PROCEEDINGS OF SCIENCE

Sterile neutrino search with the ICARUS T600 in the CNGS beam

Robert Sulej[1]
National Centre for Nuclear Research
A. Soltana 7, 05-400 Otwock, Swierk, Poland
E-mail: robert.sulej@cern.ch

We report an early result from the ICARUS experiment on the search for a $\nu_\mu \rightarrow \nu_e$ signal due to the LSND anomaly. The search was performed with the ICARUS T600 detector located at the Gran Sasso Laboratory, receiving CNGS neutrinos from CERN at an average energy of about 20 GeV, at a distance to source of about 730 km. At the L/E_ν = 36.5 m/MeV of the ICARUS experiment the LSND anomaly would manifest as an excess of ν_e events, characterized by a fast energy oscillation averaging approximately to $\sin^2(1.27\Delta m^2_{new}\ L/E_\nu) \approx 1/2$ with probability $P_{\nu\mu\rightarrow\nu e} = 1/2\sin^2(2\theta_{new})$. The present analysis is based on 1091 neutrino events, which are about 50% of the ICARUS data collected in 2010–2011. Two clear ν_e events have been found, compared with the expectation of 3.7±0.6 events from conventional sources. Within the range of observations, this result is compatible with the absence of a LSND anomaly. At 90% and 99% confidence levels the limits of 3.4 and 7.3 events, corresponding to oscillation probabilities $\langle P_{\nu\mu\rightarrow\nu e}\rangle \leq 5.4\times10^{-3}$ and $\langle P_{\nu\mu\rightarrow\nu e}\rangle \leq 1.1\times10^{-2}$, are respectively set. The result strongly limits the window of open options for the LSND anomaly to a region around $(\Delta m^2, \sin^2(2\theta))_{new} = (0.5\text{eV}^2, 0.005)$, where there is an overall 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 Speaker, on behalf of the ICARUS Collaboration

 http://pos.sissa.it

PoS(Neutel 2013)013

PROCEEDINGS OF SCIENCE

XV Workshop on Neutrino Telescopes
March 11-15, 2013
Venice, Italy

1. Introduction

Neutrino oscillations have so far established a consistent picture, with the mixing of three neutrino flavours ν_e, ν_μ and ν_τ and mass eigenstates ν_1, ν_2 and ν_3. However, the possible presence of neutrino oscillations into sterile states has been proposed by B. Pontecorvo [1]. Such "sterile" states may not see fully the ordinary electro-weak interactions but still introduce mixing oscillations with ordinary neutrinos. An experimental search for an anomalous anti-ν_e production at short distances has been performed by the LSND experiment [2] at the Los Alamos 800 MeV proton accelerator, which reported an anomalous excess of anti-ν_e from anti-ν_μ originated by muons from pions at rest with $\langle E_\nu \rangle \approx 30$ MeV and $L \approx 30$ m. The LSND signal $P_{\text{anti-}\nu\mu\rightarrow\text{anti-}\nu e} = (2.64\pm0.67\pm0.45)\times10^{-3}$ corresponds to a rate of 87.9±22.4±6.0 events, which is a 3.8 σ effect at $L/E_\nu \sim 0.5-1.0$ m/MeV.

A recent result from MiniBooNE [3], performed with neutrinos from the 8 GeV FNAL-Booster in a similar L/E_ν range has confirmed in both the neutrino and antineutrino channels a combined 3.8 σ LSND-like oscillation signal. With the formula

$$P_{\nu_\mu\rightarrow\nu_e} = \sin^2(2\theta_{new})\sin^2\left(\frac{1.27\Delta m^2_{new}(\mathrm{eV}^2)L(\mathrm{m})}{E_\nu(\mathrm{MeV})}\right) \quad (1)$$

these results correspond to a new signal within a wide interval $\Delta m^2_{\text{new}} \approx 0.01$ to $1.0\ \mathrm{eV}^2$ and a corresponding associated value of $\sin^2(2\theta_{\text{new}})$.

In addition, an apparent ν_e or anti-ν_e disappearance anomaly has been detected from nearby nuclear reactors [4] and from Mega-Curie k-capture calibration sources [5,6]. Also these effects seem to occur for a Δm^2_{new} much higher than the experimentally measured ones for the three neutrino oscillation scenario, in the order of magnitude of the LSND anomaly. These anomalies may indeed represent an unified approach, in which one or more Δm^2_{new} may have a common origin, with the values of $\sin^2(2\theta_{\text{new}})$ for different channels reflecting the so far unknown structure of the $\mathbf{U}_{(j,k)}$ matrix, with j, k representing the number of ordinary and sterile neutrinos.

With the help of a novel development of a large mass "Gargamelle class" LAr-TPC imaging detector, the ICARUS experiment [7] at the Gran Sasso underground laboratory (LNGS) is hereby visually searching for the signature of such a signal due to a LSND-like anomaly in the CERN to Gran Sasso neutrino beam (CNGS).

2. The experimental setup

The CNGS facility [8] provides a neutrino beam composed mainly of ν_μ peaked in the range $10 \leq E\nu \leq 30$ GeV. The CERN-SPS 400 GeV proton beam with about 2×10^{13} protons on target (pot) per spill is sent to a segmented carbon target followed by a magnetic horn and a reflector, focusing charged secondary mesons into a 1 km long decay tunnel. Produced neutrinos are pointing down with a 52 mrad slope toward the Gran Sasso laboratory (LNGS) located at a distance of 732 km.

According to detailed Monte Carlo (MC) calculations of the neutrino beam, about 2850 charged current (CC) events/kt/year are expected at LNGS for a nominal beam intensity of 4.5×10^{19} pot/year with a spectral contamination from anti-ν of about 2% and an electron component of about 1%. The neutrino flux and spectra expectations are obtained with a simulation of the beam line elements based on the FLUKA MC code [9, 10]. Conservatively, a 10% systematics, introduced by the hadron production model in the computed fluxes, can be assessed when averaging over the angular acceptance of about 30 mrad of the beam optics.

According to the full neutrino beam calculation, 75% of ν_μ are coming from decays of pion produced at the target, the rest is due to kaons (6%) and tertiary decays (19%). ν_e's are originated by pions through the subsequent muon decay (37%) as well as by kaons (43%), the remaining 20% is due to tertiary decays. Therefore, due to correlations between the ν_μ and ν_e common origins, significant cancellations occur in the systematics of the ν_e / ν_μ ratio. The resulting integral error on the ν_e / ν_μ ratio is estimated to be better than 7%.

The ICARUS experiment is operated at $L/E_\nu \approx 36.5$ m/MeV, a value much larger than the one of the experiments where anomalies appeared. In the first approximation, a hypothetical $\nu_\mu \rightarrow \nu_e$ LSND anomaly will produce very fast oscillations as a function of the neutrino energy E_ν, averaging to $\sin^2(1.27\Delta m^2_{new} L/E_\nu) \approx 1/2$ and $\langle P_{\nu\mu\rightarrow\nu e}\rangle = 1/2\sin^2(2\theta_{new})$. This signal will have to be compared with the small, but significant, backgrounds due to other and more conventional neutrino sources.

The LAr-TPC detector developed by the ICARUS group [7] offers a completely uniform imaging with high accuracy of massive LAr volumes. The new method, proposed by C. Rubbia [11] observes the true image of the track with an accuracy of the order of few mm^3, extending to a liquid the TPC already described for a gas by G. Charpak et al. [12]. The passage of the capability of several meters of free electron drift from a gas to a liquid is not straightforward. 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 electrons can be transported in high purity LAr, preserving practically undistorted particle tracks, by a uniform electric field over macroscopic distances (meters). Imaging is provided by a set of wires placed at the end of the drift path continuously 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, that allows for space point reconstruction and precise calorimetric measurement. The prompt scintillation light, produced along with the ionization by any charged particle crossing LAr, is detected by a set of photomultipliers (PMT's) and used to trigger physical events of interest. These are important differences with respect to the previously reported observations of LSND and MiniBooNE which were based on the 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. Data selection and analysis

A few CNGS ν interactions per day with primary vertex in the fiducial volume are recorded, as expected. Events are triggered by PMT signal inside the SPS proton extraction gate, with application of automatic filter for empty events rejection, based on charge deposition. Fiducial volume cuts include 5 cm from each side of the LAr active volume, and 50 cm from the

PoS(Neutel 2013)013

downstream wall. This initial cuts allow for shower identification, but are not enough for the reconstruction of neutrino energies, nor for the ν_μ CC vs NC discrimination. Events with a deposited energy above 30 GeV are rejected, in order to optimize the signal over background ratio.

Muon neutrino CC events are identified with the requirement of a track exiting the primary vertex and travelling at least 250 cm in the detector without secondary interactions except electromagnetic activity.

Since the reliable estimation of efficiency of ν_e events selection is essential in the presented analysis, the overall procedures are carefully validated on MC simulation, using a sophisticated simulation package dedicated to the ICARUS T600 detector. Neutrino events are generated according to the expected spectra with uniform vertex position within the T600 sensitive volume. The adopted neutrino event generator [13] includes quasi-elastic, resonant and deep inelastic processes and is embedded in the nuclear reaction model of FLUKA. All reaction products are transported in the T600 volume, with detailed simulation of energy losses by ionisation, delta ray production, electromagnetic and hadronic interactions. Ionisation charge along the track is subject to the experimentally observed recombination effects [14]. Energy depositions are registered in grid structures that reproduce the actual wire orientation and spacing, with a fine granularity (0.2 mm) in the drift direction. The resulting charge is convoluted with the readout channel response, including wire signal induction and electronics response, and noise parameters extracted from the real data.

The agreement between the observed and predicted signals is shown in Fig. 1a for d*E*/d*x* of muon tracks recorded in CC events. The agreement on the average value is at the level of 2.5%. The distribution of d*E*/d*x* for each track has been fitted with the convolution of a Landau function with a gaussian. The most probable d*E*/d*x* value agrees at 2% level with MC, and the fitted gaussian σ is about 10%, as expected for the hit charge signal to noise ratio. Similar agreement is obtained for protons and pions [15]. Fig. 1b shows the raw energy distribution for the observed ν_μ CC interactions compared with the MC expectations [16].

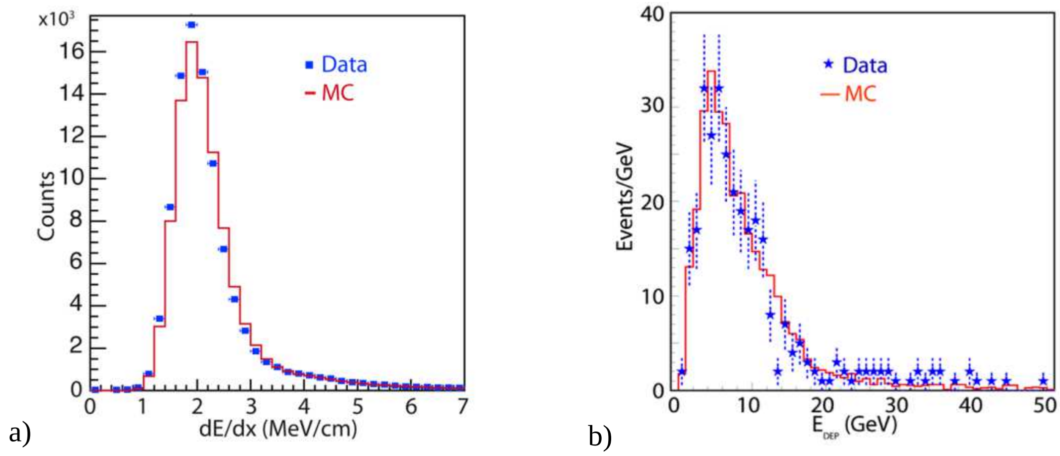


Figure 1. a) Energy loss density, d*E*/d*x*, for μ tracks recorded in CC events; b) the raw energy distribution for the observed ν_μ and anti-ν_μ CC interactions compared with the MC, the average value of the energy deposited in the detector is reproduced within 2.5% and its RMS within 10%.

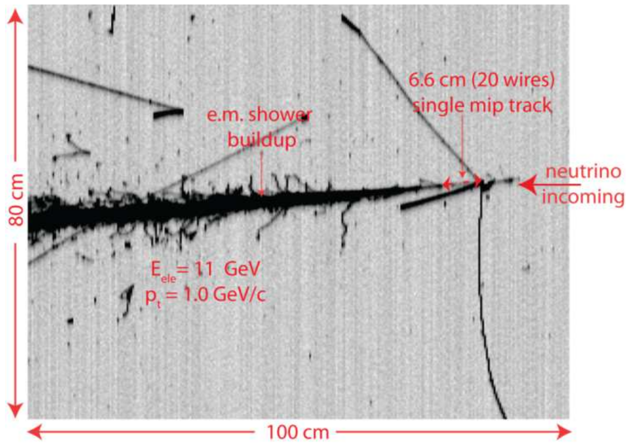


Figure 2. Typical MC generated $\nu_\mu \rightarrow \nu_e$ event from the ICARUS full simulation program with $E_e = 11$ GeV and p_T = 1.0 GeV/c.

The identification of $\nu_\mu \rightarrow \nu_e$ oscillated events has been performed as follows. The data sample has been based on a total of 1091 observed neutrino events, including 168 events collected in 2010 (5.8×10^{18} pot) and 923 events collected in 2011 (2.7×10^{19} pot), with the overall event number in agreement within 6%, with the MC expectation. To this sample, an initial cuts on fiducial volume and energy deposit have been applied, as earlier described.

In order to estimate systematic errors induced by the initial cut on the energy deposit, the fraction of background and oscillated events has been evaluated on MC samples of 104 events for each neutrino flavor. Since the cut concerns only 15% of the events it introduces a negligible systematic error on the signal and background expectation, except the ν_e beam component whose energy spectrum extends to higher energies. On the basis of the comparisons shown in Fig. 1, a conservative 10% systematic error has been assumed on the effect of the energy cut on the beam ν_e background, that is to be added to the error on the prediction of the ν_e / ν_μ ratio.

The presence of an electron emitted in the primary neutrino interaction vertex is indicated with the ionization density of the initial part of the candidate electron track, before the electromagnetic showering has occurred. This information, examined wire by wire, is used to discriminate γ-conversion induced, double ionizing, $e^+ e^-$ pairs. The 14 cm radiation length of LAr corresponds to about 45 readout wires in a close to beam direction. The rejection factor based on ionisation increases with increasing photon energies, while the electron identification efficiency is almost constant. The possible photon misidentification is due Compton scattering of photons, however its cross section becomes negligible with respect to the pair production above a few hundreds of MeV. Monte Carlo studies indicate a residual contamination of about 0.18 % for the energy spectrum of photons from pion decays in CNGS events, rising to a few per cent in the sub-GeV energy region. The loss in efficiency for electron showers is 10%. Results from an ongoing study on low energy showers from isolated secondary π^0's in the T600 CNGS data confirm the good agreement between data and simulations, including the low ionisation tail of events related to Compton interactions.

In the present analysis, the electron signature has been defined as follows:

(a) vertex of the event inside the fiducial volume;

(b) visible event energy smaller than 30 GeV, in order to reduce the beam ν_e background;

(c) the presence of a charged track starting directly from the vertex, fully consistent over at least 8 wires with a minimum ionising relativistic particle, i.e. the average d*E*/d*x* lower than 3.1MeV/cm after removal of visible delta rays, and subsequently building up into a shower;

(d) visible spatial separation from other ionising tracks within 150 mrad in the immediate vicinity of the vertex in at least one of the two transverse views (±60°), except for short proton like recoils due to nuclear interactions.

In order to determine the electron signature selection efficiency η, ν_e events have been generated with MC according to the ν_μ CC spectrum. An example of simulated event is shown in Fig. 2. Out of an initial sample of 171 $\nu_\mu \rightarrow \nu_e$ MC events, 146 events have a visible energy smaller than 30 GeV, 122 of which satisfy the fiducial volume cuts (a). These events have been visually and independently scanned by three people in different locations. An agreement has been found with differences in less than 3% of the sample. The average number of positively identified electron-like neutrino events is 90, corresponding to a selection efficiency $\eta = 0.74 \pm 0.05$. The systematic error on η induced by the d*E*/d*x* cut is bound to be smaller than 1% from the already discussed agreement to better than 2.5% between the measured and the predicted scale of the d*E*/d*x* for muons in ν_μ CC (see Fig. 1a).

A scan of 800 simulated NC events has shown no presence of apparent $\nu_\mu \rightarrow \nu_e$ events, consistent for our sample with an estimated upper limit of 0.3 events (including possibly misidentified ν_μ CC events). Moreover, an independent estimation of the background rejection efficiency has been performed on a much larger MC sample with a fast simulation and reconstruction algorithm. All CNGS beam original and oscillated neutrino flavors have been taken into account. Automatic cuts mimicking the data cuts have been applied to the simulated events. After the fiducial and deposited energy cuts (C1 in Table 1), background neutral current and charged current events have been retained as “electron” candidates if no muon-like track could be identified, and at least one energetic photon (at least 100 MeV) pointing to the primary vertex was present (C2).

Sel. cut	ν_e CC beam	ν_e CC θ_{13}	ν_τ CC	NC	ν_μ CC	ν_e CC signal
C1	0.47	0.92	0.93	0.89	0.89	0.81
C2	0.47	0.92	0.17	0.66	0.19	0.81
C3	0.33	0.79	0.14	0.10	0.03	0.66
C4	0.30	0.71	0.13	0.0002	0.00005	0.60

Table 1. Fraction of MC events surviving the automatic selection cuts: C1: $E_{dep} < 30$ GeV; C2: no identified muon, at least one shower; C3: one shower with initial point (conversion point in case of a photon) at a distance smaller than 1 cm from the ν interaction vertex, separated from other tracks; C4: single ionisation in the first 8 samples. All event categories are reduced to 0.93 after the cut on fiducial volume. The signal selection efficiency (after the fiducial and energy cuts) results to be 0.6/0.81 = 0.74.

The requirements for the shower isolation and for a conversion distance smaller than 1 cm were then applied (C3). Finally, the discrimination based on the specific ionization was applied as an average factor (C4). The effect of the various cuts is summarized in Table 1.With this method, that is not fully equivalent to the visual scan, the estimated background from misidentified NC and ν_μ CC events amounts to 0.09 events, and the simulated efficiency on ν_e CC events (after the fiducial and energy cuts) is found to be 74% in agreement with the scanning method. The contribution from a 2.5% uncertainty on the dE/dx scale would modify this background estimate by less than 10%. The expected number of ν_e events due to conventional sources in the energy range and fiducial volumes defined in (a) and (b) are:

– 3.0±0.4 ν_e events due to the estimated beam contamination;
– 1.3±0.3 ν_e events due to the θ_{13} oscillations with $\sin^2(\theta_{13}) = 0.0242 \pm 0.0026$ [17];
– 0.7±0.05 ν_τ with $\tau \rightarrow e$ from the three neutrino mixing standard model predictions [18],

giving a total of 5.0±0.6 expected events, where the uncertainty on the NC and CC contaminations has been included. The expected visible background is then 3.7±0.6 events (syst. error only), after that the selection efficiency reduction has been applied. Given the smallness of the number of electron like signal expected in absence of LSND anomaly, the estimated systematic uncertainty on the predicted number is clearly negligible w.r.t. its statistical fluctuation.

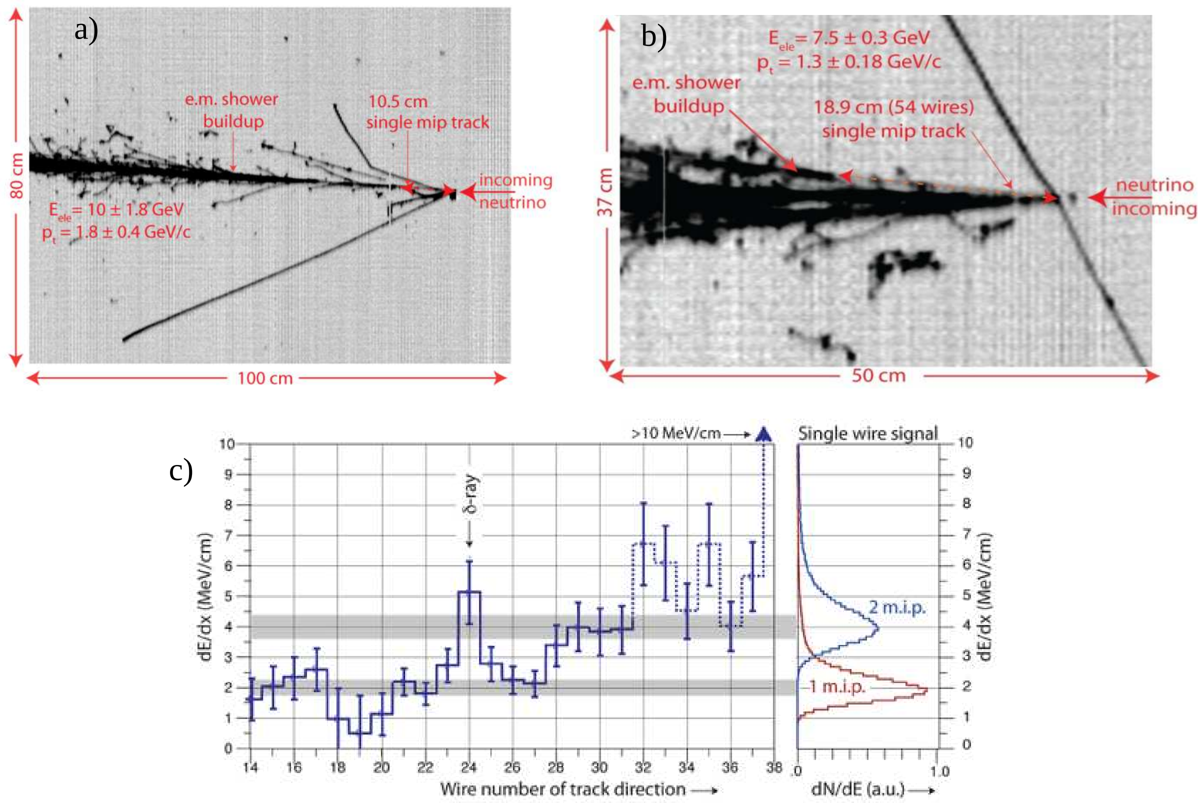


Figure 3. The two observed events (a) and (b) with electron signature; (c): the actual *dE/dx* along individual wires of the electron shower shown in (a). More detailed event description in the text.

In the recorded sample, two events in which a ν_e signature have been identified, to be compared with the expectation of 3.7 events for conventional sources. The event in Fig. 3a has a total energy of 11.5±2.0 GeV and an electron of 10±1.8 GeV taking into account a partially missing component of the electromagnetic shower. The event in Fig. 3b has 17 GeV of visible energy and an electron of 7.5±0.3 GeV. In both events the single electron shower in the transverse plane is opposite to the remaining of the event, with the electron transverse momentum of 1.8±0.4 GeV/c and 1.3±0.18 GeV/c, respectively.

Fig. 3c shows the actual d*E*/d*x* along individual wires of the single ionising electron developing into shower shown in Fig. 3a, in the region (≥4.5 cm from primary vertex), where the track is well separated from other tracks and heavily ionising nuclear prongs. As a reference, d*E*/d*x* distribution for single and double minimum ionising tracks, are also displayed.

4. Results

Within the range of our observations, the result is compatible with the absence of a LSND anomaly. At statistical confidence levels of 90% and 99% and taking into account the detection efficiency, the limits due to the LSND anomaly are respectively 3.4 and 7.1 events. According to the above described experimental sample and the number of recorded events, the corresponding limits on the oscillation probability are $\langle P_{\nu\mu\rightarrow\nu e}\rangle = 5.4\times10^{-3}$ and $\langle P_{\nu\mu\rightarrow\nu e}\rangle = 1.1\times10^{-2}$, respectively. The exclusion area of the ICARUS experiment is shown in Fig. 4 in terms of the two-dimensional plot of $\sin^2(2\theta_{new})$ and Δm^2_{new}. In most of the area covered by ICARUS and allowed by LSND and MiniBooNE, the oscillation averages approximately to a half of its highest value, $\sin^2(1.27\Delta m^2_{new}L/E_\nu) \approx 1/2$. For lower values of Δm^2_{new}, the longer baseline strongly enhances the oscillation probability with respect to the one of the short baseline experiments. In ICARUS, considering for instance with $(\Delta m^2, \sin^2(2\theta))_{new} = (0.11\text{eV}^2, 0.10)$, as many as 30 anomalous $\nu_\mu\rightarrow\nu_e$ events should have been observed with $E_\nu \leq 30$GeV.

The oscillation probabilities from LSND are in the $L/E_\nu \leq 1$ m/MeV region. The MiniBooNE result has extended the data to values in the region $L/E_\nu \geq 1$ m/MeV (Fig. 5), corresponding to a signal peak at smaller values of E_ν. The actual origin of the excess may need further clarification, as pointed out by the MiniBooNE Collaboration. In the low mass peak region the dominant signal is due to ν_μ misidentified background adding to the observed LNSD signal. As already mentioned, the present experiment explores much larger values of L/E_ν, but the ICARUS results exclude also a substantial fraction of the $(\Delta m^2, \sin^2(2\theta))_{new}$ MiniBooNE curves shown in Fig. 5, in particular the ones labeled from 1 to 5. A detailed comparison among the various results on different oscillation phenomena, between different pairs of neutrino flavours, each having specific mixing angles and Δm^2 is shown in Fig. 6 [18]. Even if disappearance and appearance results should not be referred to a single effective θ and Δm^2, the plot allows situating the residual "LSND anomaly" in the framework of the present neutrino oscillation results. While for $\Delta m^2_{new} >> 1\text{eV}^2$ there is already disagreement between the allowed regions from the published experiments, for $\Delta m^2_{new} \leq 1\text{eV}^2$ the ICARUS result now allows to define a much narrower region centered around $(\Delta m^2, \sin^2(2\theta))_{new} = (0.5 \text{ eV}^2, 0.005)$ 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.

Acknowledgements

The ICARUS Collaboration acknowledges the fundamental contribution to the construction and operation of the experiment given by INFN and, in particular, by the LNGS Laboratory and its

Directors. The Polish groups acknowledge the support of the Ministry of Science and Higher Education, and of National Science Centre, Poland. Finally, we thank CERN, in particular the CNGS staff, for the successful operation of the neutrino beam facility.

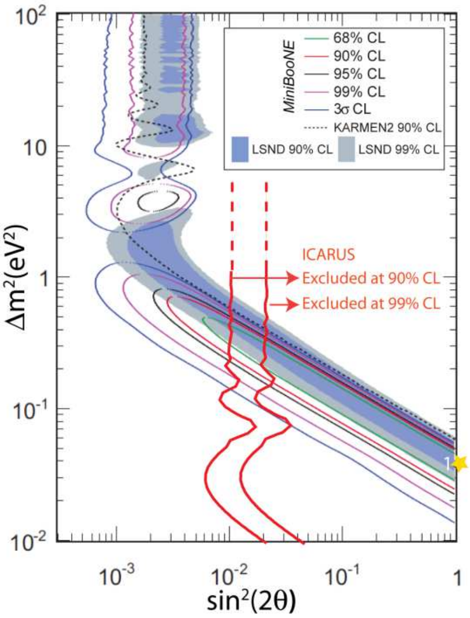
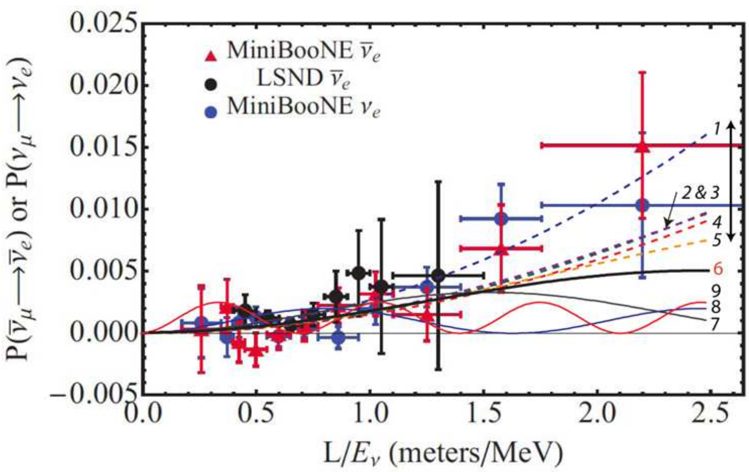


Figure 4. Two-dimensional plot of Δm^2 vs $\sin^2(2\theta_{new})$ for the main published experiments sensitive to the $\nu_\mu \rightarrow \nu_e$ anomaly and the present ICARUS result. The ICARUS limits to the oscillation probability are $\langle P_{\nu\mu\rightarrow\nu e}\rangle \leq 5.4\times10^{-3}$ and $\langle P_{\nu\mu\rightarrow\nu e}\rangle \leq 1.1\times10^{-2}$, corresponding to $\sin^2(2\theta_{new}) \leq 1.1\times10^{-2}$ and $\sin^2(2\theta_{new}) \leq 2.2\times10^{-2}$ respectively at 90% and 99% CL. Limits correspond to 3.41 and to 7.13 events.



#	sin²(2θ)	Δm²(eV²)
1	1	0.04
2	0.3	0.07
3	0.1	0.11
4	3.0E-2	0.21
5	1.0E-2	0.37
6	5.0E-3	0.50
7	3.3E-3	0.8
8	2.0E-3	1.5
9	2.5E-3	3.5

Figure 5. $\langle P_{\nu\mu\rightarrow\nu e}\rangle$ as a function of the distance L/E_ν observed by LSND and MiniBooNE. The *lines* are examples of oscillation patterns with sets of parameters chosen within the MiniBoone allowed region. In particular, *line 1* corresponds to the MiniBoone best fit in the combined 3 + 1 model. All *lines* are consistent with data at low L/E_ν values. *Solid lines*, labeled from *6* to *9*, are also compatible with the present ICARUS result. Instead, parameter sets indicated by *1–5* (*dashed lines*), are driven by the additional signal recorded by MiniBooNE for $L/E\nu$ > 1 m/MeV, but they are entirely ruled out by the present result because they would imply an excessive oscillation probability at the large L/E_ν values investigated by ICARUS. *Line 6* shows the “best value” including ICARUS results, with $(\Delta m^2, \sin^2(2\theta))_{new} = (0.5\ \text{eV}^2, 0.005)$.

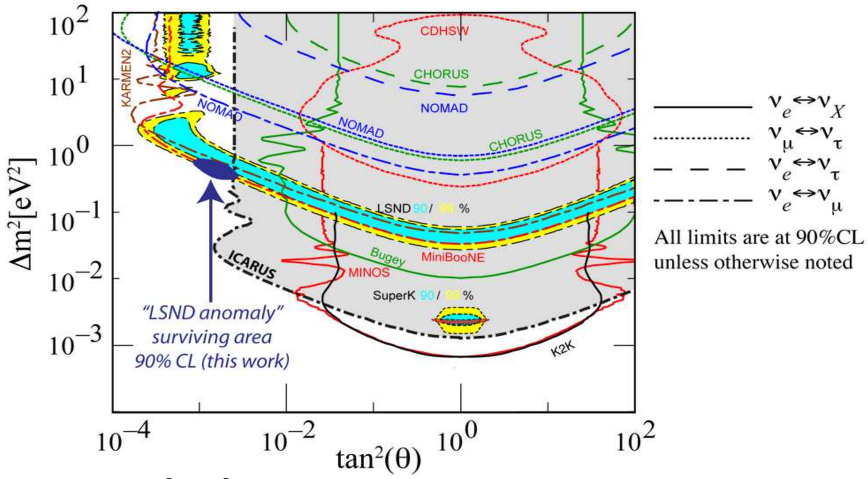


Figure 6. Regions in the (Δm^2, $\tan^2(\theta)$) plane excluded by the ICARUS experiment compared with the published results [18].

References

[1] B. Pontecorvo, Zh. Eksp. Teor. Fiz. **53**, 1717 (1967), Sov. Phys. JETP **26**, 984 (1968)

[2] A. Aguilar et al., Phys. Rev. D **64**, 112007 (2001)

[3] A. Aguilar-Arevalo et al., [hep-ex/1207.4809v1] (2012)

[4] G. Mention et al., Phys. Rev. D **83**, 073006 (2011)

[5] J.N. Abdurashitov et al., Phys. Rev. C **80**, 015807 (2009)

[6] F. Kaether,W. Hampel, G. Heusser, J. Kiko, T. Kirsten, Phys. Lett. B **685**, 47 (2010)

[7] C. Rubbia et al., J. Instrum. **6**, P07011 (2011)

[8] G. Aquistapace et al., [CERN 98-02, INFN/AE-89-05] (1998)

[9] A. Ferrari et al., [CERN-2005-10, INFN/TC-05/11] (2005)

[10] G. Battistoni et al., in proceedings of AIP **896**, 31–49 (2007)

[11] C. Rubbia, [CERN-EP-77-08] 1977

[12] G. Charpak et al., Nucl. Instrum. and Meth. 80 13 (1970)

[13] G. Battistoni et al., in proceedings of *12th Int. conf. on nuclear reaction mechanisms*, Varenna, Italy, June 15–19 (2009)

[14] S. Amoruso et al., Nucl. Instrum. Methods Phys. Res., Sect. A **523**, 275 (2004)

[15] M. Antonello et al., Adv.High Energy Phys. 2013 (2013) 260820

[16] M. Antonello et al., Phys. Lett. B **711**, 270 (2012)

[17] G.L. Fogli et al., [hep-ph/1205.5254] (2012)

[18] J. Beringer et al. (Particle Data Group), Phys. Rev. D **86**, 010001 (2012)