Pillar 1 roadmap
CHIPP workshop editing

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Contents

1 The present Swiss landscape

[(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?]

1.1 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?]

Higgs physics

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.

Other SM and BSM physics

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.

Heavy Flavour

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 experiment and 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.

Detector & computing

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 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.

Dark Sector

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 experiment 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?)]

1.2 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.

2 Major successes (2017-2020)

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

2.1 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.]

Higgs physics

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.

Other SM and BSM physics

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.

Heavy Flavour

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.

Detector & computing

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.

Dark Sector

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 [1, 2]. 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 [3], 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.

2.2 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.) [4] 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 [5].

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 $\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$ [6]. 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 $\mu^+ \to e^+X, X \to \gamma\gamma$ [7].

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 [8]. To this aim the Mu-MASS collaboration demonstrated the creation of a muonium 2S metastable beam [9]. The piHe collaboration succeeded in a first time ever laser spectroscopy of a pionic atom [10] 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 [11]. 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 [12].

3 The international context

[(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 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.

4 Synergies with other scientific fields

[(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?]

4.1 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 [13]. 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?]

4.2 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.

5 Vision for the future

[(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.?]

5.1 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 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_μ with a mass in sub-GeV range, which is coupled predominantly to the second and third lepton generations. The existence of Z_μ would provide an explanation of the muon g-2 anomaly and is complementary to NA64 in electron mode to search for DS at higher masses [14]. 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.

5.2 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 [15, 16] and a stringent test of the CPT theorem [17].

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.

References

[1] D. Banerjee et al. Search for invisible decays of sub-GeV dark photons in missing-energy events at the CERN SPS. *Phys. Rev. Lett.*, 118(1):011802, 2017.

[2] D. Banerjee et al. Dark matter search in missing energy events with NA64. *Phys. Rev. Lett.*, 123(12):121801, 2019.

[3] The NA64 collaboration. Search for axionlike and scalar particles with the na64 experiment, 2020.

[4] C. Abel et al. Measurement of the permanent electric dipole moment of the neutron. *Phys. Rev. Lett.*, 124(8):081803, 2020.

[5] C. Abel et al. Search for Axionlike Dark Matter through Nuclear Spin Precession in Electric and Magnetic Fields. *Phys. Rev. X*, 7(4):041034, 2017.

[6] AM Baldini, Y Bao, E Baracchini, Carlo Bemporad, F Berg, M Biasotti, G Boca, M Cascella, PW Cattaneo, G Cavoto, et al. Search for the lepton flavour violating decay $\mu^+ \to e^+\gamma$ with the full dataset of the MEG experiment. *The European Physical Journal C*, 76(8):434, 2016.

[7] A.M. Baldini et al. Search for lepton flavour violating muon decay mediated by a new light particle in the MEG experiment. 5 2020.

[8] P. Crivelli. The mu-mass (muonium laser spectroscopy) experiment. *Hyperfine Interactions*, 239(1), Nov 2018.

[9] G. Janka, B. Ohayon, Z. Burkley, L. Gerchow, N. Kuroda, X. Ni, R. Nishi, Z. Salman, A. Suter, M. Tuzi, C. Vigo, T. Prokscha, and P. Crivelli. Intense beam of metastable muonium, 2020.

[10] M. Hori et al. Laser spectroscopy of pionic helium atoms. *Nature*, 581:37, 2020.

[11] A. Antognini et al. Demonstration of Muon-Beam Transverse Phase-Space Compression. 3 2020.

[12] C. Vigo, L. Gerchow, B. Radics, M. Raaijmakers, A. Rubbia, and P. Crivelli. New bounds from positronium decays on massless mirror dark photons. *Physical Review Letters*, 124(10), Mar 2020.

[13] Philip W. Anderson. Plasmons, Gauge Invariance, and Mass. *Phys. Rev.*, 130:439–442, 1963.

[14] The NA64 collaboration. Proposal for an experiment to search for dark sector particles weakly coupled to muon at the SPS. Technical Report CERN-SPSC-2019-002. SPSC-P-359, CERN, Geneva, Jan 2019.

[15] G. Chardin et al. Proposal to measure the Gravitational Behaviour of Antihydrogen at Rest. 9 2011.

[16] P. Pérez et al. The GBAR antimatter gravity experiment. *Hyperfine Interact.*, 233(1-3):21–27, 2015.

[17] P. Crivelli, D. Cooke, and M. W. Heiss. Antiproton charge radius. *Phys. Rev. D*, 94:052008, Sep 2016.