Whitepaper for neutrino physics in Switzerland

Additional information to inform the SNSF FLARE instrument 2021-24
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for the Pillar 2 community

1 Introduction

The last neutrino white paper was written in 2015. Since then, tremendous progress has been achieved and the projects have proceeded incrementally to next stages. Continuous developments have also led to major new pieces of information that have precised the scientific landscape and justify an update of the document and of its recommendations. In the present document we summarize the current status and plans, and update recommendations. This document was prepared in parallel to the drafting of the "CHIPP Roadmap for Research and Infrastructure 2025-2028 and beyond" and its recommendations are also reflected in the prioritisation input to the FLARE Panel for 2021-2024 (link).

In 2015, the whitepaper referred the reader seeking the details on the funding expected for the neutrino pillar from FLARE and other instruments to the CHIPP tables. Overall, it gave some general points, relevant for the years 2016-2020. It put a focus on the research and development to be performed at the CERN neutrino platform in view of the DUNE and T2K/HK long baseline experiments. **This effort has now been successfully conducted and accomplished providing vital results for future steps.** It also recommended the involvement of the Bern researchers in the running MicroBooNE experiment, first detector of the SBN complex and major milestone of the US based neutrino program using liquid argon TPCs, and continued with investments in the SBND near detector. **The SBN construction effort is nearing completion and the SBN exploitation phase is starting soon.** It stressed the importance to continue the Swiss participation in the Japanese long-baseline neutrino experiment T2K, for full science exploitation, maintenance and upkeep. It stated that the DUNE involvement will develop and lead to major investment, and if the T2K upgrade would be approved, it would lead to a proposal to be submitted to FLARE for funding. **These are now the case, as outlined in the following sections of the present whitepaper**. It was noted that GERDA would require an integrated operation funding. **GERDA has now been successfully completed at the Gran Sasso Laboratory, and the follow-up project, LEGEND-200, is under construction**. Despite the fact that EPFL did not continue activities in IceCube, UniGe took over from 2011 and consolidated them into an SNF multi-messenger program. This connects IceCube science to CTA, through the study of black holes, dark matter indirect searches (Pillar 3). In the next future, PINGU will be implemented for more precise neutrino oscillation studies.

More detailed and up-to-date information on the above mentioned progress is included in the following sections of this whitepaper. See sections 3 and beyond.

Concerning the current period, the 2015 neutrino paper concluded the following:

- Pending approval of the DUNE program an approximate investment of 1 MCHF/year from FLARE to be shared among Swiss groups involved (at the time ETHZ and Bern) during a total period of 10 years was envisioned. **FLARE funds have been made available to successfully perform the R&D program towards DUNE (ProtoDUNE, ArgonCube). In addition, SERI also made available specific infrastructure funds to support the construction of LBNF/DUNE via the involvement of CERN in the far detector cryostat and cryogenic infrastructure**.

- The approval of Hyper-K might also lead to a FLARE funding request. **This has now recently happened and has dramatically changed the perspective of discovering CP violation in the neutrino sector, by opening the path to this science as a natural and effective continuation of the T2K program, to which Swiss groups have participated and made extremely significant and leading contributions in the field of hardware, software, physics and management for more than a decade.**

- The 2015 whitepaper stated that the approval of SHiP might also lead to a FLARE funding request. The need for the facility at CERN was not recommended in the latest ESPP.

- Starting from last year IceCube started construction again of its extension. The first phase of the extension concerns PINGU, a detector for atmospheric neutrino oscillations which will complement the neutrino accelerator program and be able to determine the neutrino ordering in 5 years at high significance. Funding are secured from NSF and international partners are contributing (Germany, Belgium and Sweden).

- The evolution of a ton-scale double beta decay experiment might also lead to a FLARE funding request. After the completion of GERDA, FLARE funding was approved for LEGEND-200, currently under construction. **More details, especially on the ton-scale experiment LEGEND-1000, are given in the following.**

The 2015 white paper also clearly stated that the recommended funding scheme would be extended in the light of future experiments, and priorities would be tuned accordingly, while providing continuity of support for already approved commitments.

The main subjects of neutrino physics in Switzerland are presently neutrino oscillations, ultra-high energetic neutrinos from the cosmos and the neutrino-less double beta decay. The measurement of neutrino properties at long baseline beam experiments is a very high priority for the neutrino pillar in Switzerland. **The development of innovative detectors has played a crucial role in all of these activities, as well as the theoretical and phenomenological aspects of neutrino physics. We are now moving in the next period in a construction phase, envisioned with commensurate Swiss participation and contribution, within the relativity small size of the Swiss neutrino community compared to the international landscape**. CERN as the European laboratory for Particle Physics being located in Switzerland is closely tied to the Swiss neutrino efforts and is an integral part of the global strategy by hosting the Neutrino Platform.

Within this context, we present, in the sections 3 and beyond, details on the Japanese long-baseline accelerator program, the long-baseline accelerator program to be conducted in the

USA, the non-accelerator based long-baseline neutrino program and the search for neutrinoless double beta decay, that Swiss physicists intend to conduct in the coming years. Our conclusions and recommendations are given in Section 6.

2 Neutrinos at the forefront

Neutrinos were first postulated by Wolfgang Pauli in 1930. Since then, much progress has been achieved to understand their properties, but still the particle is so elusive that many questions remain unanswered. Neutrinos play a crucial role in our understanding of the fundamental laws of Nature. Due to their very low interaction rate it is a challenge to obtain high statistics experimental data. Nevertheless, neutrino physics has seen important advances over the last decades, with important results and discoveries about their properties, especially their mass and the related oscillation behaviour. With this, neutrinos, are firmly established as prime research topic and one of three pillars of particle physics in Switzerland. Neutrinos have, furthermore, an important role in cosmology and astro-particle physics as messengers of the far universe. The study of the neutrino oscillations has involved a suite of experimental measurements worldwide on reactor, solar, atmospheric, and neutrino beams. The parameters of the neutrino mixing described by PMNS matrix have almost all been determined. Most recently the angle θ_{13} has been measured and a wide range of values for the complex phase δ_{CP} have been excluded [1], including vanishing CP violation. **Neutrino masses and their flavor oscillations are so far a tantalizing sign for new physics beyond the SM and thus a goal for further measurements to find answer to remaining open questions such as the absolute neutrino masses, the mass hierarchy and the exact size of the CP violating phase. The nature of the neutrino – the only electrically neutral elementary fermion which could very well be a Majorana particle – is also of utmost scientific relevance.** Discoveries of additional neutrino states could require more advanced changes in our current understanding of the neutrinos. Dedicated large-size experiments are planned in the USA, DUNE/LBNF and Japan, Hyper-Kamiokande and IceCube/PINGU. They will address the neutrino mass hierarchy and CP violation, besides serving as more general purpose observatories for supernova neutrinos, indirect dark matter, proton decay searches, high-energy neutrino interaction studies (e.g. Glashow resonance, oscillations through extreme baselines of the cosmos, oscillations in the sun or supernova matter). The fundamental nature of neutrino, namely whether they are Majorana or Dirac particles is also still open. A neutrino-less double-beta decay requires a Majorana neutrino mass, independent of the mass generation mechanism, and its discovery would thus reveal the neutrino nature. This is a further goal of the neutrino pillar in Switzerland, with the world-leading sensitivity experiment GERDA and the future LEGEND[1]. The experimental measurements will also be able to address the question of the absolute scale of neutrino masses, together with the constraints from cosmology and dedicated experiments, such a KATRIN.

Neutrinos travel basically undisturbed through the interior of dense environments of astrophysical sources and through the universe radiation background and magnetic fields. Hence, it is an excellent messenger, as initially proved by the observation of a neutrino burst few hours before the light signal from the SN1987A. Neutrinos from the Sun first revealed the

[1]For completeness, we note that also XENON and DARWIN could also address neutrinoless double beta decay, see Pillar 3.

oscillation phenomenon in matter followed by atmospheric neutrinos, leading to precise measurements of the parameters of the neutrino mass matrix. The cubic-kilometer neutrino telescope, IceCube, proved the existence of > 100 TeV astrophysical flux which brings information of the super-high energy beams of the universe, on neutrino oscillations on extremely long baselines, on PeV scale neutrino cross sections (e.g. Glashow resonance) and other possible exotic phenomena at energy scale which cannot be probed at accelerators. This neutrino from the cosmos in connection to other messengers, such as gravitational waves, gamma-rays and photon in lower energy bands and charge cosmic rays are providing exciting scientific results often published on Science or Nature by more than 1000 scientists from tens of observatories.

3 The Japanese neutrino program

After the recent approval of the HyperKamiokande project, the HyperKamiokande collaboration has been officially constituted. Two Swiss institutions (ETHZ and the UniGe) are founding members of the collaboration and willing to contribute to its success. In parallel to this approval, T2K has been discussing with the host institution on the continuation for T2K. KEK has recently committed the laboratory to the operation of T2K for 4 months/year until the beginning of HyperKamiokande. The main goals of the T2K running until the beginning of HyperKamiokande are:

- Improvements of the statistical significance through the increase of beam power from the actual 500 kW to 1.2 kW by the beginning of HyperKamiokande. This will double the statistics accumulated so far by the experiment.
- the operation of SuperKamiokande with loaded Gadolinum salt to enhance the neutron detector capabilities.
- upgrade of the near detector that will allow us to improve on the systematic uncertainties.

The achievement of these goals will have as an immediate consequence the improvement on the CP violation phase measurements up to 3 σ but it will also have a large impact on the preparation of the HyperKamiokande experiment. The operation of the new upgrade detector will allow to reduce uncertainties related to flux and neutrino cross-sections before the HyperKamiokande starts operation. These measurements will increase significantly the physics reach of the experiment already during the first year of operation. In addition, this run will allow T2K and HyperKamiokande to train researchers that will be ready to deploy their skills from the first day of the operation. A key element in this agreement is the the near detector which operation will be transferred to HyperKamiokande at the end of T2K, a MoU is being prepared between the two collaborations on this specific matter.

Since both projects are intrinsically connected, we keep them tightly together. The schedule and FLARE request profile is determine by the experiment landmarks:

- ND280 and beam upgrade will be ready in spring 2023.

- HyperKamiokande is expected to start operation during the Japanese Fiscal Year 2027 (JFY2027 ends on March 2028).

Swiss groups (ETHZ and UniGE) work tightly together on the T2K upgrade following the very successful experience in T2K, and intend to do so also in the HyperK era. Swiss groups (ETHZ) hold the convener-ship for the SFGD detector. They are responsible for the mechanical engineering of the SFGD and the ToF subdetector, as well as the full integration of the upgraded detectors into the ND280 basket. They are performing the static and dynamical analysis, very delicate in a seismic area as Japan.

The profile of the FLARE request will also follow this schedule:

- T2K Common-Fund until 2027.
- Completion of the ND280 detector upgrade:
  - Completion of the sFGD electronics
  - Electronic engineer x 2 years
  - Assembly and test of the SFGD at CERN
  - Design and procurement of the assembly box of the sFGD
  - Shipment of detectors from CERN to JPARC
  - Installation at JPARC of SFGD
  - Installation at JPARC of ToF
  - Installation of electronics at J-PARC
  - Commissioning and calibration of the upgraded ND280 detector
- We will start from 2021 on the R&D for the HyperKamiokande where we expect to contribute to the electronics, HV and possibly new ideas such as an online reconstruction. Following the recent formation of the HyperKamiokande collaboration in August 2020, this is in the process to be defined but we expect the attributions of the tasks to follow very rapidly and be in the position to settle them by the fall of 2020 along the following guidelines:
  - A major responsibility in a Swiss designed electronics for the inner detector readout for the total of the 20'000 20-inch PMTs of HyperKamiokande.
  - A Swiss responsibility for the entire PMT HV system and associated distribution cables.
  - Deployment of an online reconstruction cluster.

The R&D will require engineering support that will be requested to the FLARE program. Prototypes and test beds need to be designed, constructed and operated during this period. The expectation is that the R&D would last a couple of years and then the production will be launch to fulfill the tight HyperKamiokande schedule. **However, given the international landscape, it is very likely that the Japanese colleagues will attempt to anticipate as much as possible all decisions and construction steps to an earlier schedule. It is likely that significant funds will be requested for HyperKamiokande by Swiss groups during the current FLARE funding cycle. This will be clarified by fall 2020.**

4 The international long-baseline neutrino program in the US

The international long-baseline neutrino program is the US originated from the merging of the LBNO project in Europe (led by ETHZ) and LBNE, an early project initiated in the USA for beams and detectors. Since 2015, much progress has been accomplished in defining the project and conducting the associated R&D. The Technical Design Report (TDR) for DUNE was published early 2020 for the overall physics program, the beam and the far site detectors (arXiv:2002.03005), the near detector Conceptual Design Report was completed in 2019 and the TDR is being prepared and expected early 2021. **For the near detector a consortium of institutions was created in 2020 as subgroup of the DUNE collaboration with a goal to build and commission the liquid argon component of the near detector**, with the University of Bern in a leading role. The near detector establishes the null hypothesis (i.e., no oscillations) under the assumption of the three neutrino paradigm by measuring the neutrino flux at the beam origin, it constrains the systematic uncertainties in a global fit, and provides essential input for the neutrino interaction model. It is key to have a target with the same element as the far detector and therefore a liquid argon component will be installed. The adopted concept is a modular TPC developed in Switzerland, which will be able to disentangle each neutrino interaction despite the pile-up in the very intense neutrino beam. The construction will be funded by the US, Switzerland and Russia. It is foreseen that MoUs will be signed in late 2020. **Prototyping for the near detector is ongoing (already funded through FLARE) and will extend through 2022**.

During the construction phase covering the period 2023-2028 (as outlined in the CHIPP tables), the following core detector components in the project are foreseen:

- Common funds
- Module structure for 41 modules
- Light detection panels ("ArcLight") covering 50% of the area
- HV and distribution
- Share of integration and testing
- Calibration systems

5 Neutrinoless double beta decay

The GERDA experiment to search for the neutrinoless double beta decay of ^{76}Ge, with significant Swiss contributions (UZH) recently reached the world-leading lower limit on the half life of $T^{0\nu}_{1/2} > 1.8 \times 10^{26}$ y (90% C.L.), for an exposure of 103.7 kg y.

GERDA [2–4] was completed at the Laboratori Nazionali del Gran Sasso (LNGS) of INFN, Italy, in December 2019, and since then the infrastructure is available for LEGEND, the next-generation ^{76}Ge experiment.

The collaboration, based on the experiments GERDA and MAJORANA together with new members, aims to build a ton-scale experiment with a large discovery potential in two phases.

The first phase, LEGEND-200, is approved and funded to be hosted at LNGS with a target mass of approximately 200 kg of enriched Ge. The second phase, LEGEND-1000, is in design phase (CDR level) with several underground laboratories as potential hosts. The goals are to achieve a sensitivity of $T_{1/2}^{0\nu\beta\beta}$ >10^{27} y and $T_{1/2}^{0\nu\beta\beta}$ >10^{28} y respectively and thus to be sensitive to the full inverted neutrino mass region for $0\nu\beta\beta$-decay via light Majorana neutrino exchange [5].

The UZH group lead by Laura Baudis has been involved in GERDA since 2007, and has major responsibilities in both GERDA and LEGEND in hardware, software and data analysis. Relevant for the FLARE request, the group is responsible for the design, construction and operation of the calibration systems [6], for the analysis of the weekly calibration runs and stability monitoring of the energy calibration and resolution of the Ge diodes, and for the production of the low neutron emission calibration sources in collaboration with PSI [7]. The group is also involved in the production and characterisation of enriched germanium diodes [8] and in the development and production of the wavelength shifting system for the liquid argon active veto [9].

The LEGEND experiment is one of the three large $0\nu\beta\beta$-decay projects with leading European contributions (together with CUPID and NEXT) recommended in the Double Beta Decay APPEC Committee Report [10].

The UZH group received funding for LEGEND-200 during the last FLARE period. For the next FLARE calls, the following costs are foreseen for LEGEND-200 and LEGEND-1000:

- Common funds and operation
- Calibration system
- Enriched Ge detectors
- Liquid argon veto

We note that the DARWIN [11] project, a next-generation xenon-based experiment for direct dark matter detection will also be able to probe the $0\nu\beta\beta$-decay of ^{136}Xe with half-life sensitivity of 2.4×10^{27} yr [12], and will thus be complementary to LEGEND and other dedicated searches.

6 Conclusions and recommendations

We list below the conclusions and the agreed upon recommendations of the neutrino community on the neutrino pillar. They consist of a number of bullet points:

- **The Swiss participation to T2K and its near detector upgrade, and the exploitation of the investments in the SBL program at FNAL, should be supported with highest priority given their current physics scope in neutrino oscillations and sterile neutrino searches and their importance for the future long-baseline neutrino programs**, providing the necessary continuity in the field, supporting the new generation of students and capitalizing on the past investments done by the Swiss neutrino community over several decades.

- **The discovery of CP-violation at 5σ level is the next scientific step for the neutrino community, therefore represents the flagship program of the pillar 2**. The results from T2K recently published in Nature show that this measurement is achievable. The landscape is now that there are two complementary efforts worldwide, one in US and the other in Japan, to perform this measurement. The Swiss participation to both DUNE and HyperK should be supported with an equivalent priority to maximize the scientific reach. The Bern group will focus on the construction of the DUNE near detector while the UniGE and ETHZ will primarily support the construction of the HyperK far detector.

- The quest for the nature of neutrino is a fundamental scientific goal which requires long-term involvements and a steady support of experiments. Capitalizing on the impressive successes of GERDA, **the construction of the neutrino-less double beta ($0\nu\beta\beta$) experiments LEGEND-200 and LEGEND-1t should be supported in the period 2021-2028. We note that the DARWIN experiment is also extremely valuable to the neutrino pillar.**

- Provided that IceCube would continue delivering important results on neutrino oscillations, a PINGU request might be submitted to FLARE in a future call (beyond 2020).

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