Experimental search for the LSND anomaly with the ICARUS LAr-TPC detector in the CNGS beam

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Abstract. We report an early result from ICARUS (CNGS2), the large mass LAr-TPC, a Gargamelle class imaging detector of novel design. A search of a $\nu_\mu \to \nu_e$ signal due to a LSND anomaly at the Gran Sasso Laboratory, located at a distance of $L = 730$ km from CERN is hereby presented. Such an anomaly, in which an electron is produced by neutrinos in the energy interval $0 \leq E_\nu \leq 30$ GeV, will be characterized by a fast energy oscillation averaging closely to $\sin^2(1.27\Delta m_{\text{new}}^2L/E_\nu) \approx 1/2$ and therefore approximately with probability $< P_{\nu_\mu \to \nu_e} > \approx \frac{1}{2}\sin^2(2\theta_{\text{new}})$. The presence of such a signal will be compared with the small but significant backgrounds due to other and more conventional neutrino origins. Within the range of our observations, our result is compatible with the absence of a LSND anomaly. At 90% and 99% confidence levels the limits on the oscillation probabilities are $< P_{\nu_\mu \to \nu_e} > \leq 5.4 \times 10^{-3}$ and $< P_{\nu_\mu \to \nu_e} > \leq 1.1 \times 10^{-2}$ respectively. The present result strongly limits the window of opened options for the LSND anomaly, reducing the remaining effect to a narrow region centered around $(\Delta m^2, sin^2(2\theta)) = (0.5 \text{ eV}^2, 0.05)$ where there is an over-all agreement (at 90 % CL) between the present ICARUS limit, the published limits of KARMEN and the published positive signals of LSND and MiniBooNE collaborations.

1. Introduction
Neutrino oscillations have so far established a beautiful picture, consistent with the mixing of three physical neutrinos $\nu_e$, $\nu_\mu$ and $\nu_\tau$ and mass eigenstates $\nu_1$, $\nu_2$ and $\nu_3$. But it is possible that neutrinos are something very different than just a neutral counterpart of charged leptons, leaving room for additional neutrinos which do not see fully the ordinary electro-weak interactions but still introduce mixing oscillations with ordinary neutrinos. Indeed there are a number of ‘anomalies’ which, provided they are confirmed experimentally, might be due to the presence of larger squared mass differences related to additional neutrino states with presumably some kind of ‘sterile’ nature. Of course the astronomical importance of neutrinos in space is immense, so is their role in the cosmic evolution. A substantially heavier additional neutrino will be inevitably a source of the dark mass. The possible presence of oscillations into sterile neutrinos has been proposed by B. Pontecorvo [1]. The experimental search for an anomalous oscillation at short distances has been reported by the experiment LSND [2] at the Los Alamos 800 MeV proton accelerator where an anomalous excess of electrons neutrinos in a muon neutrino beam with $< E_\nu > \approx 30$ MeV and $L \approx 30 m$ has been found. The LSND signal would imply an additional mass-squared difference largely in excess of the Standard Model values. The LSND $\nu_\mu \to \bar{\nu}_e$ signal $< P_{\nu_\mu \to \bar{\nu}_e} > = (2.64 \pm 0.67 \pm 0.45) \times 10^{-3}$ corresponds to an excess of $(87.9 \pm 22.4 \pm 6.0)$ events and it gives a 3.8 $\sigma$ effect at $L/E_\nu$ distances of about 0.5 - 1.0 m/MeV. The recent result from
MiniBooNe [3], performed with neutrinos from the 8 GeV FNAL-Booster, confirms a neutrino oscillation signal in the similar $L/E_\nu$ range at 3.8 $\sigma$, present in both the neutrino and antineutrino channels. Using the simple formula $< P_{\nu_\mu \rightarrow \nu_e}> = \sin^2(2\theta_{\text{new}})\sin^2(1.27\Delta m_{\text{new}}^2 L/E_\nu)$ one finds a very wide interval $\Delta m_{\text{new}}^2 \approx 0.01$ to $1.0$ $eV^2$, depending on the actual and unknown value of $\sin^2(2\theta_{\text{new}})$. In addition more recently an apparent disappearance signal of $\nu_e$ has been detected from (a) near-by nuclear reactors [4] and (b) from Mega-Curie k- capture calibration sources [5], originally developed for the Gallium experiments to detect solar $\nu_e$. This signal is occurring for $\Delta m_{\text{new}}^2$ largely in excess of the ones expected for ordinary neutrinos, maybe in the same order of magnitude of the LSND anomalies. All these anomalies which have accumulated an impressive number of standard deviations, may indeed represent an unified approach in which the values of $\Delta m_{\text{new}}^2$ may have a common origin, the different values of $\sin^2(2\theta_{\text{new}})$ for different channels reflecting the so far unknown structure of the $U_{(j,k)}$ matrix.

2. ICARUS search at CNGS

The CNGS facility [6] delivers a neutrino beam essentially composed of muon neutrinos peaked in the range $10 \leq E_\nu \leq 30$ GeV, with an expected contamination from anti-neutrinos at the level of 2% and an intrinsic electron component of slightly less than 1%. With the help of a novel development of a large mass Gargamelle class LAr-TPC imaging detector, the ICARUS experiment [7] is hereby searching visually the signature of $\nu_\mu \rightarrow \nu_e$ signal due to a LSND anomaly. The present experiment is at a much longer distance, $L = 730$ km, corresponding to a much larger $L/E_\nu \approx 36.5$ m/MeV for a typical neutrino energy $E_\nu \approx 20$ GeV. An hypothetical $\nu_\mu \rightarrow \nu_e$ LSND/MiniBooNE anomaly will therefore produce very fast oscillations as a function of the neutrino energy $E_\nu$, averaging closely to the value $\sin^2(1.27\Delta m_{\text{new}}^2 L/E_\nu) \approx 1/2$ and therefore approximately with a signal $< P_{\nu_\mu \rightarrow \nu_e}> \approx 1/2\sin^2(2\theta_{\text{new}})$. This signal will have to be compared with the small but significant backgrounds due to other and more conventional neutrino origins. LAr-TPC developed by the ICARUS group since about two decades [7] produces a completely uniform imaging with high accuracy of massive LAr volumes (up to about 700 ton). The new method observes the true image of the track with an accuracy of the order of few mm$^3$, thus extending to a liquid the TPC already described for a gas, originally proposed by G. Charpak et al. [8]. The passage from a gas to a liquid capable of several meters of free electron drift is not entirely trivial. A three orders of magnitude larger purity is necessary with equivalent Oxygen contents of the order of a few tens of ppt (parts per trillion). Ionization tracks

![Figure 1. Typical Montecarlo generated event from the ICARUS full simulation programme [9] with $E_e = 11$ GeV and $p_T = 1.0$ GeV/c.](image-url)
can be transported in ultra high purity LAr practically undistorted by a uniform electric field over macroscopic distances (meters). Imaging is provided by a suitable set of electrodes (wires) placed at the end of the drift path continuously sensing and recording the signals induced by the drifting electrons. Non-destructive read-out of ionization electrons by charge induction allows detecting the entire signal of electrons crossing subsequent wire planes with different orientations. This provides simultaneously several projective views of the same event, hence allowing space point reconstruction and precise calorimetric measurement. A set of photomultipliers (PMTs) is installed in order to detect the prompt scintillation light to trigger ionizing events. These are important differences with respect to the previously reported observations of LSND and MiniBooNE which were based on the more primitive observation of Cherenkov rings recorded with PMTs at the surface of the detector volume and mostly limited to quasi-elastic events and with a less easy discrimination between gamma rays and electrons.

3. Monte Carlo simulation

The radiation length of LAr is 14 cm (≈ 45 readout wires), corresponding to a $\gamma$-conversion length of 18 cm. The LAr-TPC detector allows identifying and measuring the ionization track by track and this allows to tag the presence of an initial electron emitted by the neutrino interaction and reject $\gamma$-converting pairs which are generally separated from the vertex and generate double minimum ionizing tracks. The detection of events has been widely simulated by a Montecarlo (MC) emulation [9]. The MC emulation is very sophisticated, reproducing in every detail the actual signals from the wire planes. Comparisons with the actual data samples are widely used to tune the reconstruction, check calibrations and optimize the identification and measurement algorithms. The agreement between MC and observed events has been excellent and it has been extensively used as a main guideline. In order to predict events caused by a LSND anomaly, a sample of MC $\nu_\tau$ CC events has been generated with the CNGS $\nu_\mu$ CC energy spectrum. A simulated event is shown in Figure 1. An electron signature has been defined by the following requirements: (a) fiducial volume for the vertex of the event, 5 cm distance from each side of the active volume and 50 cm distance from the exit plane; (b) the visible neutrino

![Figure 2](image-url). Experimental picture of the two observed events (a) and (b) with a clearly identified electron signature from a total sample of 1091 neutrino interactions. Event in (a) has a total energy of $11.5 \pm 1.8 \text{ GeV}$, and a transverse electron momentum of $1.8 \pm 0.4 \text{ GeV/c}$. Event in (b) has a visible energy of $17 \text{ GeV}$ and a transverse momentum of $1.3 \pm 0.18 \text{ GeV/c}$. In both events the single electron shower in the transverse plane is clearly opposite to the remaining of the event.
energy less than 40 GeV, in order to reduce the intrinsic beam induced background (c) the presence of a minimum ionizing relativistic electron track of sufficient length present from the vertex, subsequently building up into a shower; (d) clear separation from the presence of the other ionizing tracks near the vertex in at least one of the two transverse views, including short proton like recoils due to nuclear interactions. Out of an initial sample of 103 reconstructed events, 88 have a visible energy $E_{VIS} \leq 40$ GeV, of which 73 satisfy the fiducial volume cut. Visibility cuts reduce the identified electron tracks to 54 events corresponding to a selection efficiency $\eta = 54/73 = 0.74 \pm 0.05$. In a good approximation the value of $\eta$ is independent of the shape of the energy spectrum.

4. Data analysis and Results

The present ICARUS experimental sample is based on 168 neutrino events ($5.8 \times 10^{18}$ pot) collected in 2010 and 923 events collected in 2011 ($2.7 \times 10^{19}$ pot) out of the $4.4 \times 10^{19}$ collected in 2011), leading to a total of 1091 initial neutrino events. In this sample only events with visible energy $\leq 30$ GeV have been included with the relevant fiducial cuts, which bring the number of events from 1091 to 839. We expect 627 $\nu_\mu$ CC, of which 204 $\nu_{NC}$ and 3 $\nu_\tau$ CC (except $\tau \rightarrow e$) are to be added. The expected number of $\nu_e$ events due to conventional sources in the same energy range and fiducial volumes are as follows: (a) 3 events due to intrinsic $\nu_e$ beam associated contamination; (b) 1.3 $\nu_e$ events due to the presence of $\theta_{13}$ oscillations; (c) 0.7 $\nu_\tau$ CC with $\tau \rightarrow e$ giving a total of 5 expected events. The expected visible signal is of 3.7 events after the $\eta = 0.74 \pm 0.05$ reduction has been applied due to visibility cuts coming from the
Figure 4. Regions in the $(\Delta m^2, \tan^2(\theta))$ plane excluded by the ICARUS experiment compared with the published results (taken from http://www.pdg.org). While for $\Delta m^2 > 1 \text{ eV}^2$ there is already disagreement for $\nu_\mu \rightarrow \nu_e$ between the allowable regions from the published experiments, for $\Delta m^2 \leq 1 \text{ eV}^2$ the ICARUS result now allows to define a much smaller, narrower allowed region centered around $(\Delta m^2, \sin^2(2\theta)) = (0.5 \text{ eV}^2, 0.05)$ in which there is a 90% C.L. overall agreement.

Figure 2 (a) has a total energy of $11.5 \pm 2.0 \text{ GeV}$, and an electron of $10 \pm 1.8 \text{ GeV}$ taking into account a partially missing component of the e.m. shower. Figure 2 (b) has $17 \text{ GeV}$ of visible energy and an electron of $7.5 \pm 0.3 \text{ GeV}$. In both events the single electron shower in the transverse plane is clearly opposite to the remaining of the event, with transverse momenta for the electron of $1.8 \pm 0.4 \text{ GeV/c}$ and $1.3 \pm 0.18 \text{ GeV/c}$ respectively. Within the range of our observations, our result is compatible with the absence of a LSN anomaly. Following ref. [10], at statistical confidence levels of 90% and 99% and taking into account the detection efficiency, the limits due to the LSN anomaly are respectively 3.41 and 7.13 events. Given the observed sample of 627 $\nu_\mu$ CC events, the limits to the oscillation probability are $5.4 \times 10^{-3}$ and $1.1 \times 10^{-2}$ respectively. The exclusion area of the ICARUS experiment is shown in figure 3 in terms of the two-dimensional plot of $\sin^2(2\theta_{\text{new}})$ and $\Delta m^2_{\text{new}}$.

5. Conclusions
The present result strongly limits the window of options from the MiniBooNE experiment. Using a likelihood-ratio technique [3], CP conservation and the same oscillation probability for neutrinos and antineutrinos, a best MiniBooNE oscillation fit for $200 \text{ MeV} < E_{\nu}^R < 3000 \text{ MeV}$...
has been given at \((\Delta m^2, \sin^2(2\theta)) = (0.037 \text{ eV}^2, 1.00)\). This is clearly excluded by the ICARUS result. A 3+2 joint oscillation fit as a function of \(E_\nu^Q\) in both neutrino and antineutrino modes has also been reported [3] with best fit values \(\Delta m^2_{31} = 0.082 \text{ eV}^2\), \(\Delta m^2_{51} = 0.476 \text{ eV}^2\), \(U_{e,4} = 0.1844\), \(U_{e,5} = U_{\mu,5} = 0.00547\), and \(\phi = 1.0005 \pi\). The MiniBooNE value is clearly incompatible with the present ICARUS result. A detailed comparison between the various results is shown in figure 4. While for \(\Delta m^2 \gg 1 \text{ eV}^2\) there is already disagreement between the allowable regions from the published experiments, for \(\Delta m^2 \leq 1 \text{ eV}^2\) the ICARUS result now allows to define a much smaller, narrower region centered around \((\Delta m^2, \sin^2(2\theta)) = (0.5 \text{ eV}^2, 0.05)\) in which there is 90% CL agreement between (1) the present ICARUS limit, (2) the limits of KARMEN and (3) the positive signals of LSND and MiniBooNE collaborations. This is the area in which the expectations from cosmology suggest a substantial contribution to the dark mass signal. This region will be better explored by the ICARUS/NESSIE proposed dual detector experiment [12] to be performed at CERN at a much shorter distances (300 m and 1.8 km) and lower neutrino energies, which increase the events rate, reduce the over-all multiplicity of the events, enlarge the angular range and therefore improve substantially the selection efficiency \(\eta\).

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