ICARUS-NESSiE: a sensitive search for sterile neutrinos at CERN SPS

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Abstract.

A new experimental search for sterile neutrinos beyond the Standard Model at a new CERN-SPS neutrino beam aiming at measuring the electron and muon neutrino events with a Near and Far detectors (1600 and 330 m from the proton target) is presented. The project will exploit the ICARUS T600 LAr-TPC moved from LNGS to the CERN Far position and a new additional LAr-TPC detector, 1/4 of the T600, located in the Near position. Two magnetic spectrometers will be placed downstream of the two LAr-TPC detectors to greatly complement the physics capabilities. Comparing the two detectors, in absence of oscillations, all cross sections and experimental biases cancel out. Any difference of the event distributions at the two locations should be attributed to the possible existence of oscillations, presumably due to additional neutrinos with a mixing angle \( \sin^2(2\theta_{\text{new}}) \) and a mass squared difference \( \Delta m^2_{\text{new}} \) larger than the measured for the standard neutrinos. The superior quality of the LAr imaging TPC, in particular its unique electron-\( \pi^0 \) discrimination allows for full rejection of backgrounds and offers a lossless \( \nu_e \) detection capability. The determination of the muon charge with the spectrometers allows for the full separation of \( \nu_\mu \) from \( \bar{\nu}_\mu \) and therefore controlling systematics from muon mis-identification mainly at high momenta.

1. Introduction

The discovery of a Higgs boson at LHC CERN collider has crowned the Standard Model (SM) of fundamental interactions calling also for a verification of the Higgs coupling to the gauge boson and to fermions.

Neutrinos, being the only elementary fermions whose basic properties are still largely unknown, must naturally be one of the main priorities to complete our knowledge of the SM. Moreover the discovery of neutrino oscillations and of the related non zero masses represents today a main experimental evidence of new physics. Albeit still unknown precisely, the incredible smallness of the neutrino rest masses, compared to those of other elementary fermions points to some specific scenario, awaiting to be elucidated. On the other hand, the astrophysical importance of neutrinos is immense: if heavy enough, they may also contribute to dark matter in the Universe.

The possible presence of sterile neutrinos which do not fully see the ordinary electro-weak interactions but still oscillating and mixing with ordinary neutrinos, was originally proposed by B. Pontecorvo in a seminal paper where he considered the existence of right-handed neutrinos,
neutrino oscillations, lepton number violation, $0\nu - \beta\beta$ decays, and other fundamental queries that have dominated neutrino physics up to now [1].

Two distinct classes of anomalies have been so far reported, although not at an entirely conclusive level. The apparent $3\sigma$ disappearance of the $\bar{\nu}_e$ low energy neutrinos events from nuclear reactor experiments [2] and from the signal from Mega-Curie calibration sources in GALLEX and Sage experiments ($R = 0.86 \pm 0.05 \sim 2.7\sigma$ away from $R = 1$ expectation) [3] could originate from $\nu_\mu$ ($\bar{\nu}_e$) conversion into “invisible” sterile components, leading to the observation of oscillatory, distance dependent, disappearance rates.

The second anomaly refers to the evidence of an electron excess originated by initial $\nu_\mu$ beam from particle accelerators as observed in LSND ($3.8\sigma$) [4] and MiniBooNe ($3\sigma$) [5] experiments where some distance dependent $\nu_\mu \rightarrow \nu_e$ oscillations may be observed as a $\nu_e$ excess, especially in the antineutrino channel.

Moreover the possible existence of additional neutrino states may be also hinted – or at least not excluded – by cosmological data [6].

All the recalled “anomalies”, having accumulated an impressive number of standard deviations, may indeed hint at an unified scheme in which the values of $\Delta m^2_{\text{new}}$ may have a common origin, the different values of $\sin^2 2\theta_{\text{new}}$ for different channels reflecting the structure of $U_{(4,k)}$ matrix (or even with an higher number of neutrinos) with $k = \mu$ and $e$. This long standing series of experimental results hinting at the hypothesis of sterile neutrinos deserve a major effort to definitely establish the existence of additional neutrino states and clarify the underlying physics.

The proposed experiment at a new CERN SPS neutrino beam may be in a unique position to be able to unambiguously investigate with high sensitivity such an oscillatory scenario by the simultaneous measurement of the neutrino fluence at two different positions. For these purposes two large mass LAr-TPC’s, ICARUS T600 presently taking data at LNGS Laboratory and a new additional smaller T150 LAr-TPC detector will be settled with two magnetic spectrometers placed downstream of the two LAr-TPC’s to greatly complement the physics capabilities. Only in this way the new values of $\Delta m^2$ and of $\sin^2 2\theta$ can be separately identified. All other experimental non accelerator programs presently under investigation will not focus with an equal sensitivity on the direct parameters of the oscillation phenomenon.

2. ICARUS-T600: a powerful detector for neutrino physics

ICARUS-T600 detector, the largest LAr-TPC ever built [7], consists of two identical adjacent cryostats, filled with 770 t of ultra-pure liquid Argon corresponding to 470 t of imaging mass, each one housing 2 TPCs separated by a central common cathode, with 1.5 m drift length. Ionization electrons, abundantly produced by charged particles along their path are drifted by an uniform electric field ($E_D = 500$ V/cm) towards the TPC anode made of 3 parallel wire planes (3 mm pitch), facing the drift volume, oriented at $0^\circ$, $\pm 60^\circ$ with respect to the horizontal direction. The relative time of each ionization signal, combined with the electron drift velocity information ($v_D \sim 1.6$ mm/$\mu$s), provides the position of the track along the drift coordinate. Globally a remarkable 1 mm$^3$ spatial resolution has been measured. Absolute event time is determined exploiting the scintillation light prompt signal from arrays of photo-multipliers installed in LAr behind the wire planes.

ICARUS is a very suited detector for rare event studies, such as neutrino oscillation physics from CNGS beam and atmospheric neutrinos, and search for nucleon decay, since it combines large mass with good spatial granularity and calorimetric accuracy. The calorimetric response ($\langle \sigma_E/E \approx 11\% / \sqrt{E(\text{GeV})} \rangle$) allows a precise measurement of energy for contained events, while the momentum of non-contained particles (mainly muons) can be measured within $\sim 20\%$ resolution by multiple scattering from the deflection angle along the track. At higher energies the estimated resolution for hadronic showers is $\sigma_E/E = 0.30/\sqrt{E(\text{GeV})}$. The measured $dE/dx$
energy loss allows a clear pion to proton separation as obtained from the last part of the residual range. Moreover, \(\pi^0 \rightarrow 2\gamma\) are recognized by detecting \(\gamma\) conversion, measuring \(dE/dx\) and the \(2\gamma\) invariant mass (radiation length in LAr is \(X_0 = 14\) cm). As a result a very efficient \(e/\pi^0\) discrimination allows to reject the neutrino NC interactions by a factor \(\approx 10^3\) in the \(\nu_e\) appearance search, while keeping more than 90% of \(\nu_e\) CC events. A typical \(\nu_\mu\) CC event, fully reconstructed, is shown in Fig. 1.

Figure 1. A reconstructed \(\nu_\mu\) CC event in ICARUS. The neutrino produces a long muon (1), a charged pion (3) and an e.m. shower (2). At a closer look the shower can be identified as generated by a \(\pi^0\); two \(e^-e^+\) pairs can be resolved, especially in Induction2 view, and the measured invariant mass of the \(2\gamma\) system \(M^*_\gamma\gamma = 125 \pm 15\) MeV is consistent with the \(\pi^0\) mass. The momentum of the escaping muon measured by multiple scattering, is \(10.5 \pm 1.8\) GeV. In the secondary vertex, the \(\pi\) interaction produces several hadrons; a \(K \rightarrow \mu \rightarrow e\) is clearly recognized (5). The 250 MeV/c total \(p_T\) is consistent with the nucleon Fermi momentum.

The highly efficient data taking at LNGS Laboratory with CNGS beam neutrino beam allowed to record an event statistics of \(8.6 \cdot 10^{19}\) pot during 2010-2012 runs, triggering on the photomultiplier signals in coincidence with the early-warning signal sent from CERN at each proton extraction. Based on 1091 neutrino events, \(\sim 50\%\) of the ICARUS data collected in 2010-2011, the ICARUS Collaboration reported an early result on the search for a \(\nu_\mu \rightarrow \nu_e\) signal due to the LSND anomaly in the CNGS beam at an average energy of about 20 GeV, after a flight path of \(\sim 730\) km [8]. The LSND anomaly would manifest as an excess of \(\nu_e\) events, characterized by a fast energy oscillation averaging approximately to \(\sin^2(1.27\Delta m^2_{\text{new}}L/E_\nu) \approx 1/2\) with probability \(P_{\nu_\mu \rightarrow \nu_e} = 1/2\sin^2(2\theta_{\text{new}})\). Two clear \(\nu_e\) events have been found, compared with the expectation of \(3.7 \pm 0.6\) events from conventional sources. The result, compatible with the absence of a LSND anomaly sets a 90% and 99% confidence level limits for the oscillation probabilities \(\langle P_{\nu_\mu \rightarrow \nu_\mu} \rangle \leq 5.4 \times 10^{-3}\) and \(\langle P_{\nu_\mu \rightarrow \nu_e} \rangle \leq 1.1 \times 10^{-2}\) respectively (Fig. 2). Moreover this result strongly limits the window of open options for the LSND anomaly to a narrow region around \((\Delta m^2, \sin^2(2\theta)) = (0.5\ eV^2, 0.005)\), where a 90 % overall agreement between the present ICARUS measurement, the published limits of KARMEN and the published positive signals of LSND and MiniBooNE Collaborations, is found.
Figure 2. Regions in the $(\Delta m^2, \tan^2 (\theta))$ plane excluded by the ICARUS experiment compared with the published results. While for $\Delta m^2 \gg 1eV^2$ there is a disagreement for $\nu_\mu \rightarrow \nu_e$ between the allowed regions from the published experiments, for $\Delta m^2 \leq 1eV^2$ the ICARUS result now allows to define a much smaller, narrower allowed region centered around $(\Delta m^2, \sin^2 (2\theta)) = (0.5eV^2, 0.005)$ in which there is a 90% C.L. overall agreement.

3. The ICARUS-NESSiE experiment

In order to definitely clarify the experimental hints for the presence of sterile neutrinos, exploring in particular the surviving LSND/MiniBooNe $(\sin^2 2\theta, \Delta m^2)_{\text{new}}$ parameter region as indicated by ICARUS measurement, the proposed experiment will operate at CERN SPS at much shorter distances with neutrino energies lower than in the CNGS beam line.

The experimental set-up [9] is based on two identical LAr-TPC’s [10] complemented by magnetized spectrometers [11] detecting electron and muon neutrino events at Far and Near positions, 1600 m and 330 m respectively from the proton target in the CERN North Area (Figure 3). A new intense 100 GeV/c fast extracted proton beam, $4.5 \times 10^{19}$ pot/year, will produce a high intensity on-axis $\nu$ beam with an energy spectrum centered around $E_\nu \sim 2$ GeV (Figure 4).

More precisely the proposed experiment will provide:

- L/E oscillation path-lengths appropriate to match to the $\Delta m^2$ window for the expected anomalies;
- “imaging” detectors capable to identify unambiguously all reaction channels with a “Gargamelle class” LAr-TPC;
- magnetic spectrometers able to determine muon charge with few % mis-identification and momentum in a broad range;
- a clean measure of interchangeable $\nu$ and anti-$\nu$ focused beams;
- very high event rates ($> 10^6 \nu_\mu$ and $\simeq 10^4 \nu_e$) due to large detector masses, allowing to record relevant effects at the % level;
- initial $\nu_e$ and $\nu_\mu$ components cleanly identified.
The project will exploit the ICARUS T600 detector, now running in the LNGS underground laboratory, moved at the CERN Far position. An additional 1/4 of the T600 detector (T150), a LAr-TPC identical to one module of T600 but a factor 2 reduced length, will be constructed and located in the Near position. Two spectrometers will be placed downstream of the two LAr-TPC detectors to greatly complement the physics capabilities. Spectrometers will exploit a classical dipole magnetic field with iron slabs, and a new concept air-magnet, to perform charge identification and muon momentum measurements in a wide energy range from sub-GeV to several GeV, over a transverse area larger than 50 m$^2$ with about 2500 m$^2$ of RPC precision trackers.

**Figure 3.** The new SPS North Area neutrino beam layout. Main parameters are: primary beam: 100 GeV; fast extraction from SPS; target station next to TCC2, ∼11 m underground; decay pipe: 100 m, 3 m diameter; beam dump: 15 m of Fe with graphite core, followed by muon stations; neutrino beam angle: pointing upwards at ∼3 m in the far detector ∼5 mrad slope.

At the two positions the energy spectra of the $\nu_e$ beam component are expected to be coincident but for second order effects which can be reliably reproduced (Figure 4). In absence of oscillations, since all cross sections and experimental biases cancel out, the observed event distributions at the near and far detectors must be the same. Any difference can be ascribed to the possible existence of $\nu$-oscillations due to additional neutrinos with new mixing angles $\sin^22\theta_{ij}$ and mass differences $\Delta m^2_{ij}$ larger than those measured in the standard three neutrino family scheme.

The superior quality of the LAr imaging TPC, now widely experimentally demonstrated, and in particular its unique electron - $\pi^0$ discrimination, allows full rejection of backgrounds with a lossless $\nu_e$ detection capability. The determination of the muon charge with the spectrometers allows the full separation of $\nu_\mu$ from $\nu_e$ and an improved control of systematics from muon mis-identification.

Compared to the ICARUS measurement at the CNGS beam, the much shorter distances and lower neutrino energies will allow to increase the event rate, reduce the overall particle multiplicity of the neutrino events, and enlarge the angular range of the secondaries substantially improving the $\nu_e$ selection efficiency. A 90% electron detection efficiency including the event energy reconstruction is expected inside a fiducial volume defined by $4X_0$ and $0.7X_0$ longitudinal and side cuts respectively. This will ensure a 90% $\nu_e$ detection efficiency while keeping the mis-interpretation probability for $\pi^0$ from NC interaction at the 0.1% level inside the fiducial volume.
All the previously described anomalies will be explored with both neutrino and anti-neutrino focused beams. The separation of $\nu_\mu$ from $\bar{\nu}_\mu$ will allow to exploit the interplay of the different possible oscillation scenarios, as well as the interplay between disappearance and appearance of different neutrino states and flavors. Moreover the NC/CC ratio will provide a sterile neutrino oscillation signal by itself and it will beautifully complement the normalization and the systematics studies. This experiment will offer remarkable discovery potentialities, collecting a very large unbiased event statistics (order of millions) both in the neutrino and antineutrino channels, largely adequate to definitely settle the origin of the $\nu$-related anomalies.

The experiment is sensitive to $\sin^22\theta$ down to $3 \times 10^{-4}$ (for $|\Delta m^2| > 1.5eV^2$) and $|\Delta m^2|$ down to 0.01eV$^2$ (for $\sin^22\theta = 1$) at 90% C.L. for the $\nu_\mu \rightarrow \nu_e$ transition with one year exposure ($4.5 \times 10^{19}$ pot). The parameter space region allowed by the LSND experiment is fully covered, except for the highest $\Delta m^2$ region (Figure 6 left). The sensitivity has been computed according to the above described particle identification efficiency and assuming a 3% systematic uncertainty in predicting the Far to Near $\nu_e$ ratio. A further control of the overall systematics

**Figure 4.** Muon (left) and electron (right) neutrino CC interaction spectra, at near and far positions.

**Figure 5.** ICARUS LAr-TPC and NESSiE spectrometer at far site.
will be provided by the LAr and spectrometer combined measurement of CC spectra in the near site and over the full energy range. In anti-neutrino focusing, twice as much exposure \((0.9 \times 10^{20} \text{ pot})\) allows to cover both the LSND region and the new MiniBooNE results (Figure 6 right). Both favored MiniBooNE parameter sets, corresponding to two different energy regions in the MiniBooNE antineutrino analysis, fall well within the reach of this proposal. In Figure 7 left the sensitivity for \(\nu_e\) disappearance search in the \(\sin^2 (2\theta), \Delta m^2\) plane is shown for one year data taking. The oscillation parameter region related to the anomalies from the combination of the published reactor neutrino experiments, GALLEX and SAGE calibration sources experiments is completely explored. The \(\nu_\mu\) disappearance signal is well studied by the spectrometers, with a very large statistics, and disentangling of \(\nu_\mu\) and \(\bar{\nu}_e\) interplay. Figure 7 right shows the sensitivity plot (at 90% C.L.) for two years negative-focusing plus one year positive-focusing. SPSC-P347 A large extension of the present limits for \(\nu_\mu\) by CDHS and the recent SciBooNE+MiniBooNE will be achievable in \(\sin^2 (2\theta), \Delta m^2\).

The ICARUS-T600 shutdown at LNGS will start in the middle 2013 with the LAr emptying phase, followed by the dismantling of the detector which components will be transported to CERN to be reassembled in a dedicated hall before being moved to the Far site in the North Area. The T150 detector of the Near site will be realized closely following the T600 specifications. Some refurbishing of the photomultiplier system, DAQ electronics and trigger system will be realized with the aim of increasing the detector performance. The different components of the NESSIE spectrometers are expected to be separately realized and then installed in the Far and Near pits downstream the LAr-TPCs. According to the CERN plan the new short baseline neutrino facility at SPS North Area is expected to be operational early 2016 with the neutrino beam commissioning followed by the data taking.

Figure 6. Expected muon to electron neutrino oscillation sensitivity for the proposed experiment exposed at the CERN-SPS neutrino beam (left) and anti-neutrino (right) for \(4.5 \times 10^{19}\) pot (1 year) and \(9.0 \times 10^{19}\) pot (2 years), respectively.

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Figure 7. Sensitivity for $\nu_e$ disappearance for 1 year data taking (left) and for $\nu_\mu$ disappearance considering 3 years of the CERN-SPS beam (2 years in anti-neutrino and 1 year in neutrino mode) from CC events fully reconstructed in NESSiE+LAr.

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