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Search for sterile neutrinos in the CC ν_μ mode at the new CERN-SBLNF

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Summary. — The possible existence of non-active neutrinos for the ElectroWeak interactions was first proposed in 1967 by B. Pontecorvo who named them "sterile" neutrinos. Recent tensions among world-wide experimental data renewed the possibility of one or more sterile neutrino states. Several "anomalies" emerged in radioactive sources and reactor neutrino experiments, as well as the long-standing LSND and the recent MiniBooNE hints for neutrino and antineutrino oscillations with a Δm^2 at the eV^2 scale, not compatible with the standard 3×3 neutrino mixing scenario. While a huge effort is being devoted to establish the standard three-neutrino mixing paradigm no conclusive experiment was carried out to unambiguously settle these anomalies sofar. Very recently an experimental search for sterile neutrinos with a new CERN-SPS neutrino beam using muon spectrometers and large LAr detectors has been proposed. The accurate disentangling of ν_μ from $\bar{\nu_\mu}$ will allow to investigate the interplay of the different possible oscillation scenarios, as well as the interplay between disappearance and appearance of different neutrino states and flavors. The proposed experiment will offer remarkable discovery potentials, collecting a very large number of unbiased events both in the neutrino and antineutrino channels, largely adequate to definitely settle the origin of the ν oscillation related anomalies. We will discuss the CERN project focussing on the measure of the Charge Current ν_μ mode.

PACS 14.60.Pq – Neutrino mass and mixing.
PACS 13.15.+g – Neutrino interactions.

1. – Physics potential and motivations

The recent LHC discoveries confirm once more the great success of the Standard Model (SM). In this rapidly emerging picture, neutrino mixing and masses represent a first established evidence of Physics beyond the Standard Model. Being the neutrinos the only elementary fermions whose basic properties are largely unknown, it is natural to push the research in this field. The mixing parameters and the small masses, differentiate neutrinos from all other known fermions. A unique and appropriate theoretical framework, which accomodate all this, would significantly drive particle physics forward. The exciting recent results by T2K [1], MINOS [2], RENO [3] and Daya Bay [4] show that all 3 mixing angles are non-vanishing and large and open a new spectrum of intriguing possibilities. A precise investigation of the oscillation probabilities as a function of energy and a comparison of neutrino and antineutrino behaviours is becoming mandatory. Such measurements will also yield a definitive understanding of the neutrino mass hierarchy and a deep exploration of CP-violation in the neutrino sector. Problem studies and prototype work targeting the next generation of long baseline neutrino oscillation experiments is part of the overall particle physics strategy at CERN and in Europe. Towards such a goal the next natural step is to establish at CERN a short baseline neutrino facility. The physics case raised by the ICARUS-NESSiE [5] collaboration for the search of the sterile neutrino [6], is a fundamental milestone which need to be adressed with priority. The proposal is to construct and operate a short baseline experiment, with two sets of neutrino detectors placed at 2 different distances from the production target (far and near detectors). In the two positions, the radial and energy spectra of the ν_e beams are practically identical. Comparing the two detectors, in absence of oscillations, all cross sections and experimental biases cancel out, and the two experimentally observed event distributions are expected to be identical. Any difference in the event distributions at the locations of the two detectors might be attributed to the possible existence of ν oscillations, presumably due to additional neutrinos with a mixing angle and a larger mass difference.

Two distinct classes of anomalies have been reported: a) apparent $\bar{\nu}_e$ disappearance signals from nuclear reactors [7] and from the Mega-Curie k-capture calibration sources in the solar ν_e Gallium experiments [8]; b) Observation of ν_e excess in accelerator experiments (LNSD [9] / MiniBooNE [10]).

These two distinct classes of anomalies will be explored with both neutrino and antineutrino focused beams. According to the first anomaly some of the ν_e ($\bar{\nu_e}$) and/or of the ν_μ ($\bar{\nu_\mu}$) events might be converted into invisible (sterile) components, leading to observation of oscillatory, distance dependent disappearance rates. The second anomaly (following LSND and MiniBooNE observations) implies that some distance dependent ν_e, ν_μ oscillations may be observed as ν_e excess, especially in the antineutrino channel.

At present the LSND experiment and the MiniBooNe experiment both claim an independent 3.8σ effect from standard neutrino physics. The recent MiniBooNe result, confirming the LNSD result, indicates a neutrino oscillation signal both in neutrino and antineutrino with $\Delta m^2_{new} \sim 0.01\,\mathrm{eV}^2$ to $1.0\,\mathrm{eV}^2$. These experiments may all point to the possible existence of additional non-standard n-states driving oscillations at small distances, with relatively large mixing angle. The existence of a 4th ν state may be also hinted, or at least not excluded, by cosmological data [11]. The disentangling of ν_μ from $\bar{\nu_\mu}$ will allow to exploit the interplay of the different possible oscillation scenario, as well as the interplay between disappearance and appearance of different neutrino states and flavors. A reasonable utilization of a new CERN-SPS neutrino beam line will offer remarkable discovery potentialities, collecting a very large number of unbiased events both in the neutrino and antineutrino channels, largely adequate to definitely settle the origin of the ν-related anomalies.

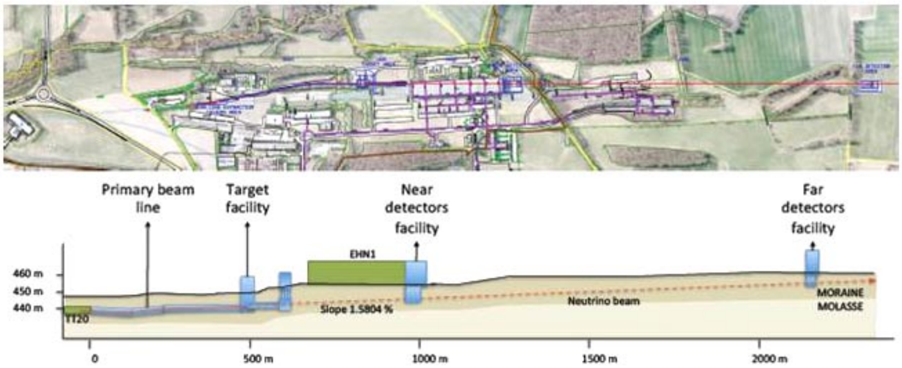

Fig. 1. – Top: layout of the facility at CERN. Bottom: vertical cut showing the TT20, EHN1 and the main components of the facility.

2. – The CERN Neutrino Facility (CENF)

The new Neutrino Facility (CENF) will be situated in the north area of the Prevessin CERN site (fig. 1). It consists of an SPS fast extraction system and a new proton transfer line bringing high-energy protons to the target area, which will be located underground. The primary target will be followed by a decay tunnel terminated by a beam dump. Two detector facilities, near and far, will be located at about 460 m and 1.6 km respectively from the production target.

100 GeV pulsed proton beams will be fast extracted from the existing SPS LSS2 straight section and transported through the TT20 beam line, which today also feeds the north area EHN1 experimental hall by a slow extracted beam from the SPS. A new tunnel of about 500 m length will be excavated at about 10–15 m depth. The 100 GeV proton beam will first bent away from the TT20 line, to avoid interference with the existing TT20 beam elements. After a straight section it will be bent back to point to the new target region, alongside the TT20 beam line. Existing and refurbished dipole and quadrupole magnets will be used to bend and focus the proton beam. The TT20 beam line, upstream of the branch-off region, will need to be further instrumented with beam diagnostics to measure fast extracted beams, work to be done preferably during the LS1 shutdown period in 2013 and 2014.

The following assumptions have been applied. The beam intensity is $3 \to 5 \times 10^{13}$ protons per cycle. For filling the LHC a dedicated super cycle will be activated on average 2 hours every 24 hours, excluding, or limiting severely, the possibilities for beam delivery to other users. Therefore only 22 hours per day are considered for non-LHC physics (*e.g.* neutrino facility and north area). The average duration of a physics run is assumed to be 200 days per year. An overall PS-SPS machine availability of 75% is considered.

The two detector sites, near (456 m from target) and far (1600 m from target) will consist of a coupled system of a Liquid Argon (LAr) detector (119 ton at near site, 476 ton at far site) and a muon spectrometer (840 ton of iron at near site, 1515 ton at far site) in order to study ν_e, and ν_μ interactions in both Neutral Current (NC) and Charge Current (CC) channels and to measure both the muon momentum and charge.

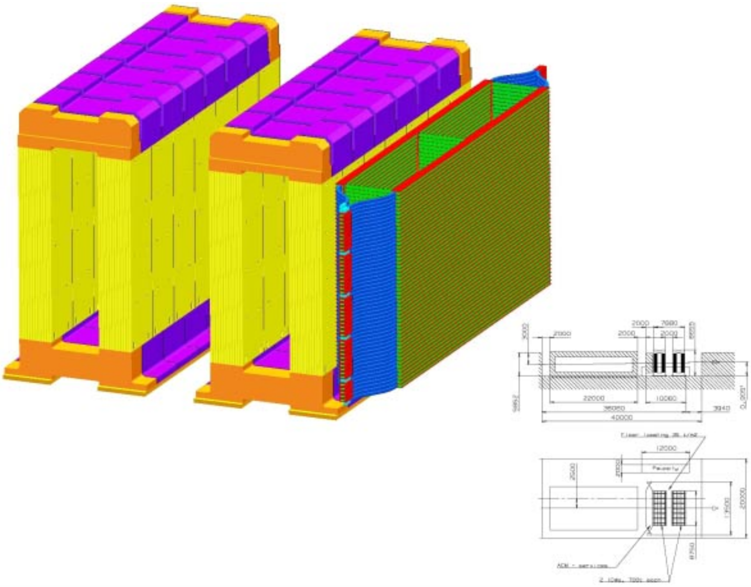

Fig. 2. – The FAR NESSIE spectrometers downstream the LAr detector. The air core magnet follwed by the iron core magnet.

3. – ICARUS LAr detector

The ICARUS T600 detector [12] consists of a large cryostat split into two identical, adjacent modules with internal dimensions $3.6 \times 3.9 \times 19.6\,\mathrm{m}^3$ filled with about 760 tons of ultrapure liquid argon. Such units are operated together as a unique detector. A uniform electric field (ED $= 500\,\mathrm{V/cm}$) is applied: each module houses two TPCs separated by a common cathode. Each TPC is made of three parallel planes of wires, 3 mm apart, facing the drift path (1.5 m). Globally, 53248 wires with length up to 9 m are installed in the detector. By appropriate voltage biasing, the first two signal sensing planes (Induction-1 and Induction-2) provide differential signals in a non-destructive way, whereas the ionization charge is finally collected by the last Collection plane. On each plane, wires are oriented at $0°, \pm 60°$ angles with respect to the horizontal direction. Therefore a three-dimensional image of the ionizing event is reconstructed by combining the wire coordinate on each plane at a given drift time. A remarkable resolution of about $1\,\mathrm{mm}^3$ is uniformly achieved over the whole detector active volume ($\sim 340\,\mathrm{m}^3$ corresponding to 476 ton).

The measurement of the absolute time of the ionizing event, combined with the electron drift velocity information ($v_D \sim 1.6\,\mathrm{mm}/\mu\mathrm{s}$ at $E_D = 500\,\mathrm{V/cm}$), provides the absolute position of the track along the drift coordinate. The absolute time of the ionizing event is given by the prompt detection of the scintillation light produced in LAr by ionizing particles. An array of several Photo Multiplier Tubes (PMTs) installed behind each of the wire chambers and coated with wavelength shifter allows the detection of VUV scintillation light ($\lambda = 128\,\mathrm{nm}$), at a LAr cryogenic temperature.

The present design of the T600 is extended to the basic structure of the internal detector of the T150 module that will be used at the near site.

4. – NESSIE Spectrometers

The NESSIE spectrometers (fig. 2) will be placed just downstream, minimising the distance with ICARUS. The main purpose of the spectrometers is to provide charge identification and momentum reconstruction of the muons produced in the neutrino interactions. In order to perform the measurement with high precision in a wide energy range, from sub-GeV to multi-GeV, a wide double iron-core dipole magnet (ICM) is coupled to an air-core magnet (ACM) in front of it. Low momentum muons will be measured by the ACM. The goal is to provide a charge misidentification probability as low as 1% over a momentum range extending from 0.1 to 10 GeV. The ICM is built assembling vertical iron plates alternated with detector layers, composed by Resistive Plate Chambers (RPC), which provide a tracking with 1 cm resolution using read-out strips with 2.6 cm pitch. Each magnet is a "clone" of OPERA [13] ones, made of two arms, each of 12 iron walls alternated to 11 RPC layers, and by two iron blocks connecting the arms in the top and the bottom. Copper coils surrounding the yokes are used to generate a magnetic field of about 1.5 T. The design and engineering of this detector largely profits from the experience gained in OPERA. Concerning the RPC system, most of the detectors from the OPERA spectrometers will be recovered and re-used. They are standard 2 mm gap chambers with high resistivity bakelite electrodes. They will operate in streamer regime with a gas mixture made of Ar/C2H2F4/I-C4H10/SF6. The high streamer amplitude signals permit to house the Front-End discriminators in racks placed on top of the spectrometer. The ACM instead is a new device. The complete air core magnet is built using 80 coils 9 meters long in the straight parts plus two half circular bending regions for the return of the conductors, outside the beam region. Aluminium is the material of choice, both for the conducting cable and the supporting structure. All coils are connected electrically and hydraulically in series. Planes of high-precision tracker (HPT) will be allocated in the ACM with a resolution of about 1 mm.

5. – Expected performance

A complete discussion of $\nu_\mu \to \nu_e$ oscillation studies both in appearance and disappearance modes has been presented in the SPSC-P345 document [14], that includes the genuine event selection and background rejection in the LAr-TPC's (see fig. 3).

In addition to the $\nu_\mu \to \nu_e$ oscillation studies mentioned above, ν_μ oscillation in disappearance mode by using large mass spectrometers with high capabilities in charge identification and muon momentum measurement was discussed in detail in [15],. It is important to note that all sterile models predict large ν_μ disappearance effects together with ν_e appearance/disappearance. To fully constrain the oscillation searches, the ν_μ disappearance studies have to be addressed. Much higher disappearance probabilities are expected than in appearance mode, where relative amplitudes as large as 10% are possible. The spectrometers will be able to correctly identify about 40% of all the CC events produced in, and escaped from, the LAr-TPC's, both in the near and far sites. That will increase the fraction of CC events with charge identification and momentum measurement, especially at high energies. Therefore complete measurement of the CC event spectra will be possible, along with the study of NC/CC event ratio (in synergy with the LAr-TPC), and the relative background systematics.

The large mass of the magnets will also allow an internal check of the NC/CC ratio in an extended energy range, and an independent measure of the CC oscillated events.

A sensitivity of $\sin^2(2\Theta_{new}) > 3\times10^{-4}$ (for $\Delta m^2_{new} > 1.5\,\text{eV}^2$) and $\Delta m^2_{new} > 0.01\,\text{eV}^2$

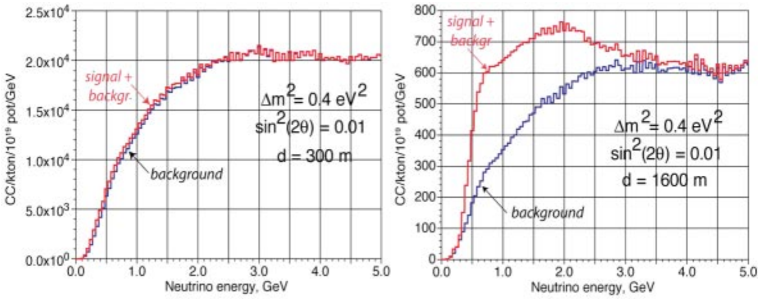

Fig. 3. – The event rate, shown both for background and oscillation + background at $d = 300\,\mathrm{m}$ (left) and $d = 1600\,\mathrm{m}$ (right) and the optimal prediction from ICARUS.

(for $\sin^2 2\Theta_{new} = 1$) at 90 % C.L. is expected for the $\nu_\mu \to \nu_e$ transition with one year exposure (4.5×10^{19} pot) at the CERN-SPS ν_μ beam (fig. 4, left). The parameter space region allowed by the LSND experiment is fully covered, except for the highest Δm^2 region. The sensitivity has been computed assuming a 3% systematic uncertainty in the prediction of "Far" to "Near" ν_e ratio. A further control of the overall systematics will be provided by the LAr and spectrometer combined measurement of CC spectra in the Near site and over the full energy range.

In antineutrino focusing, twice as much exposure (0.9×10^{20} pot) allows to cover both the LSND region and the new MiniBooNE results (fig. 4, right). Both favoured MiniBooNE parameter sets, corresponding to two different energy regions in the MiniBooNE antineutrino analysis, fall well within the reach of this proposal.

In fig. 5, left the sensitivity for ν_e disappearance search in the $\sin^2(2\Theta_{new})$-Δm^2_{new} plane is shown for the presently proposed experiment with an integrated intensity of 4.5×10^{19} pot, corresponding to one year of data taking at the presently available beam intensity. The oscillation parameter region related to the "anomalies" from the combination of the published reactor neutrino experiments, Gallex and Sage calibration sources experiments [16] is completely explored.

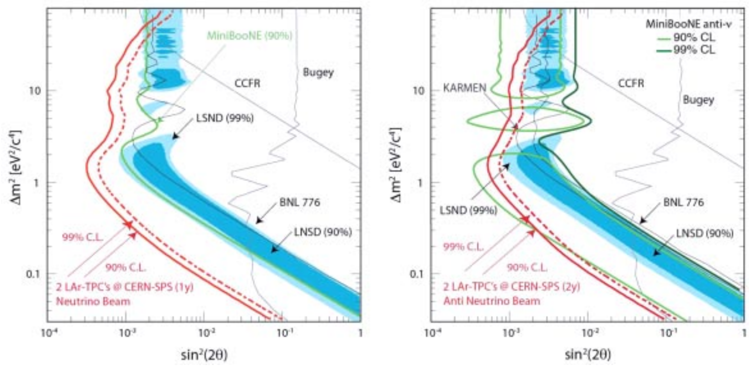

Fig. 4. – Expected sensitivity to $\nu_\mu \to \nu_e$ transition for the proposed experiment exposed at the CERN-SPS neutrino beam (left) and antineutrino beam (right) for 4.5×10^{19} pot (1 year) and 9.0×10^{19} pot (2 years), respectively. The LSND allowed region is fully explored in both cases.

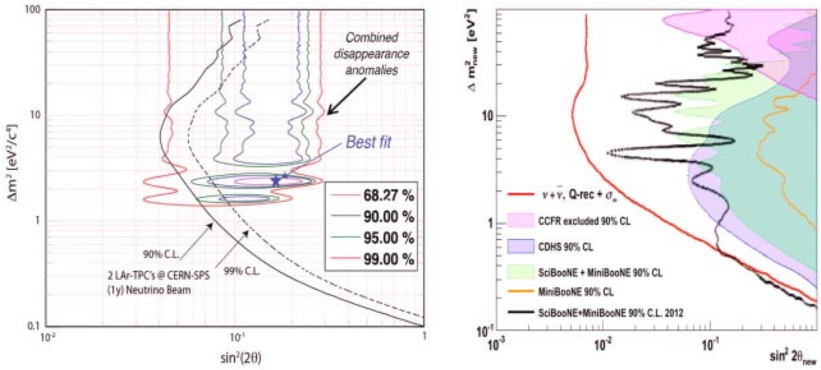

Fig. 5. – Left: Oscillation sensitivity in the $\sin^2(2\Theta_{new})$ *vs.* Δm^2_{new} plane for the CERN-SPS neutrino beam (1 year). A 1% overall and 3% bin-to-bin systematic uncertainty on the energy spectrum is included. Right: The sensitivity plot (at 90% CL) for the negative-focusing option considering three years of the CERN-SPS beam (2 years in antineutrino and 1 year in neutrino mode) from CC events fully reconstructed in NESSiE+LAr. Red line: ν_μ exclusion limit.

		NEAR (ν-bar)	NEAR(ν)	FAR(ν-bar)	FAR(ν)
produced	$\nu_e + \nu_e$-bar (LAr)	35 K	54 K	4.2 K	6.4 K
	$\nu_\mu + \nu_\mu$-bar (LAr)	2000 K	5250 K	270 K	670 K
	Appear. test point	590	1900	360	910
detected	ν_μ (LAr+NESSiE)	230 K	1200 K	21 K	110 K
	ν_μ (NESSiE)	1150 K	3600 K	94 K	280 K
	ν_μ-bar (Lar+NESSiE)	370 K	56 K	33 K	6.9 K
	ν_μ-bar (NESSiE)	1100 K	300 K	89 K	22 K
	Disappear. test point	1800	4700	1700	5000

Fig. 6. – The expected rates in LAr TPC and NESSIE spectrometers.

Moreover the ν_μ disappearance signal is well studied by the spectrometers, with a very large statistics and disentangling of ν_μ and ν_μ interplay [17]. As an example, fig. 5, right shows the sensitivity plot (at 90% CL) for two years negative-focusing plus one year positive-focusing. A large extension of the present limits for ν_μ by CDHS and the recent SciBooNE+MiniBooNE will be achievable in $\sin^2(2\Theta)$-Δm^2. Both ν_e and ν_μ disappearance modes will be used to add "conclusive" information on the sterile mixing angles. In fig. 6, the expected rates in both near and far, ICARUS LAr TPC and NESSIE spectrometers are shown both for the negative and positive focusing for 4.5×10^{19} pot. Also the appearance and disappearance expected events at the test point Δm^2 around $2\,\text{eV}^2$ are shown.

6. – Conclusions

The proposed Short Baseline Neutrino Facility at CERN, with two equal detectors at near and far sites, will allow to determine both the mass difference and the value of the mixing angle keeping completely under control the systematics. The large volume detectors and the proposed neutrino fluxes will allow to collect a large amount of statistics, allowing to explore the region of low $\sin^2 2\Theta$ values. Moreover, the combined use of the LAr detector and the spectrometers, will permit to test low Δm^2 vlaues and to fully clarify the current reactor and neutrino beam anomalies characterizng the properties of sterile neutrino(s), if any. This experimental program represents an opportunity for a revival of the neutrino activity in Europe and is an important probe for physics beyond the standard model. The proposed reuse of working detectors allowsp for a favorable time scale.

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