14 November 2015

Experimental neutrino physics: Switzerland in the global context, a white paper

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Following the Higgs boson discovery, massive neutrinos are firmly set at the frontier of knowledge in particle physics. The nature of the neutrino mass generation, the pattern of mixing angles and masses with the possibility of CP violation, the absolute neutrino mass scale, the fundamental nature of neutrinos, the search for the elusive right-handed neutrinos, will all constitute conceptual and experimental problems for decades to come. The rewards are potentially very high and far-reaching: the understanding of the nature of dark matter, the origin of the dominance of matter over anti-matter in the universe, and the unification of forces at very high energy. The Swiss particle physics activities in neutrino physics and astrophysics should grow correspondingly, in agreement with the role they have in the Swiss Particle Physics Road Map.

Here we give a synthetic overview of the experimental activities. However, one should not neglect the important work being carried out in several institutions on the theoretical aspects of neutrino physics. This document depicts a snapshot of the current and realistically planned status in the field and could be updated in the future to take into account the evolution of the scenario and of the scientific priorities.

1) Neutrino oscillation physics with accelerator beams

Neutrino oscillation is the only phenomenon in which neutrino masses have so far manifested themselves. Many aspects of this process remain uncharted: the mass hierarchy among neutrino flavors, the possibility of CP symmetry violation in neutrino oscillations, and more generally a detailed study of the phenomenon, justify a commensurate experimental program.

A major scientific success of the Swiss groups of Bern, ETHZ and Geneva has been represented by the T2K oscillation experiment in Japan, backed-up with the NA61/SHINE hadro-production experiment at CERN. The coherent Swiss effort over several years has represented a considerable investment and produced discoveries, new measurements, a large number of theses by training young researchers, a strong international visibility, and has paved the way to ambitious follow up projects on neutrino oscillations. Just two emblematic examples are given by the over 1000 citations of the paper: *Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam,* http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.107.041801, where the first indication from a non-zero θ_{13} angle was reported, and by the unambiguous discovery of the existence of the $\nu_\mu \rightarrow \nu_e$ transition, reported in http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.112.061802.

The T2K experiment is looking towards a 10-fold increase in statistics by 2020, in which sensitivity to a first evidence (3σ) of CP violation could be obtained when results are combined with other experiments such as NOvA. At present, the J-PARC accelerator complex has achieved 371 kW on the neutrino target in June 2015 and individual bunch intensities equivalent to 520 kW. An accelerator upgrade, aiming at doubling the repetition rate is being proposed to collect an exposure of 10 MW x year by 2026 and reaching a beam power of up to 1.3 MW for further T2K running and future plans (see Hyper-K below). The NA61 experiment at CERN continues to be a useful tool for understanding the neutrino fluxes for cross-section and oscillation measurements of present and future neutrino experiments.

Another outstanding achievement has been constituted by the recent discovery of $\nu_\mu \rightarrow \nu_\tau$ appearance by the OPERA collaboration (http://arxiv.org/abs/1507.01417), for which the Bern and ETHZ groups have substantially contributed over many years.

Recognizing the growing importance of the field and the need for a worldwide coordination, the European Strategy for Particle Physics (ESPP) in 2013 has classified the long baseline neutrino program as one of the four scientific objectives with required international infrastructure:

CERN should develop a neutrino program to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

In the recent months, the US scenario has been clarified with a series of strategic and scientific decisions of the major involved players, the funding agencies, the large laboratories and the international community as a whole. For the latter, the contribution of Swiss researchers has been crucial, given their long-standing experience and the technology detector approaches they have been proposing since many years. In particular, the recent strategic US "P5" report has emphasized the high priority given to the future research on neutrino oscillation physics. Collaboration with the US has been widely endorsed by the CERN Council.

Recommendation 12 of the P5 report reads:

In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab (LBNF).

While recommendation 15 stresses:

Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino *paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.*

It is worth noting that the liquid argon TPC technology, advocated for the comprehensive US based program, has been initially developed in Europe, and Switzerland hosts some of the most advanced technological knowledge in this domain, at the University of Bern and ETHZ.

Starting from the solid foundations laid by LBNE in USA and LBNO in Europe with many years of very detailed studies supported by FP7, CERN and ApPEC, a new process towards the international LBNF was initiated by the Fermilab management and the CERN Director of Research, giving an International Interim Executive Committee (IIEB), of which both Antonio Ereditato and André Rubbia were members, the mission to develop and submit a Letter of Intent to the FNAL Physics Advisory Committee (PAC) and foster the participation of international partners and agencies. The LoI for the LBNF/DUNE project signed by several Bern and ETHZ researchers was submitted to the FNAL PAC in December 2014 and positively recommended.

DUNE has successfully passed the DOE CD-1 review in July 2015 for which a very extensive Conceptual Design Report (CDR) comprising 19 volumes has been submitted:
https://web.fnal.gov/project/LBNF/ReviewsAndAssessments/LBNF_DUNE%20DOE%20CD-1%20Refresh%20Review/SitePages/Home.aspx.
A CD3A approval for the excavation of the Sanford Underground Research Facility (SURF) Far Site Facilities is planned for December 2015.

DUNE will deploy a 40 kton liquid argon TPC detector situated at SURF, at a distance of 1300 km from FNAL, where a new 1.2 MW neutrino beam line upgradable to 2.4 MW and a highly-capable near detector will be constructed. The first 10 kton detector should be put in operation around 2022. Physics goals include both mass hierarchy and CP violation, as well as an extensive science program delivered by deep-underground massive far detectors of unprecedented precision and resolution. DUNE will coherently use the SBN program at FNAL and the CERN Neutrino Platform (see below) to further develop the LAr TPC technology needed for the DUNE Far Detectors.

DUNE has already over 770 members from more than 144 institutions worldwide and is still growing. André Rubbia and Mark Thomson (from UK) have been elected co-spokespeople of the collaboration. LBNF/DUNE is the flagship program of FNAL and has very strong support from the DOE. DUNE will be the first international "megascience" project hosted in the USA and has become a "policy issue" of importance to the White House. A DOE-CERN-NSF agreement has been signed on May 7th, 2015 at the White House by the CERN DG Heuer. According to Heuer, "*this agreement is historic since it formalizes CERN's participation in US-based programs such as the prospective neutrino facilities for the first time*." Based on the successful LHC model, the first DUNE Resources Review Board (RRB) has taken place on September 3rd, 2015.

The other PAC recommendation 15 materialized in the SBN facility at FNAL (http://arxiv.org/abs/1503.01520), a multi-detector, liquid argon TPC based facility with its science program *per se*, but also acting as a test bench for several options being considered for DUNE. This includes detector technology solutions, cryogenics, software reconstruction methods, experience with neutrino physics with LAr TPCs and, last but not least, training of young researchers to be ready to bridge the long time period from today to the commissioning of DUNE. The international SBN project features an intense low-energy neutrino beam from the Fermilab Booster and the three liquid argon detectors SBND, MicroBooNE and ICARUS. For the first two, there is a visible participation of Bern researchers. First commissioning results from MicroBooNE have been obtained very recently.

The Hyper-K project in Japan, a Megaton-scale water Cherenkov detector using the upgraded J-PARC neutrino beam is also getting momentum (http://arxiv.org/abs/1109.3262, http://arxiv.org/abs/1412.4673). The project LoI was ranked among the 27 MEXT highest priority scientific projects in Japan in 2014, requesting a detailed international proposal. A formal MoU was signed between KEK and the Institute for Cosmic Ray Research (ICRR) of the University of Tokyo in January 2015, for the preparation of a Conceptual Design Report to be submitted at the end of 2015 for a review by the two laboratories. The target date for approval is 2017, for first physics run in 2025/26. An international collaboration has been formed, including a Steering Committee including Alain Blondel among four non-Japanese members.

In this scientific context, the three Swiss neutrino groups of Bern, ETHZ and Geneva are already involved in the CERN Neutrino Platform activities of WA105 (ETHZ) and in SBN at FNAL (Bern), in ARGONCUBE, a new LAr TPC implementation under study (Bern), in T2K (Bern and Geneva), in the DUNE project (Bern and ETHZ), and in the T2K upgrade and Hyper-K (Geneva). For all projects, there is a strong involvement and large international scientific, technical and managerial visibility of the Swiss groups.

In the next few years the international long-baseline scenario will further clarify. The Swiss groups have already played a crucial role and are currently very active on physics studies, detector R&D and collaboration management. It is reasonable to expect their active participation in the future long-baseline program be eventually approved and funded. The participation of Swiss groups builds up of the long-standing and outstanding experience of their researchers with the physics and with the detector technologies. The above-mentioned activities add up to the existing rich scientific program conducted by the three Swiss neutrino groups.

2. Non-accelerator oscillation physics

The discovery of CP violation in neutrino oscillation requires appearance experiments, specific of accelerator-based experimentation. The question of the mass hierarchy can be addressed also by non-accelerator experiments, either by a fine analysis of the solar-atmospheric interference in a long baseline reactor experiment (JUNO in China), or using atmospheric neutrinos as in the case of the PINGU experiment.

Non-accelerator experiments, such as IceCube and Super-Kamiokande, have obtained interesting results on the neutrino oscillation parameters. IceCube first results on the mass difference and mixing angle are very interesting (http://journals.aps.org/prd/abstract/10.1103/PhysRevD.91.072004). IceCube can also test sterile neutrinos in the 1 eV^2 parameter region.

While the discovery of CP violation in the neutrino sector requires long baseline accelerator-based experiments, the determination of the mass ordering or mass hierarchy can well be performed by non-accelerator experiments, as well.

The Precision IceCube Next Generation Upgrade (PINGU) is a proposed low-energy infill extension to the IceCube Observatory. With detection technology modeled closely on the successful IceCube example, PINGU will feature the world's largest effective volume for neutrinos at an energy threshold of a few GeV, allowing to reach sensitivity to the neutrino mass hierarchy (Normal or Inverted MH) on a relatively short time schedule and at modest cost. Although PINGU cannot distinguish between ν and anti-ν events, the different cross-sections, kinematics and different ν and anti-ν contributions to the atmospheric flux make it possible, thanks to high statistics, to distinguish an oscillation pattern generated by the Normal MH from the Inverted one. The ability to perform successfully this measurement in a definite fashion will depend on mastering of a number of systematic uncertainties in the energy reconstruction and in the ice properties, which are still under development.

Besides a rich program on neutrino oscillations, PINGU will increase the IceCube sensitivity for dark matter, supernova neutrinos and neutrino earth tomography. The group of Teresa Montaruli at Geneva is member of the PINGU project through its participation in IceCube. Recently, the IceCube Gen 2 Collaboration was formed incorporating new institutions for the program of low and high-energy extensions of IceCube. Although no construction funds will be requested in the short term to the FLARE program for PINGU, the group will continue making substantial contributions to IceCube Gen 2.

One should also add that in perspective the DUNE and the Hyper-K detectors would act as powerful underground neutrino observatories for non accelerator physics, in particular for the detection of supernova and atmospheric neutrinos, nucleon decay searches, dark matter searches, etc.

3. Neutrinoless double beta decay

Double beta decay searches provide a fundamental probe of the nature of neutrinos and of lepton number violation. The observation of the neutrinoless double beta ($0\nu\beta\beta$) decay would prove that the neutrino is a Majorana fermion (particle and antiparticle are identical) and that fermion number is violated in Nature. The observation of the decay would have far reaching implications, as it would point to the existence of a new mass generation mechanism, beyond the Standard Model, and to possible scenarios to generate the matter-antimatter asymmetry in our universe. The measurement of its rate is also expressed in terms of the so-called effective "Majorana electron-neutrino mass", m_{eff}. While many isotopes are available to search for this rare decay, currently the best limits on its half-life come from experiments using ^{76}Ge, ^{130}Te and ^{136}Xe. Two world-leading experiments, GERDA (^{76}Ge) and EXO (^{136}Xe), featured significant Swiss contributions (Zürich and Bern, respectively) and the capability to probe the inverted mass hierarchy scenario in their next phase. Since 2015, the EXO experiment does not include a Swiss participation anymore.

The NSAC Subcommittee on Double Beta Decay wrote in their report from April 2014: *"the pursuit of neutrinoless double beta decay addresses urgent scientific questions of the highest importance, and sufficiently sensitive second generation experiments would have excellent prospects for a major discovery."* and *"The observation of neutrinoless double beta decay would indeed generate a fundamental shift in our understanding of elementary particles. Therefore, it is timely and compelling to embark on a discovery quest to observe neutrinoless double beta decay."* (http://science.energy.gov/~/media/np/nsac/pdf/docs/2014/NLDBD_Report_2014_Final.pdf).

GERDA searches for the $0\nu\beta\beta$-decay in enriched ^{76}Ge detectors at the Gran Sasso Laboratory (LNGS). It uses a novel shielding concept, with Ge crystals being operated directly in liquid argon, surrounded by a water Cerenkov shielding. The experiment is proceeding in several phases. Phase I used an array of 16 enriched, HPGe detectors and achieved a result excluding the existing hints of a signal from the Heidelberg-Moscow experiment.

These first results, published in 2013, have already reached more than 200 citations (http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.111.122503). GERDA phase II, currently under commissioning at LNGS, is using 30 additional enriched broad-energy germanium detectors, aiming at a total exposure of 100 kg x year and a background that is 10 times lower than for Phase I. The half-life sensitivity will be $T_{1/2}>2x10^{26}$ years, corresponding to a range of effective neutrino masses of 0.09 - 0.15 eV^2.

After Phase II, GERDA will proceed to a ton-scale Ge experiment, within an international collaboration. An MoU with the Majorana experiment in the USA is already in place. The Zürich group led by Laura Baudis has been involved in the

GERDA project since 2007. It has crucial responsibilities for the hardware, software and data analysis, and plans to maintain its leading contribution in the future, as well.

4. Search for right-handed neutrinos

The existence of neutrino oscillations implies that neutrinos have mass. There is no unique way to upgrade the Standard Model to provide neutrinos a mass. There are two possible mass terms for a neutral particle: 1) the Dirac mass term similar to those of the other charged fermions, and represented in the Standard Model by their Yukawa couplings to the Higgs boson; 2) the Majorana mass term, in which a neutrino is transformed into its (opposite helicity) anti-particle. The situation in which both terms are present generates the well-known see-saw mechanism in which appear (mostly) right-handed, sterile, neutrinos of different masses than their left-handed partners, designated as Heavy Neutral Leptons HNL. Traditionally, the HNLs have been considered to be very heavy (10^{10} GeV), but it has been pointed out that masses in the range of a few keV up to the TeV scale are plausible; the resulting states can still play a role for the dark matter, and generator of the baryon asymmetry of the universe, while their small couplings to the neutrinos of the Standard Model have so far prevented observation.

A development has recently taken place in the search for right-handed neutrinos, in which Swiss physicists have played a seminal role, showing that neutrino physics is likely to expand well beyond its traditional experimental techniques in the not so far future. The SHiP experiment proposal, following an observation by Mikhail Shaposhnikov from EPFL, is based on the possibility to search for the decays in flight of long-lived HNL produced in a beam dump experiment in a long instrumented decay channel. The experiment is sensitive to masses comprised between the pion mass and the charmed meson mass.

The experiment is sensitive to many other dark sector phenomena, and is able to perform a rich program of tau neutrino interactions. The SHiP proto-collaboration LoI has received encouragement from CERN to prepare a technical proposal by a strengthened collaboration. The Swiss institutes involved in this project are EPFL and the universities of Geneva and Zürich. Mikhail Shaposhnikov is responsible for the theory support to the experiment, while Nicola Serra is convener of the physics performances and background studies. The Swiss groups will define their actual long-term funding request strategy when the experiment is approved by CERN.

5. Timeline and financial plans

We define the Swiss neutrino prioritization by the actual phase of the projects. In particular, we recognize the highest scientific priority in pursuing the running T2K experiment, the GERDA project and the IceCube related activities. Further measurements with NA61 could be relevant for present and future experiments. For most of these experiments, there have been significant Swiss investments during the past years and outstanding science results, prelude to further science achievements.

As far as the financial investments in R&D and detector construction **for the period 2016-2020** are concerned, we define priorities such that:

A) first priority for Swiss funding, notably FLARE, should be given to the approved WA105 and SBN projects.
B) The Swiss involvement in DUNE will be developed in the coming years within the international context. A coherent Swiss DUNE proposal for FLARE will be eventually submitted.
C) The evolution of the Hyper-K project might also lead to a proposal to be submitted to FLARE, which will propose upgrades of the T2K experiment and participation to the Hyper-K construction.
D) After approval by CERN and pending more precise timescales, SHiP will also request support from FLARE.
E) The evolution of a ton-scale double beta decay experiment might also lead to a proposal to be submitted to FLARE.

Details on the funding expected for the *neutrino pillar* from FLARE and other instruments are presented in the CHIPP tables. We give here some general points, relevant for **the next 5 years (2016-2020)**:

1. WA105 currently constructing the $3x1x1m^3$ dual phase prototype will develop as a major test facility at the CERN EHN1 area where the $6x6x6m^3$ demonstrator will be built and operated. The ETHZ group will take care of most of the hardware activities, with specific contributions on the dual-phase TPC, field-cage cathode mechanics and HV, cryogenics, and readout and slow-control electronics. One will request an integrated FLARE funding of 2050 kCHF.
2. The involvement of the Swiss researchers in the running MicroBooNE experiment, first detector of the SBN complex, will continue with investments in the SBND near detector. The major Swiss hardware responsibilities will be on the UV-laser calibration system, on the HV and on the large cosmic tagger made of scintillator strips. An expected total of 3000 kCHF (including operation money and upgrade) will be requested.
3. To continue the T2K/NA61 participation, maintenance and upkeep will require 100 kCHF per year.
4. If the T2K upgrade will be approved, this might lead to a proposal to be submitted to FLARE for an investment estimated to about 500 kCHF.
5. GERDA will require an integrated operation funding of about 250 kCHF.

In perspective:

6. Following the ongoing DOE Critical Decision Process (DUNE/LBNF CD-1 passed in July 2015, CD3a review in December 2015, CD2 in 2019) and

decisions at the DUNE Collaboration Resources Review Board, a FLARE proposal will be submitted where the envisioned Swiss contribution will be presented. At present we foresee an approximate investment of 1 MCHF/year from FLARE during a total period of 10 years. SERI large infrastructure money could well contribute to funding.

7. The approval of Hyper-K might also lead to a FLARE funding request.
8. The approval of SHiP might also lead to a FLARE funding request.
9. Provided that IceCube will continue providing important results on neutrino oscillations and that PINGU funding will be secured at the international level, a PINGU request might be submitted to FLARE.
10. The evolution of a ton-scale double beta decay experiment might also lead to a FLARE funding request.

The above funding scheme will be extended in the light of future experiments, and priorities will be tuned accordingly, while providing continuity of support for already approved commitments. We assume that the funding of any new project 6-10 (by any possible funding source) could affect the planned funding scheme/profile and the manpower of the corresponding projects 1-5.