CHIPP Pillar 1 Whitepaper 2018:

Input to the Strategic Workshops in Switzerland

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1 The overarching theme of Pillar 1 research activities in Switzerland

Our present understanding of fundamental interactions is based on the Standard Model (SM), the Quantum Field Theory that describes in a coherent way the nature and non-gravitational interactions of the fundamental constituents of matter. The SM has been successfully tested over a huge range of energies: from the few eV of atomic bonds up to the few TeV of proton-proton collisions at CERN's Large Hadron Collider (LHC). However, compelling arguments from cosmological observations and theoretical considerations indicate that this Theory is only an effective theory, namely that the SM is only valid over a limited range of energies and also over a limited range of interaction strengths. The search for physics beyond the SM (BSM) is the overarching theme of CHIPP "Pillar 1", *i.e.* the experimental and theoretical activities of the Swiss particle community exploiting data of accelerator experiments at the energy frontier to study the high-energy/short-distance interactions between fundamental particles, as well as data of high-precision experiments using accelerators with low centre-of-mass energy but high intensity/luminosity.

Since the discovery of the Higgs boson, announced in 2012 by ATLAS and CMS, the spectrum of the SM is complete: all the particles predicted by this Theory have been observed and, to a good extent, all its free parameters have been measured with good accuracy. Somehow for the first time in history, having fully determined the properties of the SM, we are in a position to test this Theory in all possible directions. This goal is pursued along two main and fully complementary research lines: the so-called direct searches of New Physics (NP), namely the search for new phenomena occurring at high (untested) energies, such as the production of new types of particles, and the indirect searches of NP, namely the search for possible failures in the SM predictions when performing high-precision experiments at any energy scale. While there are no clear clues about possible extensions of the SM, the key open issues of the SM allow us to identify some particularly promising directions within these two main avenues, as discussed below.

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 Planck scale, of the order of 10^{19} GeV) is one of the big open issues in fundamental physics, often referred to as the *electroweak hierarchy* or *"Naturalness" problem*.

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 the Pillar 1 programme. In this respect, it is worth stressing that such exploration has only been started at the LHC. While a significant fraction of the BSM frameworks addressing this problem has already been ruled out, a large fraction remains to be explored, and a thorough exploration of the TeV scale cannot be achieved without increasing the energy of the LHC.

The NP stabilizing the Fermi scale (or the Higgs sector) is expected to manifest itself also indirectly via modifications of the couplings of the Higgs boson, and more generally, of the more massive particles of the SM (the W and Z bosons, and the top quark). The detailed investigation of decay and production processes involving these particles is the complementary indirect way to probe the NP addressing the electroweak hierarchy problem. A significant step forward in this direction is expected in the high-luminosity phase of the LHC, and a further boost could occur with a new high-energy lepton collider.

The flavour puzzle. Within the SM, the basic constituents of matter are the three families of quarks and leptons. Each family contains four fermions (two quarks and two leptons) with different quantum numbers, which determine completely their properties under the 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 families 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 other key open issues in fundamental physics often referred to as the *flavour puzzle*. The observed excess of baryons over anti-baryons in the Universe (*Baryon Asymmetry of the Universe*, BAU), 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 this question. 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 the LHC. Still, their effect could show up indirectly in deviations from the SM predictions in various rare flavour-violating processes (such as the decays of the heavy quarks and leptons). These processes have been extensively studied in various experiments since decades, without clear evidences of a possible breakdown of the SM. But also in this case we are only at the beginning of the exploration of interesting regions in the parameter space of motivated BSM. Actually the recent *anomalies*, namely the deviations from SM predictions, reported by LHCb and other experiments in a series of B meson decays, could be the first concrete hints of some BSM physics around the TeV scale.

On general grounds, a thorough programme in flavour physics is a necessary ingredient to identify the nature of BSM physics, independently if this can be directly accessed or not. Such programme requires more than one facility. 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 tau leptons, and the widest spectrum of interesting measurements. However, rare decays with missing energy in the final state are best probed in dedicated fixed-target experiments (K decays) and/or at lepton colliders (B and D decays). A unique role is also played by the search for flavour violation in charged leptons (a phenomenon that is forbidden in the SM), that is best probed in dedicated experiments at high-intensity muon beams, as uniquely possible at the Paul Scherrer Institute (PSI) for coincidence measurements (muon decays to more than one visible particle). Searches for additional CP violation, largely motivated by the BAU, are being pursued in mixing and decay studies again at colliders, flavour factories and high-intensity secondary particle beams. Particularly sensitive are the searches of CP-violating permanent electric dipole moments (EDM) of the electron, the neutron, various nuclei and, in view of the recent anomalies (including the muon $g-2$ and the discrepancy in proton radius determinations), also of the muon.

Dark sectors. 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 that have not been identified yet because of their weak coupling to ordinary matter (so-called *dark* or *hidden sectors*). Dark sectors are natural candidates to explain the phenomena of dark matter. While a large fraction of the parameter space of these candidates 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, again, with high-intensity particle beams also at low energies.

2 Current implementation of Pillar 1 research in Switzerland

2.1 Overview

CHIPP members belonging to Pillar 1 represent the largest fraction of the Swiss particle physics community and are involved in a large portfolio of diverse activities that are briefly described as a “bird’s eyes view” in this section. The flagship experimental facility continues to be the LHC, with sizeable contributions of the Swiss Pillar 1 community to the ATLAS, CMS and LHCb experiments. The LHC physics programme, exploring the high energy frontier, is laid out until the mid 2030’s, including a significant upgrade of both accelerator and experiments in the mid 2020’s (see below). The proton beam facilities at PSI allow a complementary approach to unlock BSM physics at the low-energy high-precision frontier. Presently starting experiments have schedules reaching the mid 2020’s. The currently ongoing replacement and upgrade programmes of the accelerator infrastructure (injector chain, power supplies, etc.) should allow for reliable operation for the next two decades. The HIPA complex serves three large communities: particle physicists, condensed matter physicists using muons at the Swiss Muon Source (SμS), and condensed matter physicists using neutrons at the Swiss spallation source (SINQ). Particle physicists at PSI are pursuing feasibility studies for high intensity and high brightness beams that could come into operation in the 2020’s.

2.2 ATLAS and CMS

The ATLAS and CMS experiments have been successfully taking data since 2009. Each experiment has submitted more than 700 publications to date. Since the discovery of the Higgs boson in 2012, a much deeper characterization of this new particle has been achieved. New results have included the observation of the Higgs boson decay to $\tau^+\tau^-$, evidence for the Higgs decay to $b\bar{b}$, 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 NP searches and further strengthened bounds on existing models for BSM physics. The large dataset delivered by the LHC since the start of Run 2 in 2015, the similar expected dataset for 2018, and the forthcoming runs promise a strong continuous physics output by ATLAS and CMS which will extend the boundaries of knowledge at the energy frontier.

The upgraded high-luminosity LHC (HL-LHC) is expected to start operations in 2026 and deliver about 250 fb^{-1} per year until 2038, which is approximately 5 times the current data rate. This increased dataset will allow precision studies of previously statistically limited observables and searches for rare processes, but will also present challenges. In order to maintain stable and efficient data taking, the ATLAS and CMS detectors must be upgraded to handle the expected increases in pileup, occupancy, trigger rates, and radiation damage.

The ATLAS and CMS experiments have developed a plan to upgrade their detectors, and have prepared Technical Design Reports for each sub-detector. A major improvement is 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 multi-purpose-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 p_{T} 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, cooling and, for CMS, the construction of the inner pixel tracker extension. In CMS the Swiss groups will also be responsible for the barrel electromagnetic calorimeter electronics, and help build the barrel timing layer. In ATLAS the Swiss groups are contributing to the TDAQ and track trigger upgrade.

2.3 LHCb

The LHCb detector is designed for precise measurements of CP violation and rare B decays, exploiting the huge heavy quark production at the LHC. The primary physics aims are to characterize in detail the flavour structure in the quark sector, and look for New Physics in the decay of charm and bottom hadrons. Up until the end of 2017, LHCb has efficiently recorded pp collisions at centre-of-mass energies of 7, 8 and 13 TeV, corresponding to integrated luminosities of 1, 2 and 3.7 fb^{-1}, respectively. With these data (in fact mostly the first 3 fb^{-1} of Run 1 in 2010–2012) the LHCb physics programme has been fully deployed.

Although much new territory has been explored, all results so far are consistent with the SM expectations. However, some measurements, especially those testing lepton flavour universality (LFU), are in tension with the SM expectations. This has raised the interest for the search for LFU violation, as well as lepton flavour violation, to an unexpectedly high level in the last couple of years. As a result, LHCb must think about new ways to improve the reconstruction and identification of electrons and tau leptons, which are much more challenging than that of muons.

The LHCb collaboration is currently preparing for a major detector upgrade during the 2019–2020 long shutdown of LHC, 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 fb^{-1} per year (from 2021 onwards) with a much improved efficiency, especially for heavy-flavour decays without muon in the final state. Looking further ahead, 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 2×10^{34} cm^{-2}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 fb^{-1}, LHCb would then take full advantage of the flavour physics opportunities at HL-LHC.

The Swiss groups at EPFL and UZH have played major roles in the experiment. They are currently responsible for the operation of the Silicon Tracker and the common readout electronics boards, which they have built. For the upgrade, they have proposed and developed the scintillating fibre (SciFi) technology for the replacement of the tracking stations downstream of the dipole magnet. After a design phase, they are now involved in the construction of the SciFi tracker and the Upstream Tracker, to be installed and commissioned in 2019–2020.

2.4 LHC computing

The vast datasets produced by the LHC experiments described above have always necessitated continued progress in computing, most notably by implementing the Worldwide LHC Computing Grid (WLCG).

The evolution of hardware technologies, in particular also network technologies, and the ready availability of high speed networks have made it possible to depart from the rigid original hierarchical models of classical Grid computing with Tier associations and job data locality. In fact the actual computing landscape has evolved into an overall combination of Grid computing and Cloud computing on a worldwide scale. For LHC computing alone, which is mostly organized and handled by the WLCG community, a large amount of resources is globally distributed. As of end 2017, the size of these WLCG resources reached the order of 10 M HS06 of computing power, ~ 400 PB of online data storage and ~ 400 PB of tape storage from over 150 official sites worldwide. Typically some 700’000 cores are continuously executing LHC jobs delivering some 210 M HS06-days/month. The data transfer rates reached regularly a level of 35–40 GB/s. These resources are primarily exploited by the HEP community for LHC simulation and analyses.

2.5 PSI High Intensity Proton Accelerator (HIPA)

The ring cyclotron at PSI delivers a quasi-continuous 50 MHz proton beam of 590 MeV and 2.4 mA, corresponding to 1.4 MW, to targets. It provides the highest intensities of low momentum pions and muons, as well as of ultracold neutrons (UCN), for fundamental physics experiments. PSI is home to some of the most sensitive NP searches at the low energy, precision frontier. Besides the main focus on CP violation (CPV) and charged lepton flavour violation (cLFV), the experiments test for multi-TeV new physics as well as very light exotic particles with feeble couplings, such as certain dark matter candidates. The flagship experiment with UCN is the search for the CPV electric dipole moment of the neutron. The n2EDM experiment (CH groups: ETHZ, U Bern, U Fribourg, PSI) will be the most sensitive experiment in the years 2020–2025 going a factor of 10 beyond the present best sensitivity, recently obtained with nEDM at PSI.

In muon physics, the best limits on all “golden” cLFV muon decays ($\mu^+ \to e^+\gamma$, $\mu^+ \to e^+e^-e^+$, $\mu^- \to e^-$ conversion) have been obtained at HIPA. New projects at J-PARC and at FNAL aim at improving the reach for $\mu^- \to e^-$ conversion. At PSI, the MEG II experiment (CH: PSI) aims at an order of magnitude improvement in sensitivity for $\mu^+ \to e^+\gamma$ (2018–2021), and the Mu3e collaboration (CH: ETHZ, UZH, U Geneva, PSI) at three orders of magnitude initially (2019–2023) for $\mu^+ \to e^+e^-e^+$. Further improvements on $\mu^+ \to e^+e^-e^+$ and other muon experiments crucially depend on the design and construction of a new high intensity muon beam line (HiMB, 2022+) to deliver almost two orders of magnitude more low momentum muons ($\sim 10^{10}\,\mathrm{s}^{-1}$). R&D in that direction goes along with activities to improve the phase space quality of slow beams of positive muons.

Another prominent research line has been established with laser spectroscopy of the light muonic atoms $\mu^- p$, $\mu^- d$ and μ^-He, measuring the 2S-2P Lamb shift and extracting the charge radii of ^{1,2}H and ^{3,4}He giving rise to the so-called “proton radius puzzle” and providing crucial input to bound-state QED tests. A complementary approach to check whether the proton radius determined with μ and e is the same is pursued by the MUSE collaboration (CH: U Basel, PSI) comparing the scattering of both species on hydrogen in the same experiment. Laser spectroscopic measurements by the CREMA collaboration (CH: ETHZ, PSI) now tackle the ground-state hyperfine splitting in μp and μ^3He (2018–2022) in order to extract the Zemach and magnetic radii. Precision spectroscopy of the muonium $\mu^+ e^-$ transition 1S–2S (2020–2025, CH: ETHZ, PSI) will again push bound-state QED tests and build up on experience with the spectroscopy of positronium 1S–2S, currently ongoing at ETHZ.

2.6 Other experimental activities

The **SHiP** (Search for Hidden Particles) experiment is a proposed beam-dump experiment at CERN's Super Proton Synchrotron (SPS). It is mainly dedicated to search for particles belonging to an hypothetical hidden sector (see Section 1) and search for light dark matter. According to simulation studies, the SHiP experiment should be able to improve current limits on various hidden sector models, such as Dark Photon, Heavy Neutral Leptons and Dark Scalar, by several orders of magnitude. Presently a dedicated detector to search for Lepton Flavour Violating tau decays is under study that would be mounted in front of the SHiP experiment, running in parasitic mode. This experiment could use between 1% and 5% of the SHiP beam and be able to explore the $\tau^+ \to \mu^+\mu^-\mu^+$ branching fraction down to 10^{-10} and below. Such values of branching fractions are predicted by many models explaining the B anomalies. At present SHiP is under evaluation by the CERN management and the relevant bodies (SPS committee and "Physics Beyond Colliders" working group), and preparing a Comprehensive Design Study (CDS) document. Three Swiss groups (EPFL, U Geneva, UZH) contribute to the CDS with leading roles in both software and hardware studies. In addition, there is a possible synergy and collaboration with the PSI target group.

The **GBAR** (Gravitational Behaviour of Anti-hydrogen at Rest) experiment started its installation in 2017. A major milestone was the commissioning of the LINAC and the production of the high intensity slow positron beam required by the experiment. The commissioning of the Extremely Low Energy Antiproton (ELENA) ring, the upgrade of the current Anti-proton Decelerator (AD), is ongoing. This upgrade is an essential ingredient for the GBAR experiment since it will deliver an unprecedented flux of low energy anti-protons. The GBAR data taking is foreseen to start in September 2018. GBAR will be the only experiment in the AD receiving particles from ELENA before the CERN long shutdown (LS2) from 2019 to 2020. A group from ETHZ is participating in GBAR.

NA64 is an experiment at CERN's SPS aimed at a direct search for sub-GeV vector mediator A' of dark matter production in invisible A' decay mode. In 2016 and 2017 the experiment collected 10^{11} electrons on target. No evidence for such a decay has been observed but stringent limits could be set on the A' mass and coupling excluding that this as an explanation of the $g-2$ muon anomaly. In 2018 the experiment will focus on its other goal to search for a new light X boson, which could explain a recently observed excess of e^+e^- events from excited ^{8}Be transitions. After LS2, the experiment plans to collect more statistics to reach the goal of $> 10^{12}$ electrons on target combining runs in 2016–2023. This will allow the coverage of the full parameter space motivated by thermal dark matter. A group from ETHZ is participating in NA64.

2.7 Theory

Theoretical activities is a key ingredient to make progress in Pillar 1 physics: the results of the experiments performed both at the high-energy and at the high-intensity frontiers need vigorous theoretical studies to be interpreted, and the development of new theoretical models is essential in order to plan new experimental efforts. The research interests of the particle theory groups at the different Swiss institutions cover a broad spectrum of topics and methodologies, frequently in close connection with experimental programmes at a larger scale. Individual groups have often a world-leading reputation in their respective field of research, with their members assuming important roles in the research community at large (*e.g.* heading future study and working groups, serving on advisory committees, *etc.*). The main lines of phenomenological theory activity are: high-energy collider physics (U Basel, U Bern, EPFL, ETHZ, PSI, U Geneva, UZH), flavour physics (U Bern, PSI, UZH), neutrino physics (U Basel, EPFL) and particle cosmology (U Basel, U Bern, EPFL, U Geneva). Important conceptual work is performed on precision calculations (ETHZ, UZH), new theories beyond the Standard Model (U Basel, EPFL, U Geneva, UZH) and on non-perturbative approaches to quantum field theory (U Bern, U Geneva, EPFL). Strong links between different Swiss institutions as well as between theory and experiment exist through common research projects and collaborative programmes. They are further fostered by a lively activity of workshops and topical programmes. Future developments should ensure the strengthening, or at least the maintenance, of the leadership role achieved in the current areas of activity and possibly allow the expansion in emerging subfields.

2.8 Accelerator R&D

Accelerator R&D in Switzerland is addressing the needs of the high-energy (CERN) and of the high-precision (PSI) frontiers of particle physics, as well as the needs of accelerators for the light and neutron sources, for medical and industrial applications. Some of the common topics include high-field superconducting magnets (towards $16-20$ T), high gradient acceleration (from 100 MeV/m RF structures for CLIC to $1\,\mathrm{GeV/m}$ laser acceleration) and very low emittance storage rings for the upgrades of the Swiss Light Source, linear collider damping rings and compact sources.

An extraordinary initial funding grant released by the State Secretariat for Education, Research and Innovation (SERI) called to life the Swiss Accelerator Research and Technology (CHART) collaboration to support the Future Circular Collider (FCC) study at CERN and the development of accelerator concepts beyond the existing technology (laser and THz high-gradient acceleration). The high-field magnet development towards a 16 T dipole has started at PSI in close collaboration with CERN, EPFL, U Geneva and the Lawrence Berkeley National Lab, aiming at technological prototypes of the so-called “canted cosine theta” magnet by 2019. The successful development of a 16–20 T dipole magnet is essential for the next generation of circular hadron colliders, such an energy-upgraded LHC and the FCC.

3 Potential future facilities as drivers for Pillar 1 research

In this section, we describe the potential future accelerator based facilities that would be able to address the physics needs at the high-energy and high-precision frontiers. There is general agreement on the need for a Higgs factory as the next physics machine. An implementation that would establish the technology for the ultimate high-energy frontier facility would be of particular importance for the future of our field. All the projected time scales are derived from technical schedules.

The **High-Luminosity LHC (HL-LHC) upgrade** is in preparation now. LHC in its present configuration aims at delivering 0.3 ab^{-1} until 2023. After 2.5 years of installation, HL-LHC is expected to deliver 3 ab^{-1} by 2038. Presently LHC has exceeded the design peak luminosity by a factor of two and luminosity leveling schemes to keep the pileup in the detectors below 140 have been successfully tested. One of the main reasons for this upgrade is that the present triplet magnets in the interaction regions will have to be replaced due to radiation damage. The new triplet magnets will be better shielded and will receive the same dose only after the detectors will collect a factor of ten higher integrated luminosity. With larger bore and peak fields of 12 T at the conductor these magnets require introducing the $\mathrm{Nb_3Sn}$ superconducting technology. Thus, the HL-LHC is also an important step on the high-field magnet R&D roadmap.

The **High Energy LHC (HE-LHC)** aims at proton-proton collisions with a centre-of-mass energy of 27 TeV using the present LHC tunnel and 16 T dipole magnets. These are under development by the FCC magnet R&D programme and may take about 20 years to produce. Removal of the present LHC and its replacement with the HE-LHC would take 6 years and would allow for a start of physics run in 2040 at the earliest, anticipating the conclusion of the HL-LHC programme to 2034. The integrated luminosity target over 20 years of running is at least 10 ab^{-1}.

The **Future Circular Collider (FCC)** study aims at raising the centre-of-mass proton-proton collision energy to 100 TeV (FCC-hh). At the same time the potential lepton-lepton (FCC-ee) and lepton-hadron (FCC-eh) collider options are studied. The magnetic field in the dipole magnets and the size of the tunnel limit the energy reach of a circular hadron collider, and the FCC-hh study goal of reaching 100 TeV requires the development of superconducting magnets with twice the field of the present LHC dipoles. This critical R&D programme is under way at CERN and at the European national laboratories in France, Italy, Spain and Switzerland, in collaboration with the US-DOE high-field magnet programme. Together with the civil construction, it constrains the possible time schedule: assuming a decision taken in 2026, the earliest start of the physics run of the FCC-hh would be in 2043.

Studies of **Future Circular Lepton Colliders** to be built in a 100 km tunnel are pursued by both the FCC collaboration and the Circular Electron Positron Collider (CEPC) effort in China. The FCC-ee is a potential first step on the way to a 100 TeV FCC-hh and CEPC plans include similar staging towards a Super Proton-Proton Collider (SPPC). Both studies aim at a similar set of parameters, with the Chinese version taking a more conservative approach (three times lower luminosity and energy limited to the HZ threshold). The energy reach of the FCC-ee option is limited by the steep energy dependence ($\propto E^4$) of the synchrotron radiation power emitted by the beam. In the present study, the total power is limited to 100 MW. The aim is to collect 2.5 ab^{-1} per experiment at 240 GeV (HZ maximum) and 0.75 ab^{-1} above the $t\bar{t}$ threshold at 340–370 GeV. Running at lower energies could produce 75 ab^{-1} at and around 90 GeV (Z pole) and 5 ab^{-1} at around 160 GeV (WW threshold). Assuming a decision taken in 2026, the earliest start of physics run would be in 2039.

The **International Linear Collider (ILC)** at 250 GeV centre-of-mass energy is presently under discussion and the Japanese high-energy physics community has expressed a strong interest in hosting it in Japan. Based on the superconducting RF technology, which has been successfully deployed by the European XFEL, it is considered ready for construction as soon as funding will be approved. Fundamentally, the energy of the linear colliders can be increased by simply extending the tunnel and acceleration structure or/and improving the superconducting RF technology for a relatively small energy step, given sufficient physics motivation. For a longer term, one can imagine replacing the acceleration structure with a more advanced one featuring a much higher acceleration gradient. The cost of such a Higgs factory is estimated to be approximately 5 GCHF and its realization would take about 10 years.

The **Compact Linear Collider (CLIC)** is a study carried out by a large international collaboration led by CERN and employs the two-beam acceleration concept. Using normal conducting accelerating structures at a frequency of 12 GHz, it aims at achieving an accelerating gradient well above 100 MeV/m to enable 1.5 to 3 TeV collision energies. The feasibility of this technology has been demonstrated at several test facilities, with Switzerland continually participating in the high-gradient R&D. Presently a 380 GeV machine that would reach the $t\bar{t}$ threshold is costed at about 6 GCHF and could be ready to start operating for physics by 2035, as the LHC programme reaches completion. The technology for a simplified CLIC klystron-based first stage for this machine is ready now and such a Higgs factory would be able to demonstrate the feasibility of a linear collider concept as a possible path towards a multi-TeV machine. Synergy with the need for compact light sources would be substantial.

Muon colliders can potentially reach collision energies well above 10 TeV. At the highest energy range they can deliver much higher luminosity per wall plug power consumption, compared to the other lepton colliders. A muon-collider-based Higgs factory operating at a centre-of-mass collision energy of 125 GeV would benefit from a substantially higher cross section for the s-channel Higgs boson production compared to the HZ channel at the electron-positron colliders. Its inherent high energy resolution could also allow a measurement of the Higgs width with good precision.

4 Appraisal of the current implementation

The current implementation of Pillar 1 research in Switzerland has been successful to pursue the goals laid out in Section 1. However, while long term goals have not changed much since the 2004 CHIPP roadmap and its 2011 update, boundary conditions have evolved and the Swiss community has developed new initiatives and directions, while deciding not to join others. This section hence is dedicated to appraise the current implementation in terms of how optimal it is to achieve the Pillar 1 research goals and how the perennial tension between depth versus breadth is resolved.

4.1 Experimental opportunities not currently pursued in Pillar 1 research

Despite the strong support by the funding agencies and intellectual prowess of the community, there are scientifically very worthwhile activities that are currently not pursued by Swiss researchers in Pillar 1. This section mentions a few prominent ones. The context in which those activities are embedded have not changed for a while, and hence it is unlikely (but not inconceivable) that the Swiss researchers will get involved in a larger scale in the efforts listed below.

Belle II The intensity frontier in flavour physics is vigorously pursued in Japan, where the energy-asymmetric KEKB electron-positron collider operating in the vicinity of the $\Upsilon(4S)$ resonance has been upgraded to reach instantaneous luminosities of 8×10^{35} cm^{-2}s^{-1} (SuperKEKB), a factor 40 above that achieved in the first decade of this century. In 2018, the machine and the new Belle II detector will complete their final commissioning phase with first recorded collisions. During the physics production phase (2019–2025), Belle II is expected to collect an integrated luminosity of 50 ab^{-1}, 50 (100) times that recorded by its predecessor Belle (BaBar), and push the indirect search of New Physics a significant step further in B-meson, charm-hadron and tau-lepton decays. Switzerland, who was involved in the Belle programme, chose to concentrate its flavour physics effort on LHCb rather than Belle II.

Muon physics outside PSI A world-leading intensity frontier programme in muon physics is being pursued at PSI with strong participation of Swiss university groups. Other exciting and complementary efforts exist at FNAL in the USA and at J-PARC in Japan, however, without Swiss participation to the experiments (obviously, some efforts of the Swiss theory community are very relevant also to those activities). The main activities covered both at FNAL and J-PARC are measurements of the anomalous magnetic moment of the muon ($g-2$) and searches for the charged lepton flavour violating (cLFV) conversion of a negative muon to an electron in a muonic atom ($\mu \to e$ conversion). The $g-2$ experiment at FNAL aims at providing a four-fold improved measurement within a few years and check on the $\sim 3.5\sigma$ difference between the measured value from BNL and the SM predictions. The J-PARC experiment uses a novel technique but will be coming online only later. The $\mu \to e$ conversion experiments at FNAL and J-PARC aim at improving the existing limit (7×10^{-13}) from PSI by several orders of magnitude ($10^{-14} - 10^{-16}$ and possibly beyond). The experiments will make use of pulsed proton beams to maximally suppress backgrounds in this single electron detection experiment. These pulsed beams cannot be obtained at PSI. The physics case is very strong, in-phase and complementary to the ongoing cLFV programme with $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^-e^+$ at PSI. Besides those two lighthouse projects, J-PARC also hosts a variety of other muon physics experiments, again with some complementarity to the PSI programme with Swiss participation. Worth mentioning are (i) activities to measure the ground-state hyperfine splitting (GS-HFS) in muonic hydrogen in direct competition to the HyperMU project at PSI (ETHZ/PSI and international CREMA collaboration), and (ii) the measurement of the GS-HFS in muonium complementary to the measurement of the muonium 1S-2S transition frequency planned for PSI (ETHZ/PSI.)

Kaon physics Similarly to the cLFV rare decays of muon physics, experiments with outstanding sensitivity to BSM physics are pursued with kaons. While there are more experiments, considerable interest is focusing on NA62 at CERN (to measure the very rare decay $K^+ \to \pi^+ \nu\bar{\nu}$) and on KOTO at J-PARC ($K_L \to \pi^0 \nu\bar{\nu}$) as formidable SM tests. There are no Swiss groups involved in these efforts.

LHeC and FCC-eh The Swiss community (ETHZ, UZH and PSI) has traditionally contributed strongly to the HERA programme at DESY (H1 experiment, operated 1992–2007) exploiting electron-proton collisions at 320 GeV. The HERA collider provided unique insights into the structure of the proton, such as the strong rise of the gluon parton distribution at low x that were vital input into the LHC physics programme. There are plans for a future lepton-hadron (LHeC and FCC-eh) facilities that would continue this line of research in the future, elucidating the strong interaction further. Currently, no Swiss researchers are involved in those activities.

4.2 Experimental opportunities with new developments and potential for (increased) Swiss involvement

In this section, some experimental opportunities are listed for which the context has recently changed or received new inputs. Such a change could trigger either an increased involvement of Swiss Pillar 1 researchers or initiate a new Swiss involvement. While the distinction to the previously listed activities is to a certain extent arbitrary (any of the activities above in principle could receive new input at any moment), the following list may help identifying fields that would currently merit a changed attitude of Swiss Pillar 1 researchers.

More intense/diversified efforts in flavour physics Presently, the only hints for physics beyond the SM in collider experiments are the so-called anomalies in B physics. In precision experiments, the anomalous magnetic moment of the muon and the proton radius puzzle stick out. If these effects were confirmed as clear evidences of BSM physics, it would be compelling to intensify the experimental efforts in heavy flavour physics and in muon physics. A natural way to achieve this goal would be stronger involvements in the LHCb Upgrade 2, in the τ-physics programme of SHiP and in the muon physics programme at PSI. In this context, a new high intensity muon beam (HiMB) could be built at PSI. A more flavour-oriented physics programme could also be conceived in the context of further ATLAS and CMS upgrades and data analyses. Last but not least, a possible future upgrade of the kaon physics programme at CERN is an option in this direction that could be worth considering.

Unconventional signatures The absence of new physics in our theory-guided searches suggests a need for a paradigm shift where the data plays the main role and is tested for any kind of deviation in a more model-agnostic way. New physics might be hidden in our current data if it is not in one of the regions covered by existing searches. A broader approach to hypothesis testing is required. A step in this direction is to include unconventional signatures, such as long-lived particles, highly ionising particles or fractionally charged particles, more systematically into the search programme, as well as to design dedicated trigger strategies and potential extensions to the current detectors. New track trigger capabilities in ATLAS and CMS in Run 3 and beyond represent opportunities in this direction. Other ideas include the MATHUSLA surface detector concept (arXiv:1606.06298), the Milliqan idea to detect milli-charged particles (arXiv:1607.04669), and the CODEX-b proposal to search for BSM long-lived particles (arXiv:1708.09395).

Fundamental physics using atomic physics methods In recent years, efforts using techniques of atomic and molecular physics to address fundamental and particle physics questions have grown significantly. Often the research is being pursued in small teams or single professorships. The field is very wide and comprises measurements of g-factors of the electron and of ions, searches for permanent electric dipole moments (EDM) of the electron using atoms and molecules, searches for EDM of nuclei using atoms, searches for Lorentz and CPT violation using atoms and/or lasers, searches for axions and other exotic particles and forces by precision atomic spectroscopy or magnetometry, searches for certain kind of dark energy signatures ("Chameleon") using atom interferometry, and many more aspects. Presently, there are only very few activities along these lines in Switzerland.

Fundamental physics with slow neutrons Besides the present nEDM/n2EDM activities with UCN at PSI and of the Bern group (Piegsa) with cold neutrons, fundamental neutron physics comprises very visible experiments in neutron beta decay (lifetime and decay correlations) being pursued around the world mainly in the USA (SNS, NIST, LANL), in Japan (J-PARC) and in Europe at the ILL. In the future new options for experiments will emerge with the advent of the ESS in Lund. Besides neutron decay measurements and studies of hadronic weak interaction, a major project under discussion is a new search for the baryon number violating oscillation of neutrons to anti-neutrons (nnbar) proposed by an international collaboration. The Bern group is studying a possible neutron beam EDM experiment for ESS and is running precursor studies at SINQ/PSI and at the ILL.

Linear collider accelerator development While a circular collider can efficiently use beam particles for achieving high luminosities, its energy reach is limited by either the energy loss due to synchrotron radiation for an e^+e^- collider, or limitation in the bending power of the magnet for a pp collider. Thus a circular collider will not be able to fully benefit from the ongoing R&D effort in acceleration technology to increase the acceleration gradient. Therefore, a linear collider could be the ultimate energy frontier machine for particle physics, once the next energy frontier is revealed.

Since beam particles are used only once in collision, reaching high luminosity is a challenge for a linear collider. Although the SLC at SLAC has successfully demonstrated the basic principle of a linear collider, a demonstration that a linear collider can provide sufficient instantaneous and integrated luminosities needed to reach the physics goals is still outstanding. Wall plug power is another critical problem for all future colliders striving to reach very high energies.

For this reason the construction of a linear collider as a physics production machine, at an energy where such a machine can be built commensurate with the available resources but still meaningful from physics point of view, is a mandatory step for the future high energy frontier physics. Such a demonstrator can be implemented either as a 250 GeV ILC (Higgs factory) or as a first phase of a 380 GeV CLIC (Higgs and top studies), where more details are given in Section 3.

FCC accelerator R&D The high field magnet programme for the FCC-hh and HE-LHC offers significant synergies with the needs for such magnets for particle therapy and synchrotron light sources. A massive Europe-wide effort is required to achieve timely progress in development of such magnets for the high energy physics needs. The energy reach of HE-LHC, given the present tunnel limitation, calls for the highest magnetic field magnets that can be developed, industrialized and reliably operated. Switzerland, with its large research facilities operated by PSI, offers unique opportunities for development of technologies based on novel superconducting materials. Advanced analytics, coupled with the initiatives in advanced manufacturing can potentially translate into a significant local advantage benefiting both the public and private sectors of the economy.

Muon colliders At very high collision energies a muon collider may be a machine of choice for high precision studies, maintaining a tighter constraint on the centre-of-mass collision energy compared to the e^+e^- collider case thanks to a much lower synchrotron radiation emitted during collisions (so-called beamstrahlung radiation). The production of high brightness muon beams to reach the requisite high luminosities is for the moment an important and urgent accelerator R&D topic.

4.3 Further opportunities, tools, and challenges

At the present time, future opportunities and challenges are also discernible. Swiss Pillar 1 research is embedded in an international context, and hence there are science drivers external to the Swiss Pillar 1 community as well. The following section mentions a few tools that have emerged as a possible opportunity or a challenge for the future.

Further advancement in software and Machine Learning Machine learning (ML) is state of the art in all Big Data fields (search engines, finance, health diagnostics, image recognition *etc.*) but HEP is only beginning to take advantage of this opportunity. Over the last decade ML has been used more frequently in HEP thanks to the introduction of TMVA (arXiv:0703039), a ROOT-integrated package for machine learning, which provides a common interface and associated support for basic neural networks (NN), boosted decision trees, *etc*. The main applications are event-level discrimination of signal and background in analyses. In the meantime, the ML community has made considerable progress and developed in particular Deep Learning concepts, which are far superior to what can be done with TMVA. Training deeper networks on larger datasets has become feasible thanks to recent advances in computing hardware addressing the so-called vanishing gradient problem. Deep Learning is state of the art for analysing data with a complex and deep structure and has recently led to significant advances in the fields of computer vision and speech recognition. The main opportunity for HEP is to improve the extraction of information from the data, to create faster algorithms and to make the whole simulation, reconstruction and analysis chain easier and more automated. Some concrete examples include improved object identification by going closer to the raw data as the inputs (*e.g.* using tracks or even hits, and by using calorimeter clusters or even cells), deep generative models, such as Variational Auto-Encoders (VAEs) and Generative Adversarial Networks (GANs) that can be used for fast simulation purposes. ML-based smart clustering algorithms have the potential to speed up charged particle tracking by orders of magnitude. Domain knowledge (*i.e.* all our physics knowledge) can be incorporated into the ML concepts, and classifiers can tuned to be insensitive to a particular set of (*e.g.* leading) systematic uncertainties. Even more ambitious ideas can be formulated, such as the inverse problem, where instead of forward modelling and predictions based on observed and simulated data, we do inference in the space of parameters of interest (and nuisance parameters). Another idea is to consider the NP searches as a search for an anomaly with respect to the SM physics.

Computing In view of the upcoming HL-LHC it is unclear as to what the computing models will be at all. It is recognized that the present HEP model of computing will not suffice to satisfy the needs of the various communities. Computing resources will need to increase by a factor of order 50 within the next 6–10 years. It is commonly agreed that this cannot be reached by a combination of “Moore’s Law” and pure scaling of today’s structures. In the past HEP faced many computing challenges before other communities and has developed over the decades a lot of community-specific solutions. But it is clear that the world changed, other communities and industry face some similar challenges, and HEP must be able to benefit from them as well. The needs of others, such as the astroparticle physics community, may well exceed those of HEP.

In order to address the upcoming challenges, a community white paper (CWP) on the future of HEP computing has been developed during 2017 under the umbrella of the HEP Software Foundation (HSF) gathering input from the entire HEP community. The main points to be addressed are: avoid HEP-specific solutions in the future; develop and adapt tools and structures; apply new data-storage concepts, enabling the use of very heterogeneous resources (new architectures, high performance computing, specialized clusters, clouds, etc); focus strongly on the development of software/libraries in a much more flexible way.

Future detector hardware development The Swiss particle physics community masters a wide range of detector technology ranging from 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.

More intense/diversified efforts in theoretical tools At present there is a very good level of interaction between the theoretical and the experimental Swiss Pillar-1 groups. However, the challenges posed by future experimental programmes may call for an even stronger collaboration or the strengthening of specific research directions in theoretical physics. In particular, the high-luminosity LHC programme would certainly benefit from the development of more efficient and more precise simulation tools for SM processes at hadron colliders. Similarly, lattice-QCD simulations for flavour-physics observables is an area of theoretical research that may be worth strengthening in view of future flavour-physics experiments. Last but not least, it would be highly desirable to strengthen the phenomenological research in astroparticle physics, with the purpose of linking (at least from the theoretical side) the BSM searches performed at colliders with those performed within the other CHIPP pillars.

5 Strategic recommendations

The overarching theme of research pursued in CHIPP Pillar 1 is the search for BSM physics. The Swiss Pillar 1 community has a diverse portfolio of experimental and theoretical activities to challenge the Standard Model. While the experimental flagship of Pillar 1 research at the high-energy frontier remains the LHC for decades to come, the precision and low-energy frontier experiments, specifically those at PSI, provide the very important alternate approach of indirectly searching for BSM that complements the Pillar 1 portfolio. Progress at the high-energy frontier has so far unfortunately not uncovered New Physics and hence, while Naturalness remains a heuristic guiding principle, the mass scale of BSM physics is unclear. Related to this, the "WIMP miracle" is under pressure as well. On the other hand, the experimental programme of the LHC has merely covered a few percent of the expected data to be taken at a centre-of-mass energy of 13–14 TeV. As the experimental searches continue to explore more and more parameter space, the balancing of the portfolio of Pillar 1 research is an important task, with the clear boundary condition that Pillar 1 experimental activities are long-term in nature.

In our analysis of the priorities for the future Pillar 1 research activities, we distinguish three time periods that naturally are confronted with increasing level of uncertainties, due to external factors as well as the intrinsic uncertainties of basic research. The **near-term period 2019–2024**, as defined by the current (2017–2020) and next (2021–2024) Education, Research and Innovation (ERI) funding cycles which each will contain two SNF FLARE calls, will be largely determined and financially constrained by the current long term-projects such as the LHC physics exploitation and the ATLAS/CMS phase-2 upgrades as well as the LHCb Upgrade1 (40 MHz DAQ/Trigger upgrade) in LS2 (2019–2020). The **midterm period 2025–2035** will see the completion and commissioning of the ATLAS/CMS phase-2 upgrades, the physics exploitation of HL-LHC and the foreseen completion of the LHC program. The **long-term vision 2035 and beyond** will hopefully be dominated by the construction and commissioning of a new flagship facility at CERN or somewhere else in the world. The latter period is obviously the one with the largest uncertainties due to factors outside the Swiss and European communities, such as the Japanese decision on the ILC and/or the planned facilities in China. What we present here is the vision of the CHIPP Pillar 1 community to address the overarching scientific questions in the period beyond 2035. In view of the challenges to secure the future of the field on that time horizon, a recent CHART2 initiative is being discussed between SERI and the ETH domain that will, if funded, have great impact in the area of accelerator R&D towards FCC and is strongly supported by the community. In the following, we assume that this initiative will be successful and hence will not draw on FLARE resources.

5.1 Near-term future 2019–2024: current and next ERI/FLARE periods

During the near-term future, the exploitation of the LHC as flagship infrastructure for Pillar 1 research should continue to be the highest priority, including the operations and upgrades of the ATLAS, CMS and LHCb experiments, that via the intertwined and complementary relationship of the flavour sector and the high energy frontier in the search for BSM physics represent the mainstay of Pillar 1 research activities. The phase-2 upgrades of ATLAS and CMS in LS3 will prepare those detectors for the HL-LHC running period (2026 onward) and the recently approved Upgrade1 (in L2) will extend LHCb's lifetime up to and including Run IV (50 fb^{-1}). Studies are under way for a possible LHCb Upgrade2 in LS4 (2029) that will ensure LHCb's viability beyond Run IV. Even in this financially constrained environment, it is important for the diversity and future of the Pillar 1 community to enable smaller scale activities within the FLARE programme, such as R&D and construction of a flagship experiment operating at the low-energy frontier at PSI as well as basic accelerator and magnet R&D. A sustained effort in the latter area is of crucial importance in order to render the ambitious long-term goals after 2035 realistic and compelling. The suggested priorities are thus as follows:

1. M&O and computing costs for the LHC experiments (as "FLARE uncuttable").
2. Construction of the ATLAS and CMS phase 2 upgrades (LS3), completion of LHCb Upgrade1 (LS2), LHCb consolidations (LS3) and R&D for LHCb Upgrade2.
3. Support for accelerator R&D towards FCC (expected to be funded by CHART2).
4. Design and construction of a flagship experiment at the low-energy frontier at PSI.
5. Funding of smaller experiments and generic detector [1] and accelerator R&D efforts.

5.2 Midterm future 2025–2035: HL-LHC phase up to the end of the LHC program

The midterm period will be still dominated by the continued exploitation of the LHC programme up to its end. After the completion of the ATLAS/CMS phase-2 upgrades, some financial degrees of freedom should become available for the envisioned LHCb Upgrade2 in LS4 (2029) as well as the upgrade of a low-energy frontier flagship experiment operating at the envisioned HiMB facility at PSI. We expect that on this timescale, the future of the "physics beyond collider" programme will have become more concrete and support of the Swiss involvement in SHiP should be feasible.

The priorities are thus as follows:

1. M&O and computing costs for the LHC experiments (as " FLARE uncuttable").
2. Completion of the ATLAS/CMS phase-2 upgrades and LHCb consolidations (LS3), R&D and construction of the LHCb Upgrade2 (LS4), if approved.
3. Continued support for accelerator R&D towards FCC (expected to be funded by CHART2)
4. Upgrade of a low-energy frontier flagship experiment at PSI, potentially at HiMB if approved; and support of a Swiss involvement in SHiP, if approved.
5. Funding of smaller experiments and generic detector[1]and accelerator R&D efforts.

5.3 Long-term vision beyond 2035

In the time period after 2035, a new flagship facility needs to be within reach to carry the field forward beyond the LHC. Apart from scientific questions to be addressed in this period, technological, sociological and even political considerations come into play. From a scientific point of view, it seems uncontroversial that the search for BSM physics will need the highest achievable beam energies possible and that a complete precision survey of the mechanism of electroweak symmetry breaking to fully exploit the sensitivity of Higgs boson properties to BSM physics requires a lepton collider of some kind. Such a facility should then preferably also allow, besides the Higgs boson sector exploration, precision electroweak measurements of the W, Z and top, perhaps as an upgrade path. The envisioned ILC programme in Japan would cover a significant part, but not all of the EWSB exploration programme, and its current fate is unclear at the time of writing. In terms of direct searches for BSM, the 100 TeV

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[1] outside of the targeted R&D for future experiments

energy range seems within reach with a 100 km tunnel assuming however a bold magnet R&D that allows to push the field strength by a factor of two or even more (in case a High Temperature Superconductor option is pursued with vigour). Ensuring the success of such an R&D programme to achieve center of mass energies of at least 100 TeV within the next decade should thus be a very high priority. The CHIPP Pillar 1 community strongly supports that a 100 km circular collider be built by CERN as the next flagship facility that would secure the future of the field beyond 2035 for decades to come. Preceeding an FCC-hh collider at $\sqrt{s} \geq 100\,\mathrm{TeV}$ with an FCC-ee option would be timely especially in the scenario where the development of suitable magnets for FCC-hh would need a longer time, and would be scientifically necessary in the scenario where the ILC programme in Japan would not go forward. The CHIPP Pillar 1 community takes note of the option of HE-LHC re-using the LHC tunnel; however at the present time it remains unclear whether HE-LHC will cover a significant enough part of the envisioned physics program that an FCC complex would provide. Further along, if a $\mu\mu$ collider option would come within reach, it could be added to whatever tunnel remains after completion of the previous circular hadron collider programme.