European Neutrino "Town" Meeting
Panel 2 – Report

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Introduction

Neutrinos are special among the other Standard Model (SM) fermions because they, being neutral, can have a Majorana mass which is linked to a new physics scale and requires the extension of the theory. In such a case, neutrinos would be their own antiparticles and lepton number would not be conserved, something that can be tested in neutrinoless double beta decay experiments and seed the excess of matter over antimatter in the Universe [1]. However, the origin and nature of neutrino masses is still an open question. The minimal models, type-I, type-II and type-III seesaws, do not involve the extension of the SM symmetries and generate the masses at tree level. Other attractive options imply the addition of extra gauge symmetries, as in the Left-Right symmetric models, or induce neutrino masses at radiative level. New physics scales close to the Electroweak (EW) scale or below can be probed via many different and complementary searches partially described below as colliders, neutrinoless double beta decay and beam dump experiments. Notice that the simplest model, which consist just in the addition of fermion singlets (sterile neutrinos) to the SM field content, can accommodate the observed neutrino masses and mixing with a new physics scale ranging from the eV to the GUT scale.

Neutrino masses suggest the existence of fundamental new physics which may also shed light on other SM open questions as the Dark Matter (DM) problem. Indeed, DM must also be composed of neutral (or very weakly interacting) particles and could thus be closely related to neutrino physics. At the experimental level, Liquid Noble gas direct DM searches have considerable overlap with neutrino experiments: similar technology, backgrounds, and same range of energy for events that are similarly very rare.

Regarding neutrino oscillation experiments, the main goal of the near future program is to complete the standard three neutrino picture but also address several experimental anomalies pointing to physics beyond the PMNS matrix as eV scale sterile neutrinos.

Neutrinoless double beta decay

The so-called neutrinoless double beta ($0\nu\beta\beta$) decay transforms simultaneously two neutrons inside a nucleus into two protons under the emission of two electrons, but without the emission of two electron anti-neutrinos, thus violating lepton number by two units. A positive detection would imply the first observation of a matter-creating process, without the balancing emission of antimatter, establishing the existence of lepton number violation (LNV) which is a fundamental requirement to generate the matter-antimatter asymmetry of the universe via Leptogenesis [1]. Many theories beyond the Standard Model predict LNV and it has been shown that any $0\nu\beta\beta$ decay mechanism induces radiatively a Majorana mass term for the light neutrinos [2]. This term is however many orders of magnitude smaller than the observed neutrino masses and thus other leading contributions to neutrino mass should exist [3]. Under the premise that light Majorana neutrino exchange is the dominant contribution to $0\nu\beta\beta$ decay, its half-live is a function of the Majorana neutrino masses and the elements of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix. The experimental sensitivities of the present generation of experiments reach half-lives up to $T^{0\nu}_{1/2} > 10^{26}$ yr, which corresponds to Majorana mass $m_{\beta\beta} < 0.1 - 0.3$ eV, with significant nuclear matrix elements uncertainties Table 1 summarizes the state-of-the-art experimental results.

Next generation experiments aim to improve the sensitivities by two orders of magnitude in half-life, from increasing the target mass, reducing interfering backgrounds, improving the energy resolution and particle identification. A high discovery potential will be the real target. The long-standing European leadership in $0\nu\beta\beta$ decay research with high resolution detectors will continue with the next generation experiments: LEGEND, CUPID, NEXT, and possibly Super-NEMO. These experiments will be able to fully test the predicted lower limit from oscillation experiments for inverted mass ordering and to cover a large part of the parameter space of $m_{\beta\beta}$ in case of normal ordering. The discovery potential is further enhanced in well-motivated extensions of the SM, such as left-right symmetric models [4] or models with GeV-scale right-handed neutrinos [5, 6].

Table 1: Lower 90% C.L. half-life limits $\mathcal{L}(\mathrm{T}_{1/2})$, sensitivities $\mathcal{S}(\mathrm{T}_{1/2})$ and Majorana masses $\mathrm{m}_{\beta\beta}$ reported by leading $0\nu\beta\beta$ decay searches with indicated isotopes and isotope exposures $\mathcal{E}$.

Experiment	Isotope	$\mathcal{E}$ kg yr	$\mathcal{L}(\mathrm{T}_{1/2})$ 10^{25} yr	$\mathcal{S}(\mathrm{T}_{1/2})$ 10^{25} yr	$\mathrm{m}_{\beta\beta}$ eV
GERDA	^{76}Ge	82.4	9	11	0.11 - 0.25
Majorana	^{76}Ge	26.0	2.7	4.8	0.20 - 0.43
CUPID-0	^{82}Se	1.83	0.24	0.23	0.38 - 0.77
CUORE	^{130}Te	24	1.5	0.7	0.11 - 0.52
KamLAND-Zen	^{136}Xe	593.5	10.7	5.6	0.07 - 0.22
EXO-200	^{136}Xe	177.6	1.8	3.7	0.15 - 0.40

The determination of the nuclear term, regulating the half-life is crucial for the phenomenological interpretation of $0\nu\beta\beta$ decay experimental data. The Nuclear Matrix Elements (NME) provided by the nuclear theory community are affected by a sizable spread. The nuclear physics community, asked to provide more reliable NME calculations, also has to pinpoint the experimental measurements that can help in fixing parameters and validate models.

Short Baseline Oscillation Experiments:

The short baseline neutrino program is currently a very active experimental field that comprises accelerator and reactor-based experiments. Those experiments use neutrino oscillations to probe the direct or indirect evidence for the existence of a sterile sterile neutrino at a specific L/E that corresponds to a squared mass difference of $\sim$1 eV^2.

On the reactor side, the Very Short Baseline (VSBL) experiments have the long standing Gallium anomaly [7] and the reactor anomaly (recently confirmed by Double-CHOOZ [8]), which are in tension with DANSS [9] and NEOS [10] results. Apart from the apparent flux reduction, the spectral shape shows a bump around 5 MeV anti-neutrino energy, which was already visible in the data from a 30-years-old experiment [11]. To resolve these issues, high precision VSBL experiments which use different detector technologies are starting up. For instance, STEREO [12] and PROSPECT [13] have published their first bounds.

The accelerator Short Baseline (SBL) experiments have provided the two persistent anomalies of MiniBooNE [14] and LSND [15], which seem comparable to findings from past experiments at CERN PS191 [16] and at BNL E816 [17] and also hint at eV scale sterile neutrino oscillations. Even though both the VSBL reactor and SBL accelerator experiments qualitatively point to the existence of eV scale sterile neutrinos, global analyses show that a consistent interpretation of all anomalies in this framework is strongly disfavored. In particular, there is a strong tension between the LSND and MiniBooNE results from the $\nu_\mu \to \nu_e$ channel and experiments sensitive to the $\nu_\mu \to \nu_\mu$ disappearance channel as MINOS/MINOS+ and IceCube. The Short-Baseline Neutrino Program (SBNP) program at Fermilab aims to clarify this picture with three new detectors SBND, MicroBooNE, and Icarus, which use the BNB beam. An interesting proposal for the continuation of these searches is nuSTORM [18, 19]. The precise knowledge of the neutrino flux and energy distribution can also lead to percent level measurements of neutrino cross sections which is a most needed input for DUNE and HyperK. Another possible future input may come from the European Spallation source (ESS), for which a neutrino facility is discussed [20]. The 300 MeV neutrino beam would allow to contribute with near and far detectors to the global picture. Also decay at rest is possible, which would allow to test a parameter space similar to the one probed by the LSND experiment.

Near detector facilities of long baseline experiments also provide a unique laboratory for the search of beyond the SM particles. This type of searches include dark matter (mainly relevant in the sub-GeV window), millicharged particles, new neutrino interactions, new gauge interactions and neutrino mass models closely related to low scale leptogenesis. There is some overlap and complementarity with dedicated beam dump experiments, like SHiP and NA62. The renewed interest in this kind of New Physics effects is expressed for example in [21–26].

Colliders:

Collider experiments have played a very important role in neutrino physics in the past. The large electron positron collider (LEP) measured the number of active neutrinos via the invisible Z width, and tested the universality of leptonic W boson decays with great precision. New physics linked to neutrino masses with scales above the EW scale can indirectly be probed through precise EW measurements. Models where the mediators inducing the Weinberg's operator are heavy fermions, as the type-I and type-III seesaws, generate deviations of the unitarity of the lepton mixing matrix modifying the neutrino couplings to the W and Z gauge bosons. Precision measurements of EW observables allow thus to test this effect via the effective non-unitarity of the PMNS matrix [27–29]. The present bounds are currently dominated by LEP and LFV searches as $\mu \to e\gamma$ and can be improved by two orders of magnitude with FCC-ee [28]. Remarkably, the indirect FCC-ee sensitivity to non-unitarity lepton flavor violating parameters in the $\tau - e$ and $\tau - \mu$ sectors is stronger than the future sensitivity of $l_\alpha \to l_\beta l_\beta l_\beta$ and $l_\alpha \to l_\beta \gamma$ experiments, cf. refs. [30] and [31], while the $\mu - e$ sector will be dominated by $\mu - e$ conversion searches [32, 33]. Moreover, it offers the possibility to study tau decays directly [34].

The LHC is probing new physics scales below the EW scale and, in particular, the existence of Heavy Neutral Leptons (HNL) predicted by the type-I and Left-Right symmetric realizations of the seesaw model. CMS searches for promptly decaying particles are now competitive with the bounds from DELPHI [35]. The search for long lived particles at LHCb provides slightly stronger constraints for a limited range of HNL masses [36]. Specialized analyses allow for better sensitivity [37], and specialized triggers may do even better. A significantly improved sensitivity is possible when the LHC is enhanced with a 60 GeV electron beam, the so-called LHeC. At this electron-proton collider $\mathcal{O}(100)$ GeV HNL can be tested with squared neutrino mixings (electron flavor) $\sim 10^{-6}$ via lepton number and flavor violation. Non-minimal models can also give rise to novel signatures as Z' or Higgs decays to a pair of HNL which, being long-lived, leave a powerful signal of two displaced vertices [38, 39].

At the Z pole the FCC-ee provides prospects to test the seesaw via searches for displaced vertices which can cimprove the present limits on HNL mixings by several orders of magnitude and probe a region of the parameter space compatible with successful baryogenesis [40–42]. These searches are sensitive to the ratios of HNL mixings to different flavours, e, μ, τ, which in simple models are strongly correlated to the light neutrino PMNS mixing matrix and most interestingly to its CP violating phases, leading to a high sensitivity to leptonic CP violation [43]. Another interesting possibility is given by lepton flavour violating Z decays [44].

The FCC-hh can test lepton-flavor violating signatures with very limited sensitivity. Better prospects come from the electron-proton collider, which can test lepton number or lepton flavor violating final states with very low backgrounds and high efficiency, the FCC-he can probe HNL (squared) mixings as small as $\sim 10^{-6}$ with the electron flavor for masses up to $\mathcal{O}(1)$ TeV, which is the best sensitivity for direct searches of HNL in this range and supersedes the direct tests at FCC-ee and FCC-hh [45].

HNL can also propagate from the primary vertex over macroscopic distances and decay in **external detectors** designed to detect light longlived particles as MATHUSLA [46]. Other proposed detectors for long lived particle searches are CODEX-b, FASER, milliQan. In particular MATHUSLA can test masses around 1 GeV and $\mathcal{O}(10^{-9})$ mixings in a model independent fashion.

Neutrino mass models such as, e.g. the type II and III seesaws or left-right symmetric models, have better discovery prospects since the mediators involve gauge interactions, providing new opportunities to observe lepton number violating signals [47, 48]. An explanation of the baryon asymmetry generation is usually more challenging in these scenarios.

Beam dump experiments

Beam dump experiments are essentially designed to look for long lived particles. These complementary searches can probe a region of the new physics scale around the GeV. In particular, HNL can be produced via mixing in meson decays, propagate into the decay volume, and decay into a number of light leptons and mesons that can be detected. The sensitivity scales with the number of protons on target and in a non-trivial way with the beam energy. NA62 yields the most stringent constraints on HNL [49], excluding heavy neutrinos with masses ~ 1 GeV and mixings down to $\sim 10^{-8}$. The future experiment SHiP (Search for Hidden Particles) could improve the ultimate NA62 reach by two orders of magnitude in a similar region of masses (between 100 MeV and 5 GeV) [50]. A HNL signal at SHiP could lead to discovery of leptonic CP violation in the minimal seesaw model with two right handed neutrinos [43], while combining it with data from neutrino oscillation and $0\nu\beta\beta$ decay experiments could be sufficient to test GeV-scale leptogenesis [51].

Near detectors of future neutrino oscillation facilities (SBND or DUNE) can test HNL that are produced via mixing in the neutrino source. HNL masses below ~ 0.5 GeV can be probed with a sensitivity to the mixing with electrons and muons which improves the present constraints [52]. However, the region below ~ 0.2 GeV is disfavored by BBN data, which reduces the window in which a positive measurement is expected.

KATRIN

The state-of-the art tritium decay spectrometer is designed to measure neutrino masses as small as 0.2 eV. Sterile neutrinos with eV masses could be detected via this measurement. Sterile neutrinos with KeV masses could be detected via a kink-like distortion of the beta spectrum after the upgrade of the detector to TRISTAN. The resulting signature investigated at KATRIN is one or several characteristic kink-like features in the energy spectrum of tritium beta decay electrons that can be resolved with enough statistics and control of systematics, for instance via sophisticated shape analysis methods, with an ultimate sensitivity to active-sterile mixing with the electron flavor $\sin^2\theta < 5\times10^{-6}$ [53]. An observation of this signal would be in conflict with cosmology [54] for minimal sterile neutrino models and would require a non trivial extension in order to circumvent the bounds.

Synergies with direct detection Dark Matter experiments:

Along with neutrino masses, dark matter and the understanding of the physical laws that govern it are among the deepest open problems in science today. Candidates for dark matter include the hypothetical weakly interacting massive particle (WIMP) and sterile neutrinos. They could be discovered via the observation of missing energy in collisions at the CERN LHC, via the by-products of its self-annihilation in cosmic rays, or via direct observation of its collisions in ultra-low energy, ultra-low background direct searches, operated in deep underground laboratories.

Direct searches for nuclear (or electron) recoils induced by collision of WIMPs on detector targets mandate the use of low-background technologies originally developed for searches for solar neutrinos and $0\nu\beta\beta$ decay. A number of direct detection experiments are currently underway using a variety of detector technologies. Current best limit for nuclear recoils comes from xenon time projection chambers [55] and from argon time projection chambers [56]. The same two classes of detectors have also produced the most stringent limits for collision of dark matter on electrons.

Searches for Dark matter via nuclear recoils is limited by the "neutrino floor", which signals the onset of nuclear recoils induced by solar or atmospheric neutrinos, which will become a very important background. The directional signal of DM could be used to defeat this background. $0\nu\beta\beta$ decay measurements at dual phase liquid xenon detectors like LZ and XENON-nT are being explored. The current size of detector allows for good sensitivity, and while it may be difficult to compete with dedicated experiments, the possibility is emerging to have a multi-purpose third generation detector.

Large-scale dual- or single-phase liquid argon detector, such as the 300-tonnes detector under consideration by the DarkSide/Global Argon Dark Matter Collaboration, could also provide the first step to a precision measurement of the remaining sources of solar neutrinos to be discovered, such as CNO and *hep* neutrinos [57]. The development of the next generation of dark matter detectors will directly benefit the technology available for both low- and high-energy neutrino experiments.

The development of dark matter detectors also directly benefits the development of liquid argon time projection chambers for long-baseline neutrino oscillation studies [58,59]. As an example, the DarkSide-50 experiment at LNGS obtained in a very compact detector, by means of a hot gas purification systems, an electron meanlife of over 5 ms [60] in liquid argon, already compatible with the baseline requirement of DUNE. The DEAP-3600 experiment hold the best limit on ^{222}Rn contamination in noble liquids at $<0.2\,\mu\mathrm{Bq\,kg^{-1}}$. The SiPM-based photosensors for DarkSide-20k have reached the best performance in the industry for photon detection efficiency, dark noise at liquid argon temperature, intrinsic radioactivity, and ease of cost and scaling [61]. At the same time, dark matter detectors will benefit from technology developed for neutrino experiments: one interesting example is the DarkSide-20k experiment at LNGS, which recently adopted the technology of membrane cryostats developed at CERN in support of the ProtoDUNE and DUNE programs [58, 59].

Coherent Neutrino Scattering

Testing this process in the laboratory was proposed about 40 years ago [62], it was measured recently by the COHERENT collaboration [63]. This first measurement opens the path to higher statistical precision measurements/experiments with the possibility to verify the compatibility with the Standard Model predictions, to probe sterile neutrinos, non-standard interactions, the neutrino magnetic moment, and neutron physics. The experimental technique overlaps with direct DM searches, and a detailed study of this process may help monitoring of nuclear reactors activity and benchmarking DM detectors [64].

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