

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 $\nu_\mu \rightarrow \nu_e$ 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 $\sin^2(1.27\Delta m_{new}^2 L/E_\nu) \simeq 1/2$ and therefore approximately with probability $\langle P_{\nu_\mu \rightarrow \nu_e} \rangle = \frac{1}{2} \sin^2(2\theta_{new})$. 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 $\langle P_{\nu_\mu \rightarrow \nu_e} \rangle \leq 5.4 \times 10^{-3}$ and $\langle P_{\nu_\mu \rightarrow \nu_e} \rangle \leq 1.1 \times 10^{-2}$ 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 ν_e , ν_μ and ν_τ and mass eigenstates ν_1 , ν_2 and ν_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 $\langle E_\nu \rangle \simeq 30 \text{ MeV}$ and $L \simeq 30 \text{ m}$ has been found. The LSND signal would imply an additional mass-squared difference largely in excess of the Standard Model values. The LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal $\langle P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e} \rangle = (2.64 \pm 0.67 \pm 0.45) \times 10^{-3}$ corresponds to an excess of $(87.9 \pm 22.4 \pm 6.0)$ events and it gives a 3.8σ effect at L/E_ν distances of about $0.5 - 1.0 \text{ m/MeV}$. 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_ν range at 3.8σ , present in both the neutrino and antineutrino channels. Using the simple formula $\langle P_{\nu_\mu \rightarrow \nu_e} \rangle = \sin^2(2\theta_{new}) \sin^2(1.27 \Delta m_{new}^2 L/E_\nu)$ one finds a very wide interval $\Delta m_{new}^2 \simeq 0.01$ to 1.0 eV^2 , depending on the actual and unknown value of $\sin^2(2\theta_{new})$. In addition more recently an apparent *disappearance signal* of ν_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 ν_e . This signal is occurring for a Δm_{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 Δm_{new}^2 may have a common origin, the different values of $\sin^2(2\theta_{new})$ 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 $10 \leq E_\nu \leq 30 \text{ GeV}$, 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, $L = 730 \text{ km}$, corresponding to a much larger $L/E_\nu \simeq 36.5 \text{ m/MeV}$ for a typical neutrino energy $E_\nu \simeq 20 \text{ GeV}$. An hypothetical $\nu_\mu \rightarrow \nu_e$ LSND/MiniBooNE anomaly will therefore produce very fast oscillations as a function of the neutrino energy E_ν , averaging closely to the value $\sin^2(1.27 \Delta m_{new}^2 L/E_\nu) \simeq 1/2$ and therefore approximately with a signal $\langle P_{\nu_\mu \rightarrow \nu_e} \rangle \simeq 1/2 \sin^2(2\theta_{new})$. 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

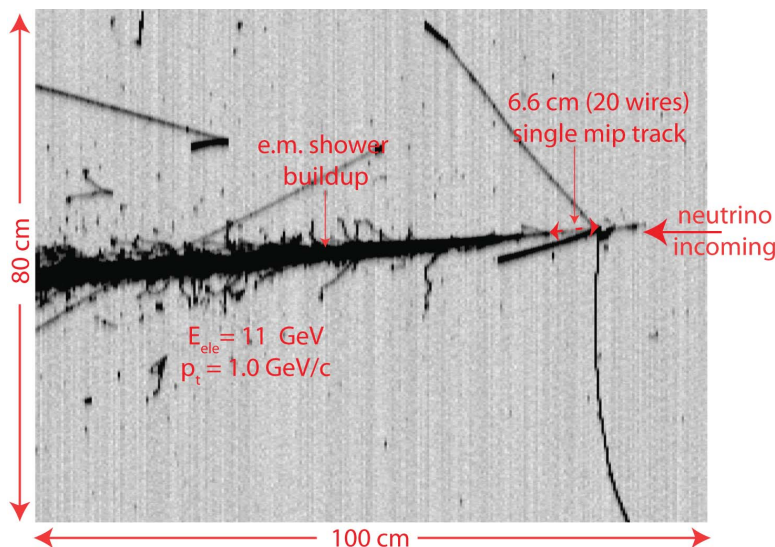


Figure 1. Typical Montecarlo generated event from the ICARUS full simulation programme [9] with $E_e = 11 \text{ GeV}$ and $p_T = 1.0 \text{ GeV}/c$.

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 ($\simeq 45$ readout wires), corresponding to a γ -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 γ -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 ν_e CC events has been generated with the CNGS ν_μ 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

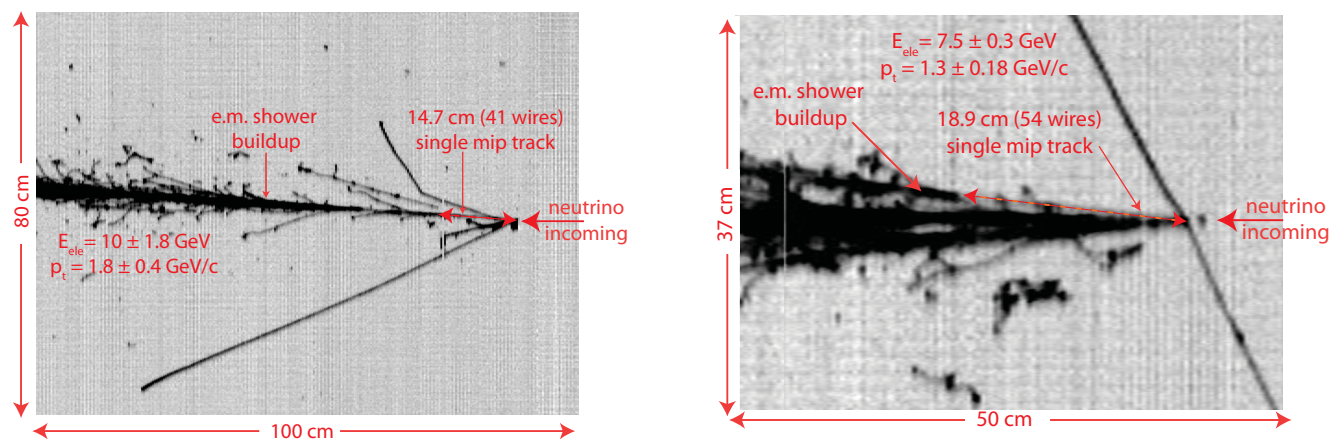


Figure 2. Experimental picture of the two observed events (a) and (b) with a clearly identified electron signature from a total sample of 1091 neutrino interactions. Event in (a) has a total energy of 11.5 ± 1.8 GeV, and a transverse electron momentum of 1.8 ± 0.4 GeV/c. Event in (b) has a visible energy of 17 GeV and a transverse momentum of 1.3 ± 0.18 GeV/c. In both events the single electron shower in the transverse plane is clearly opposite to the remaining of the event.

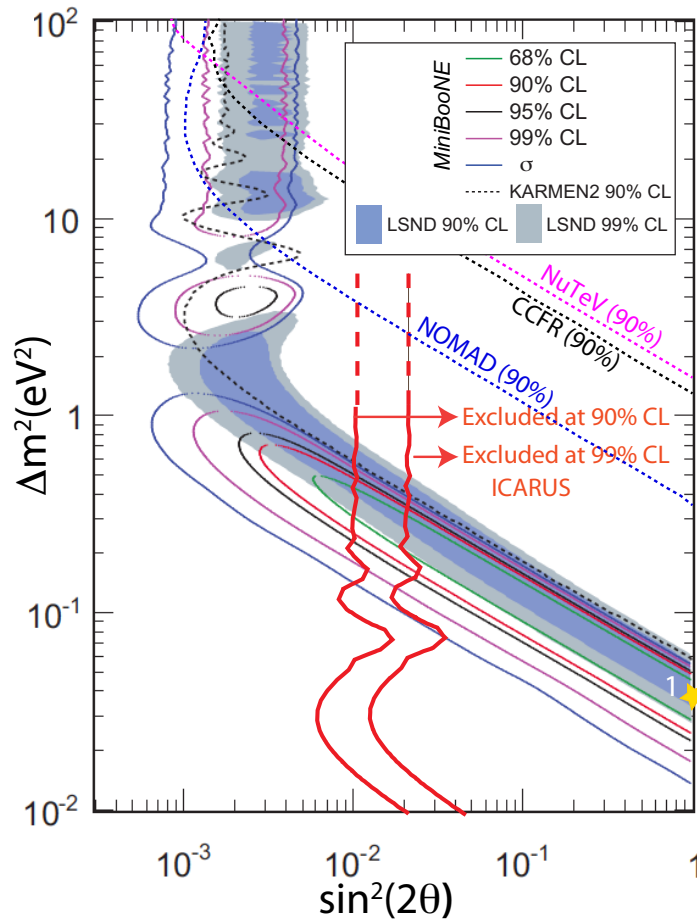


Figure 3. Two-dimensional plot of Δm^2 vs $\sin^2(2\theta)$ for the main published experiments sensitive to the anomaly [2], [3], [11] and the present ICARUS result. The ICARUS limits to the oscillation probability are 5.4×10^3 and 1.1×10^2 , corresponding to 3.41 and to 7.13 excess events respectively at 90% and 99% confidence level.

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 η 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 (5.8×10^{18} pot) collected in 2010 and 923 events collected in 2011 (2.7×10^{19} pot) out of the 4.4×10^{19} collected in 2011), leading to a total of 1091 initial neutrino events. In this sample only events with visible energy ≤ 30 GeV have been included with the relevant fiducial cuts, which bring the number of events from 1091 to 839. We expect 627 ν_μ CC, of which 204 ν_{NC} and 3 ν_τ CC (except $\tau \rightarrow e$) are to be added. The expected number of ν_e events due to conventional sources in the same energy range and fiducial volumes are as follows: (a) 3 events due to intrinsic ν_e beam associated contamination; (b) 1.3 ν_e events due to the presence of θ_{13} oscillations; (c) 0.7 ν_τ 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

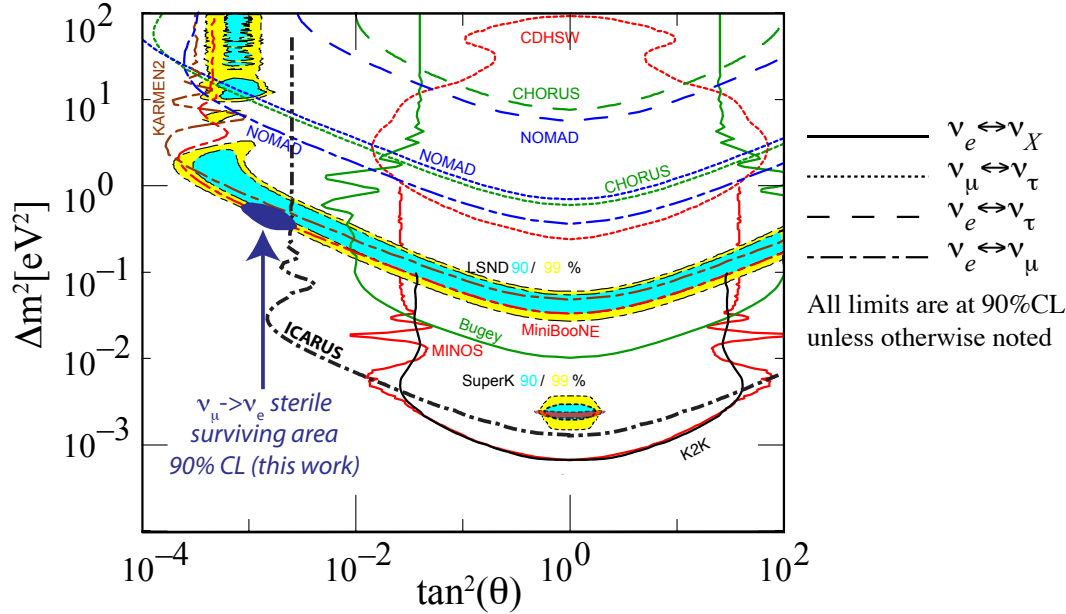


Figure 4. Regions in the $(\Delta m^2, \tan^2(\theta))$ plane excluded by the ICARUS experiment compared with the published results (taken from <http://www.pdg.org>). While for $\Delta m^2 \gg 1 \text{ eV}^2$ there is already disagreement for $\nu_\mu \rightarrow \nu_e$ between the allowable regions 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.

general complexity of the events. In the recorded experimental sample, two events with a clear ν_e have been identified (Figure 2), to be compared with the above expectation of 3.7 events for conventional sources.

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 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 LSND anomaly. Following ref. [10], at statistical confidence levels of 90% and 99% and taking into account the detection efficiency, the limits due to the LSND anomaly are respectively 3.41 and 7.13 events. Given the observed sample of 627 ν_μ CC events, the limits to the oscillation probability are 5.4×10^{-3} and 1.1×10^{-2} respectively. The exclusion area of the ICARUS experiment is shown in figure 3 in terms of the two-dimensional plot of $\sin^2(2\theta_{new})$ and Δm_{new}^2 .

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 $200 \text{ MeV} < E_\nu^{QE} < 3000 \text{ MeV}$

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_ν^{QE} in both neutrino and antineutrino modes has also been reported [3] with best fit values $\Delta m_{41}^2 = 0.082 \text{ eV}^2$, $\Delta m_{51}^2 = 0.476 \text{ eV}^2$, $U_{e,4} = U_{\mu,4} = 0.1844$, $U_{e,5} = U_{\mu,5} = 0.00547$, 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 η .

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References

- [1] Pontecorvo B 1967 *Zh. Eksp. Teor. Fiz.* **53** 1717 [1969 *Sov. Phys. JETP* **26** 984]
- [2] Aguilar A et al. (LSND Collaboration) 2001 *Phys. Rev. D* **64** 112007
- [3] Aguilar-Arevalo A A (MiniBooNE Collaboration), arXiv:1207.4809v1 [hep-ex] 19 Jul 2012
- [4] Mention G et al., arXiv:1101.2755v1 [hep-ex], 2011 *Phys. Rev. D* **83** 073006
- [5] Abdurashitov J N et al. (SAGE Collaboration) 2009 *Phys. Rev. C* **80** 015807
Kaether F, Hampel H, Heusser H, Kiko J, and Kirsten T, 2010 *Phys. Lett. B* **685**, 47
- [6] Aquistapace G et al. 1998 *CERN98-02, INFN/AE-89-05*
- [7] Rubbia C et al. 2011 *JINST* **6** P07011
Amerio S et al. 2004 *Nucl. Instr. and Meth. A* **527** 329
- [8] Charpak G et al. 1970 *Nucl. Instrum. and Meth.* **80** 13
- [9] Battistoni G et al. 2007 *AIP Conf. Proc.* **896** 31-49
Battistoni G et al. 2009 *Proceedings of the 12th International conference on nuclear reaction mechanisms, Varenna (Italy)* p. 307
Ferrari N et al. 2005 CERN-2005-10, INFN/TC-05/11
- [10] Feldman G J and Cousins R D 1988 *Phys. Rev. D* **57** 3873
- [11] Astier P et al. (Nomad Collaboration) 2003 *Phys. Lett. B* **570** 19-31
Romosan A et al. (CCFR Collaboration) 1997 *Phys. Rev. Lett.* **78** 2912
Avvakumov S et al. (NuTeV Collaboration) 2002 *Phys. Rev. Lett.* **89** 011804
- [12] Antonello M et al. 2012 *SPSC-P-347*
Rubbia C et al. 2011 *SPSC-P-345*