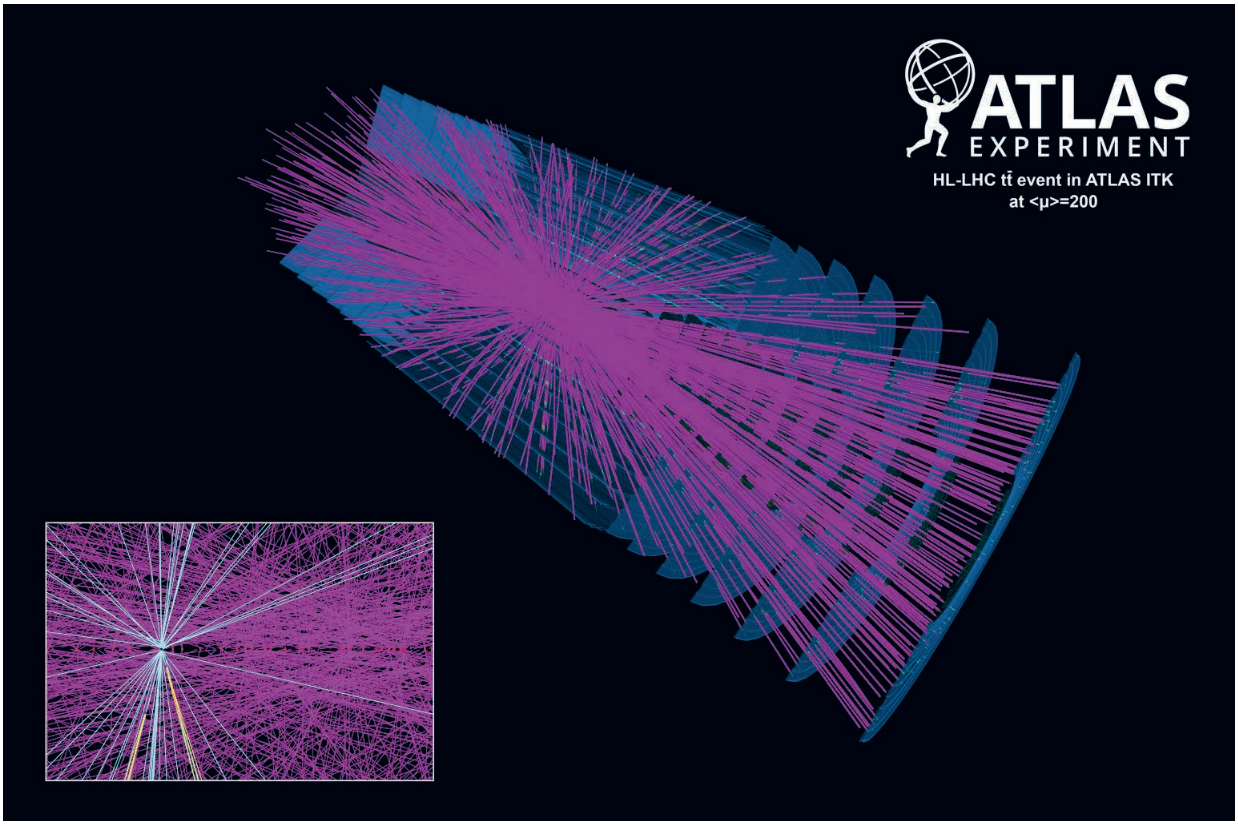


Figure 30: Display of a simulated HL-LHC collision event in an upgraded ATLAS detector. The event has an average of 200 collisions per particle bunch crossing (Image: ATLAS Experiment/CERN)

One of the major goals of the HL-LHC is to obtain first evidence for the self-coupling of the Higgs boson, leading to double-Higgs-boson production. The best signal significance for this process is expected to come from the golden channel $HH \to b\bar{b}\gamma\gamma$. Swiss physicists, who have been active in $H \to b\bar{b}$ and $H \to \gamma\gamma$ measurements, are now leading the current $HH \to b\bar{b}\gamma\gamma$ analysis, and are continuing to develop detectors and triggering systems that are specialised for observing such processes.

A significant observation of the Higgs boson coupling to muons is expected during Run 3 of the LHC. Swiss physicists will be investigating rare Higgs-boson decays to second-generation vector mesons and photons, as well as flavour-violating interactions of the Higgs boson, such as $H \to \mu\tau$.

Searches for new physics will carry outstanding importance in the HL-LHC programme, where the large datasets will increase the ability to probe rare phenomena, which would not have been previously accessible. In order to extend the discovery reach of the LHC, the use of indirect approaches to analyse possible deviations from the SM, such as Effective Field Theories (EFTs), are expected to take centre stage in the near future. This complementary approach allows for searches to probe the existence of new particles that are too heavy to be directly produced at the LHC, but which could still modify kinematic distributions of SM particles via interference or virtual effects. Precise measurements of total cross-sections and differential distributions can be compared to SM predictions, and may provide hints of BSM dynamics in the interactions between SM particles. Recently, experimental measurements have started to become sensitive enough to test directly the interactions between the top quark and Z, W, γ, and Higgs bosons. The future ATLAS and CMS datasets will provide an intriguing opportunity to study these processes in more detail in the context of EFTs.

The resonance search programme will be extended to challenging domains, including areas with low signal rates, large signal widths, the tails of distributions, and the hard-to-trigger low-mass region. The di-boson resonance programme will be extended to non-standard boson polarisations. The Higgs physics programme will be further expanded to include various exotic Higgs scenarios. The SUSY physics programme will further probe feeble cross-sections, including those associated with electroweak production, explore R-parity-violating models, and expand towards compressed mass spectra and smaller couplings which result in soft and displaced objects in the final state. The search for HNLs in leptonic decays of W bosons will be further extended to searches in B decays, taking full advantage of improved triggering strategies. This vast increase in statistics from B decays will also benefit other indirect searches for new physics in the context of lepton-flavour violation.

Improvements to the ATLAS and CMS detectors are an important part of achieving these research goals. In particular, the new timing layer upgrade at CMS, being built with Swiss participation, will improve object identification efficiency amid pile-up; it will also improve the identification and energy reconstruction of photons in the central detector region, thus maintaining support for high-quality $H \to \gamma\gamma$ measurements. The new inner trackers of both ATLAS and CMS, being built with major participation, from Swiss institutions, will greatly improve measurements of $H \to b\bar{b}$ and $H \to \tau\tau$, as well as reduce the effects of pile-up in all analyses. The introduction of tracking reconstruction early on in the triggering process will be of paramount importance to maximising the acceptance of rare phenomena, which are typically swamped under the large rates of SM processes; this is a driving motivation behind the ATLAS and CMS trigger architecture upgrades.

Following the optimisation of detector designs, it is important to improve resource efficiency in the aforementioned areas of triggering, reconstruction, and simulation. Improvements in these areas directly translate into increased precision of SM measurements and enhanced sensitivity to new physics as a result of higher trigger efficiencies, improved reconstruction algorithms, and increased statistics of simulated data for the optimisation of analysis strategies. Areas of particular interest to Swiss research teams are searches for new physics phenomena leading to unconventional signatures in the tracking volume, or to anomalous jet substructure, as well as the combination of both. Modern tools based on machine learning provide cutting-edge technology that can be used to take full advantage of the unique LHC dataset, and at the same time, revolutionise the way in which science is conducted far beyond high-energy physics.

Flavour physics with LHCb at the HL-LHC

Flavour physics plays a unique role in the search for BSM physics, allowing for the exploration of a region of mass and coupling parameter space, which is inaccessible to current and planned direct-detection experiments; this complementary approach could pave the way to a new physics discovery. Flavour physics is strongly linked to theoretical QCD computations on the lattice as some measurements require knowledge of the hadronic system to be interpreted. Correlations between the different measurements are a powerful tool in flavour physics to disentangle new physics from hadronic effects, and can be used to advance theoretical knowledge of low-energy QCD.

Since most key measurements in heavy flavour physics are statistically limited, it is of paramount importance to have a flavour physics experiment running throughout the HL-LHC era. Multi-purpose flavour experiments at colliders, such as LHCb, offer the highest yields of hadrons containing bottom and charm quarks, as well as of tau leptons, and the widest spectrum of interesting measurements. An expression of interest for a second LHCb upgrade (Upgrade 2), which is planned to be installed after Run 4 (in ~ 2031), was submitted in February 2017 to the LHC committee. The idea is to operate LHCb at a luminosity of 2×10^{34} cm^{-2}s^{-1}, ten times that of the first upgraded detector, in addition to further improving the performance of the detector in key areas. With an accumulated dataset size of at least 300 fb^{-1}, LHCb would then take full advantage of the flavour physics opportunities available at the HL-LHC. In addition, the experiment would be capable of major discoveries in hadron spectroscopy, and would pursue a wide and unique programme of general physics measurements in the forward region of proton-proton collisions, complementary to those done by ATLAS and CMS. Switzerland intends to play a crucial role in this endeavour, building upon the experience of the Uni Zürich and EPFL groups in the current LHCb Experiment and its upgrade.

At the same time, LHCb remains the only running flavour physics experiment at a hadron collider, and could potentially be the only flavour physics experiment in the world in Run 5 and beyond. Hence it is in a unique position, and under enormous pressure, to provide new results beyond just an incremental update of the state-of-the-art in flavour physics. The current detector upgrade, installed from 2019 to 2021, ensures that LHCb will be able to operate during the initial phase of the HL-LHC, allowing for the collection of one order of magnitude more data of a higher quality than previously possible, taking advantage of an almost-fully-replaced detector and rethought data-taking strategy. In a strategy unique within the LHC experiments, and indeed to collider experiments in general, LHCb will remove all of its hardware limitations in the data collection process by running a fully software-based trigger on every LHC collision delivered to the LHCb Experiment. These detector and data-taking advances provide access to a new level of sensitivity for the research programme pursued by Swiss physicists, such as testing lepton-flavour anomalies, looking for evidence of lepton-flavour violation, searching for new particles, and performing precision measurements of rare decay properties in the beauty and charm quark sectors. Swiss groups have actively participated in the creation and deployment of this revolutionary strategy, and are developing new reconstruction techniques for the measurements to be carried out with the new data. Such a strong setting also motivates other LHC collaborations, CMS being a great example, to devote significant effort to their flavour physics programme.

The second upgrade of LHCb, which will be needed to maintain the excellent detector performance beyond Run 4 and throughout the HL-LHC phase as necessary to achieve its full flavour potential, requires a major R&D effort to be started immediately and then a significant investment for the construction of the upgraded detector in a few years from now. While the LHCb Collaboration is organising itself to submit a framework Technical Design Report (TDR) to the LHC committee soon, Swiss groups have decided to join their detector efforts on the tracking stations, which will need to be completely rebuilt with next-generation technologies, which have yet to be developed.

Detectors and computing for the HL-LHC

The Swiss particle physics community has mastered a wide range of detector technologies, including tracking detectors, calorimetry, and triggering and DAQ. Due to the diverse expertise present across institutions, the Swiss community is well poised to develop or adapt any hardware technology that would be needed for future facilities. Hardware expertise is therefore not perceived to be a limiting factor in the pursuit of future directions in the field. Both in the close future and beyond 2025, the focus of Swiss scientists is expected to be threefold: the commissioning and operation of the HL-LHC detectors, detector and trigger upgrades within the HL-LHC, and R&D for future facilities. This plan is also in line with the European strategy recommendations.

While the initial HL-LHC detector upgrades for Run 4 of the LHC are well underway, discussions are now starting within the LHC experimental collaborations on detector upgrades for Run 5. These upgrades will accommodate for flexibility and challenges, which are not expected to be fully addressed beforehand. They will also allow the experiments to respond to potential changes in the physics landscape, for example, in case an anomaly is observed in data. As an example, the ATLAS Collaboration envisages the replacement of the innermost tracking layers to account for radiation damage; this could be complemented by upgraded read-out electronics, which would allow for an evolution of the trigger and DAQ architecture.

The HL-LHC will require an increase in computing resources by roughly a factor of 50. A combination of scaling the present resources with the expected processor performance increase from Moore’s law will most probably not be enough to cover this increased demand. The present solution pursued by the HEP community is instead to enhance the parallelism of the algorithms and use more heterogeneous computing architectures, including GPUs and FPGAs. Machine learning will play a definite role in the shaping of reconstruction algorithms (e.g. tracking and clustering running on GPUs), boosting the speed of simulations, and generally increasing the efficiency in extracting information from data. The investment in hardware facilities will have to be paralleled by an investment in developing the software needed to accomplish these goals. To facilitate cooperation within the HEP community towards the development of software and computing infrastructures, several fora have been created, among which are the HEP Software Foundation (HSF) and the CERN ‘Scientific Computing Forum’.

Other experiments at CERN

As indicated in the European Strategy, new experiments beyond collider-based general-purpose detectors have a rich future, especially those which are exploring the DS.

The NA64 Experiment is currently being upgraded and will resume data-taking activities after LS2, with the goal of probing most of the parameter space of an interesting and motivated class of light DM models. Moreover, a pilot run using the unique 150 GeV muon beamline at the SPS was approved, allowing for the search for a new dark boson Z_μ with a mass in the sub-GeV range, which is coupled predominantly to the second and third lepton generations. The existence of Z_μ would provide an explanation of the muon $g-2$ anomaly and is complementary to the electron mode of NA64 in the search for DS at higher masses.[24]

The FASER Collaboration is exploring ways to increase the detector precision and acceptance in what will become the FASER2 Experiment, rendering it sensitive to a variety of additional physics channels that are currently inaccessible. Such a FASER2 detector would start after FASER is commissioned in 2022, and would aim to be installed during LS3, in preparation for data-taking activities at the HL-LHC. Another exciting prospect arises from a proposed Forward Physics Facility (FPF) to be created for the HL-LHC, enlarging an existing cavern in the far forward region of ATLAS to house a suite of experiments with groundbreaking new capabilities for neutrinos, LLP searches, QCD, DM, DS, and cosmic rays. Such a facility would open up an entire new physics programme to be explored in the far forward region. Both FASER2 and FPF are extensively discussed in the context of the USA’s Snowmass process.

The SHiP Experiment in the proposed BDF offers a unique opportunity to enter a new era of direct exploration at the intensity frontier, which is complementary to the high-energy and precision frontiers. The EPPS Update concluded that 'among the proposals for larger-scale new facilities investigated within the Physics Beyond Colliders study, the BDF at the SPS emerged as one of the front-runners'. The strategy, however, recognised the financial challenges associated with the implementation of the BDF; such a facility would require the prioritisation of the exploration of the intensity frontier at CERN, and R&D plans would need to be formulated as part of continued studies. The time scale of the implementation of the BDF is still uncertain; however, we believe that the physics potential and the complementarity with other projects is such that a SHiP-like experiment should be supported by the community in case of approval.

After LS2, the new ELENA ring at the CERN AD will provide an unprecedented flux of low-energy antiprotons, opening a new era for precision tests with antimatter. There is increasing Swiss participation in antiproton and antihydrogen research, especially within the BASE and GBAR Collaborations. These AD experiments focus on stringent tests of the CPT symmetry and the precision determination of fundamental constants related to antimatter, while different methods are being developed to test directly the gravitational interaction of antihydrogen atoms.

Low-energy, high-intensity particle physics experiments at PSI

A realistic goal for the future, although by no means guaranteed, is the discovery of new physics in low-energy precision observables and/or forbidden decays. Ideally, this would come together with the observation of clear direct signals from high-energy collisions. The chances for such an occurrence are good and some of the most promising and sensitive discovery channels are searches for a violation of the symmetry between matter and antimatter (CP) and between leptons from different families. As such discoveries cannot be guaranteed; measurements of SM parameters at the highest precision are also important: they provide crucial input to confirm our theoretical understanding in detail and to exclude BSM theories.

PSI offers world-leading beams of low-momentum pions, muons, and ultracold neutrons used by a large and growing community, which includes strong Swiss participation and leadership. There is a unique opportunity to maintain leadership in this attractive field and to upgrade substantially these facilities in terms of beam intensity and quality. While important installations at other international facilities will be driven by the international community, partially with strong Swiss participation, the installations at PSI will be driven by the Swiss community (with strong international participation in experiments and applications).

A substantial upgrade of these facilities at PSI will translate into a significantly enhanced reach of the experiments and their associated physics potential. One aspect of such an upgrade concerns the intensity of the source of ultracold neutrons (UCN) at PSI, as the search for the neutron electric dipole moment will still be statistically limited in five to ten years. From another perspective, the intensity of PSI's secondary muon beams could be boosted by almost two orders of magnitude by the HIMB project; this represents the single most important facility project of the next five to ten years, and comes with a potential exploitation timeline of more than 20 years. Many experiments would benefit not only from more muons, but also from an improved muon beam quality; the muCool project promises a seven orders of magnitude improvement to the brilliance of slow positive muon beams, with a plethora of applications in fundamental particle physics and in applied sciences. Clearly, the combination of muCool and HIMB will be highly attractive to many PSI users. An additional project improving the cooling of slow, negative muons would enable many more applications; muonic atom research would directly benefit from such an improvement, as would material surface studies, but the benefits may also extend further to studies of future muon colliders.

Accelerator technologies. In addition to the large involvement in R&D for the FCC, the Swiss CHART project is also involved in the exploration of high-gradient acceleration schemes utilising micron-scale accelerator structures and high-power lasers. The PSI HIPA facility provides very competitive performance with respect to proton-beam power and the intensity of generated low-energy muon beams. The beam intensity of HIPA is limited by beam losses in the 10^{-4} range. With an upgrade of the cyclotron RF system, which would use a new design of the third harmonic cavity, the intensity could be further increased towards 3 mA. Together with the other consolidation measures, this upgrade is planned for the medium-term future. While this would increase the muon beam intensity, further gains to the beam intensity are possible by improving to the muon conversion efficiency. The proposed new target configuration and capture optics of the HIMB project will enhance the energy efficiency of the facility by increasing the muon beam intensity without increasing power consumption.

Experiments. A very strong science driver on the particle physics side is the search for charged-lepton flavour violation (cLFV), which is ongoing at the MEG II and Mu3e Experiments. The international Mu3e Collaboration, with leading contributions by Swiss groups, has devised a phased approach which ultimately needs HIMB to push the limits of cLFV searches with muons. The construction of HIMB at the PSI HIPA is of great interest for the Swiss particle physics community and beyond. Besides Mu3e, many particle physics experiments with muons can be tailored to benefit from a HIMB, and with the installation of two such beamlines a second one could serve materials science applications with unprecedented statistical power.

11.4 Neutrino physics

The field of neutrino physics, similar to the high-energy physics frontier, faces long timescales for answering the major open scientific questions. From the identification of the measurement goals to the development of the technology and detection methods, design and construction of the experiments, and final collection of the data and subsequent exploitation, two decades may pass, with each of the phases lasting several years. The roadmap for neutrino physics, both internationally and as reflected in the Swiss plans, currently includes several major infrastructure projects, which are in the final design phase or under construction, many of which are expected to start collecting data well before the end of this decade. It is, therefore, a very exciting time in the field, with new fundamental results expected on key parameters, such as the matter-antimatter asymmetry and neutrino mass hierarchy.

The most relevant of these facilities, from the perspective of Swiss participation, include the long-baseline experiments in the USA and Japan, as well as DARWIN, all of which are aiming to start operations around 2027. Upgrades of existing facilities, namely the T2K Experiment in Japan and the IceCube Experiment at the South Pole, are expected to be completed in the next few years and will provide physics results and training for young scientists. With these upgrades and new facilities, a phase of exploitation of about a decade will follow, extending well into the 2030s. There are ideas about the farther future of the field and the possible facilities; however, the physics case will depend on the findings of the already planned experiments. Concrete planning and design for the next facilities will therefore only start several years from now.

Figure 31 shows the timescales for the construction and exploitation of the various experiments in neutrino physics.

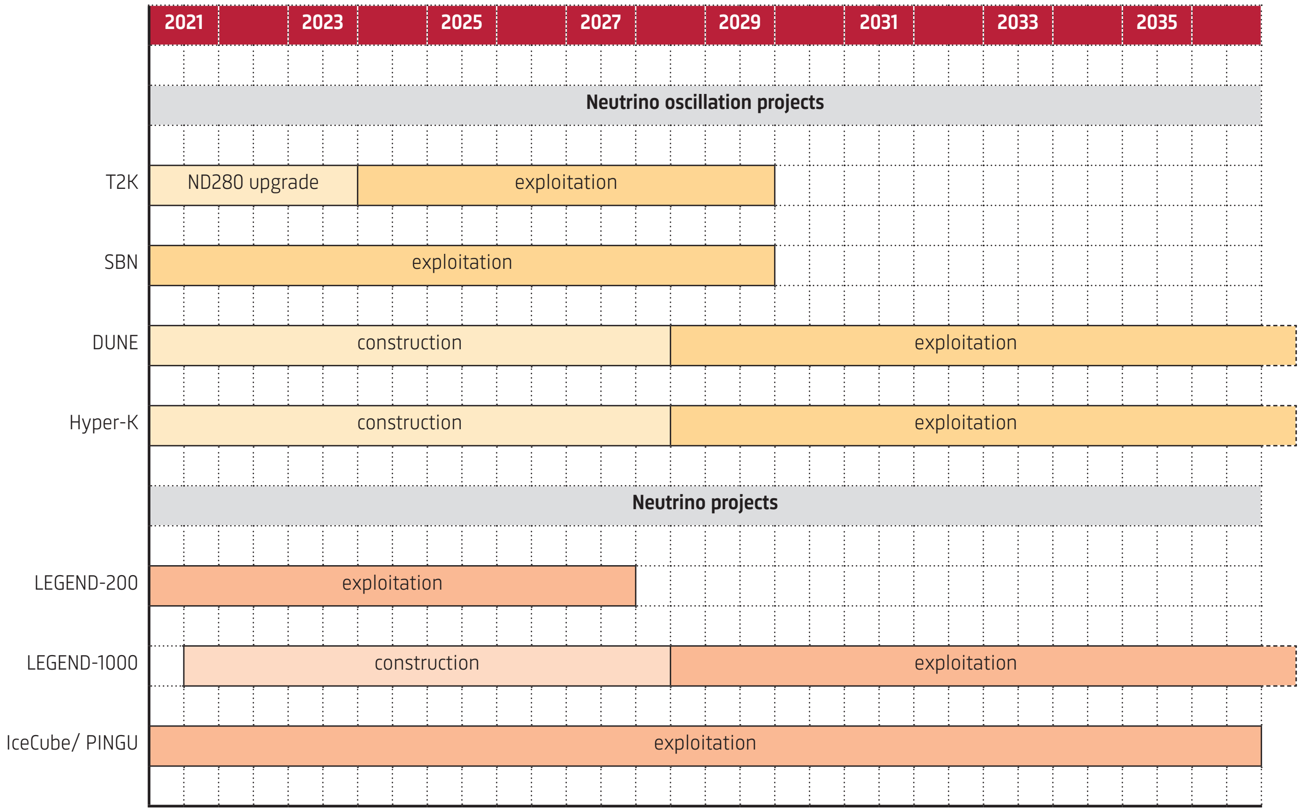


Figure 31: The timeline of major neutrino projects with strong Swiss engagement. The intensity of a given colour indicates the project phase, differentiating between construction (light colour) and exploitation of the machine (dark colour). The timeline of DARWIN is shown in Figure 32.

Long-baseline experiments

Hyper-K. T2K is in the process of signing a Memorandum of Understanding to initiate the transfer of the Near Detector complex to Hyper-K, thereby serving as a near detector of the new experiment. In addition, Swiss groups are exploring a possible contribution to the readout electronics for the future Hyper-K inner detector sensors, based on electronics boards developed at PSI, as well as promoting possible contributions of CERN on the accelerator upgrade of the J-PARC facility. Both projects are seeking to optimise the visibility of the Swiss contributions by coordinating the efforts with CERN and trying to enhance the physics reach of the experiment.

T2K plans to operate the experiment until the start of Hyper-K, with the goal of improving their recent results on the CP phase measurement, while paving the road towards Hyper-K by performing analyses that will reduce its initial systematic uncertainty budget. These additional runs will profit from the beam upgrade scheduled for 2021 to 2022, which will increase the beam power by approximately 50%, and by a second upgrade in 2025 that will bring the beam power to 1 MW, thereby doubling the current running power. Both upgrades will increase the size of the total accumulated data samples by more than a factor of two.

DUNE. Following the founding of the DUNE Collaboration in early 2015, the groundbreaking of the far site took place in 2017. In 2019, the start of the construction of the beam facility began at Fermilab. Two large detector prototypes were successfully tested during 2018 at CERN. The TDR was published in early 2020 for the overall physics programme, the beam, and the far-site detectors; the near-detector Conceptual Design Review was completed in 2019 and the TDR is expected in early 2021. An initial configuration of the far- and near-site detectors is expected to finish construction in 2026, with the neutrino beam turning on in 2027. For the near detector, a consortium of institutions led by Uni Bern was created in 2020 as subgroup of the DUNE Collaboration, with the goal of building and commissioning its liquid argon component. A modular approach, conceived by Swiss scientists, will allow for measurements of the flux of neutrinos produced at Fermilab with detailed neutrino interaction studies. Despite the very-low interaction probability of neutrinos, the rate measured in the near detector will be relatively high due to the extremely intense neutrino beam; it will thus be necessary to take measures in order to disentangle individual neutrino interactions. The liquid argon technology planned to be used is particularly well suited to perform such precision measurements.

In addition to the unique relevance of the DUNE and Hyper-K Experiments, recent studies of their physics reach have shown a strong synergy between the two projects. The detection technology used and baseline length selected influence physical aspects of the experiments, such as the dominant neutrino interaction channel, the neutrino energy reconstruction, and the contribution of matter effects to the oscillations. In addition to the neutrino flux prediction, these aspects constitute the core of the experimental systematic uncertainties. The union of both experimental approaches will thus provide additional control of the systematic uncertainties on measurements of critical parameters of the SM, such as the neutrino mass ordering and the difference in neutrino and antineutrino oscillations (CP violation). This statement can also be applied to a certain degree to the IceCube neutrino oscillation programme. Close collaboration among Swiss institutions involved in DUNE, Hyper-K, and IceCube will place our community in a strong position to explore these synergies.

Based on our knowledge and experience, as well as our cooperation with previous experiments and industry partners, it is expected that Switzerland will play an important role in the mechanical infrastructure and cryogenic equipment for LBNF/DUNE. Contributions to Hyper-K infrastructure are also expected for the near detector facility, such as magnet or gas systems, and the J-PARC beam upgrade, in cooperation with CERN. PSI could bring additional experience in accelerator technology for high-intensity beams to both of these efforts.

Passive experiments

IceCube. IceCube is currently undergoing its Phase 1 upgrade, during which the size of its dense core detector will be increased with an additional seven strings holding 700 new and enhanced optical modules (already financed by the USA's NSF). This detector, which in the final configuration of 26 additional strings will be called PINGU, lowers IceCube's neutrino energy detection threshold down to 1 GeV. This upgrade aims to determine more precisely the neutrino oscillation parameters and to determine the neutrino ordering. It has been shown that a combined analysis of JUNO and IceCube results will determine the neutrino mass ordering at a significance beyond the 5σ discovery threshold within the expected operation times of both experiments, even for a more conservative scenario and for unfavourable regions of parameter space. It should also be remembered that IceCube is in the supernova early warning system for the detection of MeV-energy bursts of neutrinos from supernovas. It is currently the most sensitive detector for signals originating from the Large Magellanic cloud.

LEGEND. The GERDA Experiment was completed at the INFN LNGS, Italy, in December 2019; since then, the infrastructure is available for LEGEND, the next-generation ^{76}Ge experiment searching for neutrinoless double-beta ($0\nu\beta\beta$) decays. The LEGEND Collaboration, based on the

GERDA and MAJORANA Experiments together with new members, aims to build a tonne-scale experiment with a large discovery potential in two phases. The first phase, LEGEND-200, has been approved and funded to be hosted at LNGS with a target mass of approximately 200 kg of enriched Ge. The second phase, LEGEND-1000, is in the design phase with several underground laboratories as potential hosts. The goals of these two phases are to achieve sensitivities of $T_{1/2}^{0\nu\beta\beta}>10^{27}$ y and $\mathrm{T}_{1/2}^{0\nu\beta\beta}>10^{28}$ y, respectively, which would imply probing the full inverted neutrino mass region for $0\nu\beta\beta$ decays via light Majorana neutrino exchange, or probing effective Majorana neutrino masses in the range 10–20 meV.

DARWIN. The DARWIN project, a next-generation xenon-based experiment for direct DM detection, will also be able to probe the $0\nu\beta\beta$-decay of ^{136}Xe with a half-life sensitivity of 2.4×10^{27} y and will thus be complementary to LEGEND and other dedicated searches. The main neutrino-physics channels in DARWIN can be briefly summarised as follows: I) *Solar neutrino flux* – The low-energy threshold, ultra-low background levels, and excellent target fiducialisation will allow for a precise measurement of the *pp*-neutrino flux from the sun at the 1% level through the use of elastic neutrino-electron scattering; II) *Neutrinoless double-beta decays* – Even without isotopic enrichment, DARWIN will contain more than 3.5 tons of ^{136}Xe, a double-beta decaying isotope with a Q-value of 2.46 MeV. This will enable the search for neutrinoless double-beta decay in an ultra-low background environment, and thus it will be possible to investigate the Majorana nature of neutrinos and lepton-number violation. The reach of neutrinoless double-beta decay measurements could be further increased with appropriate modifications of the isotope compositions of the xenon target; III) *Supernova neutrinos* – DARWIN will be a continuous monitor for supernova neutrinos, with sensitivity to all (active) neutrino species. A galactic supernova will generate hundreds of events within the target through coherent scattering off of xenon nuclei; IV) *Neutrino magnetic moment* – With an energy threshold of 1 keV for electronic recoils, DARWIN can search for a non-standard enhanced neutrino magnetic moment using solar neutrinos.

11.5 Astroparticle physics

The Swiss astroparticle physics community plans to develop further its investments in direct DM detection. The experiments aimed at WIMP detection will continue to improve their sensitivity down to the ultimate solar-neutrino floor. The next xenon-based observatory, DARWIN, will be Swiss-led; it also has several other important scientific goals beyond WIMP detection. Going forward, special emphasis will also be placed on observational signatures of more complex models of an entire dark sector. Astroparticle observations will increasingly follow the multi-messenger approach in the next decade, including the concurrent detection of neutrinos, γ-rays, cosmic rays, and also gravitational waves. The timeline of major astroparticle physics projects with substantial Swiss engagement is shown in Fig. 32.

Some concrete near-term goals are listed below.

Dark Matter direct detection

XENONnT will improve on the sensitivity to WIMP DM from XENON1T, the previous experiment, by one order of magnitude. It will also probe light DM via DM-electron scattering, as well as ALPs and dark photons via absorption in liquid xenon. It will search for solar axions with unprecedented sensitivity, and detect solar neutrinos via coherent neutrino-nucleus scattering.

DARWIN will probe WIMP dark matter down to the neutrino floor, and continue to broaden the DM reach by using only the ionisation signal, the Migdal effect, and Bremsstrahlung, as well as DM-electron scattering. It will search for neutrinoless double-beta decay of ^{136}Xe with sensitivity of 2×10^{27} y in the baseline scenario, along with several other double-beta processes. The experiment will additionally measure the solar pp-neutrino flux via neutrino-electron scattering with <1% precision, and the weak mixing angle at low energies. DARWIN will also search for solar axions, DM ALPs and dark photons, nucleon decay, and many other processes.

DAMIC-M is set to begin in 2024, and will probe several theoretically viable models for low-energy interactions between dark matter and matter. It is positioned to be the world-leading experiment in studying hidden-photon DM, hidden photons mediating the interactions of DM, and electron scattering of DM at low energy scales. It has a broad reach, and is able to probe ten orders of magnitude in DM mass over a range of theoretical scenarios. OSCURA, whose feasibility studies are supported by a grant from the USA's DOE, has a timeline after DAMIC-M. OSCURA will have thousands of CCD detector modules, making its production similar in scale to detector production for the LHC experiments. The Swiss group that is presently involved in DAMIC-M also plans play a leading role in this international and large-scale successor project.

Multi-messenger astrophysics

CTA has very high potential for the exploration of the Universe's most violent processes that lead to the formation of compact objects and the acceleration of particles to extreme energies. It also has high potential for the exploration of DM, irrespective of its composition (e.g. axions vs. WIMPs). CTA will be an extremely important observatory, which will drive multi-messenger observations where information is combined from high-energy γ-rays, neutrinos, GW, and charged cosmic rays. CTA will improve the energy coverage and sensitivity of current ground-based γ-ray observatories by about one order of magnitude; taking into account those that are background-dominated, this corresponds to increasing the observation time by a factor of almost 100. The Swiss CTA community has concentrated its efforts on the LST project, which provides the Large-Size Telescopes of CTA, and which are the telescopes with the largest scientific reach. Future Swiss efforts concern not only the completion of three additional telescopes, but also the proposal for a further four telescopes for the Southern site of the CTA in Chile within the LST Consortium.

IceCube will extend its reach to cover neutrino oscillations and detect on the order of 100 additional cosmic events per year. Taken together with CTA and advanced GW detectors, IceCube will significantly enhance the reach of multi-messenger astrophysics.

In the next few decades, CHIPP institutes will also play a significant role in a very rich research programme at the forefront of space astroparticle physics. There are three main themes: 1) high-energy astroparticle physics with direct particle detection in space from the GeV to PeV regime (AMS-02, DAMPE, and HERD); 2) multi-messenger astrophysics with X-ray and γ-ray missions (POLAR-2, HERD, and eXTP); and 3) multidisciplinary particle detection instruments development for deep space (PAN). Another space experiment with Swiss involvement, EUSO, plans to investigate ultra-high-energy cosmic rays from space.

The multi-messenger field is advancing and opening exciting new observational methodologies. The astroparticle community is organised in Europe under the hat of APPEC, as the big challenges of the future involve not only the construction of huge research infrastructures, such as CTA, the ET, and the upgraded IceCube, but also the securing of long term operational support and involvement. The multi-messenger approach is at the forefront of big data, as well as open data science, and offers a bright future of open and accessible science to the broader public.

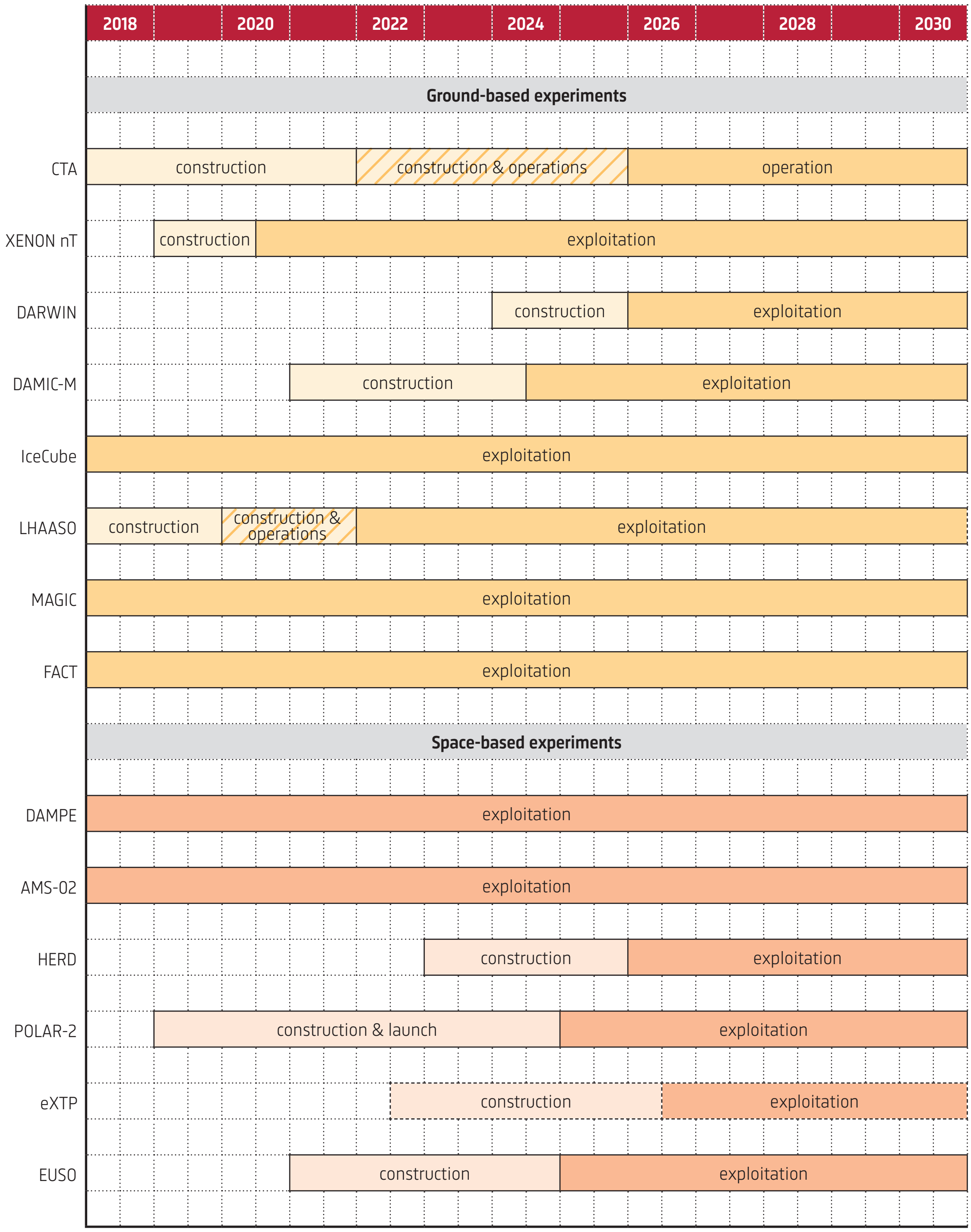


Figure 32: The timeline of major astroparticle physics projects in which Switzerland is engaged. The colour intensity and style indicates the project phases: construction [& launch for the space-based experiments] (light colours), exploitation of the facility (dark colours), and mixed construction and exploitation (line-filled).

12 Development of national infrastructures (2025–2028)

There are a series of research infrastructures at the national level, but with international relevance, that continue to be developed and made available to researchers. The most relevant such example to CHIPP is PSI, which provides the infrastructure for a series of dedicated experiments at low energy and/or requiring the highest-intensity beams. CHIPP strongly supports our national laboratory and regards the addition of new facilities, like the HIMB, as a most favourable development (Fig. 33).

An upgrade of the HIPA facility at PSI is essential. There are several aspects of this upgrade; of particular importance to the Swiss particle physics community are a new meson-production target station and the construction of two new lines. One of these beams should serve particle physics at CHRISP with an intensity increased by almost two orders of magnitude. The physics programme of such a beam is very rich: in addition to enabling completely new particle physics experiments with muons and muonium, it will also allow for vastly improved searches for charged-lepton-flavour-violating decays of muons, presently already pursued at PSI by the world-leading international MEG II and Mu3e Experiments. The other beamline would be part of the Swiss Muon Source (SmuS), and would serve a very broad Swiss and international community pursuing materials science and condensed matter physics with muon spin rotation spectroscopy. An upgrade of the UCN spallation source will provide an increase in UCN yield and benefit all experiments using such particles at CHRISP, including the world-leading search for the electric dipole moment of the neutron. Another part of the HIPA upgrade concerns the TATTOOS project, which will use a new split proton beam after the ring cyclotron and a target station to pursue the production of therapeutically important isotopes as a joint collaboration between radiochemistry and radiopharmacy. This effort is technically outside of the scope of the particle physics roadmap, but it has enormous synergies in its successful implementation at HIPA. The backbone of all of these activities is the HIPA accelerator chain; for continued, reliable operation and improved efficiency, it must undergo a performance-improving consolidation programme. This involves, for example, the replacement of the flat-top cavity in the ring cyclotron, benefiting four large Swiss and international communities: particle physics at CHRISP, condensed matter physics at SmuS and at the spallation neutron source, and radiochemistry and radiopharmacy with its isotope production.

Figure 33: The planned HIMB facility utilises the Megawatt-class PSI proton beam to generate continuous low-energy muon beams with unprecedented intensity. The artist's view shows the high-intensity muon beam to the left and right of the proton-beam transmission-target station. In operation, the proton beam and target region will be covered with heavy shielding as seen further downstream (Image: PSI)

> The computing needs for the High-Luminosity LHC (HL-LHC) era (operating until the mid-to-late 2030s) are expected to grow by a factor of about 50 with respect to the present. Technology advance alone is expected to accommodate a factor of about five, leaving roughly an order of magnitude increase to be adsorbed in other ways. The particle physics community has started a global effort to expand its computing horizons beyond the classic customised cluster model, and has begun investing in software development to support heterogeneous architectures (mixtures of CPUs, GPUs, FGPAs, and possibly more), which are expected to help in bridging the gap to the HL-LHC computing needs.

Scientific computing and the management of huge datasets are essential for the future of particle physics, and are also fields that are evolving extremely fast. The use of heterogeneous architectures (mixtures of CPUs, GPUs, FPGAs, and possibly more) and machine learning techniques present new opportunities, not only for particle physics and not only for the design and operation of complex particle accelerators, but for science at large. CHIPP itself does not have the resources for detailed follow-ups of all of the developments in the commercial and international scientific computing worlds. In the coming years, various new computing resources will become available in international scientific computing clouds (such as EOSC and PRACE). CSCS (Fig. 34), being involved in many of these efforts, serves as a national competence centre for Swiss

Figure 34: Swiss National Supercomputing Centre (Image: CSCS)

academia, and CHIPP will be able to profit from their competence. To give a scale of the computing power delivered by CSCS, in the year 2020, CSCS delivered a total of about 150 kHSPEC06[9] (split among ATLAS, CMS, and LHCb with an approximate share of 40% each for ATLAS and CMS and 20% for LHCb), and provided about 5 PB of disk space. The worldwide computing resources available for HEP amount to about 7 MHSPEC06 of computing power, over 570 PB of online disk storage, and 800 PB of tape storage as distributed over 150 large official sites worldwide. CSCS resources are open to academia, but also to users from industry and the business sector. Cooperation with the CSCS as a nationally supported and acknowledged computing centre of excellence represents a strategic advantage for CHIPP. The support and advice of experts from the CSCS is important for particle physics progress in a multitude of aspects relating to future computing, in particular in such a fast and specialised field of architectures, computing models, and specific software frameworks.

CHART, the Swiss Centre for Accelerator Research and Technology, was founded to support the future-oriented accelerator project of the FCC at CERN, as well as the development of advanced accelerator concepts in Switzerland that go beyond existing technologies. Particle accelerators enable a broad range of research activities and applications. The CHART programme is of strategic importance not only for CERN, but also for Switzerland. Research and development efforts in CHART are addressing a number of technological topics, including high-field superconducting magnets, but also conceptual and beam-dynamics aspects for future accelerator facilities.

The Swiss Accelerator and Technology Initiative CHART is a joint effort of Swiss Universities, PSI, and CERN to foster the development of particle accelerator concepts and technologies for a next generation of research infrastructures. An important component of the CHART initiative is to prepare for large future CERN projects by creating a national centre of competence in applied superconductivity. SERI, the ETH Board, Uni Genève, EPFL, ETH Zürich, and PSI, in collaboration with CERN, all strongly support this initiative. National facilities needed to build and test all aspects of high-field superconducting magnets must be put in place in view of pushing both Nb_3Sn and high-temperature superconducting-material-based magnet technology to their practical limits. This research will utilise the advanced analytic platforms available at the PSI hard X-Ray and neutron-scattering facilities. Another CHART activity is to build up expertise at EPFL for advanced simulation and optimisation of the particle dynamics for future collider facilities. A goal with increasing relevance is the need to maximise the luminosity of particle beam interactions per unit of power drawn from the grid. This will be achieved by implementing smart collider concepts and by optimising the complex parameter space of colliding beams. Modern scientific computing methods will be applied, including large-scale tracking simulations using parallelisation and machine learning methods.

---

[9] A computing performance figure for a HEP-specific benchmark.

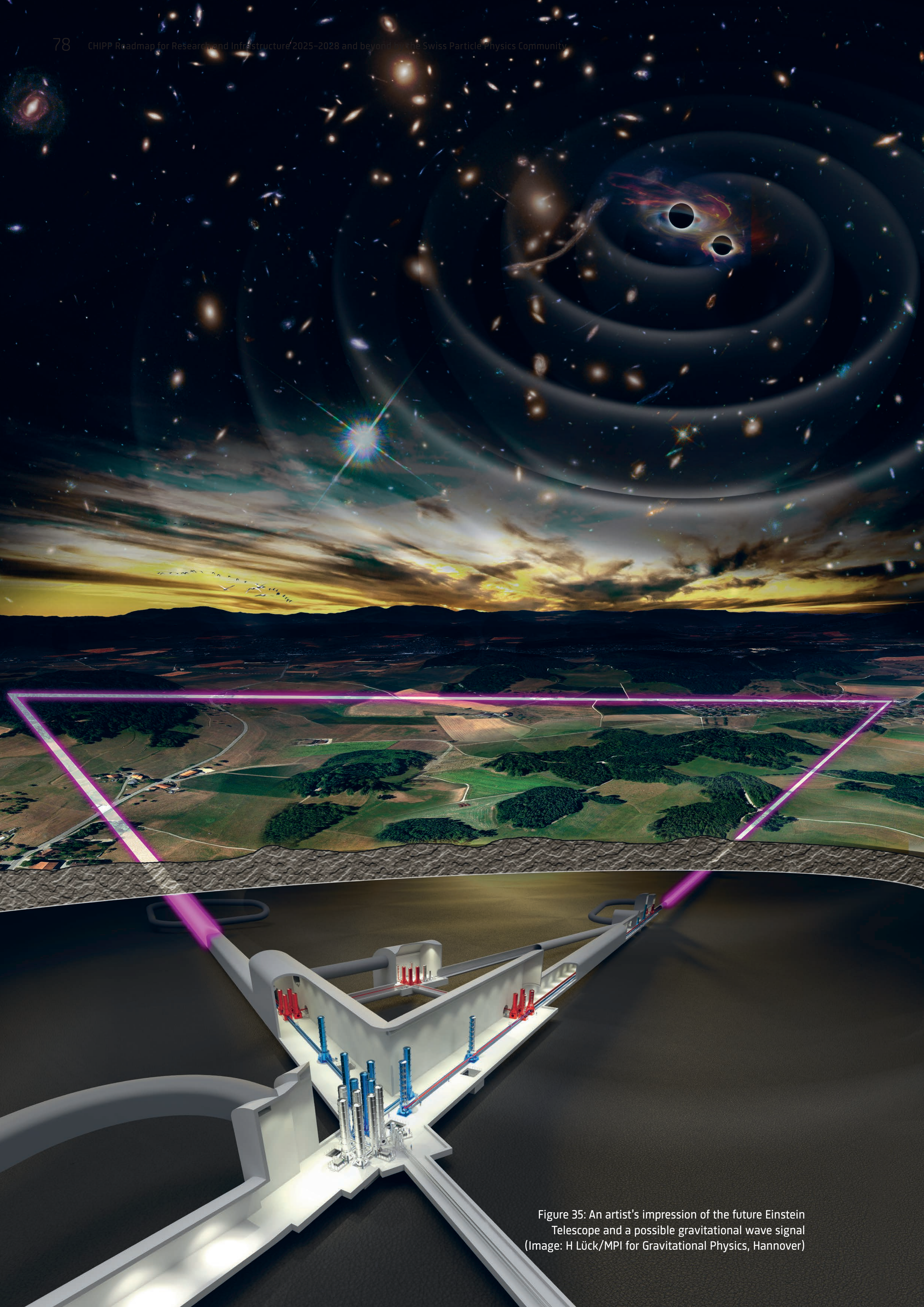


Figure 35: An artist's impression of the future Einstein Telescope and a possible gravitational wave signal (Image: H Lück/MPI for Gravitational Physics, Hannover)

13 Swiss participation in international organisations (2025–2028)

Participation in international organisations and access to large research infrastructures and facilities is a necessary part of modern particle and astroparticle physics. Involvement in such groups is based on a series of agreements at different levels of political and scientific organisations, in order to guarantee access and the means for participation to Swiss researchers.

CERN, as the world-leading organisation in this field, continues to play a crucial role for the Swiss particle physics community. Switzerland is a host state and founding member of CERN, and its participation is regulated by an international law agreement at the federal government level. This commitment is an important foundation for CHIPP, and we rely on the long term continuation of this agreement, notably in view of future frontier projects such as the FCC, as also shown throughout this document. Similarly relevant at the federal level in this respect are Swiss partnerships with organisations that operate accelerator-based, reactor-based, or other large research infrastructures of relevance to the CHIPP community: ILL in Grenoble, the European Synchrotron Radiation Facility (ESRF), ESS, the European XFEL, and the European Southern Observatory (ESO).

Swiss astroparticle physics groups collaborate closely with international space agencies, including the European Space Agency (ESA), the USA's National Aeronautics and Space Administration (NASA), the National Space Science Centre (NSSC) of the Chinese Academy of Sciences, and the Chinese Manned Space Agency (CMSA).

CHIPP is very grateful for the support that it receives from the Swiss Confederation through SERI, including the dedicated contributions in support of Swiss participation in new international research infrastructures during their construction and establishment phase. CTA as next-generation high-energy gamma-ray observatory will be run as a European Research Infrastructure Consortium (ERIC), with solid Swiss participation and a possible cooperation on future R&D for the LST. It is not yet clear if Switzerland will be a founding member or will have another status, such as a strategic partnership; the final decision about Switzerland joining the ERIC will require the approval of the Swiss Parliament. CTA is a priority of the APPEC Roadmap and roadmaps in many countries.

A few projects with major CHIPP participation are listed in the Swiss Roadmap for Research infrastructures 2019. This includes the DARWIN observatory for DM searches and neutrino measurements. An infrastructure for common data processing (CDCI) is also listed with relevance to a number of CHIPP-related activities. Future participation in the neutrino experimental facilities in the USA and Japan will be achieved through contributions to the experiments. Research infrastructure supported by CHIPP and CHAPS for the measurement of GW, such as the Einstein Telescope (Fig. 35), could lead to the need for funding an overall Swiss participation in the 2025 to 2028 timescale.

In addition to participating in research facilities, experiments in particle and astroparticle physics also require dedicated contributions. The long term nature of this type of research requires stability in the commitment to and associated funding for projects over extended periods of time. The engagement is usually made through (legally non-binding) Memoranda of Understanding with international organisations or consortia, in the context of resource review bodies (such as RRBs for the LHC and long-baseline neutrino collaborations). The FLARE funding instrument, with funds provided by the Swiss confederation (as requested to the Parliament through the dispatch on the promotion of education, research and innovation), has supported the hardware, consumables, operation cost, and technical personpower needs of the particle physics and astronomy communities since 2013. This funding instrument, which provides prioritisation guidelines to an international evaluation panel for proposed activities through a bottom-up process, is vital to achieving the scientific goals of CHIPP. The participation of this funding option at the experiment level also supports activities at national laboratories, which are not directly co-funded through Swiss membership, such as the Fermi National Accelerator Laboratory (Fermilab) in the USA, the High-Energy Accelerator Research Organisation (KEK) in Japan, or the Deutsches Elektronen-Synchrotron (DESY) in Germany.

Financial participation in smaller-scale (but not less internationally relevant) experiments is provided through Universities and cantonal support. National initiatives and collaborations of Swiss institutions with federal support have had great impact internationally. One key example is the Swiss accelerator research and technology collaboration (CHART), which supports Swiss participation in future large-scale CERN projects like the FCC, and which also creates synergies between particle physics and other accelerator-driven fields of science.

14 Conclusions

Particle physics addresses some of the most fundamental questions about Nature: what is matter made of, and how do the matter constituents 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.

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 the outmost importance for the field.

Swiss researchers are well invested in international projects in particle and astroparticle physics, as 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 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 centre 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. The dominance of matter over antimatter in the Universe is a further open question, which requires a detailed study of the phenomenon of CP violation in both the quark and lepton sectors. Gravitational interactions, presently described by General Relativity, so far defy a complete description in the ‘lingua franca’ of particle physics, Quantum Field Theory. The study of the nature of gravity is thus a topic of increasing interest also within the CHIPP community. Common research interest with the CHAPS community, such as the exploration and exploitation of gravitational waves for multi-messenger astrophysics, is obvious and should be further strengthened, building on already existing ties.

Handling the analysis and processing of ever-increasing big data necessitates extensive computing infrastructure, and is becoming a challenge across many disciplines. Engaging in research and development on how to share efficiently this costly computing infrastructure between various big data facilities in particle physics, astroparticle physics, astrophysics, and cosmology is an obvious next step, and requires sufficient resources in funding and personpower from the participating institutes. A national initiative would be most welcome in this regard to jump start the effort.

Last but not least, our field depends crucially on educating the next generation of researchers. Early career researchers are an invaluable asset of our field, and should be appropriately supported and nurtured. CHIPP will strive to continue to support their careers, and to improve the education and networking opportunities available to young CHIPP physicists. Equally important is having lines of dialogue with the public, one of our main stakeholders. The number of scientists engaged in outreach steadily increases, as does the variety and ingenuity of their efforts. Particular efforts are hereby taken to attract the young generation to STEM-related subjects.

Fundamental physics serves no immediately obvious direct or applied purpose, other than to gain fundamental insights into nature and to gain knowledge about the Universe. This purely curiosity-driven gain of knowledge is actually a basic aspect of human culture. Besides the intellectual added value that our research provides, there are also tangible benefits that fundamental physics brings to society, such as the development of new technologies (the World Wide Web and touch screen technology come to mind), technology transfer to other fields such as medical physics, education of young scientists eventually seeking opportunities outside of physics, and the strengthening and fostering of international relations. The example of the discovery of electromagnetism teaches us that yesterday’s philosophical ‘l’art pour l’art’ endeavour can lay the foundation for a multi-trillion CHF enterprise a hundred years or so later. As with any investment portfolio, investment in longer-term assets, such as fundamental physics, will likely, while requiring some patience and endurance, also provide substantial non-intellectual dividends.

15 Appendix

15.1 Experiments

15.1.1 Experiments with Swiss contributions at particle accelerators (energy and intensity frontiers)

ATLAS: (A Toroidal LHC ApparatuS) is the largest general-purpose particle detector at the LHC. The ATLAS Detector is 46 metres long, 25 metres in diameter, and weighs about 7,000 tonnes. The ATLAS Collaboration consists of approximately 5,000 members and about 3,000 scientific authors from 183 institutions in 38 countries.
https://atlas.cern

Beam EDM: The Beam EDM (Electric Dipole Moment) Experiment will measure the neutron EDM using a pulsed cold neutron beam. The experiment is intended to be conducted at the future European Spallation Source.
https://www.lhep.unibe.ch/research/neutron_and_precision

CMS: (Compact Muon Solenoid) is one of two large general-purpose particle physics detectors at the LHC. The CMS Detector is 21 metres long, 15 metres in diameter, and weighs about 14,000 tonnes. The CMS Collaboration is formed by more than 4,000 people from 206 institutes in 47 countries.
https://cms.cern

CREMA: (Charge Radius Experiments with Muonic Atoms) is an international collaboration aiming at high-accuracy measurements of the Lamb shift in muonic atoms, to be conducted using laser spectroscopy.
https://www.psi.ch/en/muonic-atoms

FASER: (ForwArd Search ExpeRiment at the LHC) is a small experiment 480 metres downstream of the ATLAS Detector at the CERN LHC. FASER is designed to capture decays of exotic particles produced in the very forward region, which are outside of the ATLAS Detector's acceptance. FASERnu, a FASER sub-detector, is designed to detect collider neutrinos for the first time and to study their properties. The experiment will take data during Run 3 of the LHC.
https://faser.web.cern.ch

GBAR: (Gravitational Behaviour of Antimatter at Rest) is an experiment that measures the gravitational free-fall acceleration of antimatter. It operates in the Antiproton Decelerator Hall at CERN, using antiprotons slowed down by the ELENA facility. GBAR first combines the antiprotons with two antielectrons, to form antihydrogen ions with a positive charge. Using laser-cooling techniques, these ions are brought to micro-Kelvin temperatures before they are stripped of their additional antielectron, transforming them into antihydrogen atoms. These antihydrogen atoms are then allowed to fall from a height of 20 centimetres, and their annihilation at the end of the fall is recorded. GBAR was approved in May 2012 and received its first beam of antiprotons in 2018.
https://gbar.web.cern.ch/public

LHCb: (Large Hadron Collider beauty) is a specialised b-physics experiment at the LHC which was primarily designed to measure the parameters of CP violation in decays of bottom (beauty) and charm hadrons. Its evolving physics scope has turned LHCb into a multi-purpose experiment uniquely sensitive to the forward region of LHC collisions, studying not only proton-proton interactions, but also collisions from heavy-ion runs and from a dedicated fixed-target programme. The detector is a forward spectrometer with a length of about 20 metres. It has a polar angular coverage from 10 to 300 milliradians in the horizontal plane and 250 milliradians in the vertical plane. The LHCb Collaboration is composed of approximately 1,500 people from 87 institutes, representing 17 countries.
https://lhcb-public.web.cern.ch

MEG: (Mu to E Gamma) was an experiment located at PSI dedicated to measuring the rate at which a muon decays into an electron and a photon; this decay mode is heavily suppressed in the SM by lepton-flavour conservation, but is enhanced in many BSM models. MEG took data from 2008 until 2013, and in doing so established the world's best limit on the decay $\mu \to e\gamma$. In order to increase the sensitivity reach by an order of magnitude, a total upgrade involving substantial changes to the experiment has been performed; this new experiment is known as MEG II.
https://meg.web.psi.ch

Mu3e: the Mu3e Experiment at PSI is designed to search for the lepton-flavour-violating decay of a positive muon converting into two positrons and one electron, which violates lepton-flavour conservation. Since this decay is extremely suppressed in the SM, to the order of $\mathcal{O}(10^{50})$, any measurement of this decay would be a clear sign of new physics. In order to reach its ultimate sensitivity, the Mu3e Experiment will observe more than 10^{16} muon decays. This enormous number of muons will be reached by using the world's most intense muon beam, located at PSI, which delivers 10^9 muon-decays/s to the Mu3e detector.
https://www.psi.ch/en/mu3e

mu-Mass: (MUoniuM lASer Spectroscopy) is an experiment at PSI which is pushing the frontier of muonium spectroscopy, with the aim of measuring the 1S-2S transition frequency of muonium, an exotic atom consisting of a positive antimuon and an electron. The mu-Mass Experiment plans to measure this transition at an unprecedented precision of 10 kHz, a 1,000-fold improvement over previous measurements. This will allow for the best determination of the muon mass at the level of one part per billion.
https://www.psi.ch/en/ltp/mu-mass

muX: The muX Experiment measures the charge radii of highly radioactive elements, in addition to measuring atomic parity violation signals in the 2S-1S transition of muonic atoms.
(https://www.psi.ch/en/ltp/mux)

NA64: (North Area 64) is a fixed-target experiment using the 100 GeV electron beam of the CERN SPS fired at a fixed target, where the target is located in the CERN experimental North Area. The primary goal of NA64 is to search for light, dark bosons that are coupled to photons. The experiment started to take data in 2016, and will resume operation with an upgraded detector after the end of LS2 in 2021.
https://na64.web.cern.ch

nEDM/n2EDM: (search for the Neutron Electric Dipole Moment) was designed to measure the electric dipole moment of the neutron with unprecedented precision. It used the ultracold neutron source at PSI, which supplies neutrons at a comparatively slow speed. The collaboration recently published the most sensitive measurement of the neutron EDM to date based on data collected during 2015 and 2016.
https://www.psi.ch/en/nedm

piHe: (PIonic HElium) was an experiment at PSI that used laser spectroscopy and exotic atoms: starting from Helium atoms, one electron was replaced by a pion. This combination enabled high-precision measurements of the mass and other properties of the pion.
https://www.psi.ch/en/ltp/experiments

SHiP: (Search for Hidden Particles) is a proposed general-purpose experiment to be installed in a beam dump facility at the CERN SPS. The primary objective of SHiP is to search for hidden particles, as predicted by models of hidden sectors, which are capable of accommodating dark matter, neutrino oscillations, and the origin of the full baryon asymmetry in the Universe. The present detector design incorporates two complementary apparatuses which are capable of searching for hidden particles through both visible decays and scattering signatures involving recoiling electrons or nuclei. Moreover, the facility is ideally suited to study the interactions of tau neutrinos.
https://ship.web.cern.ch

15.1.2 Experiments with Swiss contributions in neutrino physics

DUNE: (Deep Underground Neutrino Experiment) is a leading-edge, international experiment for neutrino science and proton decay studies supported by the Long-Baseline Neutrino Facility (LBNF). DUNE will consist of two neutrino detectors positioned in the path of an intense neutrino beam. One detector will be located close to the source of the beam, at the Fermi National Accelerator Laboratory in Illinois, USA. A second detector will be deep underground, and 1300 km away from the source, at the Sanford Underground Research Laboratory in South Dakota. Two prototype far detectors are at CERN; the first started taking data in September 2018 and the second is under construction.
https://www.dunescience.org

GERDA: (GERmanium Detector Array) was an experiment searching for neutrinoless double-beta decay ($0\nu\beta\beta$) in ^{76}Ge at the underground Laboratori Nazionali del Gran Sasso (LNGS) in Italy. Evidence of such decays would prove that neutrinos and antineutrinos are identical particles. The observation of $0\nu\beta\beta$, a lepton-number-conservation-violating process, is beyond the Standard Model of particle physics. Such an observation could reveal the nature of neutrinos and give hints on both the neutrino absolute mass scale and ordering.
https://www.mpi-hd.mpg.de/gerda

Hyper-K: (HYPER-Kamiokande) is a neutrino observatory being constructed at the site of the Kamioka Observatory, near Kamioka, Japan. It will be the next generation of large-scale water Cherenkov detector, consisting of a tank with a billion litres of ultra-pure water. The first data-taking period is planned for 2027.
https://www.hyperk.org

K2K: (KEK to Kamioka) was a neutrino experiment that ran from 1999 to 2004 in Japan. It was the first experiment that measured neutrino oscillations in a neutrino beam.
https://neutrino.kek.jp

LEGEND: (Large Enriched Germanium Experiment for Neutrinoless double-beta Decay) is the next-generation experiment searching for neutrinoless double-beta decay ($0\nu\beta\beta$) in ^{76}Ge. In the first phase of LEGEND, approximately 200 kg of enriched ^{76}Ge detectors will be operated. LEGEND-200 will be located at LNGS, and will largely reuse the existing GERDA infrastructure, including some of the germanium detectors, the outer water tank, and the inner cryostat. The first data-taking period is planned for mid-2021.
http://legend-exp.org

MicroBooNE: (Micro BOOster Neutrino Experiment) is a large neutrino experiment based at the Fermilab Booster neutrino beamline. The experiment first started to take data in 2015. It uses a large 170-tonne liquid argon time projection chamber for neutrino detection.
https://microboone.fnal.gov

OPERA: (Oscillation Project with Emulsion tRacking Apparatus) was a neutrino experiment at LNGS. It used the CERN neutrino beam and was optimised for detecting tau neutrinos from muon neutrino oscillations. The data-taking period ended in 2012.
http://operaweb.lngs.infn.it

T2K: (Tokai to Kamioka) is a neutrino experiment in Japan studying accelerator neutrino oscillations. T2K was the first experiment which observed the appearance of electron neutrinos in a beam of muon neutrinos. It uses an intense beam of muon neutrinos produced in the J-PARC facility (Japan Proton Accelerator Research Complex) in Tokai; neutrinos are then detected at the Super-K far detector located 295 km away.
https://t2k-experiment.org

Other neutrino physics experiments are described in Sect. 15.1.4

15.1.3 Experiments with Swiss contributions in astroparticle physics from space

AMS-02: (Alpha Magnetic Spectrometer) is installed on the international space station (ISS) and is designed to detect particles and antiparticles. It has been taking data for more than nine years and has measured cosmic ray nuclei, electron, positron, and antiproton fluxes in great detail in the GeV to TeV range.
https://ams02.space/de

DAMPE: (DArk Matter Particle Explorer) is a space telescope used for the detection of high-energy γ-rays, electrons, and cosmic ray ions, as well as for the search for dark matter. It was designed to look for signals of dark matter decays and for direct cosmic ray measurements in the 1 TeV to 100 TeV range. DAMPE was launched by the Chinese Space Agency in 2015.
http://dpnc.unige.ch/dampe

EUSO: (Extreme Universe Space Observatory) is a 2.5-metre-aperture wide-field-of-view fluorescence telescope, intended for the detection of traces of Ultra-High-Energy Cosmic Rays (UHECR) in the atmosphere. It is planned for installation in the Russian segment of the ISS around 2024. EUSO's goal is to add an ultra-high-energy channel to the multi-messenger astronomy programme by building the first all-sky high-statistics map of the arrival directions of UHECR.
http://jem-euso.roma2.infn.it

eXTP: (Enhanced X-ray Timing and Polarimetry) is designed to study the state of matter under extreme conditions of density, gravity, and magnetic fields. The primary goals of the experiment are the determination of the equation of state of matter at supranuclear density, the measurement of QED effects in highly magnetised stars, and the study of accretion in the strong-field regime of gravity. The main targets include isolated and binary neutron stars, strong magnetic field systems like magnetars, and stellar-mass and supermassive black holes. The mission carries a unique and unprecedented suite of scientific instruments enabling, for the first time, simultaneous

spectral-timing-polarimetry studies of cosmic sources in the energy range from 0.5 to 30 keV and beyond. The mission is expected to be adopted in 2021 and is planned to be launched in 2027.
https://www.isdc.unige.ch/extp

HERD: the (High-Energy cosmic Radiation Detection) facility is a flagship science mission planned to be launched around 2025 and to be installed on board China's Space Station. HERD will extend direct cosmic ray measurements to the PeV regime, allowing for connections to ground-based observations. The main science objectives are the detection of dark matter particles, the study of cosmic ray flux and composition, and high-energy γ-ray observations.
http://herd.ihep.ac.cn

INTEGRAL: (INTErnational Gamma-Ray Astrophysics Laboratory) was the first space observatory that can simultaneously observe objects in γ-rays, X-rays, and visible light. It was an ESA Horizon 2000 project, and was launched in 2002. The ground station collecting its data (the Integral Science Data Centre, ISDC) is located in Versoix, near Genève. INTEGRAL is the most sensitive γ-ray observatory ever launched, and it has led to many discoveries on black holes, active galactic nuclei, γ-ray bursts, and more.
https://sci.esa.int/web/integral

POLAR-2: (gamma-ray burst POLARimetry on the China space station) is a compact detector for soft γ-rays with energies below 1 MeV. Its goal is to measure the polarisation of photons from γ-ray bursts, thereby discriminating between different physics models which have been put forward to explain the mechanism leading to these single most luminous events in the Universe. POLAR-2 is now being constructed in Genève and is planned to be put on the Chinese space station in 2024.
https://www.astro.unige.ch/polar-2

15.1.4 Ground-based experiments with Swiss contributions in neutrino and astroparticle physics

CTA: (Cherenkov Telescope Array) is the next-generation array of Imaging Atmospheric Cherenkov Telescopes, which is now entering the implementation phase and expected to be completed in 2025. The CTA Consortium has defined three Key Science Cases on the themes of: understanding the origin and the role of relativistic cosmic particles; probing extreme environments, such as supernova, neutron stars, black holes, and γ-ray bursts; and exploring frontiers in physics, such as the nature of dark matter, axions and their interplay with magnetic fields, and quantum gravitational effects in photon propagation. The CTAO (CTA Observatory) will be composed of two arrays with more than 100 telescopes of three different mirror sizes to cover an energy range from about 20 GeV to 300 TeV. One is located in the Northern hemisphere (La Palma), and one in the Southern hemisphere (ESO site of Paranal in Chile), both at about 2,000 m above sea level. The three different telescope mirror diameters that will be deployed are 24 metres (LSTs, Large-Size Telescopes), 12 metres (MSTs, Middle-Size Telescopes) and 4 metres (SSTs, Small-Size Telescopes). CTA will be an international open-access observatory governed by the CTAO ERIC, which will become operational in mid-2021.
https://www.cta-observatory.org

FACT: (First g-Apd Cherenkov Telescope) is a small 4-metre Cherenkov telescope pioneering the usage of silicon photomultipliers (also called G-APD: Geiger-mode Avalanche PhotoDiodes) and performing the first unbiased monitoring of variable extragalactic objects at energies above 1 TeV. It is located on the island of La Palma, situated between MAGIC and the first LST of CTA; FACT also supports the commissioning of the first LST.
https://www.isdc.unige.ch/fact

IceCube: is a 1 cubic kilometre instrumented volume of ice, between 1.5 to 2.5 kilometres below the South Pole surface, which was designed to detect high-energy neutrinos. The surface facility detects the electromagnetic component of cosmic ray showers, thus measuring the cosmic ray composition. The in-ice detector consists of 5,600 photomultipliers attached to 86 strings. These photomultipliers detect Cherenkov light produced by charged particles induced through neutrino interactions.
IceCube is undergoing upgrades in two phases. In a first Phase 1, the size of its dense core detector (Precision Icecube Next Generation Upgrade, PINGU) is increased with an additional 7 strings, holding 700 new and enhanced optical modules. This upgrade lowers the energy threshold for neutrino detection down to 1 GeV. The next IceCube upgrade (IceCube Gen-2) will add photosensor-strings to increase the instrumented ice volume by about a factor of 10, extend the surface veto array, and add a radio-detector array exploiting the Askaryan effect to focus on signals induced by high-energy cosmogenic neutrinos.
https://icecube.wisc.edu

LHAASO: (Large High Altitude Air Shower Observatory) is located 4,400 metres above sea level in the mountains of the Sichuan province of China. It is a new-generation Extensive Air Shower (EAS) array for cosmic ray detection in the energy range from 10^{11} to 10^{18} eV, and for γ-rays above 1 TeV. The observatory is currently under construction; it is currently 50% in place, and is expected to be completed by the end of 2021. The data-taking activities started in 2019 and the analysis of the data is ongoing. LHAASO is expected to be the most sensitive project to the open questions in Galactic cosmic ray physics, with the unique ability to detect cosmic ray sources and heavy dark matter in the galactic halo. With its large field of view and almost 100% duty cycle, LHAASO has a unique potential to detect the PeVatron(s) in the Galaxy, which also contribute to the cosmic neutrino flux as detected by IceCube.
http://english.ihep.cas.cn/lhaaso

MAGIC : (Major Atmospheric Gamma-Imaging Cherenkov telescopes) is a system of two imaging atmospheric Cherenkov telescopes situated at the Roque de los Muchachos Observatory on the island of La Palma, at about 2,200 metres above sea level. MAGIC detects particle showers released by γ-rays through their Cherenkov radiation. The telescopes have two 17 metre-diameter reflectors, now surpassed in size by the first LST of CTA of 24 metres and by the H.E.S.S. II telescope. Together with H.E.S.S. and VERITAS, MAGIC has opened the ground-based γ-ray field to Big Science, covering a range from the observation of the pulsation of pulsars above 100 GeV to the extension of the γ-ray burst spectrum up to above 300 GeV.
https://magic.mpp.mpg.de

15.1.5 Experiments with Swiss contributions for direct dark matter detection

DAMIC and DAMIC-SNOLAB: (DArk Matter In Ccds) is an experiment, located at SNOLAB in Canada, that is based on the idea that DM is a relic from an entire dark or hidden sector; this hidden sector is expected to contain a hidden photon, which then interacts very weakly with the 'visible' sector representing ordinary matter. DAMIC has sensitivity to many orders of magnitude in DM mass for various assumptions on how the hidden photon relates to the dark matter and the formation of dark matter in the early Universe. The subsequent DAMIC-SNOLAB Experiment increased the mass, decreased backgrounds, and concluded in 2019 after having producing several world-leading results extending beyond the standard searches for WIMP dark matter into the domain of hidden-photon DM.
https://www.snolab.ca/science/experiments/damic

DAMIC-M and OSCURA: DAMIC-M is an approved and funded international experiment, to be located at the Modane Underground laboratory in France, that is set to begin in 2024. It has a mass ten times larger, a background rate ten times smaller, and an energy threshold ten times lower than DAMIC-SNOLAB. Its ability to detect single ionisation electrons has been made possible through the use of a novel 'skipper' electronics readout. DAMIC-M will probe ten orders of magnitude in DM mass over a range of theoretical scenarios. Studies have also been undertaken for a new experiment to be named OSCURA; this new experiment would be ten times bigger than DAMIC-M and would have an even lower background rate and energy threshold.
https://damic.uchicago.edu/index.php, https://astro.fnal.gov/science/dark-matter/oscura

DARWIN: (DARk matter WImp search with liquid xenoN) is the ultimate DM detector based on liquid xenon, which will explore the full WIMP parameter space (using an exposure of 200 tonne-years) above the so-called 'neutrino floor' where neutrinos will start to dominate the signal. The project is presently in the R&D and design phase, with a CDR planned for 2022 (an invitation was issued by LNGS, after a successful LoI submission and review), and a TDR in 2024. At the earliest, data-taking activities would start in 2026 or 2027. DARWIN will have a similar reach to dedicated future neutrinoless double-beta decay experiments through studies of the decay of ^{136}Xe, and will enable high-statistics observations of *pp* neutrinos from the Sun. It will also search for solar axions, galactic ALPs and dark photons, a magnetic moment of the neutrino, and measure coherent-elastic neutrino-nucleus scattering from ^{8}B solar neutrinos and eventually from supernovae.
https://darwin.physik.uzh.ch/index.html

XENON1T: The XENON1T Experiment was a 3,500 kg liquid xenon detector designed to search for dark matter. It acquired data at LNGS from 2016 to 2018, and set the world's best limits on the WIMP-nucleon elastic scattering cross-section for DM masses above 85 MeV, as well as on the DM-electron scattering cross-section for masses above 30 MeV.
http://www.xenon1t.org

XENONnT: The XENONnT Experiment was installed at LNGS in early 2020, and is currently under commissioning. With a fiducial liquid xenon mass of 4 tonnes and an exposure of 20 tonne-years, the expected sensitivity to spin-independent interactions will reach a cross-section of 1.4×10^{-48} cm^2 for a 50 GeV/c^2 mass WIMP, which is a factor of 10 improvement compared to XENON1T. XENONnT will also search for the neutrino less double-beta decay of ^{136}Xe, and will be able to probe the excess of events observed by XENON1T in the 1.7

keV region within a few months of the start of data-taking activities; it will additionally be able to distinguish between this excess as originating from a tritium component or a solar axion signal.
http://www.xenonnt.org

15.2 Links

ABB: https://new.abb.com/ch

Advanced Accelerator Technologies AG (AAT): https://aa-t.ch

AMPEGON Power Electronics: https://ampegon.com

AMS-02: https://ams02.space/de

Anaxam: https://www.anaxam.ch

APPEG: https://appec.org

ATLAS: https://atlas.cern

Arktis Radiation Detectors Ltd: https://www.arktis-detectors.com

Arktis detectors: https://www.arktis-detectors.com/security-radiation-portal-monitors

ASCOM Systec AG: https://www.ascom.com

ATTRACT: https://attract-eu.com

BAS: https://www.basf.com/ch/de/who-we-are/BASF-in-Switzerland/group-companies/BASF-Schweiz- AG.html

Beam EDM: https://www.lhep.unibe.ch/research/neutron_and_precision

Bolleter Composites AG: https://bolletercomposites.ch

CAEN SpA: https://www.caen.it

CERN Open Data Policy: https://cds.cern.ch/record/2745133/files/CERN-OPEN-2020–013.pdf

CERN Open Data Portal: http://opendata.cern.ch

CERN's Science Gateway project: https://sciencegateway.cern

CERN summer student programme: https://home.cern/summer-student-programme

CERN Teacher programme: https://teacher-programmes.web.cern.ch

CHIPP worshops: https://chipp.ch/en/meetings_documentation/strategic_workshops

CMS: https://cms.cern

Cosylab: https://swiss-aerospace-cluster.ch/portfolio-item/cosylab

Createch AG: https://www.createch.ch

CREMA: https://www.psi.ch/en/muonic-atoms

CTA: https://www.cta-observatory.org

DAES: https://daes.pro/en

Daetwyler Industries: https://www.daetwyler.com/en

DAMIC: https://www.snolab.ca/science/experiments/damic

DAMIC-M: https://damic.uchicago.edu

DAMPE: http://dpnc.unige.ch/dampe

DARWIN: https://darwin.physik.uzh.ch/index.html

Dectris: https://www.dectris.com

D-Pace: https://www.d-pace.com

DRS4: https://www.psi.ch/en/drs

DUNE: https://www.dunescience.org

Energiebericht: https://www.sbfi.admin.ch/sbfi/en/home/services/publications/data-base-publications/report-energy-research.html

e-Péron: https://eperon.omp.eu

EPPCN: https://espace.cern.ch/EPPCN-site

EPS: www.eps.org

Espace Ballon exhibition: https://www.chateau-doex.ch/de/P395/ballonraum-espace-ballon

ESPROS photonics corporation – EPC: https://www.espros.com

Eulitha: https://www.eulitha.com

EUSO: http://jem-euso.roma2.infn.it/

eXTP: https://www.isdc.unige.ch/extp

FACT: https://www.isdc.unige.ch/fact

FASER: https://faser.web.cern.ch

Ferrovac GmbH: https://www.ferrovac.com

FRM-2: https://www.frm2.tum.de/en/home

GBAR: https://gbar.web.cern.ch/public

GE-General Electric: https://www.s-ge.com/en/company/general-electric-switzerland-gmbh

GERDA: https://www.mpi-hd.mpg.de/gerda

GratXRay: https://www.gratxray.com

HABA: https://www.haba.ch/en

Hamamatsu: https://www.hamamatsu.com/jp/en/index.html

HERD: http://herd.ihep.ac.cn

HEV: https://hev.web.cern.ch

HSSIP: https://hssip.web.cern.ch

HyperKamiokande: https://www.hyperk.org/

IceCube: https://icecube.wisc.edu

INTEGRAL: https://sci.esa.int/web/integral

International Particle Physics Masterclass: https://physicsmasterclasses.org

iLab: https://www.psi.ch/ilab

IngCH: https://ingch.ch

InterAx: https://interaxbiotech.com

IPPOG: http://ippog.org

K2K: https://neutrino.kek.jp

Kabelwerke Brugg AG: https://bruggcables.com

KM3NeT: https://www.km3net.org

LEGEND: http://legend-exp.org

LHAASO: http://english.ihep.cas.cn/lhaaso

LHCb: https://lhcb-public.web.cern.ch

MAGIC : https://magic.mpp.mpg.de

MEDELEC SA: https://resonetics.com/innovations/medelec-swiss-precision-tubing

MEG: https://meg.web.psi.ch

MicroBooNE: https://microboone.fnal.gov

Mu3e: https://www.psi.ch/en/mu3e

muCool: https://edm.ethz.ch/research/muoncooling.html

mu-Mass: https://www.psi.ch/en/ltp/mu-mass

muX: https://www.psi.ch/en/ltp/mux

NA64: https://na64.web.cern.ch/

Nacht der Forschung: https://www.nachtderforschung.unibe.ch

nEDM: https://www.psi.ch/en/nedm

Nestlé: https://www.nestle.ch

Netzwerk Teilchenwelt: https//www.teilchenwelt.de

Neutrino Platform: https://home.cern/science/experiments/cern-neutrino-platform

Nexans: https://www.nexans.ch

Novartis: https://www.novartis.com

Nuits de la Science: http://www.ville-ge.ch/lanuitdelascience

OPERA: http://operaweb.lngs.infn.it

OSCURA: https://astro.fnal.gov/science/dark-matter/oscura

Physiscope: https://dqmp.unige.ch/physics-for-all/physiscope

POLAR-2: https://www.astro.unige.ch/polar-2

Positrigo AG: https://www.positrigo.com

Roche: https://www.roche.com/careers/our-locations/europe/switzerland.htm

RADEC GmbH: https://www.radec.ch

SATW: https://www.satw.ch

Science Lab: http://www.sciencelab.uzh.ch

Scientifica: https://www.scientifica.ch

SCNAT: https://naturalsciences.ch

SCS-Super Computing Systems: https://www.scs.ch

SE2S GmbH: http://www.se2s.ch

SENSIRION: https://www.sensirion.com

SHiP: https://ship.web.cern.ch

Sichuan Tianle Photonics Co.: https://sctlxd.en.china.cn

Spalinger Präzisionsmechanik GmbH: https://www.spalinger.info

SURCOTEC: http://surcotec.ch/en/surcotec-2

SWAN Isotopen AG: https://www.swanisotopen.ch/en

Swiss Physical Society (SPS): www.sps.ch

Swiss Roadmap for Research Infrastructures 2019: https://www.sbfi.admin.ch/sbfi/en/home/research- and-innovation/research-and-innovation-in-switzerland/swiss-roadmap-for-research-infrastructures.html

SwissNeutronics:https://www.swissneutronics.ch

T2K: https://t2k-experiment.org

TecDays: https://www.satw.ch/en/tecdays

Technology and IT weeks: https://ingch.ch/en/angebote/technik-und-informatikwochen

Thin Film Physics: http://www.tfpag.ch

Transmutex SA: https://www.transmutex.com

UNSOLVeD: https://www.un-solved.com

Varian: https://www.varian.com/en-ch

YouTube channel 'Das verflixte Higgs': www.youtube.com/user/verflixteshiggs

YouTube video 'How particle-physics works: hope and worries on the *B*-physics anomalies': https://www.youtube.com/watch?v=9dLyTS0Xscw

XENON1T: http://www.xenon1t.org

XENONnT: http://www.xenonnt.org

Acronyms

ACHIP	Accelerator on a Chip
AD	Antiproton Deaccelerator.
AdS	Anti-de Sitter space time
ADS	Accelerator Driven Subcritical
ALP	Axion Like Particle
AMS-02	Alpha Magnetic Spectrometer (on the ISS)
ANITA	Antarctic Impulsive Transient Antenna
ANTARES	Astronomy with a Neutrino Telescope and Abyss environmental RESearch
APPEC	Astroparticle Physics European Consortium
ARIES	Accelerator Research and Innovation for European Science and Society
ASIC	Application-Specific Integrated Circuits
ATLAS	A Toroidal LHC Apparatus (LHC Experiment)
BASE	Baryon Antibaryon Symmetry Experiment
BBH	Binary Black Hole
BDF	Beam Dump Facility
BH	Black Hole
BNS	Binary Neutron Star
BSM	Beyond the Standard Model
CCD	Charge-Coupled Device
CDR	Critical Design Review
CE	Cosmic Explorer
CEPC	Circular Electron Positron Collider in China
CERN	European Organization for Nuclear Research
CFT	Conformal Field Theory
CHAPS	College of Helvetic Astronomy Professors
CHART	Swiss Accelerator Research and Technology
CHIPP	Swiss Institute of Particle Physics
CHRISP	Swiss Research Infrastructure for Particle Physics
cLFV	Charged Lepton Flavour Violating reaction
CLIC	Compact Linear Collider
CMB	Cosmic Microwave Background
CMS	Compact Muon Solenoid (LHC Experiment)
CMSA	Chinese Manned Space Agency
CP	Charge-conjugation and Parity symmetry
CPT	Charge-conjugation Parity and Time symmetry
CPU	Central Processing Unit
CREMA	Charge Radius Experiments with Muonic Atoms
CSCS	Swiss National Supercomputing Centre
CTA	Cherenkov Telescope Array
CTAO	CTA Observatory
DAMIC	Dark matter in CCDs (experiment at SNOLAB)
DAMIC-M	Dark matter in CCDs experiment at Modane (experiment at Laboratoire Souterrain de Modane, France)
DAMPE	Dark Matter Particle Explorer (space telescope)
DAQ	Data Acquisition
DARWIN	Dark Matter Wimp Search with Liquid Xenon (planned experiment at LNGS, Italy)
DM	Dark Matter
DS	Dark Sector
DUNE	Deep Underground Neutrino Experiment
EAS	Extensive Air Showers
EC	European Commission
ECFA	European Committee for Future Accelerators
EDM	Electron Electric Dipole Moment
EFT	Effective Field Theories
ELENA	Extra Low Energy Antiproton ring
EPFL	École Polytechnique Fédérale de Lausanne
EPPCN	European Particle Physics Communication Network
EPS-AG	Accelerator Group of the European Physical Society
ERC	European Research Council
ERIC	European Research Infrastructure Consortium
ESA	European Space Agency
ESFRI	European Strategy Forum on Research Infrastructures
ESO	European Southern Observatory
ESPP	European Strategy for Particle Physics
ESRF	European Synchrotron Radiation Facility
ESS	European Spallation Source
ET	Einstein Telescope
ETHZ	Eidgenössisch Techniche Hochschule Zürich
EUSO	Extreme Universe Space Observatory
eV	Electron Volts
eXTP	Enhanced X-ray Timing and Polarimetry
FACT	First g-Apd Cherenkov Telescope
FASER	Forward Search Experiment at the LHC
FCC	Future Circular Collider at CERN
FCC-ee	Future Circular Collider, colliding electrons and positrons
FCC-ep	Future Circular Collider, colliding electrons and protons
FCC-hh	Future Circular Collider, colliding hadrons
FLARE	Funding Large international Research projects
FPF	Forward Physics Facility
FPGA	Field-Programmable Gate Array
G-APD	Geiger Mode Avalanche Photodiodes

GBAR	Gravitational Behaviour of Antimatter at Rest
GERDA	Germanium Detector Array (Experiment at LNGS)
GPU	Graphics Processing Unit
GRB	Gamma Ray Burst
GW	Gravitational Wave
H.E.S.S.	High Energy Stereoscopic System (telescope in Namibia)
HEP	High-Energy Physics
HERD	High-Energy Cosmic Radiation Detection (on board of China's Space Station)
HEV	High-Energy Ventilator
HIMB	High-Intensity Muon Beam at PSI
HIPA	High-Intensity Accelerator complex at PSI
HL	High Luminosity
HL-LHC	High-Luminosity LHC
HNL	Heavy Neutral Leptons
HPC	High-Performance Computer
HSF	HEP Software Foundation
HSSIP	High-School Students Internship Programme
HTS	High-Temperature Superconductors
Hyper-K	HYPER-Kamiokande (Neutrino observatory near Kamioka, Japan)
ICFA	International Committee for Future Accelerators
ILC	International Linear Collider
ILL	Institut Laue-Langevin in Grenoble
INFN	Istituto Nazionale di Fisica Nucleare
INTEGRAL	International Gamma-Ray Astrophysics Laboratory
IPAC	International Particle Accelerator Conference
IPPOG	International Particle Physics Outreach Group IR Infrared
IR	Infrared
ISFEE	Inertial Sensor Front End Electronics
ISS	International Space Station
J-PARC	Japan Proton Accelerator Research Complex
JUNO	Jiangmen Underground Neutrino Observatory
K2K	KEK to Kamioka (neutrino experiment in Japan)
KEKB	Electron Positron collider (at KEK, Japan)
LANL	Los Alamos National Laboratory
LBNF	Long-Baseline Neutrino Facility
LBNL	Lawrence Berkeley National Laboratory
LDM	Light Dark Matter
LEGEND	Large Enriched Germanium Experiment for Neutrinoless Double-Beta Decay (at LNGS, Italy)
LHAASO	Large High Altitude Air Shower Observatory (in Sichuan province, China)
LHC	Large Hadron Collider (at CERN)
LHCb	Large Hadron Collider beauty (LHC experiment)
LHEP	Laboratory for High-Energy Physics
LIGO	Laser Interferometer Gravitational-Wave Observatory
LINAC	Linear Accelerator
LISA	Laser Interferometer Space Antenna
LNGS	Laboratori Nazionali del Gran Sasso
LS2(LS3)	Long Shutdown 2(3) (of the LHC)
LSS	Cosmological Large-Scale Structure
LSST	Vera C Rubin Observatory Large Synoptic Survey Telescope
LST	Large-Size Telescope
LXe	Liquid Xenon
MAGIC	Major Atmospheric Gamma Imaging Cherenkov Telescopes (La Palma)
MEG/MEG II	$\mu \to e\gamma$ (Experiment at PSI)
MICE	Muon Ionisation Cooling Experiment
MicroBooNE	Micro Booster Neutrino Experiment (experiment at Fermilab, USA)
ML	Machine Learning
MST	Medium-Size Telescope
mu-Mass	Muonium Laser Spectroscopy (Experiment at PSI)
Mu3e	$\mu \to eee$ (Experiment at PSI)
muX	muX (Experiment at PSI)
NA64	North Area 64 (experiment at CERN SPS)
NASA	National Aeronautics and Space Administration
ND280	Near Detector of the T2K experiment
nEDM/n2EDM	Search for the Neutron Electric Dipole Moment (Experiment at PSI)
NIST	National Institute of Standards and Technology (USA)
N^{3}LO	Next to next to next to leading order
NLO	Next to leading order
NNLO	Next to next to leading order
NS	Neutron Star
NSF	National Science Foundation
NSSC	National Space Science Center
NuPECC	Nuclear Physics European Collaboration Committee
OPERA	Oscillation Project with Emulsion Tracking Apparatus (neutrino experiment at LNGS, Italy)
OSCURA	Observatory of Skipper CCDs Unveiling Recoiling Atoms
PAN	Penetrating particle ANalyzer
PET	Positron Emission Tomography
PeV	Peta Electron Volts
piHe	Pionic Helium
PINGU	Precision IceCube Next Generation Upgrade (dense inner detector of IceCube)
PMNS	Pontecorvo-Maki-Nakagawa-Sakata
POLAR-2	Detector for Gamma Ray Bursts Photon Polarization Measurements (on the Chinese space station)
ppm	parts per million

PRODEX	Programme de Développement d'Expériences scientifiques
PSI	Paul Scherrer Institute
QCD	Quantum Chromodynamics
QED	Quantum Electrodynamics
QFT	Quantum Field Theory
R&D	Research & Development
RAL	Rutherford Appleton Laboratory (near Oxfordshire, GB)
RF	Radio Frequency
RI	Research Infrastructure
RRB	Resource Review Board
SATW	Swiss Academy of Engineering Sciences
SBN	Short Baseline Near detector
SciFi	Scintillating Fibre
SCNAT	Swiss Academy of Sciences
SENSEI	Sub-Electron-Noise SKIPPER-CCD Experimental Instrument
SERI	State Secretariat for Education, Research, and Innovation
SESAME	Synchrotron-light for Experimental Science and Applications in the Middle East
SHiP	Search for Hidden Particles (proposed experiment)
SKA	Square Kilometre Array
SLS	Swiss Light Source
SM	Standard Model
SMUS	Swiss Muon Source
SND	Scattering and Neutrino Detector
SNOLAB	Underground Science Laboratory (near Sudbury, Ontario, Canada)
SNS	Spallation Neutron Source
SNSF	Swiss National Science Foundation
SOC	System on Chip
SPS	Super Proton Synchrotron
SSO	Swiss Space Office
SST	Small-Size Telescope
STEM	Science, Technology, Engineering, and Mathematics
STK	Silicon-Tungsten Tracker
SUSY	Supersymmetry
SWISSFEL	Swiss Free Electron Laser
T2K	Tokai to Kamioka (neutrino experiment in Japan)
TDR	Technical Design Report
TeV	Tera Electron Volts
TPC	Time Projection Chamber
TRIUMF	Canada's National Laboratory for Particle and Nuclear Physics (formerly an acronym: Tri-University Meson Facility)
UCN	UltraCold Neutrons
UHECR	Ultra-High-Energy Cosmic Rays
UV	Ultraviolet
VERITAS	Very Energetic Radiation Imaging Telescope Array System
WIMP	Weakly Interacting Massive Particle
WLCG	Worldwide LHC Computing Grid
XFEL	X-ray Free Electron Laser

16 References

1 CHIPP (May 2004) **Status and outlook of research and education.** SCNAT weblink.

2 CHIPP (May 2010) **Achievements, status and outlook: Implementation of the roadmap 2005–2010.** SCNAT weblink.

3 NuPPEC (2017) **NuPECC long range plan 2017 perspectives.** NuPPEC weblink.

4 APPEC (August 2017) **European astroparticle physics strategy 2017–2026.** APPEC weblink.

5 CERN Council (2020) **2020 Update of the European Strategy for Particle Physics**, Geneva.

6 https://www.chipp.ch

7 http://www.snf.ch/en/funding/infrastructures/flare

8 https://twiki.cern.ch/twiki/bin/view/AtlasPublic

9 http://cms-results.web.cern.ch/cms-results/public-results/publications/

10 https://lhcbproject.web.cern.ch/Publications/LHCbProjectPublic/Summary_all.html

11 Banerjee D et al. (2017) **Search for invisible decays of sub-GeV dark photons in missing-energy events at the CERN SPS,** Phys. Rev. Lett., vol. 118, no. 1, p. 011802.

12 Banderjee D et al. (2019) **Dark matter search in missing energy events with NA64,** Phys. Rev. Lett., vol. 123, no. 12, p. 121801.

13 Abel C et al. (2020) **Measurement of the permanent electric dipole moment of the neutron,** Phys. Rev. Lett., vol. 124, no. 8, p. 081803.

14 Baldini A, Bao Y, Baracchini E, Bemporad C, Berg F, Biasotti M, Boca G, Cascella M, Cattaneo P, Cavoto G et al. (2016) **Search for the lepton flavour violating decay μ+ → e+γ with the full dataset of the MEG experiment,** The European Physical Journal C, vol. 76, no. 8, p. 434.

15 Yakovlev V, Grillenberger J, Kim S-H, Seidel M, Yoshii M (May 2017) **The Energy Efficiency of High Intensity Proton Driver Concepts, in Proc. of International Particle Accelerator Conference** (IPAC ’17), Copenhagen, Denmark, 19 May, 2017, no. 8 in International Particle Accelerator Conference, (Geneva, Switzerland), pp. 4842–4847, JACoW.
https://doi.org/10.18429/JACoW-IPAC2017-FRXCB1

16 Aartsen MG et al. (Sep 2014) **Observation of high-energy astrophysical neutrinos in three years of IceCube data,** Phys. Rev. Lett., vol. 113, p. 101101.

17 Aartsen MG et al. (2017) **Observation of Astrophysical Neutrinos in Six Years of IceCube Data in The IceCube Neutrino Observatory – Contributions to ICRC 2017 Part I: Searches for the Sources of Astrophysical Neutrinos**.

18 The IceCube Collaboration and Fermi-LAT and MAGIC and AGILE and ASAS-SN and HAWC and H.E.S.S. and INTEGRAL (2018) **Multimessenger observations of a flaring blazar coincident with highenergy neutrino IceCube-170922A,** Science.

19 Aublin E et al. (2019) **Search for a correlation between the UHECRs measured by the Pierre Auger Observatory and the Telescope Array and the neutrino candidate events from IceCube and ANTARES,** EPJ Web Conf., vol. 210, p. 03003.

20 Aprile E et al. (2019) **Observation of two-neutrino double electron capture in 124Xe with XENON1T,** Nature, vol. 568, no. 7753, pp. 532–535.

21 Abbott BP et al. (2016) **Observation of Gravitational Waves from a Binary Black Hole Merger,** Phys. Rev. Lett., vol. 116, p. 061102.

22 Blondel A, Graverini E, Serra N, Shaposhnikov M (2016) **Search for Heavy Right Handed Neutrinos at the FCC-ee,** Nucl. Part. Phys. Proc., vol. 273-275, pp. 1883–1890.

23 Blondel A, Zimmermann F (Dec/2011) **A High Luminosity e^+e^- Collider in the LHC tunnel to study the Higgs Boson**.

24 The NA64 collaboration (Jan 2019) **Proposal for an experiment to search for dark sector particles weakly coupled to muon at the SPS,** Tech. Rep. CERN-SPSC-2019-002. SPSC-P-359, CERN, Geneva.

SCNAT – network of knowledge for the benefit of society

The **Swiss Academy of Sciences (SCNAT)** and its network of 35,000 experts works at regional, national and international level for the future of science and society. It strengthens the awareness for the sciences as a central pillar of cultural and economic development. The breadth of its support makes it a representative partner for politics. The SCNAT links the sciences, provides expertise, promotes the dialogue between science and society, identifies and evaluates scientific developments and lays the foundation for the next generation of natural scientists. It is part of the association of the Swiss Academies of Arts and Sciences..

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.