# CHIPP Roadmap 2020:

# Status and Outlook on
# Particle Physics in Switzerland

Swiss Institute of
Particle Physics

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# 1 Executive summary

[Main Editor: Rainer] [(1-2 pages) – Summary of the scope, the national and international landscape, the future trends and the major challenges in the field. Identification of the major findings and recommendations.]

# 2 Findings and recommendations

[Main Editor: Rainer] [(2-4 pages) – More specifically identify here a series of findings and related recommendations. These can be already imbedded in the various sections of the document and listed again here for easier overview and reference. Simplistic example: Finding 1: Infrastructure XYZ is essential for our community in the field ABC, but it will no more meet the international standards in 5 years. Recommendation 1: There is the need for a major upgrade of this facility or the building of a new infrastructure serving the whole Swiss community.]

# 3 Foreword

[Main Editor: Rainer] [ (1-2 pages) – Describe the process that led to this roadmap and its endorsement by the community. Explain how you tried to reach out to the whole community.]

# 4 List of authors

[Main Editor: Angela] [(1 page) – Provide the list of the authors with affiliations and possibly separating the main editors from other contributors. Possibly add here thanks for support received for the layout work, etc. ]

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# 5 Table of contents

[Main Editor: Angela] [(1-2 pages) – Include a table of contents with page numbers. Possibly with in addition a list of figures and/or of tables, but this is probably only useful for a really long document.]

# 6 Purpose scope

[Main Editor: Rainer] [(1-3 pages) – Clarify what is very generically meant by the overall field (e.g. "biology"), because this is not necessarily obvious to the target audience. What are the main scientific questions and challenges in this field? What is the objective of the document and the point of view adopted (very inclusive or more focused)? Clarify the separation with nearby disciplines (i.e. what is or is not covered here). State whether or not there was an attempt to prioritize the needs of specific infrastructures and how this is reflected in the document.]

[AS: Intro from Klaus, can be used here if needed]

Testing the Standard Model (SM) and searching for physics beyond this theory is done in direct and indirect ways at the high energy frontier at the LHC and future colliders. It can be done in a complementary way also at lower and much lower energies where often much larger intensities of certain particle species allow studying rare processes and small effects at high precision.

Two scenarios are usually considered: Either the mass scale of new physics is too high to be directly probed, or the coupling to known particles is so weak that it has escaped detection so far. In both cases, deviations of precision observables from their SM prediction or the occurence of SM-forbidden effects could 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. Often direct and indirect detection experiments investigate the same underlying physics scenarios and have thus been grouped together into the CHIPP pillar-1. Here we deal with the low-energy, high-intensity and precision frontier.

[(1-3 pages) – Clarify what is very generically meant by the overall field (e.g. "biology"), because this is not necessarily obvious to the target audience. What are the main scientific questions and challenges in this field? What is the objective of the document and the point of view adopted (very inclusive or more focused)? Clarify the separation with nearby disciplines (i.e. what is or is not covered here). State whether or not there was an attempt to prioritize the needs of specific infrastructures and how this is reflected in the document. ]

[Pillar III scope by Ruth]
Particle physics is concerned with the quest for the fundamental laws of nature and its elementary constituents. At the present stage of our knowledge the fundamental interactions are the combination of the Standard Model (SM), described as an $SU(3) \times SU(2) \times U(1)$ gauge theory together with the Yukawa interactions with a Higgs field, and of gravity, described by General Relativity (GR). So far no deviations from these laws have been found, but severe open theoretical problems remain. Also some

experimental tensions exist, e.g. in the flavor sector and on the generation of neutrino masses. Finally, the nature of dark matter and dark energy, the dominant constituents of our Universe, discovered so far only via gravitational interactions, is completely unknown.

These questions are addressed on the one hand by direct, controlled experiments as described in pillars I and II, but also via searches, direct and indirect, for dark matter (DM), dark energy, and for new interactions beyond the standard model at very high energies. This is the approach taken in pillar III.

The advantage of indirect searches via astrophysical objects and events is that we can use objects/events in our Universe as high-energy accelerators. Sufficient precision and the combination of data from diverse observations are needed in order to draw solid conclusions. These very challenging endeavours relate pillar III to astrophysics. We want to investigate whether the very high-energy sources and events we observe in the Universe can occur within the standard model of particle physics or whether we have to go beyond. As a goal at its own right, we also want to better understand the Universe, its origin and evolution.

In order to understand the physics of the most energetic events in the Universe, observations in all wavelength bands of electromagnetic radiation, from radio over microwave, optical and X-rays to $\gamma$-ray are needed. These are combined with cosmic ray detections as well as neutrino and gravitational wave observations. It has become clear that this multi-messenger approach is required for a full picture. Only the combination of all of these data allows us to understand astrophysical accelerators sufficiently well, to determine whether or not we see deviations from the standard model of particle physics at very high energies. The present 'showcase' example is the binary neutron-star coalescence GW170817 discovered first with LIGO/Virgo and later seen by many electromagnetic counter parts in X-ray, optical, IR, UV and radio. These data allow us to address long standing questions about the interior of neutron stars: is there a quark gluon plasma phase, do hyperons form inside neutron stars? But they also provide a measurement of the Hubble constant and show that, as in GR, the speed of gravitons is equal to the speed of light. This fact excludes entire classes of theories modifying GR which were proposed as explanations of dark energy. Other important examples with significant Swiss involvement will be mentioned below.

Clearly, pillar III is very complementary to the pillars I and II. Most statements of pillar III are model dependent and request confirmation either by more direct experiments as they are performed in pillars I and II or, if the energy scale is not available at terrestrial accelerators, via independent observations of another messenger. Furthermore, only pillar III is sensitive to gravitational interactions.

In the quest for dark matter both direct and indirect searches are part of pillar III. But also here, a signal even in a direct search experiment, requires a significant amount of interpretation and requires confirmation by another, direct or indirect experiment, or at accelerators, before firm conclusions can be drawn. A very recent example is the 2-7keV recoil-electron excess detected by Xenon1t. Is it a hint of axions from the sun or just a contamination of the experiment by Tritium, or something completely else?

[Theory scope by Gino]

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 research in particle physics, both on the experimental and on the theoretical side. We can roughly divide the research directions in theoretical particle physics in four main categories:

I. **Precise SM physics.** An essential ingredient to make progress in the field is to develop precise predictions, within the SM, for particle-physics experiments: without precise predictions to compare with, 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, which requires sophisticated tools, both from the analytical and the numerical side.

II. **Model-building and beyond-the-SM (BSM) phenomenology.** A similarly core ingredient of the theoretical research in particle physics is to develop new models of fundamental interactions, able to address some of the shortcomings of the SM, and to understand how these models could possibly be tested in present and future experiments.

III. **Cosmology, astroparticle, gravitational physics.** A growing aspects 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.

IV **Formal theory developments.** The last essential ingredient of the theoretical research in fundamental physics deals with more formal aspects. There are still many regimes of QFT that are poorly understood, especially when going beyond a four-dimensional flat geometry, as required by General Relativity. A rich structure of symmetries connecting seemingly different QFT regimes has also emerged in the last few years. A deeper investigation of these aspects, as well as the development of theoretical frameworks able to go beyond QFT, such as String Theory, are the subject of this more formal line of research.

# 7 The present Swiss landscape

[Main Editor: Rainer and whoever is willing to help] [(5-15 pages) – This section will be very specific to each field. It can be subdivided into research topics and/or per methodology (theoretical versus experimental, laboratory versus field study, and so on). Alternatively, it could be per geographical location, if there are well defined topics covered by different institutions. It shall be as much as possible inclusive of all the community to leave nobody out. It shall also show what are the major topics in Switzerland, which institutes are leaders in specific research areas, and possibly also what is less developed yet (especially if a new infrastructure is foreseen to fill this gap). How strong is the Swiss network: how much do the scientists of different institutes collaborate together? What are the main infrastructures used? Are they accessible to researchers from other institutions? ]

[The following split in sections is intended as an intermediate step for collection of the necessary material. The main editor of the chapter will merge accordingly after the material is available.]

## Input from accelerator research

[Editor: Lenny]

## 7.1 Accelerator Physics and Technology

### 7.1.1 Swiss Landscape

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 material sciences. Switzerland maintains a strong tradition of accelerator R&D, both at Paul Scherrer Institute 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, it resulted in such state of the art synchrotron light sources as Swiss Light Source (SLS) and SwissFEL. The Swiss Accelerator Research and Technology CHART – Collaboration between CERN, ETHZ, EPFL, University of Geneva and PSI – is maintaining this tradition. The mission of CHART is to support the future oriented accelerator project FCC at CERN and the development of accelerator concepts beyond the existing technology. With extraordinary support by SERI, ETH Board and participating institutions CHART contributes to future accelerator driven research infrastructures benefiting science and society.

## Input from Pillar 1

[Editor: Anna]

## 7.2 High energy

Swiss institutes are founding members and significant contributors to three of the four high energy physics experiments at CERN: ATLAS (U Bern and U Geneva), CMS (UZH, PSI and ETHZ) and LHCb (EPFL and UZH). The activities of the Swiss scientists have been spanning a very broad spectrum of physics pursuits: from precision measurements of the Standard Model (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 characterization of this new particle has been achieved. After the long shutdown from 2013 to 2014 to consolidate the LHC magnets to achieve higher bending fields, Run 2 data was collected from 2015 to 2018 at a center-of-mass energy of 13 TeV. This higher energy provided increased cross section of production processes, and along with record performances of instantaneous luminosity, led to enhanced statistics of acquired datasets. These large datasets have allowed for a better understanding of the detectors, new sophisticated developments in reconstruction algorithms, and reduced 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 Run 2 LHC physics program more compelling than ever before. New results have included the observation of the Higgs boson decay to $\tau^+\tau^-$, evidence for the Higgs decay to $bb^-$, the observation of electroweak same-sign $WW$ production, and evidence for top-quark pairs produced in association with a Higgs boson. Moreover, ATLAS and CMS results have opened up new phase space for new physics searches and further strengthened bounds on existing models for Beyond the Standard Model (BSM) physics. The large dataset delivered by the LHC so far and the forthcoming runs promise a strong continuous physics output, which will extend the boundaries of knowledge at the energy frontier.

[TODO: Should mention somewhere the visibility of Swiss scientists in the large collaborations - convenorships, coordination roles etc, as a global comment maybe rather than providing specific examples? ]

The most significant discovery in particle physics in the last few decades has been of the Higgs boson, the physical manifestation of the Higgs field, which 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.

The Higgs boson was discovered, and can currently only be studied, by the ATLAS and CMS experiments at the CERN Large Hadron Collider (LHC). The LHC has been delivering significant rates of proton-proton collisions to ATLAS and CMS since 2010. The CDF and D0 experiments in the U.S. had been searching for the Higgs boson using proton-antiproton collisions at the Fermilab Tevatron for the previous decade, but had concluded operation in 2011, reporting evidence of the Higgs boson in its decay to b-quarks by July 2012. At the same time, after collecting data at center-of-mass energies of 7 and 8 TeV, the ATLAS and CMS collaborations each announced definitive observations of a new particle, consistent with the Higgs boson, on July 4th, 2012. The observations were driven by unmistakable, coincident signals of the Higgs boson decaying to photons, which occurs due to the interaction of the Higgs boson with fermions, as well as the decaying to Z bosons, which occurs due to the interaction of the Higgs boson with the electroweak bosons. Both the ATLAS and CMS collaborations observed these two signals, with all four signals appearing at the same mass of approximately 125 GeV/$c^2$, and with comparable rates that were consistent with the expectation from the standard model. These results were a magnificent success of the LHC and the ATLAS and CMS collaborations, and marked the dawn of a new age of study of the Higgs boson.

Of immediate interest was whether the new particle discovered had the correct couplings, spin, parity, and width to be the standard model Higgs boson. All significant Higgs boson production modes and decay modes needed to be established to determine whether any deviations from the standard model rates would reveal themselves. The mass of the Higgs boson also became a high priority to understand, since its value is considered theoretically unnatural, due to large radiative corrections that would tend for it to be at the Planck mass, $10^{16}$ orders of magnitude larger than the measured value. In the standard model, once the mass of the Higgs boson is known, all branching fractions and production modes can be predicted, although often with large theoretical uncertainties. And while the standard model was constructed with the simplest Higgs mechanism of only one Higgs boson particle, many extensions to the standard model that more complete predict a richer sector of particles with multiple Higgs bosons, as well as new interactions with standard model and BSM particles.

Since the discovery of the new particle, ATLAS and CMS have succeeded in measuring the overall production and decay rate of the new particle to within 20% at $\sqrt{s} = 7$ and 8 TeV, and to within 10% at 13 TeV, finding consistent results in all final states with expectations from the standard model 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 an accepted component of the standard model of particle physics.

Swiss physicists have made leading contributions towards the discovery and measurements of the Higgs boson, beginning with major contributions to the inner trackers of ATLAS and CMS, which are crucial for identifying the largest decay mode of $H \to b\bar{b}$, as well as the electromagnetic calorimeter of CMS that provides precise measurements of photons and electrons necessary for establishing the $H \to \gamma\gamma$, $H \to ZZ \to e^+e^- + X$, and $H \to WW \to e\nu + X$ channels. In the first years after the discovery, Swiss physicists helped establish the observation and precise measurements of the $H \to \gamma\gamma$ process, measuring its mass and production rates precisely at 7 and 8 TeV center-of-mass energies. With combined results from $\sqrt{s} = 7$, 8 TeV, Swiss physicists established direct evidence of the Higgs boson decaying to fermions through the $H \to b\bar{b}$ and $H \to \tau\tau$ processes. With just a few years of data and analysis, the Higgs boson mass was measured to 0.2% precision in the $H \to ZZ$ and $H \to \gamma\gamma$ channels, with Swiss contributions ensuring well-calibrated electromagnetic energy scale and resolution, precise momentum resolution of the trackers, as well as direct contributions to the $H \to \gamma\gamma$ analysis.

Beyond the study of the Higgs properties, the precise measurement of the parameters of the SM is a pillar of the physics program of the LHC. Parameters of the SM, such as the weak mixing angle and the masses of the top quark and the $W$ boson are theoretically predicted within the SM and are also measured with high precision at collider experiments. The comparison of predicted and measured values of these parameters 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. It is unique among the SM quarks since it decays before forming hadronic bound states. The top quark has been a natural probe of new physics due to its large mass and strong coupling to the electroweak symmetry breaking sector. Measurements involving top quarks bring key information on fundamental interactions at the electroweak symmetry-breaking scale and also of the strong interactions. The production of SM processes with top quarks is a vital component of the LHC search program as it represents some of the most significant background sources to new physics searches. A better understanding of the properties and the characteristics of top-quark production and decay mechanisms has a direct impact on the constraints on new physics processes.

Direct searches for BSM physics have a high priority in the present Swiss landscape and are strongly represented by all Swiss LHC groups. The search program is broad, covering and expanding the whole existing landscape while several centres of expertise guarantee a high impact of Swiss contributions. Such a diverse portfolio has many benefits. First of all it puts Switzerland in an excellent position when signs of new phenomena are found. Searches performed by Swiss physicists cover the "classical" signatures, such as SUSY or heavy resonances produced by new hypothetic particles, and extend to more unconventional signatures, including rare and forbidden decays from flavour physics phynomena, originating from more exotic, yet viable and interesting models. This approach is a logical consequence of the increase of LHC's integrated luminosity and the confidence that is gained with operating over many years the LHC detectors. Instead of turning the crank, rapid progress by the Swiss groups is made by innovation, both in covering new ground in the phase space of experimental signatures, and in designing new powerful tools in the areas of trigger, simulation, reconstruction and data analysis, as to optimally exploit the unique LHC data set and guide the way for future experiments. Among the most interesting examples is the use of advanced triggering methods to scout the data for rare signatures in ways that conventional trigger strategies would not allow.

In recent years, the exploration of heavy flavour has been dominated by results of the LHCb experiment, which has been designed for precise measurements of CP violation and rare heavy hadron decays, exploiting the large heavy quark production at the LHC. The primary physics goals are to characterize in detail the flavour structure in the quark sector, and look for NP effects in the decay of charm and bottom hadrons. The Swiss groups have played major roles in the LHCb experimentand have carried out a variety of physics analyses, mostly in flavour physics, but also in other areas such as direct searches of long-lived particles. They have pioneered important measurements, among which an angular analysis that showed a yet-to-be-understood significant discrepancy with respect to the Standard Model. They have also performed a number of CP violation measurements exploring a large territory where BSM physics may have appeared. They are looking for hints of lepton flavour violation either by measurements of lepton flavour universality, or direct searches in decays of hadrons.

In the HEP research, Switzerland is fully embracing the ongoing transformative period, which was heralded by the Higgs boson discovery in 2012. The enormous amounts of data collected by the LHC experiments allow for the data themselves to move into the limelight, giving way to modern data analysis tools, such as machine learning (ML), which are being pioneered in Switzerland. Such approaches include model-agnostic searches by use of anomaly detection techniques. Use of machine learning is being employed at all levels of event processing, from triggering to reconstruction and to data analysis, creating tools that can enable precision in measurements and reach in searches that was never achieved before.

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

In the past, Swiss groups have played major roles in the development of the detectors that have been in operation during Run 1 and Run 2. Swiss groups have also lead upgrades of or additions to the existing detector. These activities were primarily focused on the tracking detectors (U Geneva and U Bern for ATLAS, UZH, PSI and ETHZ for CMS and EPFL and UZH for LHCb) with design, construction and commissioning of the entire system (sensors, mechanics, read-out electronics, cooling). There have also been major contributions to the calorimeter (ETHZ for CMS) with substantial involvement in construction, commissioning and operation of the ECAL detector. Swiss groups have also been involved in developments in the trigger and data acquisition systems (U Geneva and U Bern for ATLAS). The LHCb collaboration is currently installing a major detector upgrade driven by the need to go to a full readout at 40 MHz and a software-only trigger. This will enable the collection of 5 $\mathrm{fb}^{-1}$ per year with a much improved efficiency, especially for heavy-flavour decays without muon in the final state. For this upgrade, the EPFL and UZH groups are involved in the design and construction of the tracker 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 high-luminosity LHC (HL-LHC) is expected to start operations in 2026 and deliver about 250 $fb^{-1}$ per year until about 2038, which is approximately 5 times the current data size. The challenge associated with data taking under these conditions will be unprecedented and the experiments have developed plans to upgrade their detectors in order to cope with those. ATLAS and CMS will proceed with a the complete replacement of the inner and outer tracker detectors, including an extension of forward tracking to higher pseudorapidity (up to $|\eta| = 4$) with extended pixel detectors and improved track trigger capabilities. In particular CMS will have a hardware-level track trigger. The inner pixel detector specifications are at the forefront of radiation tolerance and rate capabilities for silicon detectors. Both experiments are upgrading the electronics of their calorimeters for faster readout, while the CMS endcap calorimeters are being replaced with high-granularity and radiation-hard silicon detectors. A new timing layer is being proposed to reduce the effects of pileup down to levels similar to current conditions.

Overall the goal of the upgrade is to replace sub-detector components as needed to retain a robust, fast and radiation-hard multipurpose-detector using as little material as possible to have the same, or better, performances in HL-LHC conditions as compared to Run 2. In particular pileup rates and occupancy need to be mitigated, while keeping low transverse momentum requirements for the main triggers and guarantee precise measurements up to large rapidity. Switzerland is playing a major role, both in ATLAS (U Geneva and U Bern) and CMS (ETHZ, UZH, PSI), in the design and construction of the inner tracking detector, including detector module and readout chip design, powering and qualification, as well as detector system electronics, mechanics and cooling. In CMS the Swiss groups will also be responsible for the barrel electromagnetic calorimeter electronics, and help build the barrel timing layer. In the ATLAS and CMS experiments, the Swiss groups are contributing to the TDAQ and track trigger upgrade.

[TODO: Should add something on generic sensor RnD here??]

Equally important to the detector construction is the computing infrastructure, without which the enormous amount of data can not be processed and analysed. The LHC computing in Switzerland has been addressed at two scales. At a small scale, user specific data analyses are performed by each Institute independently adopting what is more convenient for their needs relying on local resources (Tier-3). On the large scale instead each country participating in a LHC experiment provides an agreed amount of computing power and storage to allow the reconstruction of the events collected by the detectors, the analysis of the data and the production of simulated data sets. 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. WLCG itself is one of the essential partners within the European Grid Infrastructure (EGI) community, which has the role of coordinating the overall operation of the European computing resources based on grid technologies.

The load on each LHC participating country is regulated by annual pledges: each country is expected to contribute to the global effort by providing both the hardware and the person power needed to operate it. The Swiss Institutes working at the LHC fulfil their pledges using Tier-2 resources in Bern and at the Swiss National Supercomputing Centre (CSCS) in Lugano. Smaller non LHC experiments, because of their typically lighter computing requirements, use dedicated resources tailored to their needs.

*Do we need subsection here?*

The lack of direct discovery of new physics by LHC experiments has stimulated people to consider alternatives. 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. ETHZ is among the original proposers and one of the main drivers of the NA64 experiment searching for DS at the SPS. NA64 is an international collaboration of about 50 scientists. It was approved in 2016 and since then has been collecting data.

Swiss groups are also involved in future experiments that will shed light in a complementary way to these obscure parts of the new particle landscape. They are involved in the FASER experiment, approved in 2019 and currently under construction, and they are discussing other experiments that will explore the DS at a smaller scale and more targeted ways than the large LHC ones. [TODO: (Following up from EU strategy see if this is a good compromise of a phrasing - everything else on SHiP is removed for now.)].

FASER (ForwArd Search ExpeRiment) is a new small that will be placed 480 meters downstream of the ATLAS experiment at the CERN LHC. FASER is designed to capture decays of exotic particles, produced in the very forward region, out of the ATLAS detector acceptance. Beyond searching for new physics, the FASER experiment will also provide capability to measure properties of neutrinos at the highest human-made energies ever recorded. The FASER experiment is being built recycling existing spare detector pieces by other experiments, thus minimising the construction cost, what makes it a low-cost high-gain project. FASER is expected to take data for the whole Run 3, leading to first results that will shed light on currently unexplored phenomena, having the potential to make a revolutionary discovery. Two Swiss universities, U Bern and U Geneva, are significantly involved in the effort since the design of the experiment. Scientist from U Bern have been among the main proponents of the neutrino extension of the experiment. Many leading roles in the collaboration are held by Swiss scientists.

[TODO: (FASERnu and other neutrino physics with forward detectors will need to be merged with other neutrino stuff?)]

## 7.3 Low energy

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 large-scale infrastructure at the national Paul Scherrer Institute (PSI), in particular the High Intensity Proton Accelerator complex HIPA. HIPA is home to the world’s highest power (1.4 MW) proton cyclotron delivering from several target stations the highest intensities of low momentum pion and muon beams, as well as of 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 carry forward the leading position in the international context, design and feasibility studies are ongoing on how to further improve beam intensities and quality. CERN houses the antiproton decelerator (AD) facility, the only place on the planet for research with low-energy antiprotons and anti-hydrogen; It is currently being upgraded with the addition of the extreme low energy antiproton (ELENA) ring, which will be fully operational for all experiments in the AD after LS2.

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 infrastructure within the immediate reach of their scientists, students and technical workforce. In what follows, the activities of Swiss groups are summarised and some strategic considerations and orientation are put forward.

Most of the Swiss activities in low-energy particle physics make use of the unique facilities at PSI. PSI's Laboratory for Particle Physics itself has three groups directly involved in the inhouse-physics program. University groups from U Basel, U Bern, U Geneva, ETHZ, and UZH 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. Smaller Swiss efforts take place at the CERN AD and its new extreme low energy antiproton ring, the neutron sources at ILL and ESS and the positron laboratory at ETHZ,

Over the past decade, particle physics at PSI has attracted an increasing number of Swiss groups and individuals, and this trend is likely to continue. On the one hand, this is due to the unique reach of low-energy precision experiments in search for new physics. Some of the tightest constraints on new physics are coming from this field. A growing effort in the global particle theory community is working on the necessary tools to quantitatively evaluate precision experiments and to allow comparisons with bounds obtained from high-energy physics. Swiss particle theory is greatly contributing or even driving the progress of the 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 conceiving ideas, via setting up measurements to producing results. PSI is the world-leading center concerning the search for CP violation with the neutron electric dipole moment, for charged lepton flavor violation experiments with muons, and for exotic atom spectroscopy with muons and pions.

## Input from Pillar 2

[Editor: Michele]

Neutrino physics is firmly established as prime research topic and one of the three pillars of particle physics in Switzerland. Neutrinos have, furthermore, an important role in the Swiss research on cosmology and astro-particle physics, as they are messengers of the far universe and as well for their large abundance in the universe and their possible role as hot dark matter.

Neutrino physics has a long history in Switzerland with groundbreaking experimental and theoretical work. Currently the Universities of Basel, Bern, Geneva and Zürich and the ETHZ are actively involved in this research, which offers training for about 20 PhD students. The main challenges in neutrino physics in Switzerland (and also in the world) concern presently neutrino oscillations, high-energy neutrinos from the cosmos and the neutrino-less double beta decay. The measurement of neutrino properties at long baseline beam experiments is the highest priority for the neutrino pillar in Switzerland and also considered as flagships in the overall experimental particle physics program. The development of innovative detectors plays a crucial role in all of these activities, as well as the theoretical and phenomenological aspects of neutrino physics and the study of new particle accelerator infrastructures and technologies, i.e. at PSI. CERN as the European laboratory for Particle Physics being located in Switzerland is closely tied to the Swiss neutrino efforts and is an integral part of the global strategy by hosting the Neutrino Platform. The Swiss groups have an extensive experience in the development of the detector technologies required to perform measurements of the elusive neutrinos and in the analysis and interpretation of the data. Very relevant, as well, is the theory group at the University of Basel contributing to the study of discovery prospects for new physics. Overall, the scientific impact and visibility of Switzerland is large and very well acknowledged internationally.

Neutrino oscillation physics is a main priority of experimental in Switzerland with major achievements of Swiss groups with the K2K (Japan), OPERA (CERN and Gran Sasso National Laboratory), T2K (Japan) and MicroBooNE (USA) experiments.

The Swiss researchers involved in the Japanese effort have been recognized 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. This discovery showed that neutrino have mass. The 2015 Nobel prize followed the 2002 Nobel prize to Raymond Davis for the first measurement of the solar neutrino deficit and to Masatoshi Koshiba for the first multi-messenger exploration of an explosion of a star, SN1987A. This showed that neutrinos can escape highly absorbing dense environments before than radiation and bring information on particle physics (e.g. neutrino oscillations in matter) or astrophysics of supernova.

Swiss groups in the University of Bern, University of Geneva and ETHZ have made considerable investments in the construction, operation and scientific exploitation of the T2K experiment. ETHZ and the University of Geneva are committed to the exploitation of the experiment until the end of the T2K operation. The University of Geneva and ETHZ 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 infrastructures, to which Swiss groups made key contributions, are considered as the precursor of the HyperKamiokande both on the hardware concept and in the development of analysis procedures.

The ETHZ and University of Bern also had key roles initiating the LBNF/DUNE long-baseline program in the USA, which originates from the merging of the LBNO project in Europe (led by ETHZ) and LBNE, an early project initiated in the USA for beams and detectors. It is a world-wide effort based on the liquid argon TPC technology developed with leading contributions from Swiss researchers. The short-baseline program at Fermilab, operating since 2015, serves as a pathway to the long-baseline LBNF/DUNE program by using the same detector technology for neutrino measurements. Swiss scientists from the University of Bern have had leading roles in the construction of MicroBooNE as well as coordinating the scientific program of the collaboration. There is currently a strong engagement in DUNE: the design concept for the near site detector was proposed by the University of Bern based on past experience and the collaboration adopted it, while ETHZ pioneered the dual-phase approach for the far apparatus.

The multi-messenger community in Switzerland is across the borders of the astronomy and particle physics communities. At the moment, Swiss groups are interested in the observation of gamma-rays, neutrinos and cosmic rays with CTA, MAGIC, FACT, LHAASO, IceCube and other space based experiments (AMS, DAMPE and future HERD). Atmospheric neutrinos had a primary role in the discovery of neutrino oscillations by SuperKamiokande in Japan [**?**] and the MACRO experiment at Gran Sasso [**?**]. The group of Prof. Montaruli at UNIGE is involved in the IceCube experiments and leads multi-messenger astrophysical neutrino analysis and achieved various results recently published in high standard journals. The group is interested to support the upgrade of IceCube in the next future, though yet it is not involved in its extension work due to the very limited manpower. The Phase 1 of the upgrade concerns a denser detector inside IceCube, called PINGU [**?**]. The statistics at final cut level of atmospheric neutrinos with DeepCore corresponds to about 50k events per year. PINGU will increase this number by about a factor of 5, also reducing systematic errors. PINGU offers a complementary measurement to accelerator neutrinos, which has the potential to individuate precisely the ordering of neutrinos in a short lag of time and also improve the precision of neutrino mass matrix elements.

Significant contributions to the neutrinoless double-beta decay searches come from the group of Laura Baudis at the University of Zurich, which has been involved in GERDA since 2007, and has crucial responsibilities in both GERDA and LEGEND in hardware, software and data analysis. In particular, the group is responsible for the design, construction and operation of the calibration systems [**?**], for the analysis of the weekly calibration runs and stability monitoring of the energy calibration and resolution of the Ge diodes, and for the production of the low neutron emission calibration sources together with PSI [**?**]. The group is also involved in 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 [**?**].

## Input from Pillar 3

[Editor: Ruth] In Switzerland we have strong groups working on different aspects of multi-messenger astrophysics ( X-rays, $\gamma$-rays, neutrinos, cosmic rays,), we are involved in the forefront of direct dark matter searches and studies of the nature of neutrino masses, and we have strong groups in theoretical cosmology studying the problem of dark energy or modifications of General Relativity. [Also these last groups are involved in observations, but these concern radio (HIRAX, SKA) microwave (Planck, SPT) and optical (Euclid, LSST) wavelengths. These observations are discussed in the CHAPS roadmap.] There are also significant theoretical activities in gravitational wave research in connection to the LIGO/Virgo, LISA and the future Einstein Telescope experiments but so far these are not complemented with experimental work by a Swiss group.

In this section we describe the main experiments with Swiss involvement and their goals in some detail.

### 7.4 Cosmic rays, neutrinos, $X$- and gamma-rays

Until the advent of the accelerators in the 60ies, about 20 particles where discovered in cosmic rays, such as the muons, the pions, the kaons and more. Cosmic rays are highly energetic particles, mostly protons, from the Universe with energies beyond those of particles accelerated by the Sun. Their energies reach upto $10^{20}$ eV and beyond (ultra-high-energy cosmic rays (UHECR)). This energy is orders of magnitudes higher than the $\sim$ 14 TeV achieved by LHC in the centre of mass. What are the mechanisms which accelerate particles in ‘cosmic accelerators’ up to these extreme energies? How do particles interact at these extreme energies? Cosmic accelerators represent impressive laboratories for studying ultra-relativistic particles on the one hand, and accelerated particles themselves are messengers of the astrophysical nature of cosmic accelerators on the other hand. The composition of cosmic rays and their energy spectra help us to unravel the nature of the sources of cosmic rays which remain puzzling in many aspects. Furthermore, some cosmic rays gamma-rays and/or high-energy neutrinos may stem from the decay or annihilation of dark matter. Cosmic rays, can inform us on dark matter accumulated in celestial bodies or in the galactic core and halo.

A multi-messenger approach, combining also gravitational waves, has the potential to study these questions, including questions related to gravitational interactions.

UNIGE is involved in the long standing very successful AMS/AMS-02, the presently running DAMPE and in the future HERD (DPNC, Wu-group) and EUSO, a space-base detector of UHECR (DA). Switzerland has a long standing interest in high energy

$\gamma$-ray observations. All groups (about 35 people at UNIGE (DPNC and DA, T. Montaruli, R. Walter, D. della Volpe), ETHZ (A. Biland), UZH (P. Saha) and now also EPFL (E. Charbon)). are currently involved in CTA [2] construction and in the definition of its scientific program, preparing its software and start of data taking of telescopes. The present 'work horses' are the first Large Size Telescope (LST-1) of CTA, the two MAGIC telescopes [1], and the small FACT [3] (see Fig. 1). In 2021 the two small size telescopes SST-1M will see first light at Ondreyov Observatory before joining the LHAASO experiment[50]. Several scientists are also participating in LHAASO.

Figure 1: Visible in the photograph, from left to right, the first Large Size Telescope of CTA LST-1 of 24 m mirror-diameter, FACT (4 m) and the MAGIC telescopes (12 m) at Los Roches de Muchachos, La Palma. The LST-1 was inaugurated on Oct. 2018.

We briefly describe these experiments with Swiss participation, which study cosmic rays and address the quests indicated above.

**From space:**

- **AMS-02 :** (Alpha Magnetic Spectrometer) is a cosmic ray detector detecting cosmic ray particles and anti-particles, aboard the international space station (ISS). It is taking data since more than 9 years and has e.g. measured in great detail the cosmic ray nuclei, electron, positron and antiproton fluxes in the GeV - TeV range.
- **DAMPE :** (DArk Matter Particle Explorer) is a space telescope used for the detection of high energy gamma rays, electrons and cosmic ray ions, to aid in the search for dark matter. It was designed to look for the indirect decay signal of dark matter and for direct cosmic ray measurements in the 1 TeV -100 TeV range. It was launched by the Chinese Space Agency in 2015.
- **HERD :** (High Energy Cosmic Radiation Detection) facility is a flagship science mission on board China's Space Station, planned to be launched around 2025. HERD will extend the direct cosmic ray measurement to the PeV region, allowing the connection to the ground-based observations at the so-called "knee" region. The main science objectives are: detecting dark matter particle, study of cosmic ray flux and composition and high energy gamma-ray observations. HERD will also

observe X-rays and gamma-rays which accompany the most energetic events in the Universe and are one of the main ingredients to understand high-energy accelerators in the Universe. They are very often used in a multi-messenger approach, since being detected with higher statistics than ultra-high energy cosmic rays, neutrinos, and gravitational waves, together with lower energy photons detected from satellites, they drive the searched for cosmic high energy sources.
Thanks to the Fiber Tracker (FIT) developed by UNIGE and EPFL, HERD also serves as a sub-GeV gamma-ray observatory with unprecedented imaging capability towards the Galactic center.

- **EUSO:** (Extreme Universe Space Observatory) is a 2.5 meter-apertures wide field of view fluorescence telescope for detection of traces of UHECR in the atmosphere. It is planned for installation at the Russian segment of the ISS around 2024. EUSO's goal is to add the ultra-high-energy channel for the multi-messenger astronomy by building the first all-sky high statistics map of arrival directions of UHECR.

- **POLAR-2 :** POLAR-2 is a compact detector of soft gamma-rays with energies below 1 MeV with the goal to measure the polarisation of photons from gamma ray bursts. This is necessary to discriminate between the different physical models which have been put forward to explain the mechanism leading to these most luminous single events in the Universe. It is right now constructed in Geneva (DPNC and DA) to be put on the Chinese space station in 2024.

- **eXTP :** (enhanced X-ray Timing and Polarimetry mission) is designed to study the state of matter under extreme conditions of density, gravity and magnetism. Primary goals are the determination of the equation of state of matter at supra-nuclear density, the measurement of QED effects in highly magnetized stars, and the study of accretion in the strong-field regime of gravity. Primary 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 ever simultaneous spectral-timing-polarimetry studies of cosmic sources in the energy range from 0.5-30 keV (and beyond). The mission adoption is expected in 2021 and the planned launch date is 2027.

**From the ground:**

- **IceCube :** Is a 1 km$^3$ instrumented volume of ice between 1.5 to 2.5 km below the South Pole surface detecting high energy neutrinos [56]. At the surface IceTop is detecting the electromagnetic component of cosmic ray showers which inform on the cosmic ray composition in the knee region. The in-ice detector has been completed in 2011. It consists of 5'600 photomultipliers attached to 86 strings lowered into the ice which is used as a shield, detecting the Cherenkov light produced by charged particles induced by neutrinos. IceCube is undergoing the Phase 1 upgrade, to increase the size of its dense core detector with additional 7 strings holding 700 new and enhanced optical modules (already financed by the US-NSF). This detector, called PINGU, lowers the energy threshold of IceCube to detect neutrinos down to 1 GeV. It aims at the determination of the more precise neutrino oscillation parameters and of the neutrino ordering. The future upgrade will focus on cosmic neutrinos (IceCube Gen-2) with extending the string to cover an area about a factor of 10 larger and with extended veto capabilities at surface. The photosensor array will be complemented by a radio array exploiting the Askaryan effect to detect signals from high energy neutrinos.

- **LHAASO :** The Large High Altitude Air Shower Observatory, located at 4'400 a.s.l. on the mountains of the Sichuan province in China, 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 gamma-rays above 1 TeV [58]. At relatively low energies, a water pond of 80'000 tons, equipped with photomultipliers (WCDA), detects gamma-rays and cosmic rays. At higher energies about 20 imaging telescopes (the

WFCTA array) can be used in Cherenkov mode and above $10^{17}$ eV in fluorescence mode. The extended array (over an area of 1 km-diameter) of electromagnetic particle and muon detectors measures the lateral and longitudinal distribution of extensive air showers. Detecting shower muons makes LHAASO very powerful for identifying the composition of primary particles in the region of the knee and above [62]. LHAASO is extremely interesting for searches of heavy dark matter, because it may have the opportunity to disentangle the diffuse gamma-ray from cosmic ray interactions in the Galaxy. The observatory is under completion, but 50% is already complete and it is taking data since the end of 2019. Some preliminary physics results will be published after summer 2020. The completion of the installation is expected by the end of 2021. Scientists at UNIGE currently involvement in this experiment and are very excited about the rapid progress and prospects. LHAASO is expected to be the most sensitive project to face the open problems in Galactic cosmic ray physics, with unique ability for detecting the cosmic ray sources and heavy dark matter eventually present in the galactic halo. With large field of view and almost 100% duty cycle it has unique potential to detect the PeVatron in the Galaxy that also contribute to the cosmic neutrino flux detected by IceCube.

- **CTA:** The Cherenkov Telescope Array [55] is the next generation array of Imaging Atmospheric Cherenkov Telescopes (IACTs), now entering the implementation phase. The CTA Key Science Cases concern three major themes: The understanding of the origin of the cosmic rays; Probing extreme environments, such as neutron stars, black holes and gamma-ray bursters; Exploring frontiers in physics, such as the nature of dark matter, axions and their interplay with magnetic fields, quantum gravitational effects in photon propagation.

  The CTAO (CTA Observatory) will be composed of two arrays: one in the Northern hemisphere located at La Palma, and one in the Southern hemispheres at the ESO site of Paranal in Chile, both at about 2000 m. The CTAO also comprises a Science Data Management Centre in Desy-Zeuthen and the Headquarter of the CTAO Project in Bologna. CTA will be an international open access observatory governed by the CTAO ERIC which will become operational in mid-2021. A part of the observation time will be reserved for the CTA Consortium exploitation of the Key Science Cases [14].

  Its two telescope arrays comprise more than 100 telescopes of three different mirror sizes to cover an energy range from about 20 GeV to 300 TeV. Three different telescopes with mirror sizes of 24m diameter (LSTs - Large Size Telescopes), 12m diameter (MSTs - Middle Size Telescopes) and 4 m (SSTs - Small Size Telescopes) will be deployed in order to span the wide energy range indicated above in the Southern Array. The first LST, LST-1 has already been built close to the MAGIC site with significant ETHZ and UNIGE involvement. Subsequently 3 more LSTs will be added in the coming 5 years and other MSTs in the Northern CTA site. The preparation of the Southern site is also starting in Chile. The telescope consortia are operative and have mandates to deliver the telescopes as in-kind contribution (IKC) to CTAO that will operate them for 30 years. Swiss groups are involved in the LST Consortium. Some CTA software work packages, such as for array control (ACADA) and data analysis and calibration (DPPS), are defined or being defined.

- **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 La Palma, at about 2200 m above sea level. MAGIC detects particle showers released by gamma rays, using their Cherenkov radiation. The telescopes have two 17 meter-diameter reflectors, now surpassed in size by the first LST of CTA of 24 m and by the H.E.S.S. II telescope. With H.E.S.S. and VERITAS, MAGIC has opened the gamma-ray field from ground to Big Science, from the observation of pulsation of pulsars above 100 GeV to the extension of the gamma-ray burst spectrum up to above 300 GeV.

- **FACT :** (First g-Apd Cherenkov Telescope) is a small 4 m Cherenkov telescope pioneering the usage of SiPM (Silicon Photomultipliers, also called GAPD: Geiger mode avalanche photodiodes) and performing the first unbiased monitoring of variable extragalactic objects at energies $> 1$ TeV. It is located at La Palma, situated between MAGIC and LST-1.
- **PORTAL :** Ideas on the post-CTA future are also being considered. One is called 'PORTAL'. Fundamental laws of optics limit the size and field of view of Cherenkov telescopes. Neutrino as well as gravitational wave detectors have intrinsically limited angular resolution, making follow-up observations rather difficult. In his PhD thesis, S.A. Mueller from ETHZ [53] developed the ingenious idea of replacing normal cameras by light-field sensors, allowing to overcome optical restrictions. It seems possible to construct instruments that could reach an energy threshold an order of magnitude lower than possible with CTA array as well as a field of view exceeding 30 degrees, and a preliminary system design named PORTAL was produced together with the civil engineering department of ETHZ. Such a $\gamma$-ray telescope would be the ideal companion to work together with future neutrino and gravitational wave telescopes. In addition, at energies below $\approx 10$ GeV the geomagnetic field repels charged cosmic ray particles, reducing the background signal by at least a factor 100.

## 7.5 Dark matter, direct detection

While there is ample evidence for the existence of dark matter via its gravitational interaction with luminous matter, its nature at the microscopic level remains unknown. The goal to discover non-gravitational interactions of dark matter is a global effort, and Swiss scientists are at the forefront of this search.

The Swiss group led by Laura Baudis (UZH) is a founding and leading member of the world's most sensitive direct dark matter detection program based on liquid xenon (LXe) time projection chambers. The XENON1T phase, which used a total of 3.2 t of LXe, acquired data at the Laboratori Nazionali del Gran Sasso (LNGS) of INFN in Italy until December 2018. Currently its successor, XENONnT, with a total of 8.4 t of LXe, is under commissioning at LNGS and will start a first science run by the end of 2020. It will be followed by DARWIN, a 50 t LXe observatory in astroparticle physics, with ultimate sensitivity to particle dark matter over a wide mass range and with a rich program in neutrino physics, and other rare-event searches.

- **XENON1T:** The XENON1T experiment [25] acquired data at LNGS from 2016-2018 and set the world's best upper limit for the WIMP-nucleon elastic scattering cross-section for DM masses above 85 MeV [26, 27, 31]. as well as on the DM-electron scattering cross section for masses above 30 MeV [31, 29]. XENON1T also sets the most restrictive direct constraints to date on pseudoscalar and vector bosonic dark matter for masses between 1 keV and 210 keV [32]. Furthermore, XENON1T observed for the first time the two neutrino double electron capture of $^{124}$Xe, with a half-life of $T_{1/2} = 1.8 \times 10^{22}$ y, the longest half-life ever measured directly [30]. The detector's core - the TPC - with leading contributions from the Swiss group, is back at UZH and will be part of the new Exploratorium on Campus Irchel.
- **XENONnT:** The XENONnT experiment was installed at LNGS in early 2020, and is under commissioning as of summer 2020. With a fiducial LXe mass of 4 t and an exposure of 20 t y, the expected sensitivity to spin-independent interactions will reach a cross-section of $1.4 \times 10^{-48}\mathrm{cm}^2$ for a 50 GeV/c$^2$ mass WIMP, a factor of 10 improvement compared to XENON1T. XENONnT will also search for the neutrinoless 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 [32] within a few months of data and distinguish between, e.g., a $^3$H component and a solar axion signal. As for XENON1T, the Swiss group has leading contributions to the design and construction of the TPC, to the characterisation of the 3-inch photosensors in LXe [38], as well as the design and

construction of their low-background voltage dividers. The group is responsible for the signal transfer between TPC and DAQ on the xenon side, for the low-noise, dual-channel amplification of the signals, for the design and construction of the light calibration system, as well as for the material screening with a dedicated high-purity germanium detector at LNGS [24].

- **DARWIN:** DARWIN is the ultimate LXe-based DM detector which will explore the full WIMP parameter space (with an exposure of 200 tons×years) above the so called 'neutrino floor' where neutrinos will start to dominate the signal [4]. The Swiss PI (Laura Baudis) is the founder and spokesperson. The project is presently in 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. The earliest data taking would start in 2026/27. The Swiss group constructs a large prototype (hosting a 2.6 m tall LXe-TPC) at UZH, with funding from an ERC Advanced Grant. DARWIN will have a similar reach to dedicated future neutrinoless double beta decay experiments on the decay of $^{136}$Xe [15], and would provide a high-statistics observation of pp neutrinos from the Sun [5]. It would also search for solar axions, galactic ALPs and dark photons, a magnetic moment of the neutrino, and measure coherent elastic neutrino nucleus scatters from $^{8}$B solar neutrinos and eventually from supernovae.
- **DAMIC, DAMIC-SNOLAB** The DAMIC (Dark Matter in CCDs) experiment 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 Swiss PI (Ben Kilminster, UZH) is a founding member of DAMIC (Dark Matter in CCDs) since its prototype phase at Fermilab in 2008, which established world-leading search results for weakly interacting, low-mass dark matter. The DAMIC-SNOLAB experiment increased the mass, and decreased backgrounds, and has concluded in 2019, after producing several world-leading results, also extending beyond searches for WIMP dark matter, to include hidden-photon DM. Several final publications are soon to be submitted.
- **DAMIC-M, OSCURA** DAMIC-M is an approved and funded international experiment at Modane Underground laboratory that is set to begin in 2024. It has a mass ten times bigger, a background rate 10 times smaller, and an energy threshold 10 times smaller than DAMIC-SNOLAB, this made possible using skipper electronics readout. DAMIC-M has a broad reach to probe 10 orders of magnitude in DM mass over a range of theoretical scenarios. The Swiss group at UZH holds major roles in low-background materials mechanics, electronics, the DCS system. Studies are being done for a new experiment, 10 times bigger than DAMIC-M, called OSCURA, with an even lower background rate and energy threshold. Figure 2 shows a comparison of the leading CCD experiments searching for dark matter.

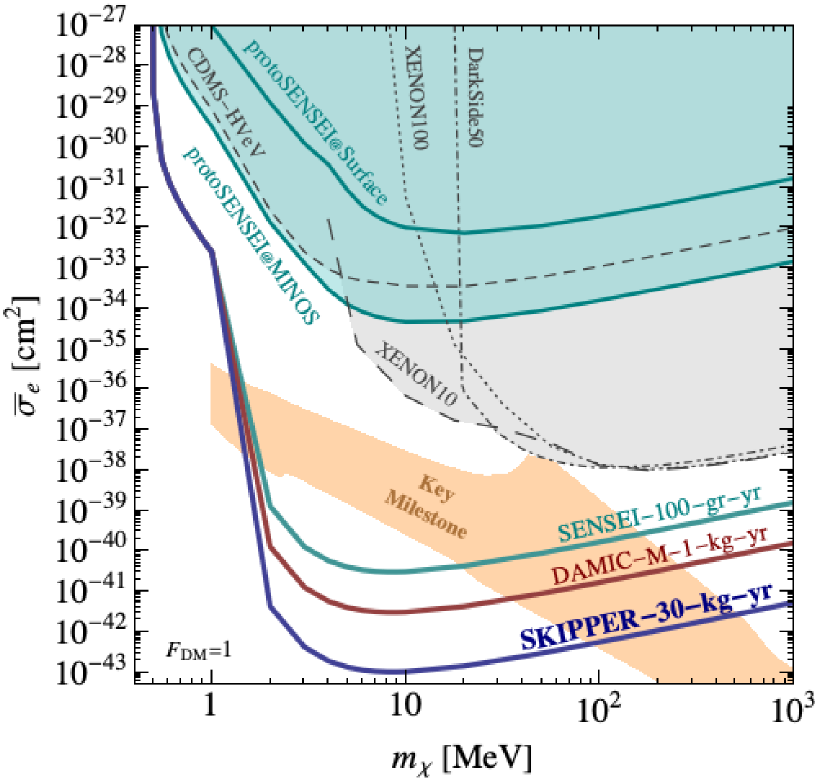

Figure 2: Future sensitivity of CCD experiments for the scattering of dark matter on electrons via a heavy hidden photon mediator. DAMIC-M is shown with its successor, a 30-kg-year proposed skipper CCD experiment named OSCURA. A key milestone is shown indicating the cross-section expected if the entire DM density observed today is due to hidden-sector DM. [48]

### 7.6 Theoretical physics

Swiss researchers are actively involved in all the main lines of theoretical research mentioned before, namely i) precise SM physics; ii) BSM phenomenology; iii) Cosmology, astroparticle, gravitational physics; iv) formal theory developments; with complementary expertise at different universities and research institutes, as qualitatively outlined in Table 1. The Swiss research in theoretical particle physics is of very high quality in all these different directions. Just to mention a representative figure of merit: 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.

## 8 Major successes (2017-2020)

[Main Editor: perhaps Gino] [(1-3 pages) – If relevant, one could identify in this section major recent (within the current ERI 4-year period) Swiss scientific achievements (are there any NCCR, NRP, awards, special EU funding, etc?). It can also be the

| Institution | Main research areas |
|---|---|
| EPFL | (II) High-energy BSM phenomenology, model-building.<br>(III) Cosmology, astroparticle physics, hidden sectors.<br>(IV) Formal aspects of QFT |
| ETH | (I) High-precision perturbative QCD, collider phenomenology.<br>(III) Physics of gravitational waves.<br>(IV) String theory and formal aspects of QFT. |
| PSI | (I) Precision low-energy physics, collider phenomenology.<br>(II) BSM phenomenology at low- and high-energies, model building. |
| University of Basel | (II) Neutrino physics, high-energy BSM phenomenology.<br>(III) Cosmology, astroparticle physics. |
| University of Bern | (I) Precision low-energy physics, lattice QCD, collider phenomenology.<br>(II) BSM phenomenology at low- and high-energies, model-building.<br>(III) Cosmology, astroparticle physics.<br>(IV) String theory and formal aspects of QFT. |
| University of Geneva | (II) High-energy BSM phenomenology, model-building.<br>(III) Cosmology, astroparticle physics, physics of GW.<br>(IV) String theory and formal aspects of QFT |
| University of Zurich | (I) High-precision perturbative QCD, simulation tools for colliders, precision flavour physics.<br>(II) BSM phenomenology at low- and high-energies, model-building.<br>(III) Physics of gravitational waves. |

Table 1: Overview of the research activitities in theoretical physics in Switzerland.

building of a new infrastructure, the Swiss participation to an international organisation, etc.]

[The following split in sections is intended as an intermediate step for collection of the necessary material. The main editor of the chapter will merge accordingly after the material is available.]

# Input from accelerator research

[Editor: Lenny]

## 8.1 Major successes 2017-2020

Thanks to the financial support provided by SERI and the matching funds in form of manpower and hardware from the participating institutes the developments in the CHART program could achieve significant results. The activities of CHART were concentrated on such research topics as high field superconducting magnet developments for FCC, FCC beam dynamic studies and novel methods of laser acceleration. The beam dynamics studies have been concentrated on both future options of the hadron colliders: FCC-hh and HE-LHC. Studies have been performed to define the operational scenario to maximize the luminosity reach of such machines. This is obtained by ensuring particle long-term stability to avoid beam parameters degradation i.e. particle losses or coherent instabilities. Studies have covered both hadron colliders options in the FCC design and have been focused on the top energy setting of 100 Tev and 26 TeV center of mass energy for the FCC-hh and HE-LHC, respectively. Stability is ensured before (called single beam stability) and during collisions (two beams effects). The effect of electron clouds and mitigation techniques to suppress these collective effects have also been addressed. For both collider options an operational scenario to reach the luminosity goals has been proposed and accepted as the baseline scenario as reported in the final conceptual design reports. Studies have covered several aspects of the design and, where possible, were supported by experimental benchmarking at the present Large Hadron Collider (LHC). The main subjects of studies are listed below with the major achievements:

- Single beam stability: impedance, Landau damping and electron cloud studies.
- Two beams dynamics: beam-beam interaction effects and long-term stability.
- Experimental development of diagnostics for Landau damping studies (i.e. Beam Transfer Function measurements).
- Feasibility studies of new Landau damping devises: electron lenses and Radio-Frequency quadrupoles.
- Explorative studies of collider performance optimization using machine learning techniques.
- Electron cloud studies and mitigation strategies.

All of the results have been documented in the FCC Conceptual Design Reports. Several open questions remain to be addressed with the aim to ensure a much higher luminosity reach and to still prove the feasibility of a 100 TeV center of mass energy collider. The main subjects arising are:

- · Alternative crossing schemes (flat optics versus round) with inclusion of relevant effects (mainly synchrotron radiation)
- Full integration of magnets multiple errors in lattice design using the compensation of beam-beam by octupole magnets. Explore the possibility to use surrogate models of the collider for design optimization with the aim to explore a larger parameters space.
- Explore the possibility of high precision luminosity measurements in the presence of beam-beam interactions and suggest possible correction methods
- Continue the study of alternative methods/devices for Landau damping (electron lenses and Radio Frequency Quadrupoles) and keep developing diagnostic devices to benchmark with models expectation in the LHC
- Different filling schemes (i.e. 5 ns bunch spacing) need to be further explored.

CHART Phase-1 engaged in superconducting-magnet R&D at Paul Scherrer Institute (PSI), ETHZ Soft Materials Group (SMG) and EPFL Swiss Plasma Center (SPC). The results included the design of an optimized 16 T Canted Cosine Theta (CCT) dipole magnet, as an option for the FCC hadron collider main magnet, the development (design and prototype) of a high-field dipole magnet with CCT technology (magnet test by the end of this year) and development of reaction resistant splicing techniques for Nb3Sn based accelerator magnets. The PSI HIPA facility generates a high intensity proton beam with a record beam power of up to 1.4MW 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 10E-4. Also the energy efficiency of the facility for conversion of grid power to beam power is outstanding in comparison to other high intensity accelerators and reaches 18% [61].

Since 2018 the SwissFEL free electron laser is operated at PSI in regular user mode. A key component of the facility is a high brightness 6 GeV electron Linac that utilizes innovative C-band accelerator technology. Normal conducting copper structures in this Linac are realized as brazed stacks of precision manufactured cups. Due to the unprecedented low machining tolerances and the high surface quality of the structures, the usual post-production mechanical tuning is not required and the structures show a good breakdown behavior. Although the primary aim for developing this technology was the generation of high quality and bright electron beams for an FEL, it can also be utilized as injector accelerator for the $e^+/e^-$ version of a future circular collider. Within the CHART project a study on developing an injector concept for FCC-ee has been launched and more details are given in a later section on CHART.

## Input from Pillar 1

[Editor: Anna]

## 8.2 High energy

The ATLAS, CMS and LHCb experiments have achieved major advancements in the understanding of the SM and the exploration of BSM phenomena.

[TODO: Here we will need to add links to LHCb, ATLAS and CMS publication pages.]

In the recent years, the highest priority pursuit has been the Higgs boson production and decay. Swiss physicists first helped re-establish the observation of the Higgs boson and its expected higher cross section, with primary contributions in the $H \to \gamma\gamma$ channel.

Swiss physicists were able to observe both the $H \to \tau\tau$ and $H \to b\bar{b}$ processes, establishing definitively the coupling of the Higgs boson to fermions. While previous data periods had established the primary Higgs-boson production modes of gluon fusion, associated production, and vector boson fusion, the 13-TeV data allowed Swiss physicists to establish the $ttH$ process, noteworthy due to its direct measurement of the only strong coupling of the Higgs boson, which is to the top quark.

The increased luminosity and larger cross-sections have provided the ATLAS and CMS collaborations with a wealth of Higgs bosons to study, allowing them to hone in on classes of events that are either more sensitive to potential BSM physics, or that are not theoretically well-predicted. Swiss physicists measured the differential production of $H \to \gamma\gamma$ and $H \to b\bar{b}$, binning events according to momentum of the Higgs boson, and associated jet multiplicity and momenta. Combined Higgs boson measurements, making use of multiple production and decay modes, have moved towards more exclusive topologies, such that the phase space relevant for specific comparisons to theoretical predictions or new-physics models are isolated. For instance, cross-sections are measured separately in events according to jet multiplicity and Higgs momentum, allowing for precise comparisons with both SM and BSM predictions.

Beyond the exploration of Higgs physics properties, many other, previously not-well-constrained SM properties, in particular those related to the top quark, are now being measured with unprecedented precision. The experimental focus is on accurately measuring the known interactions and establishing rare processes, while looking for indirect effects in the interactions of known particles. During the Run 2 of the LHC, new rare interactions such as the production of Higgs bosons in association with top quarks, $ttH$ and the production of 4-top quarks, $t\bar{t}t\bar{t}$, have been established. One of the main uncertainties in these measurement rises from the modeling of the production of a pair of top quarks in association with jets, a process that also constitutes a common background to NP searches. Swiss scientists have played a leading role in improving the understanding of the $t\bar{t}$ production associated with jets; at ATLAS, they have performed extended measurements of $t\bar{t}$+jets production, while at CMS, they have studied in detail the case where the extra jets originate from $b-$quarks, with the goal of reducing the uncertainty in future $ttH$ measurements and other similar rare processes. Top-quark events are crucial for developing algorithms for identifying $b$-jets and evaluating the performance of new reconstruction techniques, such as taggers of boosted topologies. Swiss scientists have also led developments in this direction.

The steady increase in luminosity and energy in Run 2 is being fully exploited by a large repertoire of well-motivated BSM searches. On the SUSY side this includes searches with missing transverse momentum, and use of powerful variables such as MT2, in the all-hadronic, lepton+jets and multilepton final state, third-generation squark searches, as well as electroweakino searches and their combinations. It is complemented by searches for dark-matter candidates and their mediator(s) motivated by several exotic theoretical models. The problems of neutrino masses and matter-antimatter asymmetry are studied by searches for heavy neutral leptons (HNLs) in prompt and displaced leptonic decays of $W$ bosons.

The LHCb experiment has achieved major results in physics including the discovery of the very rare $B_s \to \mu\mu$ decay and the discovery of CP violation in charm decays. For the latter, Tatsuya Nakada from EPFL was awarded the 2019 Enrico Fermi Prize.

The successes in physics pursuits would not have been possible without excellent functioning of the detectors, a common success among all LHC experiments. More than 95% of the millions of channels the detectors are made of have been operational at any time during the Run 2 data taking of the LHC. This can be considered a big achievement for the Swiss groups when accounting for the fact that the number of channels is dominated by those present in tracking detectors, whose design, construction and operation have been led by teams within Switzerland. Excellent is also the understanding of the detectors, a fact that has lead to novelties in triggering, reconstruction and data analysis techniques. These efforts constitute the continuous focus of Swiss physicists and are documented in the previous chapter. The developments are staged and exploited in major measurements and searches that are described above. Looking in the future, Swiss groups are currently participating to HL-LHC detector and trigger & data acquisition projects that have been approved and are steadily proceeding towards realisation with significant efforts from all Swiss institutes.

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

In the search for DS and possible dark matter candidates, NA64 set the most stringent limit for light thermal dark matter below 0.1 GeV [36, 37]. It also reported the first limits on a new vector boson $X-e^{-}$ excluding part of the parameter space suggested by the so called X17 anomaly. New bounds could also be set on the mixing strength of photons with dark photons. The latest NA64 results set new limits on the scalar/axion like particles (ALP) photon coupling strength [45], in a phase-space that closes the gap in the ALP parameter space between previous fixed target and collider experiments.

Extending the pursuit for BSM phenomena beyond what can be done at the LHC, attempting to cover unexplored parts of the parameter phase-space, which cannot be accessed by NA64, a significant recent achievement has been the approval by the CERN

Research Board of the FASER experiment. The experiment has been primarily funded by the US Heising and Simons-Heising foundations and SNF supports it with project funding. The construction of the experiment is progressing in a speedy way and the experiment will collect data in Run 3.

## 8.3 Low energy

For low energy experiments, major results were obtained with high sensitivity searches for BSM physics as well as for high precision measurements of SM benchmarks and fundamental constants. Four ERC grants were recently (2016-2018) granted, two in neutron EDM searches and two in exotic atom laser spectroscopy with muons, which reflects the considerable progress and impact made over several years now.

The nEDM collaboration at PSI has in 2020 released the most stringent limit on the permanent electric dipole moment of the neutron, $d_n < 1.8 \times 10^{-26}$ecm (90% C.L.) [10] with direct impact on theories explaining the matter-antimatter asymmetry of the universe. The nEDM data was also analyzed for an oscillating neutron electric dipole moment which could be induced by coupling of ultralight axion-like particles (ALPs) to gluons. Assuming that these ALPs would constitute the dark matter in the universe, first laboratory limits on ALP-gluon coupling for ultralight ALP masses were established [9].

The MEG collaboration at PSI established the limit for the lepton flavor violating decay $\mu^+ \to e^+\gamma$, which is the most stringent upper limit on any branching ratio in physics $\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$ [34]. From their data set, 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 $\mu^+ \to e^+X, X \to \gamma\gamma$ [35].

After their successful measurements of the 2S-2P Lambshift in muonic hydrogen and muonic deuterium (2010-16), the CREMA collaboration at PSI has recently measured the 2S-2P Lambshift 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 become possible [46]. To this aim the Mu-MASS collaboration demonstrated the creation of a muonium 2S metastable beam [52]. The piHe collaboration succeeded in a first time ever laser spectroscopy of a pionic atom [51] further extending the reach of precision optical methods into the realm of particle physics. The muX collaboration succeeded in demonstrating 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.

Towards the development of a new High intensity Muon Beam (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, benefiting many muon experiments. The muCool project at PSI succeeded in demonstrating transverse phase space cooling of a positive muon distribution [23]. 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.

At ETHZ, on a table top experiment, positronium is being used to search for the specific case of massless dark photons which cannot be probed in fixed target or accelerator experiments. Recently the experiment has reached a sensitivity comparable with cosmological bounds [60].

## Input from Pillar 2

[Editor: Michele]

## Input from Pillar 3

[Editor: Ruth]

## 8.4 Cosmic rays, high energy neutrinos, X- and γ-rays

Despite the small Swiss groups working in IceCube and MAGIC, some of the relevant scientific outcomes would not have been possible without their contribution. Let us mention some recent highlights:
By today about 7.5 yrs of data have been published by IceCube and the significance of the cosmic neutrino flux rose to well above 5σs [6, 7]. The energy spectrum of its muonic component can be fitted by $E^{-2.13}$. The PeV muon-neutrino event, IC-170922A, with energy of about 4.5 PeV has triggered an alert in the astronomer's network[40]. A blazar, TXS 0506+056, located inside the directional uncertainty contour of IC-170922A, was discovered in a flaring state by Fermi-LAT. This strong hint on the discovery of the first cosmic high-energy neutrino source [57] was supported by MAGIC observations revealing also flaring activity between $100-400$ GeV [22]. Enhanced emission was confirmed by VERITAS [11].
Lately, MAGIC performed the first detection of very high energy gamma-ray emission from a gamma-ray burst, GRB 190114C, from ground [42, 13, 12].
More recently, a new probable neutrino source in a close-by starburst galaxy was dicovered by UNIGE. It was published in [8] and awarded the Prix Wurth for the best doctoral thesis of the Science Faculty of 2019.
A time-dependent search for coincident IceCube neutrino events with two extremely high-energy neutrino events seen by the ANITA polar balloon flight was recently published [49] and appeared in many journals are possible hint of new physics in extreme energy domain.
A multi-messenger group of UHECRs (P. Auger and Telescope Array) and neutrinos (ANTARES, KM3NeT and IceCube), led by UNIGE, looks for common sources of UHECRs and neutrinos [33].
Of great importance for the construction of LST telescopes of CTA is the recent detection of the pulsations of the Crab Nebula pulsar at energies of the order of 100 GeV [59].

UNIGE and ETHZ were leading institutes for development and the construction of the AMS-02 Silicon Tracker, key to the unprecedented precision of the AMS-02 mission launched in 2011. UNIGE now contributes significantly to AMS-02 data analysis, in particular in tracker charge calibration and most precise flux measurements of heavy nuclei (eg. He, Li, O, Si, Mg) in the GeV - TeV range [17].
UNIGE proposed, designed and led the construction of the Silicon-Tungsten Tracker (STK) of the DAMPE mission that is key to the tracking and photon detection capability of DAMPE, launched in 2015. UNIGE contributes significantly to DAMPE operation, data processing data analysis, in particular in tracker calibration and alignment, track reconstruction, MC simulation and the most precise flux measurements of cosmic electron, proton and Helium in the TeV -100 TeV range [19, 20].
UNIGE (DPNC and DA) and PSI were leading institutes for development and the construction of POLAR, the first large dedicated

Gamma-Ray Burst polarimeter launched in 2016. UNIGE (DPNC and DA) led the POLAR data processing and data analysis, including the high statistic polarization measurement of 5 GRBs, including a time resolved study of one GRB [63].

### 8.5 Dark matter, direct detection

XENON1T has the leading sensitivity to light dark matter (LDM) in the mass ranges 3-6 GeV for DM-nucleon scattering and above 30 MeV for DM-electron scattering, and in the mass range 0.2-1 keV for the absorption of dark photons and ALPs (axion like particles) [29].
XENON1T has improved sensitivity to LDM via electron recoil signals induced by the Migdal effect and bremsstrahlung. It actually has presently the best sensitivity for DM masses between 85 MeV and 2 GeV [31].
XENON1T has observed two-neutrino double electron capture events in 124-Xe, with $T_{1/2} = 1.8 \times 10^{22}$ y and it has the lowest background ever reached in a direct detection experiment [30].
First results of XENON1T on the scalar WIMP-pion coupling have been published [28].
DARWIN: a detailed study of the sensitivity to the neutrinoless double beta decay of $^{136}$Xe; competitive to dedicated double beta experiments without additional costs are possible [15].

DAMIC at SNOLAB has been collecting data from 2017 to 2019 has produced the world's best sensitivity for electronic scattering of dark matter and hidden-photon dark matter in some mass ranges [18].

### 8.6 Theoretical physics

[Editor: Gino] In the following we illustrate in more detail the main motivations the various activities in theoretical physics in Switzerland and briefly outline recent highlights and future prospects.

**QCD at colliders.** 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 is going to be limited by theoretical uncertainties.

Perturbative calculations including NLO corrections in both the QCD and EW couplings are nowadays supported by automated tools, and their systematic application to hadron-collider studies is mandatory in order to reach a precision of $\mathcal{O}(10\%)$. To reach percent-level accuracy NNLO corrections in the QCD coupling are required. For selected benchmark processes, even N$^3$LO accuracy may be required.

Several NNLO QCD calculations have been completed in recent years for relatively simple hadron-collider processes. The range of processes for which NNLO accuracy can be reached is currently limited by the difficulty in computing two-loop amplitudes in process involving more the four external particles. The precise modelling of complex processes requires to go beyond this limitation. The computation of the relevant loop amplitudes is a formidable challenge from both the algebraic and analytic viewpoint, and the relevant integrals often involve genuinely new classes of functions. At present several directions to break this bottleneck are explored, including the clever use of unitarity, new geometric approaches, and fully numerical techniques.

In parallel, an effort is ongoing to improve available methods to handle and cancel infrared singularities and to extend them to more complex processes. This step is also essential to ultimately build flexible tools that are able to fully deploy the achieved theoretical precision into experimental analyses.

Members of the particle theory groups at ETH and the University of Zurich work at the forefront of all these activities. Highlights of their recent research activity in this area includes the first ever $N^3LO$ calculation for a collider process, namely the Higgs production via gluon fusion at the LHC; the completion of fully differential NNLO calculations for a wide class of processes; the development of parton-level Monte Carlo generator for collider processes incorporating NNLO corrections; the development of new techniques for analytical and numerical calculations of multi-loop amplitudes.

Related activities are carried out also at PSI and at the University of Bern. At Bern, in particular, the issue of all-order resummations of soft-and collinear parton emissions, which is particularly relevant for an accurate description jet physics, is investigated via the development of an appropriate effective theory approach.

Future efforts in this direction will be targeted towards key processes for the HL-LHC physics program, as well as for future FCC scenarios. The conceptual frontiers to be addressed are high-multiplicity processes where novel approaches to virtual and real radiation corrections are being developed, multi-scale problems combing QCD and electroweak effects or involving top quarks, as well as ultimate precision at $N^3LO$ for selected benchmark processes.

**Precision low-energy physics.** Beside the direct searches for new phenomena performed at high-energy colliders, a complementary way to search for BSM physics is the so-called intensity frontier, namely the search for possible failures in the SM predictions when performing high-precision experiments. Particularly interesting in this respect are high-statistics low-energy experiments testing exact or approximate symmetry properties of SM, such as the absence of flavour-changing processes in the charged-lepton sector, the strong suppression of flavour-changing neutral-current processes in the quark sector, and the approximate matter-antimatter asymmetry in both the quark and the charged-lepton sector.

Also in this case an essential ingredient to make progress in the field is the development of accurate SM predictions, a task which is particularly complicated at low-energies due to the phenomenon of quark confinement. A further complication is also the extreme high 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 PSI, the University of Bern and the University of Zurich are particularly active on this research line. Highlights of their recent research activity in this area includes precise predictions for the anomalous magnetic moment of the muon; detailed estimates of signals and backgrounds for rare muon experiments at PSI; precise predictions for experiments on rare $B$ meson decays performed at the LHCb experiment at CERN. Future efforts in this direction will be addressed to the new generations of experiments in this field, with special emphasis on planned experiments at PSI, as well as the LHCb upgrades.

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 and determine the properties of hadron physics from first principles. Swiss theoreticians at the University of Bern coordinates the so-called FLAG report, which compiles and critically reviews the results from various lattice collaborations worldwide, and are members of the ETMC (European Twisted Mass Collaboration): one the largest lattice QCD collaborations worldwide.

**Model-building and BSM phenomenology.** The phenomenological attempts to build motivated extensions of the SM, with direct implications for current and near-future experimental efforts in particle physics, can be conveniently organised into three distinct but largely complementary research directions which address different aspects of BSM physics.

The first direction is focused on understanding 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 elementary particles, but is highly unstable with respect to quantum corrections: it would naturally tend to be heavier in presence of heavier degrees of freedom in the theory. Why such scale is much lighter than the fundamental mass scale associated to gravitational interactions (the Plank scale, of the order of $10^{19}$ GeV) is one of the big open issues in 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 EPFL, PSI, the University of Geneva, and the University of Zurich are working on this front developing explicit models of TeV-scale dynamics and, most important, 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; the development of new theoretical methods to deals with QFT theories in the strong-interaction regime. Future efforts in this direction will be addressed to the HL-LHC physics program but, most important, to evaluate the physics reach of future high-energy facilities.

**The flavour puzzle.** The second direction in BSM phenomenology is focused on understanding the origin of fermion masses. 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 determine completely their properties under strong, weak and electromagnetic interactions. Ordinary matter consists essentially of particles of the first family, while the (unstable) quarks and leptons of the second and third family appear to be identical copies of those in the first family except for their different (heavier) masses. Why we have three almost identical replicas of quarks and leptons, and what the origin of their different masses is, are among the key open issues in the SM. The observed excess of baryons (over anti-baryons) in the Universe, unexplained in the SM and requiring additional sources of CP violation besides that present in the quark mass matrices, is likely to be related to these questions.

In many proposed BSM extensions, the flavour puzzle is addressed by a series of new interactions (and new symmetry principles), whose elementary nature manifests itself only at very high energies. The mediators of such new interactions may be too heavy to be directly produced at high-energy colliders. Still, their effect could show up indirectly in deviations from the SM predictions in various rare low-energy processes, such as the decays of the heavy quarks and leptons.

Swiss theory groups at PSI and the University of Zurich are particularly active on this front. In the last few years their research activity has been focused on understanding the interesting phenomenon of the so-called $B$-physics anomalies: a series of deviations from the SM predictions in various rare $B$-meson decays. While the statistical significance of these anomalies is not extremely high yet, the overall picture is quite coherent and might represent a first clue of BSM physics. If confirmed, this BSM physics would certainly have a non-trivial flavour structure. Highlights of the recent research activity in this area include the development of consistent models able to describe these anomalies; the detailed investigation of the implications of these models for future experiments, both at low and at high energies. If the anomalies will persist, future efforts in this direction will further intensified with special emphasis on the LHCb upgrades, the LFV experiments at PSI, and ultimately the flavour-physics program at the FCC.

**Dark sectors and neutrino masses.** The SM could be extended not only by the presence of new heavy states, which have not been identified yet because of the energy limitations of existing colliders, but also by new light states, which have not been identified yet because of their weak coupling to ordinary matter, generically denoted as dark sectors. Dark sectors, which are natural candidates to explain the phenomena of dark matter, have received considerable attention in the last few years. While a large fraction of the parameter space of these modes 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 also 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 anti-matter asymmetry in the universe.

Swiss theory groups at EPFL and the University of Basel work on both 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. Highlights of their recent research activity in this area include the development of consistent modes 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; systematic analyses of the impact of the DUNE experiment in constraining unified models predicting neutrino masses. Future efforts in this direction will continue at the interface of particle-physics experiments and astrophysical observations, with a special emphasis on exploiting the physics reach of the forthcoming long-baseline neutrino experiments, and in planning new dedicated experiments targeting unexplored regions of motivated feebly-interacting exotic sectors.

**Formal theory developments.** Many recent developments in formal theory have been concerned with the AdS/CFT correspondence that relates superstring theory on a $d$-dimensional Anti-de Sitter background to the large $N$ limit of a conformal gauge theory living on the $(d-1)$-dimensional boundary of AdS. The most promising example is $\mathcal{N}=4$ super Yang-Mills theory in 4 dimensions that is believed to be equivalent to superstring theory on $\mathrm{AdS}_5 \times \mathrm{S}^5$. The AdS/CFT correspondence has powerful consequences since the regime where $\mathcal{N}=4$ SYM is strongly coupled is mapped to the supergravity regime on $\mathrm{AdS}_5 \times \mathrm{S}^5$ which is under good quantitative control, 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 corresponds to (nearly) free super Yang Mills theory.

Over the years many precision tests of the duality have been performed, and beautiful confirmation has been found. Swiss theory groups at ETH and Geneva have significantly contributed to these developments. In particular, using techniques of integrability, theorists at ETH have used these ideas to make highly non-trivial predictions about the spectrum of $\mathcal{N}=4$ super Yang-Mills theory for arbitrary values of the coupling constant; to the extent that they are accessible by perturbation theory, these predictions have been confirmed by explicit computations. More recently, the focus has moved towards identifying correlation functions between the two theories. An independent development carried out at ETH focused on a low-dimensional version of the duality, relating string theory on $\mathrm{AdS}_3 \times \mathrm{S}^3 \times \mathbf{T}^4$ to the $2d$ conformal field theory that is described by the symmetric orbifold of $\mathbf{T}^4$. In particular, they managed to prove that the complete spectrum agrees between the two descriptions, and their techniques may be strong enough to lead to a complete proof of the duality in this setting. The AdS/CFT correspondence has also been applied to strongly coupled condensed matter systems.

Another important development concerns the so-called modern (or numerical) conformal bootstrap program that was initiated at EPFL. The bootstrap method is based on the insight that one can characterise correlation functions of a (conformal) quantum field theory based on intrinsic consistency conditions, without any direct reference to an underlying action (that may sometimes not even exist). While this general idea had been known for some time, it was only realised recently that, using in particular numerical methods, these constraints are very powerful indeed and allow one to make significant progress for theories that are otherwise out of perturbative control. One highlight has been the high precision determination of various anomalous dimensions for the $3d$ Ising model, but these (and related) techniques have now also been successfully applied to $3+1$ dimensional QFTs. There has also been interesting progress towards understanding sectors of conformal field theories at large global charge developed at the University of Bern, and the application of resurgence techniques to QFTs carried out at the Univerisity of Geneva.

# 9 The international context

[Main Editor: Guenther] [(2-6 pages) – Explain the main trends and the evolution of research in the field in Europe and in the world. How does Switzerland position itself in this global landscape: are we at the forefront or a small player? Add something on international collaborations: are there many large collaborations or is the research done in smaller groups?]

[The following split in sections is intended as an intermediate step for collection of the necessary material. The main editor of the chapter will merge accordingly after the material is available.]

## Input from accelerator research

[Editor: Lenny]

## Input from Pillar 1

[Editor: Anna]

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 1339 members from 83 institutes in 19 countries. 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 with standard computing clusters located in Bern for ATLAS and High Performance Computer (HPC) at CSCS for ATLAS, CMS and LHCb.

While the energy frontier is currently dominated by the CERN experiments, the intensity frontier in flavour physics is vigorously pursued in Japan, where the energy-asymmetric KEKB electron-positron collider provides beams to the Belle II experiment, which pursues a physics program complementary to the one of LHCb. Even more diverse is the international effort for dark matter searches with dedicated experiments: In addition to NA64 and FASER, other experiments composed of international collaborations, such as MATHUSLA and CODEX-B, have been proposed at CERN.

Looking into the low-energy domain, CERN provides the only source for low energy antiprotons and PSI provides the world's highest intensities of low energy pions, muons and ultracold neutrons (UCN). In Europe, other UCN source are located at ILL Grenoble (France) and TRIGA Mainz (Germany). ILL also provides the highest intensity beams of cold neutrons for fundamental physics. Cold neutrons are also available at FRM-2, in Munich (Germany), while at the European Spallation Source (ESS), in Lund (Sweden), at least one fundamental physics beamline should be built. In a global context, more sources for cold and ultracold neutrons with particle physics as part of their program exist, e.g. at LANL (US), SNS (US), NIST (US), TRIUMF (Canada), J-PARC (Japan).

Muon beams with different properties than those of PSI are produced at J-PARC (Japan) and FNAL (US). 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. FNAL 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 material science, and at lower rates. Some new facilites study the implementation of a muon physics program. The present beams of surface muons at PSI with rates exceeding $10^8$/s are leading the field. PSI aims to carry forward its leading position in muon beam intensities for the next 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.

## Input from Pillar 2

[Editor: Michele]

Neutrinos play a crucial role in our understanding of the fundamental laws of Nature. Due to their very low interaction rate it is a challenge to obtain high statistics experimental data. Nevertheless, neutrino physics has seen important advances over the last decades, with important results and discoveries about their properties, especially their mass and the related oscillation behaviour. The latter has involved a suite of experimental measurements worldwide on reactor, solar, atmospheric, and neutrino beams. The parameters of the neutrino mixing described by PMNS matrix have almost all been determined. Most recently the angle $\theta_{13}$ has been measured and a wide range of values for the complex phase $\delta_{CP}$ have been excluded[**?**], including vanishing CP violation. Neutrino oscillations are a tantalizing sign for new physics beyond the Standard Model and thus a goal for further measurements to find answer to remaining open questions such as the absolute neutrino masses, the mass hierarchy and the exact size of the CP violating phase. Three neutrino flavours are know to exist and searches for additional states, for which some hints exist, have not been experimentally confirmed or in many cases have been excluded. The fundamental nature of neutrinos, namely whether they are Majorana or Dirac particles is also still open. The existence of neutrinoless double-beta decay ($0\nu\beta\beta$) requires a Majorana neutrino mass, independent of the mass generation mechanism, and its discovery would thus reveal the neutrino nature. Neutrinos are also interesting as a tool e.g. for astro-particle physics. They travel essentially undisturbed through the interior of dense environments of astrophysical sources and through the universe radiation background and magnetic fields. Hence, they are an excellent messenger, as initially proved by the observation of a neutrino burst few hours before the light signal from the SN1987A. In connection with other messengers, such as gravitational waves, gamma-rays and charged cosmic rays, neutrinos provide exciting insights into cosmology.

## 9.1 Long baseline neutrino experiments

The primary science objectives of long-baseline neutrino programs is to carry out neutrino oscillation investigations to test CP violation in the lepton sector, determine the ordering of the neutrino masses, and to test the three-neutrino paradigm. This is done by measuring independently the propagation of neutrinos and antineutrinos through matter and identifying their flavour and measuring the flux at the site where neutrinos are generated (near site) and several hundred kilometers away at the far site. The experiments will also enable ancillary science programs, such as the very precise measurements of neutrino interactions and cross-sections, studies of nuclear effects in such interactions, measurements of the structure of nucleons, as well as precise tests of the electroweak theory. These measurements are also necessary to achieve the best sensitivities in the long-baseline neutrino oscillation program.

At present, there are two major accelerators based long-baseline neutrino facilities in the world. One is in Japan at the Japan Proton Accelerator Research Complex – J-PARC (Tokai) and the other at the Fermi National Accelerator Laboratory – Fermilab (near Chicago, USA). They produce high intensity neutrino beams which are probed locally and at a detection site several hundred kilometers away. Swiss groups have been involved in long baseline experiments in Japan for more than a decade, while the US long-baseline program has been focused on the NOvA experiment with no Swiss participation. The Long-Baseline Neutrino Facility (LBNF) together with the Deep Underground Neutrino Experiment (DUNE) in the USA, will be a world-class multi-purpose observatory for neutrinos from beam and astrophysical origin and for matter instability searches. LBNF/DUNE is a global organization with currently 1100 scientists and engineers from 175 institutes in 31 countries. LBNF/DUNE is among the top priorities in scientific and infrastructure roadmaps in Europe and the Americas. Two complexes will be built, with a “near” site facility at Fermilab and a “far” site at the Sanford Underground Research Facility (SURF). The world’s most intense beam of neutrinos will be produced at Fermilab and aimed at the SURF site at a distance of 1300 km from Fermilab. The design of the LBNF/DUNE facilities and detectors are driven by the primary scientific goals of carrying out a comprehensive program of neutrino oscillation measurements, besides also improving the search sensitivity for proton decays, detecting and measuring neutrinos from core-collapse supernovae and be ready for unexpected discoveries. One main goal is to reach sensitivity to measure charge-parity symmetry violation (CPV) in neutrino oscillations, which would give insight into the origin of the mentioned matter-antimatter asymmetry. 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. The main excavation at the far site in South Dakota has started and the beginning of beam operation is planned for 2026 and will last for at least 10 years. HyperKamiokande is an extension of the highly successful program that started with the Kamiokande experiment and continues with SuperKamiokande, which has yielded two Nobel prizes. HyperKamiokande is a water Cherenkov detector centered on a huge underground tank containing 300,000 tonnes of water, with a sensitive volume about a factor of 10 larger than its predecessor SuperKamiokande. Like SuperKamiokande, HyperKamiokande 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, SuperKamiokande formed the “T2K” long-baseline neutrino program. An order of magnitude more sensitive than SuperKamiokande, HyperKamiokande will serve as the next far-detector for Tokai-to-Kamiokande experiments, with a rich physics portfolio. This ranges from the study of the CP violation in the leptonic sector and measurements of neutrino-mixing parameters, to studies of proton decay, atmospheric neutrinos and neutrinos from astrophysical sources. The staged Japanese neutrino program allows for continuous production of world class physics results from T2K to the future HyperKamiokande experiments at the time it ensures the training of the new generation of neutrino physicists. The knowledge acquired both in detector operation and the understanding of physics processes will improve the precision of future experimental results. The Hyper-K collaboration was formally formed in 2020.

## 9.2 Non-accelerator experiments

From the world-wide perspective, three neutrino telescopes will dominate the scene in the next years concerning the observation of the natural beams of neutrinos: IceCube and its extension for oscillation physics PINGU, the KM3NeT sea-based cubic-kilometer neutrino telescope in the Mediterranean and GVD in the Lake Baikal. The IceCube Observatory [2] at the South Pole includes a 1 km$^3$ instrumented volume of ice between 1.5 to 2.5 km below the South Pole surface, which detects high energy atmospheric neutrinos. At the surface IceTop detects the electromagnetic component of cosmic ray showers and also vetoes atmospheric muons, a background to the atmospheric neutrino detection in the deep detector. The in-ice detector, at 1.5 to 2.5 km before surface, hosts 5600 photomultipliers attached to 86 string. It was completed in 2011. Muon neutrinos are detected as tracks up to energies of the order of few PeV and showers for other flavors and all-flavor neutral current interactions.

The core of IceCube is called DeepCore [**?**]. DeepCore has a module density roughly 5 times higher than that of the standard IceCube array, and uses photomultiplier tubes (PMTs) with high quantum efficiency of about 35%, higher than the standard IceCube PMTs. It brings down the energy threshold for neutrinos to about 5 GeV and has produced many results on neutrino oscillations. Remarkably, IceCube severely constrains the region of LSND for sterile neutrinos in the 3+1 scenario [**?**, **?**] (see Fig. 3-Left. On the right of the same figure, the results from 3 years of IceCube DeepCore data on neutrino ordering are provided [**?**]. In addition, we remind the results on the neutrino tau search [**?**], which measures with two independent analyses a tau neutrino normalization of $0.73^{+0.30}_{-0.24}(0.57^{+0.36}_{-0.30})$ and exclude the absence of tau neutrino oscillations at a significance of $3.2\sigma(2.0\sigma)$ for 3 years of data.

## 9.3 Neutrino-less double-beta decay experiments

Double beta decay searches provide a fundamental probe of the nature of neutrinos and of lepton number violation. The observation of the neutrinoless double beta ($0\nu\beta\beta$) decay would prove that the neutrino is a Majorana fermion (particle and antiparticle are identical) and that fermion number is violated in Nature. The observation of the decay would have far reaching implications, as it would point to the existence of a new mass generation mechanism, beyond the Standard Model, and to possible scenarios to generate the matter-antimatter asymmetry in our Universe.

The rate of the extremely rate nuclear process is proportional to the effective Majorana neutrino mass, $\langle m_{\beta\beta}\rangle = |\Sigma_i U_{ei}^2 m_i|$, where the sum is over the mass eigenstates $m_i$, and $U_{ei}$, the corresponding entries in the lepton mixing matrix, are complex numbers. The experimental observable in $0\nu\beta\beta$-decay is the half-life, and current estimates and experimental constraints predict a range between $\mathrm{T}_{1/2} \sim 10^{26} - 10^{28}$ y for the so-called inverted neutrino mass ordering, and $\mathrm{T}_{1/2} > 10^{28}$ y for the normal mass ordering.

While many isotopes are available to search for this rare decay, currently the best limits on its half-life come from experiments using $^{76}$Ge, $^{130}$Te and $^{136}$Xe. In particular, the GERDA experiment, with significant Swiss contributions (UZH) recently reached a world-leading lower limit on the half life of $T^{0\nu}_{1/2} > 1.8 \times 10^{26}$ y (90% C.L.), for an exposure of 103.7 kg y.

We note that the DARWIN [4] project, a next-generation xenon-based experiment for direct dark matter detection will also be

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[2] http://icecube.wisc.edu

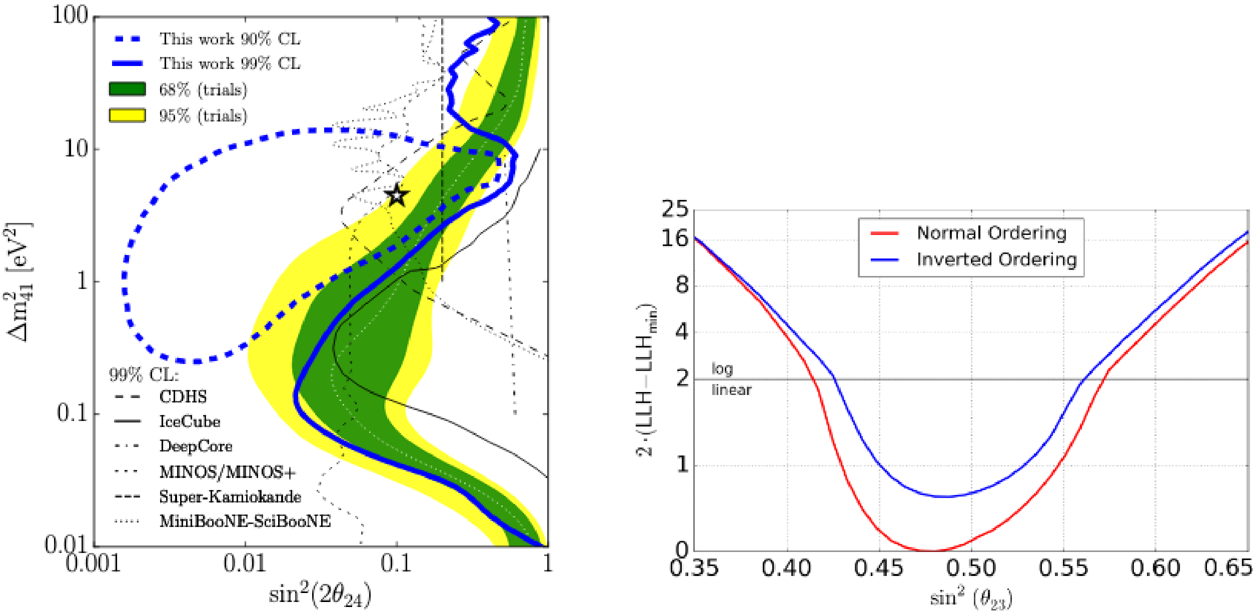

Figure 3: Left: the currently excluded region of IceCube at 90 and 99% C.L. with a blue solid and dashed lines, respectively, and the star marks the best-fit point location [**?**]. Right: IceCube indicates slight preference for normal ordering over inverted as visible over all the range of $\sin^2\theta_{23}$ with the best-fit for both orderings being in the lower octant $\sin^2\theta_{23} < 0.5$ [**?**].

able to probe the $0\nu\beta\beta$-decay of $^{136}$Xe with half-life sensitivity of $2.4\times10^{27}$ yr [15], and will thus be complementary to LEGEND and other dedicated searches.

## Input from Pillar 3

[Editor: Ruth] All experiments are built within international collaborations. Here we give more details for some of them.

DARWIN includes the XENON collaboration with additional groups from Europe and the US. DAMIC-M has collaborators from Europe and the U.S. The future experiment, OSCURA, will unite two international collaborations that search for DM with CCD detectors, DAMIC-M and SENSEI, bringing in additional North and South American institutions. IceCube is a collaboration of abut 300 people from from 52 institutions in 12 countries. The full Phase 1 upgrade of IceCube has been financed by NSF on June 2019, extending its scientific capabilities to lower energies and thus enabling IceCube to reach neutrino energies that overlap with the energy range of few GeV of smaller existing neutrino detectors worldwide. The seven strings of optical modules of the Phase 1 upgrade are funded by NSF and the second phase of the upgrade foresees the addition of an acoustic array of antennas and further strings (IceCube-Gen2).

CTA is a Consortium of about 1500 scientists from more than 200 Institutes in 31 countries all over the world. In order to start construction, CTA defined a baseline asset (e.g. 50 SSTs instead of 70 and no LST at the Southern site instead of 4) and more than 90% of funding are achieved. At La Palma Northern site the first large size telescope (LST-1) is under commissioning and all Swiss groups are members of the LST Consortium. Notice that, as long as LST-1 is not formally approved by CTAO as a CTA element, LST-1 has proprietary access to data and is handled as an individual project. Financial responsibility on its operation is independent from CTAO but relies on the LST Consortium.

The MAGIC collaboration encompasses about 150 scientist 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 also get access to data as associate scientists. Such non-members have no other duties than keeping information confidential and are included in the author-list if they contribute significantly to a publication. The operation mode of MAGIC beyond 2025 when the CTA array at La Palma will become operational is not yet decided. One likely option is to integrate MAGIC into CTAO operation as an independent sub-array. The small FACT collaboration under leadership of ETHZ consists of scientists from ETHZ, UNIGE and the German universities Dortmund and Wuerzburg (and close association with RWTH Aachen). Its fate beyond 2025 depends on final operation plans of CTAO. One option could be to relocate FACT to the HAWC detector in Mexico to allow hybrid observations.

DAMPE is a China-EU collaboration. The EU participation, under the leadership of UNIGE, consisting of 5 institutes from Switzerland and Italy.

The POLAR-2 international collaboration, under the leadership of UNIGE, consists of institutes from Switzerland, Germany, Poland and China.

The HERD international consortium includes major institutes from China, Italy, Switzerland and Spain.

The eXTP international consortium includes major institutions of the Chinese Academy of Sciences and Universities in China, as well as major institutions in several European countries and other International partners.

# 10 Synergies with other scientific fields

[Main Editor: Mike, Ruth] [(2-6 pages) – Are there synergies with other disciplines (e.g. biology with chemistry, or physics, or medicine, etc.)? Are you benefitting from advances in other fields (e.g. computing, imaging/analysis tools)? Are you using common infrastructures (e.g. SLS at PSI)? Is there transdisciplinary research being pursued? ]

[The following split in sections is intended as an intermediate step for collection of the necessary material. The main editor of the chapter will merge accordingly after the material is available.]

## Input from accelerator research

[Editor: Lenny]

## 10.1 Synergies with other scientific fields

Cancer treatment using particle beams from an accelerator is an established concept with strong advantages over X-ray treatments for a range of indications. PSI in Switzerland has pioneered the technology of pencil beam scanning for precision treatments of deep seated tumors since 1996. In spite of those obvious advantages the technology is expensive, and particularly the treatment gantries with iron-pole electromagnets are large and heavy, involving cost driving mechanics. Superconducting accelerator magnet technology, that was developed for particle colliders, provides the potential for reducing the weight of todays gantries by an order of magnitude. In addition a superconducting final bending section could be realized as an achromat 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. In summary particle therapy has significant potential for enhancements of the treatment quality, and with regard to size and weight of facilities by utilizing modern superconducting technology. Accelerator driven subcritical reactors can be used to reduce the storage time of radioactive waste of nuclear power stations significantly. Due to the coupling with an accelerator, generating a fraction of the neutrons needed to fission high level waste incorporated in the sub-critical core, such reactors are passively safe. This application of high intensity proton accelerators could contribute to the solution of a major problem for the public society in CH. The cyclotron based High Intensity Proton Accelerator HIPA at PSI generates 1.4 MW proton beam power, and represents a prototype solution for an ADS 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. A collider facility with high energy reach and luminosity will consume significant electrical energy, of the order of TWh/y. With an increasing fraction of sustainable energy sources like wind and solar power in the future European energy mix, the production of energy will fluctuate significantly. One way to mitigate the impact of HEP facilities is to actively manage their energy consumption. The aim should be to avoid high loads on the grid during low supply conditions, and instead using preferentially “excess energy”. The possibilities of energy management using dynamic operation of facilities and energy storage systems are investigated for industrial applications and potentially synergies with HEP infrastructures could be realised. It is necessary to invest R&D efforts improving the energy efficiency of HEP facilities through critical technologies. In certain areas such R&D will have an immediate impact on research facilities operated today, and the savings in energy consumption may be used to co-finance the investments. Certain improved technologies may also serve the society. The fields of R&D include optimized 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 foresees the extensive use of permanent magnets and through the realization of the project the technology will be refined. Another area is the development of efficient klystron based RF sources by improved beam dynamics or the use of HTS superconducting focusing coils.

### Input from Pillar 1

[Editor: Anna]

## 10.2 High energy

In order to discover and measure the Higgs boson, silicon tracking and calorimeter detectors, as well as superconducting-magnet technologies have been pushed to new limits, with technologies being transferred into the medical sector for biomedical imaging, as well as molecular and atomic structures. Advances in machine learning for signal processing have also cross-pollinated both particle physics. Some of the foundational research in solving the mystery of electroweak symmetry breaking in particle physics was done within the context of superconductivity in condensed-matter physics [21]. A synergy between solid-state processes and particle-physics processes has cross-pollinated both fields over the years. Also, with the explanation of a scalar Higgs field filling the universe being confirmed, its impact on cosmology has become a topic of interest, sometimes known as Higgs cosmology. The effect of the Higgs field on the inflationary period of the beginning of our known universe, as well as cosmological phase transitions and the stability of the electroweak vacuum have meant that cosmology is discussed in particle physics conferences and vice versa. Indeed, the future stability of the universe depends on the precise form of the Higgs boson field, and our very existence depends on whether we are in a stable minimum of the Higgs vacuum potential or not.

For the last several decades modern 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. What is needed is faster MC simulation of synthetic data, faster data reconstruction algorithms, and to alleviate the data storage bottleneck: a move towards real-time data analysis. Modern machine learning can provide solutions to these problems. It can also provide a more efficient approach, given both human and computing resources, to analyzing the LHC data and inferring physics knowledge, e.g. for the identication of physics objects, event classication, measurements of properties through regression, and a more unified approach to searches for BSM physics by aid of anomaly detection techniques. In addition LHC's real-world science questions define realistic new benchmarks, which are of relevance for the ML community as a whole. This approach is complemented by modern engineering commodity hardware, such as very fast FPGAs, including System-on-Chip (SoC) devices, GPUs and powerful computing farms, to address the challenge of real-time data analysis.

Synergies flourish in the area of detector development. Collaborations are required between material science and particle physics for the development of sensors and between electrical engineering and particle physics for the development of fast electronics and triggering systems. Technologies that are developed for particle physics experiments find applications elsewhere, for example in medicine, where the applications of detector RnD are numerous and in particular in positron emission tomography (PET) design. A team from ETHZ is working on a new generation of PET scanners using crystal detector technologies that are based on developments made for the CMS calorimeter. Teams from U Geneva and U Bern are developing fast silicon sensors that will constitute the building block of a Time-Of-Flight PET scanner of high granularity for ultimate use in a MRI scanner; this work is done in close collaboration with the University Hospital in Geneva.

While HEP has very peculiar computing requirements because of the need to process large volumes of data (pushing the use of fast networks, fast processors and large storage sites), many synergies with other disciplines can be found in the development of flexible software to allow running on different clusters technologies and sites. [TODO: make the statement more concrete with examples?]

## 10.3 Low energy

In low-energy particle physics there are three types of synergies that can be outlined: (i) Technology transfer leading to the use of equipment and know-how developed for particle physics in other applications. (ii) The use of the particles as probes, e.g. in material science and chemistry, or their application in irradiation, medical physics or isotope production. This is connected to the application of particle physics techniques to other fields. (iii) Transfer of technology and techniques from other fields leading to progress in particle physics.

Examples for (i) concern detector technology and electronics. At PSI, technologies for wire chambers, scintillators and light read-out found their way from particle physics to instrumentation in muon spin rotation and neutron scattering. Chip design from particle physics (originally coming from the high-energy physics developments at PSI for CMS) found many applications. Cutting-edge Si pixel detector technology for X-ray detectors in light sources and for medical applications was derived and commercialized. The DRS4 chip, originally developed for the MEG experiment, is used in many more experiments world-wide and way beyond particle physics. Space applications have been derived from various chips developed for particle physics and photon science at PSI. Also certain software, such as the data acquisition system MIDAS and electronic logbook ELOG from PSI low-energy particle physics, found a very large and versatile user base.

Examples for (ii) are material science and solid state physics research and chemistry with muons and positrons. Spins of positive muons can be tracked to give information on local magnetic fields. Lifetimes of positrons in material can inform about electron densities. Detection technology is usually transferred from low energy particle and nuclear physics. Negative muons allow for non-destructive material analysis techniques with depth information.

Examples for (iii) are found, e.g., from laser physics and radio-chemistry. In the precision spectroscopy of exotic atoms new types of high-power laser systems are being developed in close cooperation of particle physics and laser science, also with interest for commercial applications. Radio-chemistry overlaps with low-energy physics in a number of nuclear physics related aspects such as provision of rare isotopes, preparation of radioactive targets and measurements of physical properties of certain isotopes.

## Input from Pillar 2

[Editor: Michele]

## Input from Pillar 3

[Editor: Ruth] To investigate the nature of dark matter, data not only from direct detection, but also from astrophysical observations, production at colliders, beam-dump experiments and indirect detection are necessary. DM searches are therefore inherently multi-disciplinary including particle and accelerator physics, solid state physics and astrophysics. DAMIC-M 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/DARWIN combine the physics of liquid noble gases with particle physics, nuclear and atomic physics, as well as detector physics.

Also cosmological observations of the matter distribution in the Universe, e.g. with the Euclid satellite scheduled for launch in 2021which has a strong Swiss participation, are relevant to unravel the nature of dark matter.

To understand galactic and extragalactic sources, multi-wavelength data are necessary, covering from radio over optical and X-ray to TeV data. CTA will contribute the $\gamma$-ray part to this multi-disciplinary 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 allow us to understand the most energetic astrophysical events/objects beyond their electromagnetic emission. The interpretation of these data requires modelling using most branches of theoretical physics, especially General Relativity, electrodynamics, plasma physics, quantum field theory and statistics.

The detection of particles of 100 MeV/nucleon to a few GeV/nucleon in deep space are of critical interest for a broad range of applications in space activities, but they have not yet been measured precisely and monitored long-term in deep space. Currently UNIGE is leading an international consortium, funded by the EU H2020 FET-OPEN program to develop a demonstrator (Mini.PAN) in 3 years (2020-2022). The PAN concept, based on a low mass magnetic spectrometer with high precision silicon strip detector, has been presented to several deep space programs, including the NASA Artemis (Lunar Orbiting Platform-Gateway.) project, the ESA European Large Logistic Lander (EL3) Call for ideas, and the Jupiter's radiation belts studies for the ESA's Voyage 2050 Call.

## Input from Theory

### 10.4 Cosmology and gravitational waves.

[Editor: Gino] There is an intimate connection between particle physics and cosmology: the aim is to build a link between the microscopic laws of physics and the macroscopic observations of the universe as a whole. In the last few years this link has been extended to gravitational-wave physics, which represent a powerful new probe of fundamental physics on the cosmological scale. Just to mention an example of such connections, 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 phase transition which could be observed with the LISA gravitational wave observatory in the near future.

Swiss theory groups at EPFL, and at the universities of Basel, Bern, Geneva, and Zurich are heavily involved in such type of research. Highlights of their recent research activity in this area include important results in the study of CMB anisotropies and large-scale structure (LSS), providing solid theoretical predictions for the LSS observables and actively participating 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 result of primordial black holes, and the corresponding analysis of gravitational waves (GWs) 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. Beside pure theoretical developments, future efforts in this field will be closely connected to the experimental developments both at the particle-physics and at the cosmological/gravitational frontier.

# 11 Relationship to industry

[Main Editor: Guenther]

The fields of experimental particle and astroparticle physics have a long-standing tradition of (i) very close collaboration with (high-tech) industry and (ii) of pushing the technological frontiers, which ultimately results in innovations that are successfully transferred to the private company sector and industry. These frontiers are typically related to forefront nuclear and particle physics instrumentation developed for and installed in small- and large-scale detectors, as well as to particle accelerator technology. In all this, 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 that are interested in the tech transfer of their ideas, developments and inventions. In the following a not comprehensive list of examples will be given, intended to provide a glimpse of the rich spectrum of tech transfer activities, spin-off companies and other relations to industry that exist in the Swiss particle physics landscape.

### 11.1 Examples of spin-off companies

Spin-off companies founded by Swiss researchers in the last years typically have their origin in novel particle detector techniques and its related data acquisition systems, such as silicon-based pixel detectors, scintillating crystals or other materials, photosensors (most notably, silicon photo multipliers in recent times), or dedicated Application-Specific Integrated Circuits (ASICs) as front-end readout elements of such detectors. In addition, know-how on 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 focus on biomedical imaging, but also the fields of (homeland) security or the handling of nuclear waste have been addressed. A few examples of such spin-off companies are shortly 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 commercialization of PSI-IP in accelerator technologies and applications, to create value beyond the shareholders' individual expertise, such as accelerator component & system design and realization, proton therapy instrumentation and services, compact accelerators such as synchrotron sources spanning various energies, neutron instrumentation, as well as services and consulting.
- *Arktis Radiation Detectors Ltd*, co-founded by ETH professor A. Rubbia and former ETH PhD students R. Chandra and G. Davatz, was built on expertise related to the detection of neutrons and high-energy photons (”gammas”) and addresses the issue of detecting radiological and nuclear materials that pose a threat to customer's safety and security. Arktis develops next generation systems that categorize, prevent, and intercept radiological and nuclear materials in addition to contaminated cargo.
- *Dectris* has been 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 4 to  130 employees by now. Its main products are 1D and 2D hybrid photon detectors for scientific, industrial and medical applications, such as the Pilatus pixel detector, the Mythen strip detectors, a new fast pixel detector with 3kHz frame rate (Eiger), or a high-Z detector for higher energy X-rays. While initially the main application was X-ray imaging at synchrotron facilities, e.g. protein crystallography, with time the product range has spread to other imaging applications in the industry and medicine (Human CT and Mammography).
- *Positrigo AG* has been co-founded by Prof. G. Dissertori and Dr. W. Lustermann (ETH Zurich), together with former ETH PhD students (Dr. M. Ahnen and Dr. J. Fischer) and colleagues from the University of Zurich (Prof. B. Weber) and the University Hospital Zurich (Prof. A. Buck). Building on their expertise on scintillating crystals and silicon-photomultipliers, that are key components for PET scanners (PET=Positron-Emission-Tomography, a biomedical imaging modality), and on previous experience with the development of a pre-clinical PET scanner, the company aims at 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, setting up of this effort was supported by a dedicated Innosuisse grant.
- *RADEC GmbH* was founded in 2017 and performs tests of existing electronic components and materials for their radiation hardness using particles generated at accelerators located at PSI or other facilities. It 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 failure due to radiation must be eliminated.
- *SE2S GmbH* - Space Environment Systems and Service, founded in 2020 by PSI researchers and based on over 30 years of experience in radiation qualification, particle detection and data analysis, offers next generation services and products in radiation effects and qualification (e.g. radiation modelling, assessment of radiation effects), detection of particles and

radiation (e.g. novel detector technologies, equipment, software), space weather services (e.g. space weather and radiation modelling, analysis of space weather data, impact assessment and risk prediction).

- *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 (Geneva University) being a 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 that have validated his idea. Furthermore, very significant advances in particle accelerators (e.g. high-power cyclotron technology) and computing power (e.g. simulation tools) have helped in building confidence that the ADS concept is ready for industrial development. Interestingly, in the recent *Energiebericht* of SERI a report by Prof. Bourquin on thorium ADS has been included. As a consequence, SERI now recommends that Switzerland should engage in that research.

## 11.2 Contacts and collaborations with industry

Besides the obvious contacts of Swiss researchers with spin-off companies, that are based on their own research and/or have been co-founded by them, 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 industry sector. The usual trigger for such collaborations arises from the need of pushing technology beyond its current boundaries, when new detectors or accelerator components are under development for specific research applications - the detectors of the experiments at CERN's LHC being a prime example, but not only. Again, 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 improve and determine their production tolerances. As an example, in the context of the upgrade of the CMS pixel detector (in particular, for its $CO_2$ cooling system), researchers from UZH, together with Swiss industry, have developed tooling for aligning components to be welded; furthermore, an UZH scientist developed for the company a testing setup to pressure-test welded stainless steel pipes to reach the standards required by the experiment. Due to such relationships maintained with these companies, the scientists have been able to convince them 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 have been interested in exploring this R&D for other future contracts with industry, as well as other interested partners at CERN. This (not isolated) example shows how industry not only profits commercially from orders received from our field, but more importantly how the companies' internal expertise, its quality management and/or its product portfolio can be enhanced thanks to the close interactions with demanding customers, namely particle physicists. A few further examples of such collaborations, by far non exhaustive, are given in the list below.

- *ESPROS photonics corporation - EPC*: Researchers at ETH Zurich, UZH and PSI, who lead the initial construction and upgrade of the CMS pixel detector, collaborate with this high-tech company located in Sargans (SG). The medium-scale company with  50 employees specializes in Integrated Circuits design and production. In particular, the Swiss researchers collaborate with EPC on the design of Monolithic Active Pixel (MAP) pixel sensors 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, UZH scientists have collaborated with a long list of Swiss

companies (such as MEDELEC SA in Puidoux-Gare, Createch AG in Langenthal, Spalinger Präzisionsmechanik GmbH in Marthalen or Bolleter Composites AG in Arbon, just to mention a few), for 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, the production of carbon-fibre or foam core based support structures, as well as complex plastic parts.

- Scientists from the University of Geneva, involved in the ATLAS experiment, collaborate with Intel, towards the development of firmware using Intel's high-end Field Programmable Gate Array (FPGA) that will be used for ATLAS' future trigger system. This joint venture results in interesting experience gained on both ends, since, e.g., ATLAS' low latency applications do not fall into the typical use case spectrum of Intel's FPGAs.
- Researchers at PSI, lead by Dr. S. Ritt, have developed the so-called DRS4 readout chip for the MEG experiment, which they sell through PSI's technology transfer program. So far, this has resulted in already more than 200 international companies and institutes as customers. As an example, the Italian company CAEN SpA (specialized in High/Low Voltage Power Supply systems and Front-End/Data Acquisition modules) has a product with 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, not only at the LHC, resulting in numerous commercial contacts and joint developments with Swiss scientists.
- In the context of the aforementioned PET scanner developments at ETH Zurich, close contacts for the production of silicon-photomultipliers (photosensors) have been established with the Japanase company Hamamatsu, and with the Chinese company Sichuan Tiangle 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.
- In the past, during the first construction of the CMS experiment, important collaborations and major industrial contracts with Swiss industry had been established, in particular for the construction of the CMS superconducting magnet cables (Kabelwerke Brugg AG and Nexans in Cortaillod) and the large-scale manufacturing of printed circuit boards (ASCOM Systec AG).
- In general, accelerator-driven large research facilities, such as PSI or CERN, give rise to a substantial number of close collaborations and joint ventures with industry, combined with tech transfer. Here we mention only a few examples, related to (a) the (co-)development of components (Daetwyler Industries, Cosylab, SCS-Super Computing Systems, Ferrovac GmbH, VDL etc.), (b) imaging and analytics (Anaxam, ABB, Roche, GE-General Electric, Novartis, Nestle, BASF, etc.), (c) medtech such as proton therapy and medical imaging (Varian, Schär Engineering AG, etc.), and (d) business development (SwissNeutronics, InterAx, GratXRay, Eulitha, etc., or Dectris and AAT as mentioned earlier).

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

[TODO: add links (as hyperlinks) to all company names? for a printer version also as dedicated references or footnotes? QUESTION: even more on accelerator technologies? is there anything worth mentioning related to computing and/or software, eg. deep learning?]

[Ruth Durrer]

From the hardware developed for CTA prototypes, silicon photomultipliers have been adopted which are now used in a project for the development of a β probe to drive surgeons in the ATTRACT program. The FET-OPEN EXCHANGE project SENSE has developed a roadmap for such low light level sensors.

Direct dark matter detection experiments with liquid Noble gases have a wide range of possible industrial applications: Development of materials with extremely low levels of radioactivity and low radon emission.
Development of low-noise, VUV sensitive SiPMs (and other photosensors) for operation in liquid xenon detectors.
Development of low-noise, low-radioactivity electronics that works at cryogenic temperatures.

DAMIC-M is pushing the way for extremely low-energy threshold detectors, which may find a use commercially measuring extremely small interaction processes. Such CCD detectors function as very small detectors that can detect low-rate nuclear processes.

# 12 Impact on education and society

[Main Editor: Katharina] [(2-6 pages) – How is your research positively impacting on education and society? What are the benefits of the pursued research? Is your field offering a service to society (e.g. health, meteorology, agriculture, environment, energy, hazard warning, etc.)? Is there a link with the politics, do you provide advice for political decisions? Do you have links with museums and scientific collections? Do you support the promotion of young talents in your field? Do you have outreach activities? Is there something to say in relation with the sustainable developments goals (SDGs) or with possible citizen science?]

## 12.1 Education

The purpose of this section is to briefly discuss the structure of particle physics education in Switzerland offered at the universities with a focus on students studying physics as a major. The success of particle physics research in Switzerland largely results from the high-qualified and innovative scientific and technical teams within Swiss institutes. To maintain that quality, the best highly motivated students must be attracted to the field. For this to achieve education in particle physics in all undergraduate physics curricula is mandatory.

### 12.1.1 Bachelor and master

At Swiss universities general courses in nuclear and particle physics are commonly included in the final year of the Bachelor programs. Some counter example exist, however. There are Bachelor programs 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 a elective or core elective modules, allowing the possibility of a student being awarded a Bachelor degree in physics without having followed these courses.

All Swiss universities offer master programs with a strong focus on particle or astroparticle physics. Some of the master programs are clearly structured, targeting towards a specialisation in the chosen topic areas, while others encourage breadth but allow specialisation, if the student so wishes. ETHZ offers a unique and very attractive joint Master's degree in High Energy Physics together with École Polytechnique (Institut Polytechnique de Paris (IP Paris)) preparing excellent students for a future research career in High Energy Physics. The two-year Master program is set up symmetrically between the two universities: students spend one year in Zurich, and one year in Paris.

### 12.1.2 PhD

CHIPP initiated a specialised education program in particle physics open to PhD students all over Switzerland with the CHIPP Winter School and the Zuoz Summer School organised bi-annually. The purpose of the schools is to learn about recent advances in elementary-particle physics from local and world-leading researchers and our PhD students are expected to participate at least once during der PhD studies. The program 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 astro-particle physics. Further education of the students is guaranteed and supported by the institutes through specialised schools offered by CERN, Fermilab, DESY or other institutions.

## 12.2 Outreach activities in Switzerland

Any new large-scale project to be proposed in particle physics will need concerted, global education, outreach, and communication efforts, with a strong and committed dialogue with the public and stakeholders, and adequately educating pupils and students at all ages. Scientific outreach fulfils important and necessary obligations to society. The activities involve direct participation of scientists active in current research of particle and astro-particle physics to improve public understanding of our field, appreciation of the benefits of fundamental research, to rise interest and enthusiasm among young people, and to strengthen the integration of science in society.

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 or museums to YouTube videos, science slams, bars or music festivals. Audiences include primary and secondary school pupils, teachers, journalists and communicators, key stakeholders and policy makers, as well as the general public. Outreach activities of all institutes and universities are thus developing broad, long-term impact, making use of current research to raise and maintain the interest of the audience, but taking also the time to address the underlying nature of the scientific process, the strength of fundamental research and its key role in society.

Outreach activities within CHIPP are intended to inform the political platform and the general public but also to target specifically potential young physicist and high-school students in general. In the view of the Swiss particle physics community, the primary aim is to convey to young secondary school students by conveying the importance, excitement and fantasy of basic physics and in particular recent particle physics and related cosmology developments. In this process the importance of a sound mathematical background is transferred 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 serve to the benefit of all STEM related subjects and fundamental research in general.

In the following we outline a few of the key activities for the general public and high-school students of the past years

- Visits to CERN: CERN as the centre of high energy research is extremely attractive for visits which are organised regularly by CHIPP members. In recent years about 50 visits a year were organised for university students in physics and other disciplines, high-school students, alumni, politicians, members of societies, media, and the general public at large.

- Talks to the general public, the industry and high schools: many CHIPP members, involving all CHIPP institutes are actively participating giving talks to the general public in addition to the regular public talks organised by the institutes.
- Teacher education: we collaborate with secondary-school teachers in the development of innovative and interesting physics demonstrations, sometimes using particle physics data. Education of secondary-school teachers is done by providing teaching material, via the CERN Teacher program ( https://teacher-programmes.web.cern.ch/) and specific topological workshops as well as open days for teacher at our institutes.
- YouTube video 'How particle-physics works: hope and worries on the B-physics anomalies': This short movie illustrates how experimental and theoretical physicists at UZH that work together to understand recent puzzling results in B-physics reported by the LHCb experiment (https://www.youtube.com/watch?v=9dLyTS0Xscw ).
- Exhibits: A multidisciplinary Art& Science exhibition at the Espace Ballon in Château-d'Oex presenting on the discovery of cosmic rays, protagonating the Swiss physicist Albert Gockel from Fribourg who established first hints in his balloon flights over a century ago. Experiments carried out at high altitudes, in balloons, airplanes 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 (https://www.chateau-doex.ch/de/P395/ballonraum-espace-ballon).
- Scientifica – the Zurich Science Days: this bi-annual event attracts typically more than 25'000 visitors. Particle and astro-particle physicists of ETHZ and University of Zurich contribute regularly with topical talks and booths. In 2019 for example the general topic of the Scientifica 'Science fiction - Science facts' was perfectly suited to discuss 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 reveals' (https://www.scientifica.ch).
- Dark Matter Day: Since a few years, the world celebrates end of October the hunt for the unseen—something that scientists refer to as dark matter. Swiss institutes regularly contribute with local events and highlight the experiments that could deepen our understanding of the mystery of dark Matter.

Specialised school labs as well as 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 our institutes that offer special courses in cosmology as well as particle, astroparticle and neutrino physics for school classes targeting different ages of young students. With hands-on experiments, visits to the labs and by meeting bachelor and master students they get in contact with state of the art research and passionate researchers (https://www.psi.ch/ilab/, http://www.sciencelab.uzh.ch,https://dqmp.unige.ch/physics-for-all/physiscope/).

### 12.2.1 International outreach network

The International Particle Physics Outreach Group (IPPOG) (http://ippog.org/) has the mission to maximise the impact of education and outreach efforts related to particle physics and is an excellent example how outreach is done in a collaborative effort. Since 2016 IPPOG is an international scientific collaboration of scientists with experience in research, education & outreach from 26 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 topics such as astro-particle, neutrino physics, radiation treatment and gravitational waves. Hans Peter Beck (University of Berne and Fribourg) served as IPPOG co-chair from 2016 – 2019.

The European Particle Physics Communication Network (EPPCN) (https://espace.cern.ch/EPPCN-site) is a network 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, with Angela Benelli for Switzerland, from each member and associate states with the mandate to support and strengthen communication between CERN and the member states.

## 12.3 Support of young talents

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

In the following the different activities to attract young talents to our field of research are summarised:

- International Particle Physics Masterclass program for high-school students (https://physicsmasterclasses.org/): This international one-day program is targeting high school students that are very interested in physics and particle physics in particular. After an introduction in the concepts of the Standard Model and the measurement techniques the students learn through hands-on experiments and interaction with physicists at CERN how to perform a simple analysis. In Switzerland the various masterclass events typically attract about 200 students each year;
- High-school internship at CERN (https://hssip.web.cern.ch/): Two weeks internship at CERN for 24 high-school students from Switzerland which is offered in 2021 for the first time. More than 60 excellent applications of extremely motivated students were received which made the selection of the candidates a challenging task;
- Individual coaching for high-school students, eg. an internship or support with the matura thesis;
- Internship for students in physics or related fields in our research groups;
- CERN summer student program for students pursuing bachelor's or master's degrees in physics, computing, engineering or mathematics (https://home.cern/summer-student-programme). Students attend lectures and perform their own research projects at CERN during eight to thirteen weeks. As this is an international project with more than 3000 applications for the 340 places, competition is high and only well prepared applications of extremely motivated students succeed;
- Mentoring of PhD students and Early Postdocs in the LHC collaborations ALICE, ATLAS, CMS and LHCb. All LHC collaborations have installed early career offices that organise trainings for newcomers and provide help and advice in the early career of young scientists. Senior scientists from the Swiss universities are actively supporting these early career efforts.

Our efforts will be further enhanced in the coming years to strongly motivate and support young talents in order to strengthen the next generation of young scientists that choose to engage in the particle physics community.

## 12.4 Service to society

Traditionally, particle physics has been a driving force for new technical developments in medicine, such as positron-emission tomography or cancer therapy with proton or heavy ion beams. In addition detectors, that have been developed for measurements of charged particles in high-energy experiments are nowadays used for precise position in medical imaging. Many tools and software applications are in fact very similar in particle physics and medical applications. With the need of even preciser and faster detectors, radiation harder detector material and readout electronics, R&D is continuously ongoing, our understanding deepens and it can thus be expected that further developments in the detector material and types, electronics and analysis algorithm will have a significant impact in other fields such as medicine, material sciences or space sciences.

## 12.5 Summary

As the number of scientists engaged in outreach increases, so do the variety and ingenuity of their efforts reflected in the wide selection of activities, ranging from Open Days to Public Lectures, from lab tours to special workshops for high-schools. Travelling and standing exhibitions attract broad audiences and various events are organised at schools, universities, museums, and science cafes to raise interest and engage the audience. Many institutes offer projects primarily aimed toward high school students and teachers. Often, as a result of these efforts, young students might become more inclined to choose a STEM-related subjects for their studies. They might 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 and appreciative of the importance of research, and thus more suited to make informed decisions about science and scientific questions in their future.

# 13 Vision for the future

[Main Editor: XXX] [(6-12pages) – Explain how the landscape is foreseen to evolve until 2025-2028. What are the future trends and the development opportunities. What fields of research are getting more momentum and what is rather to stay constant or get less interest in the future? Are there game-changing new technological possibilities to be expected (e.g. Big Data, artificial intelligence, new imaging/analysis capabilities, etc.)? Are there new infrastructures already being built in the years to come? Are there new international collaborations foreseen? Where shall Switzerland reinforce its position, follow-up new international trends, etc.?]

[The following split in sections is intended as an intermediate step for collection of the necessary material. The main editor of the chapter will merge accordingly after the material is available.]

### Input from Theory

[Editor: Gino]

### Input from accelerator research

[Editor: Lenny]

## 13.1 Vision for the future

The Swiss Accelerator Research and Technology CHART projects contribute to one of the highest priorities of the European Strategy for Particle Physics – to focus on advanced accelerator technologies, in particular the high-field superconducting magnets, including high-temperature superconductors. Swiss scientists in close collaboration with international partners are investigating the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage [39]. Work on full understanding of the subsurface geology that will be crossed by both the tunnel and the access shafts is being carried out as one of the CHART projects at the University of Geneva's Geology Department. The innovative Linac technology developed for SwissFEL can be used advantageously for the realization of an injector concept for FCC-ee. Established low tolerance manufacturing methods allow for a cost effective mass production and good performance at the same time. A CHART project aims at developing an injector concept including an efficient positron source. As compared to an FEL the collider facility requires significantly higher bunch charges for maximum luminosity and positron production by the Linac beam. Controlling the collective effects triggered by the high intensity beam is one of the challenges for this project. Another challenge is the realization of a positron source that delivers the desired beam intensity for a collider. In particular the conversion efficiency from electrons to positrons must be maximized, while keeping the thermal and thermomechanical requirements for the conversion target realistic. It is planned to test a prototype of this newly developed positron source in the SwissFEL facility at 6 GeV. Any future collider facility serving particle physics research will represent a large accelerator based research infrastructure (RI) with significant investment and operating cost, as well as electrical power consumption which is not only a cost factor. For the realization of such projects sustainability aspects as energy efficiency and other factors impacting the environment are becoming increasingly important. A proposal for a competitive European RI must be optimized in view of many aspects, foremost the physics reach and the cost, and also in view of these sustainability aspects. The particle and accelerator physics community should work towards developing technological and conceptual advancements in multiple fields that contribute to an overall optimization of the concept. In the field of accelerator R&D the CHART program focuses on important developments in this context, such as the development of high field s.c. magnets aimed at maximizing the energy reach of a circular collider facility for a given size. CHART is addressing the most pressing problems in the design and construction of superconducting accelerator magnets:

- establishing a magnet laboratory at PSI capable of the design and construction of superconducting accelerator magnets in Nb3Sn and HTS (REBCO tape) technologies,
- providing generic enabling-technology R&D and apply the results to improve the performance of Nb3Sn canted-cosine-theta (CCT) magnets, as demonstrated by the delivery of a CCT technology demonstrator
- integrating with CERN's HTS technology-coil program, delivering a number of technology-coil assemblies that are to be tested in PSI's upgraded cryogen-free test station, and thereby introducing the full chain of HTS magnet design, construction and testing at PSI
- Investigation of the superconducting wire at the University of Geneva in order to increase its performance under transverse stress.
- Investigation of novel epoxy systems by the collaboration with the ETHZ Soft-Materials-Group, in order to provide optimal mechanical support to the superconducting wire in the coil matrix.

The luminosity production per grid power is maximized through beam dynamics studies and advanced collision schemes. Alternative collider scenarios with potential performance and efficiency related advantages like the muon collider may be studied in parallel.

- perhaps comment on high power target expertise for muon production at PSI

Another topic is the exploration of high gradient acceleration schemes utilizing micron scale accelerator structures and high power lasers. With regard to proton beam power and the intensity of generated low energy muon beams, the PSI HIPA facility provides a very competitive performance. While a significant further increase of the primary proton beam intensity is difficult to achieve, the conversion efficiency to muons has a good potential for further improvements. The improved target configuration and capture optics will not contribute to a higher power consumption but rather enhance the energy efficiency of the facility. The High Intensity Muon Beam (HIMB) project at PSI has the potential to enhance the intensity by more than an order of magnitude.

## Input from Pillar 1

[Editor: Anna]

## 13.2 High energy

**Physics pursuits with the HL-LHC ATLAS and CMS experiments**

The major motivation for the HL-LHC program, being installed from 2025 to 2027, and running from approximately 2027-2036, is to measure with high precision the least known Higgs boson properties, as well as to probe in depth the weak scale, using a dataset approximately 10 times larger than the previously existing dataset. With this dataset, improved ATLAS and CMS detectors for mitigating the pile-up due to higher instantaneous luminosity, and improvements on 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-section measurements, which are currently statistically limited, will also provide more opportunities for the discovery of new physics.

One of the major goals of the HL-LHC will be to find evidence for the self-coupling of the Higgs boson. This effect leads to SM double Higgs production, $HH$, will not be observed or constrained strongly during the LHC running period. Both CMS and ATLAS have endeavored to estimate their sensitivity to this process, which requires two Higgs bosons to be identified in a single event. The best signal significance for this process is expected to be in the combination of one high-rate, high-background Higgs boson decay, with one of low-rate and low-background, leading to the golden channel of $HH \to b\bar{b}\gamma\gamma$. Swiss physicists have been active in $H \to b\bar{b}$ and $H \to \gamma\gamma$, are now leading the current $HH \to b\bar{b}\gamma\gamma$ analyses, and are continuing to develop detectors and triggering systems that are specialized for measuring these processes.

The coupling of the Higgs boson to fermions in the first and second generation has not yet been observed. An observation of the Higgs boson coupling to muons is expected during run 3 of the LHC, however, since the branching ratio $H \to c\bar{c}$ is 20 times lower than that of $H \to b\bar{b}$, and $c$ jets are identified with efficiencies 10 times lower than $b$ jets, a measurement of the SM $H \to c\bar{c}$ process is not expected at the HL-LHC. There is, however, an opportunity for discovery of new physics in the rare decays of the Higgs boson to various second-generation vector mesons and photons which have a SM branching ratio of the order of $10^{-6}$ and, while sensitivity to SM rates is not expected, BSM contributions can greatly enhance these rates. Swiss physicists will be investigating such rare Higgs-boson decays, as well as flavor-violating interactions of the Higgs boson such as $H \to \mu\tau$.

Searches for new physics will carry outstanding importance in the HL-LHC program, with the large datasets giving the opportunity to probe rare phenomena where we would not have had access previously. The top quark, being the heaviest of the particles in the SM, will carry a central role in the future searches for NP due to its potentially increased sensitivity to BSM effects. In order to extend the discovery reach of the LHC, the use of indirect approaches such as automatized calculations, commonly done in the context of effective field theory (EFT) to analyse possible deviations with the SM is expected to take centre stage in the near future. Only recently have experimental measurements started to test directly the coupling of the top quark to Z, W, and Higgs bosons. The current and future ATLAS and CMS datasets will provide an intriguing opportunity to study these processes in more detail. The resonance search program will be extended to challenging areas of low signal rate, large signal width, including tails of distributions, as well as hard-to-trigger low mass region. The di-boson resonance program will be extended to non-standard boson polarisations. The Higgs physics program will be further expanded to various exotic Higgs scenarios. The SUSY physics program will further probe feeble cross-sections, such as those associated with electroweak production; it will explore R-parity-violating models; and it will be expanded towards compressed mass spectra and smaller couplings, resulting in soft and displaced objects in the final state. The search for HNLs in leptonic decays of W bosons will be extended to searches in B decays, taking full advantage of improved triggers strategies. This vast increase in statistics of B decays will also benefit other indirect searches for new physics in the context of lepton flavor violation.

Important to achieving these research goals are improvements in the ATLAS and CMS detectors. In particular, the new timing layer upgrade at CMS, being built with Swiss participation, will improve object identification efficiency amid pileup, and will improve identification and energy reconstruction of photons in the central detector region to maintain high-quality $H \to \gamma\gamma$ measurements. The new inner trackers of both ATLAS anc CMS, being built with major participation from Swiss institutions will greatly improve measurements of $H \to b\bar{b}$ and $H \to \tau\tau$ measurements, as well as reduce the effects of pileup in all analyses. The introduction of tracking reconstruction early on in the triggering stages will equally be paramount for maximizing the acceptance to rare phenomena that are typically swamped in large rates of SM processes; this is a driving motivation behind the ATLAS and CMS trigger architectures.

Optimized detector design will be followed by resource efficiency in the aforementioned areas of triggering, reconstruction and simulation. These translate directly to improved precision of SM measurements and increased sensitivity to NP given higher trigger efficiencies, improved reconstruction algorithms and higher statistics of simulated data to optimise the analysis strategies. Areas of particular interest to the Swiss research teams are searches for new physics objects leading to unconventional signatures in the tracking volume, or to anomalous jet substructure, as well as the combination of both phenomena. Modern tools based on machine learning provide cutting-edge technology that can be used to take full advantage of the unique LHC data set and at the same time to revolutionise the way we do science 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 the exploration of a region of mass and coupling inaccessible to current and planned direct detection experiments that could pave the way to NP discovery. Flavour physics is strongly linked to theoretical QCD computations on a lattice since some measurements require knowledge of the hadronic system to be interpreted. The correlations between the different measurements is a powerful weapon in flavour physics to disentangle NP from hadronic effects and can be used to advance theoretical knowledge of low-energy QCD. Since most key measurements in heavy flavour are statistically limited, it is of paramount importance to have a flavour physics experiment in the HL-LHC era. Multi-purpose flavour experiments at colliders, such as LHCb, are those offering 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 has been submitted in February 2017 to the LHC committee for a second upgrade (Upgrade 2) after Run 4 (in $\sim 2030$). The idea is to operate at a luminosity of $2 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, i.e. ten times that of the first upgraded detector, and improve the performance of the detector in key areas. With an accumulated sample of at least 300 $\text{fb}^{-1}$, LHCb would then take full advantage of the flavour physics opportunities at HL-LHC. Switzerland intends to play a crucial role in this endeavour thanks to the experience of the EPFL and UZH groups in the current LHCb experiment and its upgrade.

**Detector and computing**

The Swiss particle physics community masters a wide range of detector technology: tracking detectors, calorimetry, triggering and DAQ. Due to the diverse expertise present in all institutions, the Swiss community is well poised to develop/adapt any hardware technology that would be needed for future facilities. Hardware expertise is therefore not perceived as a limiting factor to pursue future directions in the field. In the close future and beyond 2025, the focus of Swiss scientists is expected to be three-fold: the commissioning and operation of the HL-LHC detectors, detector and trigger upgrades within HL-LHC, and R&D for future facilities, in line with the European strategy recommendations.

While the initial HL-LHC detector upgrades for the LHC Run 4 are well underway, discussions are now starting within the LHC experiments on detector upgrades for Run5. These upgrades will accommodate flexibility and challenges that are expected not to be fully addressed beforehand. They will also allow the experiments to respond to potential change in the physics landscape, in the case of an observed anomaly in data. As an example, the ATLAS collaboration is envisaging the replacement of the innermost tracking layers to account for radiation damage; at the same time, it considers an upgrade in the read-out electronics, which will in turns allow for an evolution in the TDAQ architecture of the experiment.

The HL-LHC will require an increase in computing resources by a factor of order 50. A combination of scaling of the present resources and increase of processors performance by Moore's law will most probably not be enough. The present solution pursued by the HEP community is instead to enhance the parallelism of the algorithms and use more heterogeneous computing architecture including GPUs and FPGAs to run them. Machine learning will play a definite role in shaping those reconstruction algorithms (e.g. tracking and clustering running on GPUs), boosting the speed of simulations and in general in increasing the efficiency in extracting information from data. The investment in the hardware facilities will have to be paralleled by an investment in developing the software needed to accomplish these goals. To facilitate the 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".[TODO: Add a reference to / quote from European strategy, chapter 4d.]

**Probing particle physics further**

As indicated in the European Strategy, new experiments beyond the ones belonging to the general purpose collider ones and which are exploring the dark sector have a rich future. The NA64 experiment is currently being upgraded and will resume data taking after LS2. The goal is to probe most of the remaining parameter space motivated by light thermal dark matter models and to completely cover the X17 anomaly parameter space. Moreover, a pilot run using the unique 150 GeV muon beamline at the SPS was approved to search for a new dark boson $Z_\mu$ with a mass in sub-GeV range, which is coupled predominantly to the second and third lepton generations. The existence of $Z_\mu$ would provide an explanation of the muon g-2 anomaly and is complementary to NA64 in electron mode to search for DS at higher masses [44]. 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 design after FASER is commissioned in 2022, aiming at being installed during LS3 for data taking at the HL-LHC.

Beyond the HL-LHC upgrades, the high energy physics community views with enthusiasm the European strategy outcome, which supports R&D for a large Future Circular Collider (FCC), opening up enormous potential in the comprehension of our world. Exploring the properties of the Higgs boson continues to be one of the most pertinent tasks of the field, both in understanding electroweak symmetry breaking, the mechanism by which particles acquire mass, as well as searching for new clues to answer deep questions in the understanding of the universe. In the coming years, the community is asked to produce design reports for future detectors to be hosted in the prospective FCC, which is expected to motivate the Swiss scientists and the younger generations alike.

## 13.3 Low energy

A goal for the future, of course, 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 are good and some of the most promising and sensitive discovery channels are searches for violation of the symmetry between matter and antimatter (CP) and between leptons from different families (lepton flavor LF, here: muons and electrons). As such discoveries cannot be planned, measurements of SM parameters at the highest precision are also important, provide crucial input, confirm theoretical understanding in detail and exclude BSM theories.

After LS2, the ELENA ring at the CERN AD will provide an unprecedented flux of low energy antiprotons. This will open a new era for precision tests with antimatter. Among those the measurement in GBAR of the gravitational acceleration $\bar{g}$ imparted to freely falling anti-hydrogen atoms which will allow for a direct experimental test of the Weak Equivalence Principle with anti-matter [41, 54] and a stringent test of the CPT theorem [47].

PSI is offering world-leading beams of low momentum pions, muons and ultracold neutrons used by a large and growing community with strong Swiss participation and leadership. There is a unique opportunity to maintain the leadership in this attractive field and to substantially upgrade these facilities in terms of beam intensity and quality. This will translate into a significantly enhanced reach of the experiments and their physics potential, and pave the way for completely new experiments and research directions.

On the one hand, this concerns the intensity of the source of ultracold neutrons (UCN) at PSI at which the search for the neutron electric dipole moment will also in 5-10 years still be statistically limited. On the other hand, this concerns the intensity of PSI's secondary muon beams which could be boosted by almost two orders of magnitude by the High Intensity Muon Beam project HiMB. In a similar direction, many experiments would benefit from improved muon beam quality, where the muCool project promises seven orders of magnitude improvement for the brilliance of slow positive muon beams with a plethora of applications in fundamental particle physics and in applied sciences. Obviously, the combination of muCool and HiMB will be highly attractive. With an additional project for cooling of slow, negative muons many more applications would show up, directly for muonic atom research and material surface studies, but it might impact future muon collider options as well.

While important installations at other international facilities, such as at the CERN AD, at ILL and ESS with their existing or envisaged fundamental neutron physics programs, 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).

The single most important facility project of the next 5-10 years, with exploitation over the next more than 20 years will be the realization of the HiMB project. One very strong science driver on the particle physics side is the search for charged lepton flavor violation (cLFV), as ongoing with the MEG II and Mu3e experiments. The international Mu3e collaboration with leading contributions by groups from PSI, U Geneva, UZH and ETHZ has layed out a phased approach which ultimately needs HiMB to push the limits of cLFV searches with muons. HiMB at HIPA at PSI 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 material science applications with unprecedented statistical power.

## Input from Pillar 2

[Editor: Michele]

The nature of the neutrino mass generation, the pattern of mixing angles and masses with the possibility of CP violation, the absolute neutrino mass scale, the fundamental nature of neutrinos, the search for the elusive right-handed neutrinos, will all constitute conceptual and experimental problems for decades to come. The rewards are potentially very high and far-reaching: the understanding of the nature of Dark Matter, the origin of the dominance of matter over anti-matter in the Universe, and the unification of forces at very high energy. The Swiss Particle Physics activities in neutrino physics and astrophysics should grow correspondingly.

Swiss groups are well position to make strong contributions to the neutrino research program in the following years. Groups are involved in the study of intrinsic neutrino properties at the leading experiments in the field. Recent experimental results show the relevance of the field and the commitment of the Swiss community to its success. All groups have long established experience, have strong reputation in the field and had made significant contributions to the recent developments. This document aims at the consolidation of this panorama and the reinforcement of the community in the next generation of experiments. This leadership is recognised by several leading positions (spokesperson) at experiments such as T2K, DUNE, DARWIN, during the last years. The international relevance of the Swiss groups in neutrino research have been larger than the size of the community might indicate. The community is also supported by a new generation of researchers fully committed to this research, with long standing experience and already taking the leadership in the field. This situation can be, with the proper support, reinforce the impact of Swiss groups in this field of research. The plan laid out in this document paves the road for a coherent research program expanding the next 15 years covering the most important aspects of this research and positioning the Swiss groups in the leading experiments in the field.

The field of neutrino physics, similar to the high energy physics frontier, has 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 to finally the collection of the data and exploitation there can be two decades, with each of the phases lasting several years. The roadmap for neutrino physics, internationally but also reflected in the Swiss plans, has currently several major infrastructures in the final design phase and construction which are expected to start collecting data well before the end of this decade. It is therefore a very exciting time with new fundamental results expected on key parameters, like the matter-antimatter asymmetry and neutrino mass hierarchy. These facilities include, most relevant for the

Swiss participation, the long-baseline experiments in the USA and Japan and DARWIN, all aiming at a start of operation 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 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 that extends to around 2030. 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 and therefore the concrete planning and design will only start in several years.

Some text on other efforts can/should be added here, to make sure that they are not to be forgotten, like FASERnu: The FASER experiment, described in more detail n the Pillar-1 part, will contribute to neutrino physics. FASER is a recently approved experiment at the CERN-LHC. It has a dedicated neutrino detector (called FASERnu) and will measure TeV-scale neutrinos from the LHC during Run 3 (2022-2024). A comprehensive study of three-flavor neutrinos (production, propagation and interaction) will be carried out. The result will contribute to the fundamental understanding of neutrinos properties, and also provides a relevant basic data for astrophysical neutrino observations by the large scale neutrino telescopes (e.g. IceCube). FASERnu will be the first experiment which makes use of neutrinos from collider. The experiment will open new possibilities of neutrino experiments with the HL-LHC and eventually the FCC.

OTHERS ?

Hyper-K T2K is in the process to sign a Memorandum of Understanding to initiate the process of transferring of the Near Detector complex to HyperKamiokande to serve as a near detector of the new experiment. In addition, the University of Geneva and ETHZ are exploring the possible contribution to the readout electronics of the future HyperKamiokande inner detector sensors based on electronics boards developed at PSI and promoting possible contributions of CERN on the accelerator upgrade of the J-PARC facility. Both projects are seeking to optimize the visibility of the Swiss contribution by coordinating the efforts with CERN and by trying to enhance the physics reach of the experiment. T2K plans to operate the experiment until the start of the HyperKamokande with the goal to improve the recent results on the CP phase measurement while paving the road towards HyperKamiokande by performing analysis that will reduce its initial systematic error budget. This additional runs will profit from the beam upgrade scheduled for 2021-22 that will increase the beam power by approximately 50% and by a second upgrade in 2025 that will bring the beam power to 1 MW doubling current running power. Both upgrades will increase the total accumulated data samples by more than a factor of two.

DUNE After 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 started at Fermilab. Two large prototypes were successfully tested in 2018 at CERN. The Technical Design Report (TDR) was published early 2020 for the overall physics program, the beam and the far site detectors (arXiv:2002.03005), the near detector Conceptual Design review was completed in 2019 and the TDR is expected early 2021. An initial configuration of the far and near site detectors are expected to complete construction in 2026 with the neutrino beam turning on in 2027. For the near detector a consortium of institutions was created in 2020 as subgroup of the DUNE collaboration with a goal to build and commission the liquid argon component of the near detector, led by the University of Bern. A modular approach, conceived by Swiss scientists will allow to measure the flux of neutrinos produced at Fermilab with detailed neutrino interaction studies. Despite the very low interaction probability if neutrinos, the rate measured in the near detector will be relatively high due to the very intense neutrino beam, requiring particular measures in order to disentangle single interactions. The liquid-argon technology is particularly well suited to perform such precision measurements.

Complementarity

In addition to the unique relevance of DUNE and HyperKamiokande experiments, recent studies on their physics reach have shown strong synergies between the two approaches. The detection technology and baseline selection influences aspects such as the dominant neutrino interaction channel, the neutrino energy reconstruction and the contribution of matter effects to the oscillations. Those aspects constitute, in addition to neutrino flux prediction, the core of the experimental systematic uncertainties. Both experimental approaches ensure additional control of the systematic uncertainties measuring critical parameters of the Standard Model such as the neutrino mass ordering or the difference in neutrino and anti-neutrino oscillations (CP violation). This statement can be also applied to certain degree to the IceCube neutrino oscillation program. Strong collaboration among Swiss institutions involved in Dune, HK and IceCube will position our community in strong position to explore those synergies.

Based on knowhow, cooperation with previous experiments and industry partners, it is expected that Switzerland will play an important role in the mechanical site infrastructure and cryogenic equipment for LBNF/DUNE. Contributions to HyperKamiokande are also expected for the near detector facility infrastructure such as magnet or gas systems and the J-PARC beam upgrade, in cooperation with CERN, PSI and the Swiss industry.

IceCube

IceCube is undergoing the Phase 1 upgrade, to increase the size of its dense core detector with additional 7 strings holding 700 new and enhanced optical modules (already financed by the US-NSF). This detector, than in the final configuration of 26 additional strings will be called PINGU [**?**], lowers the energy threshold of IceCube to detect neutrinos down to 1 GeV. It aims at the determination of the more precise neutrino oscillation parameters and of the neutrino ordering. It has been shown that a combined analysis with JUNO and IceCube will determine the neutrino mass ordering at a significance beyond the $5\sigma$ within the expected operation times of both experiments, even for a more conservative scenario and for unfavorable regions of parameter space [**?**].

It should be remembered also that IceCube is in the SNEWS alert system for the detecton of MeV-energy burst of neutrinos from supernovas. It is actually the currently existing most sensitive detector to the Large Magellanic cloud.

LEGEND / DARWIN

The LEGEND experiment is one of the three large $0\nu\beta\beta$-decay projects with leading European contributions (together with CUPID and NEXT) recommended in the Double Beta Decay APPEC Committee Report [**?**].

The GERDA experiment [**?**, **?**, 16] was completed at the Laboratori Nazionali del Gran Sasso (LNGS) of INFN, Italy, in December 2019, and since then the infrastructure is available for LEGEND, the next-generation $^{76}$Ge experiment. The collaboration, based of the experiments GERDA and MAJORANA together with new members, aims to build a ton-scale experiment with a large discovery potential in two phases. The first phase, LEGEND-200, is 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 design phase (CDR level) with several underground laboratories as potential hosts. The goals are to achieve a sensitivity of $T_{1/2}^{0\nu\beta\beta} > 10^{27}$ y and $T_{1/2}^{0\nu\beta\beta} > 10^{28}$ y respectively and thus to be sensitive to the full inverted neutrino mass region for $0\nu\beta\beta$-decay via light Majorana neutrino exchange [**?**].

We note that the DARWIN [4] project, a next-generation xenon-based experiment for direct dark matter detection will also be able to probe the $0\nu\beta\beta$-decay of $^{136}$Xe with half-life sensitivity of $2.4 \times 10^{27}$ yr [15], and will thus be complementary to LEGEND and other dedicated searches. We briefly list here the main neutrino physics channels in DARWIN:

- The low energy threshold, ultra-low background levels and excellent target fiducialization will allow for a precise measurement of the **solar pp-neutrino** flux at the 1% level through elastic neutrino-electron scattering. It will provide access to **solar neutrinos** from other production channels as well and constrain the oscillation probability $P_{ee}$ at lowest energies [**?**, 5]. DARWIN will also measure the $^8$**B solar neutrino** flux via coherent elastic neutrino-nucleus scattering and could distinguish between vector and scalar interactions [**?**].
- Even without isotopic enrichment, DARWIN will contain more than 3.5 tons of $^{136}$Xe, a double beta decaying isotope with $Q$-value of 2.46 MeV. This will enable the search for the **neutrinoless double beta decay** ($0\nu\beta\beta$) in an ultra-low background environment to investigate the Majorana nature of neutrinos and lepton number violation [**?**]. The projected half-life sensitivity of $2.4 \times 10^{27}$ yr is competitive to dedicated $0\nu\beta\beta$ searches [15].
- Other **rare decays** accessible to DARWIN are **double electron capture** processes in $^{124}$Xe. XENON1T has recently observed the 2-neutrino double electron capture for the first time – it is the slowest process in the Universe ever measured directly [30]. The increased target mass of DARWIN will allow to probe the neutrinoless decay mode as well ($Q$-value=2.79 MeV) [**?**]. A target depleted in $^{136}$Xe would also allow exploring double beta decays of $^{134}$Xe and $^{126}$Xe [**?**].
- DARWIN will be a continuous monitor for **supernova neutrinos**, with sensitivity to all (active) neutrino species. A galactic supernova will generate hundreds of events in the target through coherent scattering off xenon nuclei [**?**]. Such a measurement will help to determine the supernovae properties, as well as the intrinsic properties of neutrinos. Thanks to its sensitivity to all neutrino flavours and uniquely low energy threshold, DARWIN will be fully complementary to the much larger neutrino detectors. It would also be sensitive to neutrinos from galactic Type Ia and failed core-collapse supernovae [**?**].
- With an energy threshold of 1 keV for ERs, DARWIN can search for an **enhanced neutrino magnetic moment** using solar neutrinos, as recently demonstrated by XENON1T [32].

## Input from Pillar 3

[Editor: Ruth]

DARWIN will probe WIMP dark matter down to the neutrino floor, and continue to broaden the DM reach by using the ionisation signal only, the Migdal effect and bremsstrahlung, as well as DM-electron scattering. It will search for the neutrinoless double beta decay of $^{136}$Xe with sensitivity of $2\times10^{27}$ y (in the baseline scenario) and several other double beta processes (see e.g., e-Print: 2002.04239) , measure the solar pp-neutrino flux (via neutrino-electron scattering) with ¡1% precision and the weak mixing angle at low energies. It will search for solar axions, DM ALPs and dark photons, nucleon decay and many other processes (a global white paper “A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics” is under preparation).

LEGEND-200 will achieve a discovery potential of the neutrinoless double beta decay of 76Ge of 1x1027 y with 1000 kg y exposure, while LEGEND-1000 will extend the sensitivity to 1x1028 y. This will allow us to cover the so-called inverted neutrino mass ordering scenario, probing effective Majorana neutrino masses in the range (10-20) meV (see also the Double Beta Decay APPEC Report, e-Print: 1910.04688).

XENONnT will improve the sensitivity to WIMP dark matter by one order of magnitude. It will also probe LDM 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 (8B) via coherent neutrino-nucleus scattering.

DAMIC-M is set to begin in 2024, and will probe several theoretically viable models for low-energy interactions between DM and matter. It is positioned to be the world-leading experiment in studying hidden-photon DM, hidden photons mediating the interactions of dark matter, and electron scattering of DM at low energy scales. It has a broad reach to probe 10 orders of magnitude in DM mass over a range of theoretical scenarios. OSCURA, whose feasability studies are supported by a U.S. DOE grant, has a timeline after DAMIC-M, and will have thousands of CCD detector modules, making its production similar in scale to detector production for the LHC experiments. The Swiss institutions plan to continue a leading role in this international and large-scale project.

CTA has very high potential for the exploration of the universe of the most violent processes forming compact objects and accelerating particles to extreme energies. It has also high potential for the exploration of dark matter, whether it is made up of axions or WIMPs. CTA will be an extremely important observer to drive multi-messenger observations, which combines information from high-energy gamma, neutrinos, gravitation waves, charged cosmic rays. It will improve energy coverage and sensitivity of current ground based gamma-ray observatories by about an order of magnitude. Taking into account those being background dominated, this corresponds to a factor 100 in observation time.

IceCube will extend its reach to cover neutrino oscillations and detect order of 100 and more cosmic events per year. Running with CTA and Advanced gravitational wave detectors, it will enhance the reach of the mult-messenger astrophsics.

In the next decades CHIPP institutes will also have a very rich research program at the forefront of space astroparticle physics. There are 3 main themes: 1) High-energy astroparticle physics with direct particle detection in space from GeV to PeV (AMS-02, DAMPE, HERD); 2) Multimessenger astrophysics with X-ray and gamma-ray missions (POLAR-2, HERD, eXTP); 3) Multidisciplinary particle detection instrument development for deep space (PAN).

# 14 Development of national infrastructures (2025-2028)

[Main Editor: XXX] [(2-8 pages) – On the basis of the previous sections, what are possible developments (in some cases even essential needs) in terms of infrastructures to maintain or strengthen the Swiss scientific expertise in the field. Are there infrastructures at national level, i.e. beyond what can be afforded by single institutes, that would be essential? Focus on the scientific benefits and the breadth of the community of users, whilst keep it very general on the size, the costs, possible geographical location, management structure, etc. These points will be defined in a second step involving the ETH-Board, swissuniversities and the institutions. They will be described in any specific proposal for a given infrastructure to be submitted by end 2021 (or early 2022) in view of an international evaluation conducted by the SNSF.]

[Ruth Durrer]

A large liquid xenon demonstrator (2.6 m tall TPC, in a 3.5 m cryostat) is in construction at UZH; this infrastructure (financed by an ERC Adv. Grant) will be available to other institutions in CH and Europe.

# 15 Swiss participation to international organisations (2025-2028)

[Main Editor: XXX] [(1-5 pages) – Is there a need for Switzerland to join an international organization to get access to one or several international facilities? Explain the benefits of this. Which specific community would benefit from this? Is it of strategic importance for Switzerland? Are there also positive implications to be expected for the industry or society? ]

[Ruth Durrer]

CTA ERIC will be a worldwide organization on governmental level with solid Swiss participation (ETHZ, UNIGE). It is not yet clear if Switzerland will be a founding member or will have another status, e.g. a strategic partnership. The final decision about Switzerland joining the ERIC will require the Swiss Parliament approval.

DARWIN is on the APPEC roadmap, the Swiss SERI roadmap and on the roadmap of several European funding agencies. LEGEND-1000 is one of the three double beta experiments under consideration by DoE in the US.

The next big international DAMIC experiment is OSCURA, planned for 2026. OSCURA will push the limits of the CCD technology to 10 kg of silicon, single-electron ionization threshold, and a detector with a background of only 0.01 events/kg/keV/day. Switzerland will continue its leading role in this experiment, which is currently a DoE BRN-funded R&D experiment.

# 16 Conclusion

[Main Editor: Rainer] [(1-2 pages) – In this section or imbedded in various recommendations in the text and listed in Sect. 2, there should be some consideration about the prioritization of investments in the field. It is a difficult topic to agree upon by the community, but leaving this completely open to decision-makers is not always the best alternative. As the funds are not infinite it would be good that the community gives basic recommendations on how to serve them optimally in case the list of possible investments clearly exceeds the available means. Some simplistic examples could be: focus on research infrastructures serving the widest community of users; avoid prestige infrastructures in areas not yet having a strong scientific community in Switzerland; rather consider joining a European facility than building something smaller in Switzerland, etc.]

# 17 Appendix

[(1-6 pages) – An appendix could be a list of people involved in the sub-groups formed in the preparation of this document. Another annex can give a list of acronyms used in the text. Concerning acronyms, try to refrain using them too widely to ease the reading by somebody not directly in the field. The same applies to references to scientific publications. Some key references can be given in appendix, if useful, but the roadmap shall not be a scientific paper with many references. Finally, the credit for figures and images shall also be included somewhere, either in the figure caption, or in an appendix, or an inside cover page.]

# test section

This is some test text. See how to use a reference, e.g. of a great recent public result [43].

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