

A proposed search for sterile neutrinos with the ICARUS detector at the CERN-PS

Francesco Pietropaolo

Istituto Nazionale di Fisica Nucleare Sezione di Padova, via Marzolo 8, 35131 Padova, Italy

E-mail: Francesco.Pietropaolo@pd.infn.it

Abstract. An experiment to search for sterile neutrinos beyond the Standard Model with the CERN-PS 19.2 GeV beam and the technology of imaging in ultra-pure cryogenic liquid Argon is proposed. The superior quality of the LAr-TPC, now widely demonstrated experimentally and in particular its unique e/π^0 discrimination allows a full rejection of backgrounds, offers the possibility to explore the neutrino conversion into sterile components as recently suggested by the analysis of different observed neutrino anomalies.

The experiment is based on two identical LAr-TPC detectors observing the electron-neutrino signal in the Near and Far positions, the first of about 150 tons at 127 m from the proton target, the second one of about 600 tons placed 850 m away. This project will exploit the largest LAr-TPC ever built, ICARUS T600 now running underground at LNGS exposed to CNGS neutrino beam, by moving it from Gran Sasso to the CERN Far position. An additional 150 t detector will be constructed in the Near position. The intrinsic ν_e beam spectra are expected practically identical in the two positions; in addition all cross-sections and experimental biases cancel out in the comparison of the two detector signals allowing to perform a sensitive search for neutrino oscillations in the presence of sterile neutrinos.

1. Introduction

Neutrino oscillations have established a coherent picture for a large number of experiments consistent with the mixing of three physical neutrino ν_e , ν_μ and ν_τ with three mass eigenstates. In particular the mass differences turn out to be relatively small, $|\Delta m_{23}^2| \sim 2.4 \cdot 10^{-3} \text{ eV}^2$, and $|\Delta m_{23}^2| \sim 8 \cdot 10^{-5} \text{ eV}^2$ [1]. There are however a number of anomalies which, if experimentally confirmed, could hint to the presence of an additional, large squared mass difference in the framework of a four-neutrinos mixing. If more than the two oscillation signals were to be observed, additional Physics beyond the Standard Model in the neutrino sector will be necessary. The possible presence of sterile neutrinos was originally proposed by B. Pontecorvo [2], and has been discussed since a very long time, but so far without conclusive evidence. Two distinct classes of phenomena have been analyzed, namely a) the apparent reduction in the $\bar{\nu}_e$ low energy neutrinos from nuclear reactors [3] and from the signal from Mega-Curie sources in the Gallium experiments [4, 5] originally designed to detect solar neutrino deficit, and b) evidence for a $\bar{\nu}_e$ excess signal of in interactions coming from neutrinos from particle accelerators [6, 7, 8]. These experiments may all point out the possible existence of the fourth non standard neutrino state driving neutrino oscillations at a small distance, with typically $|\Delta m_{new}^2| \geq 1 \text{ eV}^2$ and relatively large mixing angle $\sin^2 \theta_{new} \simeq 0.1$ [9].

The class a) of phenomena hint at a significant fast disappearance rate in the initial $\bar{\nu}_e$ production

and the class b) predicts an anomalous $\nu_\mu \rightarrow \nu_e$ oscillation with similar, large $|\Delta m_{new}^2|$ values, much greater than the ones of the current three neutrino mixing model. More recently the existence of a fourth neutrino state may be also hinted or at least not excluded by cosmological data mainly coming from WMAP and other observations [10]. It is only because the masses of known neutrino species are so small, that their contribution to the Dark Matter of the Universe can be excluded. The situation could be altered by the additional presence of sterile neutrinos, provided that they are massive enough. Therefore, the presence of massive sterile neutrinos, will also contribute to clarify the Dark Matter problem.

2. A more direct approach to neutrino oscillations

In order to definitely clarify the existence of a fourth non standard neutrino state in the above mentioned parameter range, a new experiment at CERN PS beam is proposed (Fig. 1). It's based on two strictly identical LAr-TPC detectors observing the electron-neutrino signal in the Near and Far positions, the first one of about 150 tons at 127 m from the proton target, the second one of about 600 tons placed 850 m away [11]. In this way, all cross sections and experimental biases cancel out. In absence of oscillations the two experimentally observed event distributions must be identical, the background electron neutrino radial and energy distributions being extremely similar in the two positions. Any difference in the event distributions between the two detectors should be attributed to the possible existence of oscillations, and both the mixing angle $\sin^2 \theta_{new}$ and the mass difference $|\Delta m_{new}^2|$ can be separately measured.

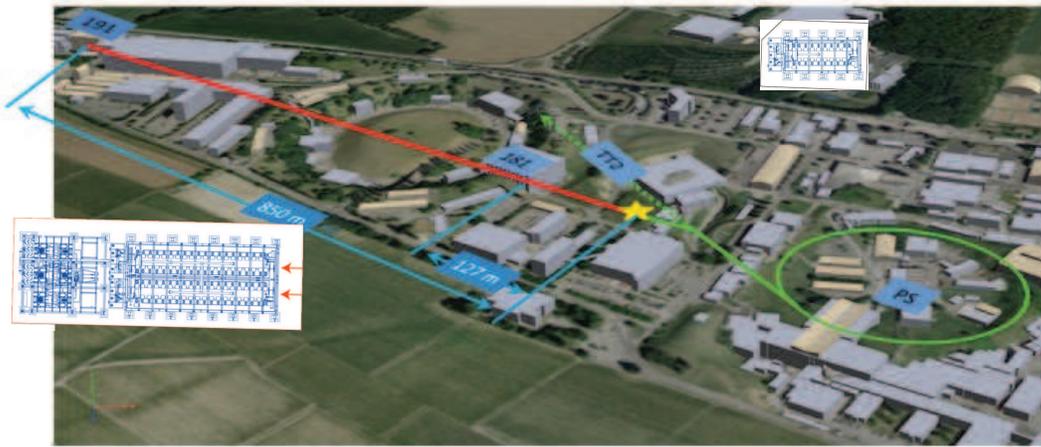


Figure 1. Experimental set-up proposed at the CERN PS neutrino beam with two LAr-TPC detectors.

The CERN-PS ν_e spectra, expected at the level of 0.5 % of ν_μ , are very closely identical in the Near and Far positions. The physical reason of this effect has to be identified in the fact that while the ν_μ spectrum is dominated by the two body $\pi \rightarrow \mu\nu_\mu$ decays, where the neutrino directions are narrowly distributed along the axis, the ν_e contamination is dominated by the three body decays of K and μ where there is a much wider neutrino angular spread. The similarity is further enhanced by the fact that the Near and Far detectors will be designed with identical internal configurations. In absence of oscillations, after some beam related small spatial corrections, the two energy spectra should be a precise copy of each other, independently of the specific experimental event signatures. Therefore, an exact observed proportionality between the two ν_e spectra, would imply directly the absence of neutrino oscillations over the measured interval of L/E.

A key issue of the proposed experiment will be the LAr-TPC detection capability of all the genuine ν_e events, allowing the reconstruction of the totality of neutrino events without restricting to the QE interactions, and the very high level of rejection of the associated background events. The LAr-TPC technique appears very well suited for this purpose, because of its excellent imaging and calorimetric capabilities, which allow very efficient electron - π^0 separation, together with unambiguous electron identification.

The ICARUS T600 detector [12], presently in operation at LNGS, consists of a large cryostat, with a size of about 500 t of active mass, split into two identical, adjacent half-modules with internal dimensions $3.6 \times 3.9 \times 19.6 \text{ m}^3$ and filled with ultra-pure liquid Argon. Each half-module houses two TPCs separated by a common cathode, with a drift length of 1.5 m.

Ionization electrons, produced by charged particles along their path are drifted under uniform electric field ($E_D = 500 \text{ V/cm}$) towards the TPC anode made of three parallel wire planes, facing the drift volume. A total of ~ 54000 wires are deployed, with a 3 mm pitch, oriented on each plane at a different angle ($0^\circ, +60^\circ, -60^\circ$) with respect to the horizontal direction. The first two planes provide signals in non-destructive way by appropriate voltage biasing; the ionization charge is collected and measured on the last collection plane. The relative time of each ionization signal, combined with the electron drift velocity information ($v_D \sim 1.6 \text{ mm}/\mu\text{s}$), provides the position of the track along the drift coordinate. Combining the wire coordinate on each plane at a given drift time, a three-dimensional image of the ionizing event can be reconstructed with a remarkable resolution of about 1 mm^3 (Fig. 2). The absolute time of the ionizing event is provided by the prompt VUV (128 nm) scintillation light emitted in LAr (~ 5000 photons/mm for minimum ionizing particles) and measured through arrays of Photo Multiplier Tubes (PMTs), installed in LAr behind the wire planes.

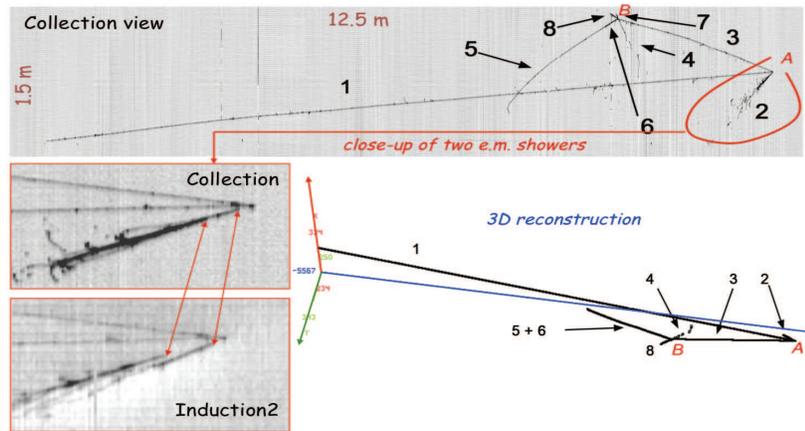


Figure 2. A fully reconstructed CNGS ν_μ -CC event. Primary vertex (A): very long leading muon (1), e.m. cascade reconstructed as a neutral pion (2), charged pion (3). Secondary vertex (B): the longest track (5) is a muon coming from stopping K (6). The muon decay is also identified. All particle momenta are measured for a complete kinematic reconstruction of the event.

According to the present proposal the ICARUS T600 detector will be moved from the LNGS laboratory into the Far position of the CERN-PS neutrino beam (Hall B-191) after the completion of the presently running CNGS2 experiment. An additional LAr-TPC using the same design of the T600 will be constructed for the Near site.

3. The CERN PS neutrino beam

The proposed experiment will exploit the CERN-PS neutrino beam-line, originally used by the BEBC-PS180 Collaboration [13] and successively re-considered by the I216/P311 Collaboration [14]. The neutrino beam will be a low energy ν_μ beam, centered at about 1 GeV, produced by 19.2 GeV protons, of intensity 1.25×10^{20} pot/yr. The CERN-PS can deliver routinely on a refurbished TT7 transfer line 3×10^{13} protons per cycle at 20 GeV/c. More than 1.25×10^{20} pot/year can be collected by the experiment in one year of data taking for an optimal machine time availability. The proton transfer line, the new target and the horn focusing system must be reconstructed. Some preliminary studies about the realization of the TT7 PS neutrino beam line [15] have been already completed at CERN.

As reference case the neutrino beam set-up used by the BEBC-PS180 experiment has been chosen. An optimized design of new and possibly improved beam optics will be the subject of further studies. The 19.2 GeV/c proton beam was extracted from the PS and impinged on a 80 cm long, 6 mm diameter beryllium target. This was followed by a pulsed magnetic horn designed to focus positive particles of momentum around 2 GeV/c into a decay tunnel of about 50 m length. Most of the muons and remaining hadrons were then absorbed by a 4 m thick iron shield and 65 m of earth.

The total accumulated number of accelerated protons from the PS in 180 days of operation is now about $\sim 3.6 \times 10^{20}$ pot/year. With one third of the protons dedicated to the neutrino beam line, the expected intensity will be about 1.25×10^{20} pot/year. Such a target value has also been already assumed for the previously proposed I216/P311 experiment. The positively and negatively focused CERN-PS neutrino spectra, originally used by the BEBC-PS180 Collaboration, are shown in Fig. 3 for the most relevant Far position at 850 m from the PS target.

Event rates in the CERN-PS beam for the un-oscillated spectra and a few parameter values of $\nu_\mu \rightarrow \nu_e$ oscillations are reported in Table 1.

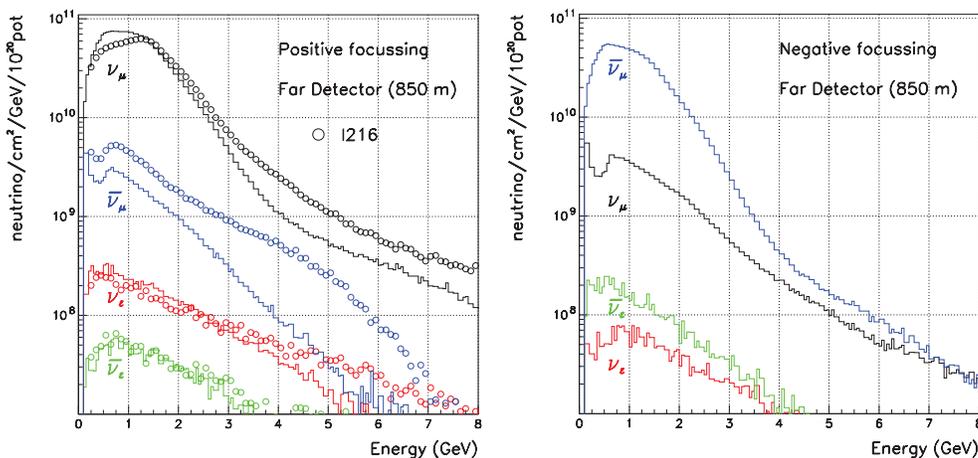


Figure 3. Expected composition of neutrino beam at Far detector position for both positive (left) and negative (right) focusing.

4. The Near and Far detectors

The two closely similar LAr-TPCs (Fig. 4) will be located respectively at 850 m and 127 from the PS target in the existing locations B-191 and B-181 respectively. The size of the buildings

Table 1. Event rates for the Far and Near detectors given for 2.5×10^{20} pot for $E_\nu < 8$ GeV. Neutrino fluxes are taken from [14]. The oscillated signals are clustered below 3 GeV of visible energy.

	Neutrino		Antineutrino	
	focus	focus	focus	focus
	FAR	NEAR	FAR	NEAR
Fiducial mass	500 t	150 t	500 t	150 t
Distance from target	850 m	127 m	850 m	127 m
ν_μ interactions	1.2×10^6	18×10^6	2.0×10^5	2.3×10^6
QE ν_μ interactions	4.5×10^5	66×10^5	87000	10^6
Intrinsic $\nu_e + \bar{\nu}_e$	9000	120000	2000	29000
Intrinsic $\nu_e + \bar{\nu}_e$ $E_\nu < 3$ GeV	3900	54000	880	13000
ν_e oscillation events:				
$\Delta m^2 = 2.0$ eV ² ; $\sin^2 2\theta = 0.002$	1194	1050	230	58
$\Delta m^2 = 0.4$ eV ² ; $\sin^2 2\theta = 0.02$	2083	2340	330	115
$\Delta m^2 = 0.064$ eV ² ; $\sin^2 2\theta = 0.96$	3350	1250	465	140
$\Delta m^2 = 4.42$ eV ² ; $\sin^2 2\theta = 0.0066$	2980	25050	490	3220

is perfectly adequate and no major civil engineering is needed. The T300 test in Pavia has demonstrated that the LAr TPC detectors can safely operate on surface.

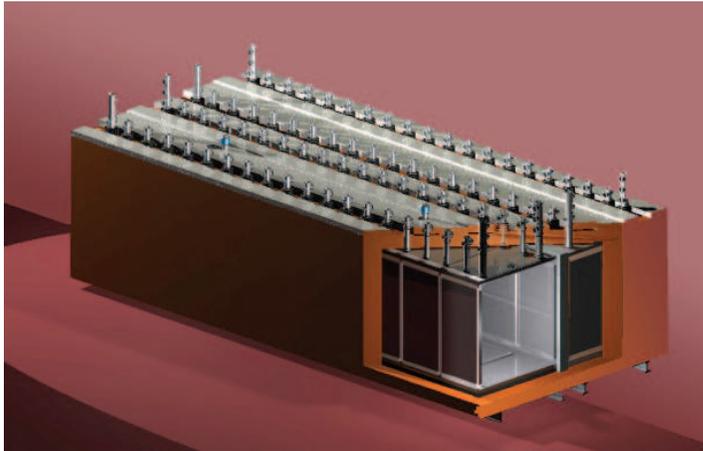


Figure 4. Schematics of T600 detector to be placed in Hall B-191.

While the Far detector is relying on the already existing T600, the Near detector must be constructed anew. In order to ensure the maximum similarity between the two detectors, required in order to ensure identical behaviors in absence of oscillations, the Near detector design will be identical to the T600 Far detector except the total mass which has been conservatively chosen to be of 150 t, namely a clone of a single T300 half-module with the length reduced by a factor 2 (about 12 m). This allows keeping untouched the inner detector layout for a total of 14200 wires. The already existing basement pit of hall B-181, previously used for neutrino oscillation experiments, fits perfectly the Near detector. Electronics and cryogenic equipments will be installed close to the detector pit. All the other component of the detector,

cryogenic elements, internal photomultipliers, front-end electronics and read-out system, DAQ and ancillary equipments, will be replicated accordingly to the downscaled detector mass. Some obvious improvements and some simplifications over the by now 10 years old T600 may be implemented with the new detector.

5. Signal selection and background rejection

In the LAr-TPC all reaction channels with electron production can be analyzed without the need to restrict the search to the quasi-elastic channel, which accounts for about one half of the events. Moreover, events due to neutral currents are also very well identified and can be rejected to a negligible level.

The energy resolution and detector granularity are largely adequate for the 1-3 GeV energy range relevant for the proposed experiment. The performance of the LAr-TPC has been extensively studied in the 2001 T300 technical run with cosmic rays and now at LNGS [12]. Electromagnetic energy resolution is $\sqrt{E}/E = 0.03 \times E(\text{GeV}) + 0.01$, in agreement with π^0 invariant mass measurements in the sub-GeV energy range. At higher energies the estimated resolution for hadronic showers is $\sqrt{E}/E = 0.30 \times E(\text{GeV})$. However the LAr-TPC detector allows to identify and measure, track by track, each hadron produced in 1 GeV neutrino interactions, through ionization and range, leading to a much better energy resolution. Indeed most of the particles, generated in the neutrino interactions, come to rest within the detector, including muons. Moreover the momentum of escaping muons will be extracted from the deflection angle along the track due to multiple scattering with a resolution which can be as good as 10 % depending mainly on track length. The measured dE/dx energy allows a clear pion to proton separation as obtained from the last part of the residual range. Moreover $\pi^0 \rightarrow 2\gamma$ events are easily recognized by detecting the two γ conversion, the measurement of dE/dx and of the two gammas invariant mass.

Quasi-elastic neutrino events in the 50 litre ICARUS LAr-TPC exposed to the CERN-WANF beam in coincidence with the NOMAD experiment [16] have been readily reconstructed in 3D with particle identification, momentum balance and π^0 rejection in a energy range which is relevant for the proposed experiment [17].

Monte Carlo simulations show that the energy reconstruction of electron neutrino interaction events at around 1.5 GeV is not affecting the signal/background ratio if a minimal cut of 50 cm in the longitudinal direction and a 10 cm cut on the sides of the sensitive volume are performed, corresponding to a fiducial volume of about 90 % of the active one. Electron identification is also ensured under these geometrical cuts. Due to the directionality of the neutrino beam, the probability that an electron escapes from the instrumented volume before initiating a shower is extremely small: only 2 % of the electrons travel through a LAr-TPC thickness smaller than $3X_0$ and 0.3 % travel less than $1X_0$ in the instrumented volume. With the previously described fiducial volume cuts, the expected average neutrino energy resolution is about 14%.

In view of the excellent imaging capability of LAr-TPC, π_0 from ν_μ NC events cannot be misidentified as electrons. In fact π^0 are almost fully separated by electrons by requiring both photon converting at least 2 cm from the ν_μ vertex, a π^0 mass reconstructed within 10 % accuracy and on the basis of dE/dX signal analysis. This method provides 90 % electron neutrino identification efficiency with a 0.1% π^0 mis-interpretation probability within the fiducial volume.

6. Sensitivity to ν_e and ν_μ disappearance signals

The intensity of the ν_e signal, much smaller than the one of the dominant ν_μ 's (about 0.5%), is largely sufficient to collect an adequate number of events.

In Figure 5 the 90% confidence levels for the actual oscillation mechanism in the $\sin^2(2\theta_{new} - \Delta m_{new}^2)$ plane are shown for the presently proposed experiment with an integrated intensity

corresponding to (a) 2.5×10^{20} pot (protons on target) for the original beam intensity of about 30 kW of the previous CERN/PS experiments, (b) to 7.5×10^{20} pot for the newly planned 90 kW neutrino beam at CERN/PS and (c) a 270 kW curve. They are also compared with the “anomalies” from the combination of the published reactor neutrino experiments, GALLEX and Sage calibration sources experiments. The disappearance signal in the same $\sin^2(2\theta_{new}) - \Delta m_{new}^2$ range may also be studied independently with the dominant ν_μ and $\bar{\nu}_\mu$.

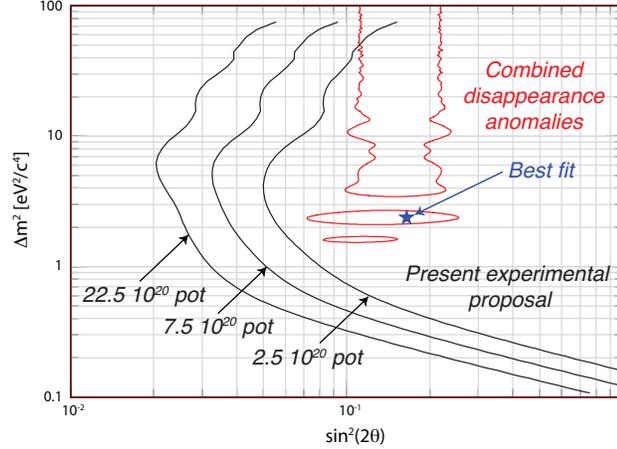


Figure 5. Sensitivities (90% C.L.) in the $(\sin^2(2\theta), |\Delta m^2|)$ region for 30, 90 and 270 kW beam power.

The $\nu_\mu \rightarrow \nu_{new}$ process has a different and independent signature than the one due to explicit $\nu_\mu \rightarrow \nu_e$ oscillations related to LSND/MiniBooNE anomalies. However the ν_μ and $\bar{\nu}_\mu$ spectral shapes, hereby primarily due to pion decays, are significantly different in the “Near” and “Far” positions. In the energy range below 3 GeV, where the effect is expected, the relative differences amount to about 30% and they may be predicted to about 1%, which is larger than what expected from the huge available statistics but quite significant for a test. The presence of the two alternate phenomena presumably with different values of $\sin^2(2\theta_{new})$, if confirmed, will hint at the presence of an appropriate fourth neutrino coupling $U_{4,k}$ with $k = \mu$ and e.

7. Sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillations and other related physics

A sensitivity of $\sin^2 2\theta < 3 \times 10^{-4}$ (for $\Delta m^2 < 2 \text{ eV}^2$) and $\Delta m^2 < 0.02 \text{ eV}^2$ (for $\sin^2 2\theta = 1$) at 90 % C.L. is expected with a two year exposure at the CERN-PS ν_μ beam (Fig. 6). 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 “Far” to “Near” ratio prediction. Similarly in anti-neutrino focusing, twice as much exposure (5.0×10^{20} pot) allows to fully cover the LSND parameter region. Very different and clearly distinguishable patterns are indeed possible depending on the actual values in the $(\Delta m^2 - \sin^2 2\theta)$ plane.

As an additional bonus, the large statistics of excellent quality data will also profit to the knowledge of neutrino cross-sections. Precise measurements in the 0-5 GeV energy range are required by present and future neutrino oscillation experiments. Existing data on charged current quasi-elastic, deep inelastic, and single pion production are affected by a large uncertainty, especially at the lower energies [18]. Owing to the very low detection threshold of the Liquid Argon technique, the exposure at the CERN-PS neutrino beams could significantly improve the neutrino cross-section knowledge. Approximately 1.2×10^6 and 1.8×10^7 charged

current events per 2.5×10^{20} pot will be recorded from the CERN-PS in the “Far” and “Near” detectors respectively, with a neutrino spectrum peaked at around 1 GeV. Neutral current cross-sections are also measured, with approximately 4.4×10^5 and 6.0×10^6 events in the “Far” and “Near” detectors respectively.

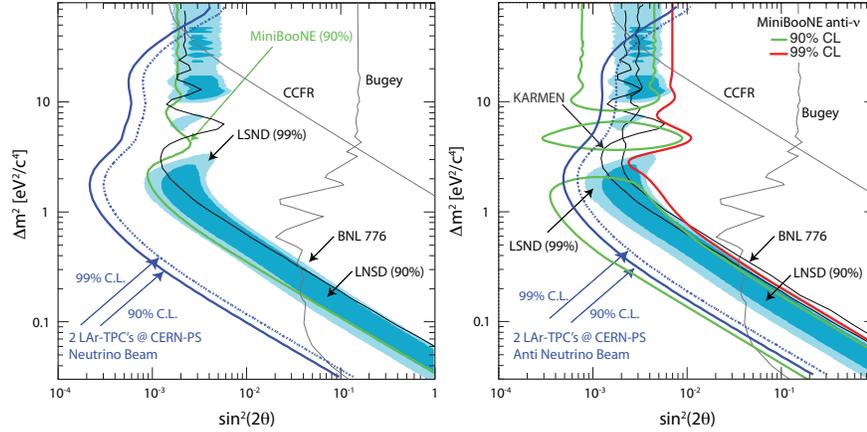


Figure 6. Expected $\nu_\mu \rightarrow \nu_e$ 90% C.L. sensitivity for the proposed experiment for both neutrino (left) and antineutrino (right) beams. MiniBooNe results are for 6.6×10^{20} pot (neutrino mode) and 8.58×10^{20} pot (antineutrino mode).

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