European Strategy for Particle Physics 2025
Portuguese input: Neutrino Physics

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1 Introduction

The observation of neutrino oscillations is the first – and so far only – confirmed phenomenon that is not explained by the Standard Model (SM) of Particle Physics. It is still early to know how deep a change is required to the theory in order to accommodate a satisfactory description of oscillations, since several observational unknowns remain, the most relevant among them are clearly the properties of charge conjugation and their behavior under the charge-parity symmetry.

A simple SM extension, in which neutrinos are described by Dirac terms similar to those of the charged leptons, is possible and consistent with current data. However, since neutrinos are the only electrically neutral fermions, it may be possible that they are "even more neutral", i.e. that they are Majorana particles. Since they require new high order operators, and couple differently to the Higgs field, the possibility of Majorana neutrinos would require, and would in fact be probing, new physics beyond the Standard Model at very high energy scales.

In addition to their utmost relevance to the theory of particle physics, those properties of neutrinos may also be deeply connected, via the mechanism of leptogenesis, to our understanding of the production of an asymmetry between matter and antimatter in the early Universe. The possible discoveries of neutrino-less double-beta decay and of leptonic CP violation will require significant investment, but both are within the grasp of the next generation of neutrino experiments. Neutrino physics is expected to remain at the forefront of particle physics for at least the near and medium term future.

2 Priorities beyond collider physics

We consider that, among the "other areas of physics", the pursuit of neutrino physics by the European particle physics community should have the top priority due mainly to its physics potential and the timing of the upcoming projects.

Beyond colliders, neutrino experiments have the highest potential of all to uncover further new physics and carry out measurements of SM (or SM extension) parameters, with a strong impact in fundamental cosmology.

Within neutrino physics, the highest priority experimental goals should be the full measurement of the neutrino oscillation parameters (CP violation phases and mass ordering), and the search for neutrinoless double beta decay, since these are the experimental avenues that can clarify the questions raised earlier.

2.1 Neutrino Oscillation Physics

In terms of oscillation experiments, the main players are JUNO, HK and DUNE. DUNE should remain the priority in this field for European, and Portuguese, participation.

JUNO is a reactor neutrino experiment already built in China with European contributions, and is expected to come online in 2025. The full exploitation of its upcoming data, that can shed light on the neutrino mass ordering, is a relevant goal that should be pursued. However, since the experiment is already built, the resource needs should be modest in the next few years.

For the medium term future, the DUNE and HK neutrino oscillation experiments with long-baseline neutrino beams, are the key players. The time scale of these experiments is a start at the end of this decade, beginning of the next, and operations through at least 10 years.

2.1.1 Physics Potential

While JUNO may provide early results in neutrino mass ordering, DUNE will have the ultimate sensitivity and should be able to provide an unambiguous measurement a few years after beam turn-on.

The sensitivities of DUNE and HK to the leptonic CP violation phase are similar (when one considers external mass ordering constraints, in the case of HK), with substantial complementarities between both: HK can reach higher statistics sooner, but DUNE can measure the mass ordering independently, and its broader energy range makes it more sensitive to new physics.

In terms of community participation, DUNE has a very strong European contribution, including a direct participation of CERN in the construction of the cryostats, and the crucial role of the Neutrino Platform in the development and test of the far detector technology with the ProtoDUNE detectors. Portugal has a leading role in the design and construction of calibration systems.

2.1.2 Long-term potential

DUNE will not be the first of these 3 experiments to provide measurements. However, with increasing statistics due to beam upgrades and further modules being deployed, and improved systematics, due to developments in far and near detector reconstruction and calibration, the ultimate performance of DUNE will allow an excellent sensitivity to all the remaining measurements of the standard

3-flavour mixing scenario, as well as unprecedented sensitivity to new physics in oscillations.

In terms of detector technology R&D, the phased approach of DUNE also provides a long-term horizon for participation in the technical developments for the Phase II detectors.

2.1.3 Financial and human resources

Projecting from current levels of national funding, and barring potential influx of European funding, it is expected that the Portuguese community may sustain a relevant participation only in one of the large oscillation experiments.

In the last few years, the participation in DUNE has successfully leveraged the installed capacity of the LIP research infrastructures for the construction of calibration hardware. This strategy will be followed in the following years for the construction of far detectors 1 and 2.

2.1.4 Timing

Due to an intensive program of beam and calibration data taking with the two ProtoDUNE detectors at CERN (2024 and 2025), the next few years of DUNE activity will combine a healthy mix of ProtoDUNE data analysis and construction for the far detectors.

Physics data-taking should start in 2029 without beam and 2031 with beam, and last for at least 10 years. Development of new detectors for DUNE Phase II, combined with higher intensity beam upgrades will likely extend that "useful life", so this experimental program is both short, medium, and long-term.

2.1.5 Careers and training

DUNE offers a typical highly international, multi-cultural, scientific environment that boosts student's scientific grounding and perspectives, motivations, skill sets and adaptation capabilities. The combination of hardware and analysis work, due to the ProtoDUNE program and phased approeach, also allows for a good diversity of skills.

2.1.6 Sustainability

The European particle physics community has decided (in a previous ESPP document), to contribute to large neutrino oscillation projects outside Europe rather than invest in new facilities within its own territory. This approach makes the best use of global resources, in terms of environmental costs associated to the excavation of underground labs, as well as the accelerator operation.

3 Neutrinoless Double Beta Decay

In broad strokes, the current global panorama of neutrinoless double beta decay is the following.

The leading experiment, KamLAND-Zen, which employed over 700 kg of enriched Xenon, has stopped taking data and is preparing a series of upgrades, that should allow it to reachm in 5 years, a sensitivity of $7 \times 10^{26} yr$ (for the half-life of ^{136}Xe), covering the whole inverted ordering region. There are plans for future high sensitivity liquid and gas TPCs with enriched Xenon (NEXT-HD and nEXO), but no approved funding.

The next best sensitivity comes from a combination of all the ^{76}Ge searches. The large-scale follow-up LEGEND-1000 is the front-runner of the US down-selection process, and has an ultimate sensitivity of $10^{28} yr$ (for 10 years running).

The best limit so far with ^{130}Te is from CUORE, at $3.8 \times 10^{25} yr$, and is not expected to improve significantly until the end of the experiment. The same technique of cryogenic bolometers is being developed for future use with Molibdnenum (CUPID).

The approach of SNO+ is to combine the use of the (currently) highest sensitivity technique – large liquid scintillation detector – with the isotope with the highest natural abundance – $^{130)Te}$. SNO+ is taking data with pure scintillator, and is expected to start loading 3.9 tonnes of natural Tellurium (0.5% per mass) in the scintillator in late 2025. With three years of data-taking, the expected lifetime sensitivity ($90\% C.L.$) is $2 \times 10^{26} yr$, but with the triple of that quantity (1.5% per mass) and 5 years of data it can reach $7 \times 10^{26} yr$. Due to the relative low cost of the isotope, that tripling would cost only about 10M$ and is being actively pursued by the collaboration. The experiment is located in SNOLAB, Canada, but there is significant European participation, especially from UK and Portugal.

3.0.1 Physics Potential

The discovery of Neutrinoless Double Beta Decay would have a very strong impact in fundamental Particle Physics. It would be an essential step to understand the neutrino mass generation mechanism and, jointly with other measurements (Cosmology and single beta decay), allow the determination of the absolute values of the neutrino masses. The implications for cosmology, astrophysics, long-scale structure of the Universe, etc. would be enormous.

In case of a positive discovery, the Physics potential of this field is very large. Therefore, it is essential to replicate the searches with multiple isotopes in order to: a) increase the community's confidence in possible positive results; b) allow a better constraint on the effective Majorana mass (given the large uncertainties of the nuclear matix elements).

3.0.2 Long-term potential

If no positive result is obtained with the existing or planned experiments with sensitivities covering the inverted neutrino mass ordering region, the steps required to go beyond that and cover the non-degenerate normal ordering region are substantial. Even with significant technological advances in order to improve resolution and reduce backgrounds, there's no way around the need to increase the isotope mass by a few orders of magnitude.

Due to high material and enrichment costs associated with several of the isotopes, it makes sense to explore to the fullest the possibilities with the least expensive isotope, $^{130)Te}$. In fact, several studies have been carried out for the use of the SNO+ Te-loading technique (or its developments) in future liquid scintillator detectors with higher mass and better light collection efficiency.

Moreover, the development of new capabilities of the liquid scintillator technology (directionality, particle identification) is an R&D direction that can bring sensitivity increases in the field of DBD, reactor and solar neutrinos, as well as high-energy beam neutrinos, bringing about a potential convergence of long baseline oscillation and low energy detectors.

3.0.3 Financial and human resources

The financial and human resources needed for a typical DBD experiment are an order of magnitude (or more) smaller that the typical large oscillation experiments. It is therefore possible, even for a country the size of Portugal, to combine the participation in a DBD and an oscillation experiment. For larger countries, more that one DBD experiment is possible (and desirable).

As as example, Portugal is a founding member of SNO+ and, since 2018, has participated with strong responsibilities in both SNO+ and DUNE.

3.0.4 Timing

Due to the long time scale of the "tonne scale" US-funded large DBD projects (potentially only LEGEND-1000), there is currently a very clear window of opportunity for a DBD search with ^{130}Te with sensitivity in the range $10^{26}-10^{27}yr$. Since the detector, scintillator and isotope infrastructure already exist, SNO+ can fill that window by carrying out that search until the end of the decade. Since this is a very cost-effective approach, and expertise/leadership already exists in Europe, this participation should be encouraged.

3.0.5 Careers and training

SNO+ is currently taking high quality physics data, and is expected to do so with DBD data starting in 2026. This provides a great opportunity for neutrino physics analysis in the years preceding the comoing online of the large oscillation detectors.

3.0.6 Sustainability

SNO+ is an already built experiment, making use to a large extent of the Sudbury Neutrino Observatory. There is no beam involved, so the resources needed for its continued operation over the next following decade are minimal.