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Letter

Search for anomalies in the ν_e appearance from a ν_μ beam

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Abstract We report an updated result from the ICARUS experiment on the search for $\nu_\mu \to \nu_e$ anomalies with the CNGS beam, produced at CERN with an average energy of 20 GeV and traveling 730 km to the Gran Sasso Laboratory. The present analysis is based on a total sample of 1995 events of CNGS neutrino interactions, which corresponds to an almost doubled sample with respect to the previously published result. Four clear ν_e events have been visually identified over the full sample, compared with an expectation of 6.4 ± 0.9 events from conventional sources. The result is compatible with the absence of additional anomalous contributions. At 90 % and 99 % confidence levels, the limits to possible oscillated events are 3.7 and 8.3 respectively. The corresponding limit to oscillation probability becomes consequently 3.4×10^{-3} and 7.6×10^{-3}, respectively. The present result confirms, with an improved sensitivity, the early result already published by the ICARUS Collaboration.

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ICARUS [1, 2] is a large mass LAr-TPC imaging detector located at the Gran Sasso underground laboratory, 730 km away from the CERN neutrino source. It has an instrumented mass in excess of 476 ton of liquid Argon (LAr) and provides a completely uniform imaging of neutrino events with accuracy, density and interaction lengths similar to the ones of a heavy Freon conventional bubble chamber. This innovative detection technique allows observing the actual "3D-image" of each charged track with a resolution of few mm^3.

The CNGS neutrino facility [3–5] provides an almost pure ν_μ beam peaked in the range $10 \leq E_\nu \leq 30$ GeV, with an electron component of less than 1 % [6]. From October 2010 to December 2012, we have collected a total of neutrino data corresponding to 8.6×10^{19} POT (400 GeV protons on target) and with the excellent recording efficiency exceeding 93 %.

The LSND experiment [7] at LANSCE Los Alamos accelerator and the MiniBooNE experiment [8] at the FNAL-Booster have previously reported significant evidence for an anomalous excess of $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ at $L/E_\nu \sim 0.5$–

1.0 m/MeV, where L is the distance from the target and E_ν is the neutrino energy. These results may imply the existence of new sterile neutrino flavors including additional mass-squared differences and new elements of the mixing matrix which will affect the $\nu_\mu \to \nu_e$ oscillation probability. The mass-squared difference allowed by LSND and MiniBooNE for an additional neutrino state will be somewhere in a wide interval $\Delta m^2_{\text{new}} \sim 0.01$ to $1.0\ \text{eV}^2$ with a corresponding associated value of $\sin^2(2\theta_{\text{new}}) = 4|U_{e4}|^2|U_{\mu 4}|^2$ [8], largely incompatible with the standard three-neutrino mixing model.

Moreover additional ν_e or $\overline{\nu}_e$ disappearance anomalies have been observed at similar Δm^2_{new} values in (a) nearby nuclear reactors [9, 10] and (b) Mega-Curie k-capture sources in solar neutrino experiments [11, 12].

All these anomalies may indeed represent an unified approach, in which one or more Δm^2_{new} may have a common origin, with the value of $\sin^2(2\theta_{\text{new}})$ for different channels reflecting the so far unknown structure of the $U(j,k)$ matrix, with j, k = number of ordinary and sterile neutrinos. Detailed analyses can be found for instance in [13–15].

In our case, such anomalies due to the ν_e appearance in a ν_μ beam will be observed at much larger values of L/E_ν, centered around $L/E_\nu \simeq 36.5$ m/MeV. These hypothetical anomalies will therefore produce very fast oscillations as a function of E_ν, averaging over the observed spectrum to $\sin^2(1.27\Delta m^2_{\text{new}} L/E_\nu) \simeq 1/2$ and $\langle P(\nu_\mu \to \nu_e)\rangle = 1/2 \cdot \sin^2(2\theta_{\text{new}})$.

A previous search for such anomalies in the CNGS neutrino beam has been recently published by the ICARUS Collaboration [6], based on 1091 neutrino events within the sensitive LAr volume and 3.3×10^{19} POT. We have shown that there is a possible agreement of all published experimental results only for a narrow surviving region centred around $(\Delta m^2, \sin^2(2\theta_{\text{new}})) \simeq (0.5\ \text{eV}^2, 0.005)$. In this paper we present an additional sample of 904 neutrino events, bringing the total to 1995 events and 6×10^{19} POT.

As described in more detail in Ref. [6] the neutrino interaction vertex and 2D projections of tracks and showers are identified visually. The event reconstruction is based on the signals recorded by the three TPC wire planes [2, 16] at angles 60° apart. After hit finding and fitting, the energy deposition is computed in the charge collecting view. A correction is introduced based on the (small) electron signal attenuation due to the drift distance directly measured with the help of cosmic ray muons. The high density of sampling—corresponding to ~2 % of a radiation length—and the remarkable signal/noise ratio of ~10/1 allow to measure the specific ionization of each wire. It is also possible to perform precise calorimetry and particle identification for stopping particles [16] and obtain a powerful electron/γ separation [6]. The total visible energy of the events has been determined from the total charge collected by the TPC wires, corrected for the electronic response [2] and for the dE/dx recombination of the signals in LAr [17].

A sophisticated Monte Carlo simulation package dedicated to the ICARUS T600 detector has been developed [6]. It includes a neutrino event generator [18] accounting for quasi-elastic, resonant and deep inelastic interactions and describes the effects of Fermi motion, Pauli blocking and other initial and final state effects like, for instance, re-interactions of the reaction products inside the target nucleus [19]. The products of the neutrino interaction are then transported, with a detailed simulation of the energy losses and electromagnetic and hadronic interactions, including recombination effects [17]. In order to realistically reproduce the actual wire signals as recorded in the events, the response of the electronics and the noise patterns estimated from the data have been carefully simulated.

Both local energy deposition by muon, proton and pion tracks and global calorimetric reconstruction for ν-CC interactions confirm that the detector response is reproduced to better than 2.5 %, and the effective noise level is correctly simulated [6]. An ongoing study on low energy showers from isolated secondary π^0's confirms that Monte Carlo reproduces experimental data for the ionization at the beginning of the e.m. showers, a key tool for the powerful electron/γ discrimination [6]. We observe a general agreement between expectations of the Monte Carlo and the actually observed number of events.

Following the previous analysis [6], interaction vertices at a distance less than 5 cm from each side of the active volume of the TPC or less than 50 cm from its downstream walls have been discarded from the recorded sample. The "electron neutrino signature" has been defined [6] requiring:

- interaction vertex located inside the previously defined fiducial volume;
- event energy $E < 30$ GeV, in order to reduce the beam ν_e background;
- a primary charged track starting directly from the vertex, fully consistent over at least 8 wire hits with a minimum ionizing relativistic particle (i.e. $dE/dx < 3.1$ MeV/cm on average after removal of visible delta rays) and subsequently building up into a shower;
- the electron candidate track has to be spatially separated from other ionizing tracks within 150 mrad in the immediate proximity of the vertex in at least one of the two transverse views (±60°), except for short proton like recoils due to nuclear interactions.

The expected number of ν_e events due to conventional sources in the energy range and fiducial volume are:

- 5.7 ± 0.8 events due to the estimated ν_e beam contamination;

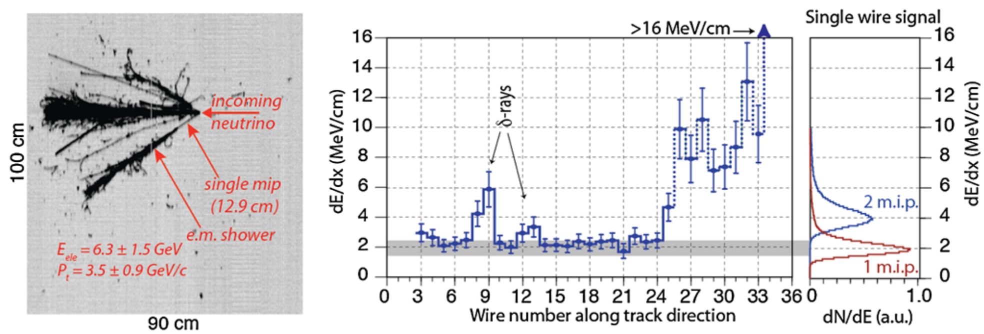

Fig. 1 Experimental picture of the first of the two events with a clear electron signature found in the additional sample of 904 neutrino interactions. The evolution of the actual dE/dx from a single track to an e.m. shower for the electron shower is shown along the individual wires. The event has a total energy of ∼27 GeV and an electron of 6.3 ± 1.5 GeV with a transverse momentum of 3.5 ± 0.9 GeV/c

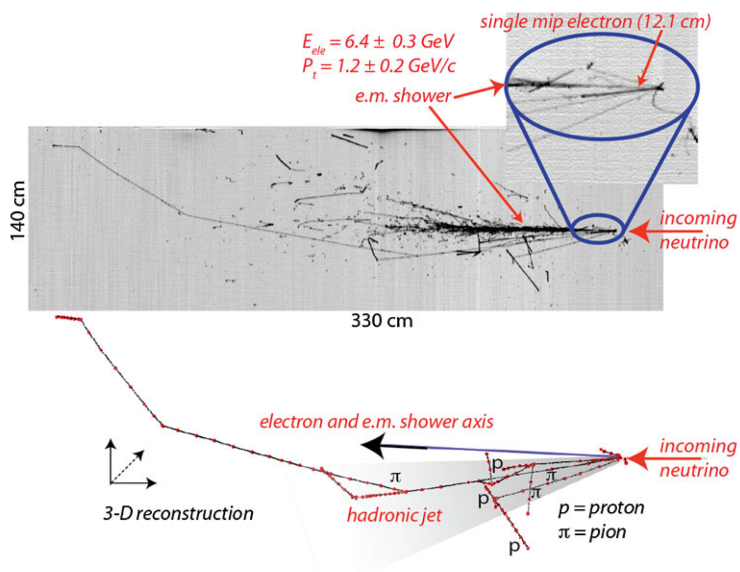

Fig. 2 Second ν_e event with a total energy of ∼14 GeV and an electron of 6.4 ± 0.3 GeV and transverse momentum of 1.2 ± 0.2 GeV/c. The 3D reconstruction of primary particles in the event is also shown (*dots* correspond to vertices of polygonal fit [16])

– 2.3 ± 0.5 ν_e events due to the $\nu_\mu \to \nu_e$ oscillations from $\sin^2(\theta_{13}) = 0.0242 \pm 0.0026$;
– 1.3 ± 0.1 ν_τ with $\tau \to e$ events from the three-neutrino mixing standard model predictions,

giving a total of 9.3 ± 0.9 expected events, where the errors represent the uncertainty on the NC and CC contributions.

The selection efficiency for the search of a ν_e anomaly has been previously estimated as $\eta = 0.74 \pm 0.05$ [6] in the selected energy region. For the intrinsic ν_e contamination the slightly lower value 0.65 ± 0.06 has been estimated since its spectrum is harder than the one of the expected anomalies, based on a sample of 300 simulated events. The contribution from misidentified ν_μ CC and ν NC interactions is negligible, as discussed in [6]. The predicted visible background is then 6.4 ± 0.9 (syst. error only) events. A thorough discussion of the estimate of the systematic uncertainties on the predicted number of ν_e events was already presented in the previous ICARUS paper on the search for the LSND anomaly [6].

In the newly added sample we have found two additional electron events that bring to four the total observed number of events. This is compatible with the expectation of 6.4 ± 0.9 due to conventional sources: the probability to observe a statistical under-fluctuation resulting in four or less ν_e events is 25 %.

The first new event, shown in Fig. 1, has a total energy of ∼27 GeV and an electron of 6.3 ± 1.5 GeV, taking into account the partially escaping fraction of the e.m. showers. The electron is clearly separated from the other tracks after 1 cm from the main vertex. The progressive evolution of the electron from the single ionizing particle to an electromagnetic shower is clearly visible in the plot of dE/dx along the individual wires in Fig. 1.

The second new event, shown in Fig. 2, has a total energy of ∼14 GeV and an electron of 6.4 ± 0.3 GeV. The corresponding three-dimensional reconstruction of the event is also shown.

In both events the single electron shower in the transverse plane is opposite to the remaining of the event, with

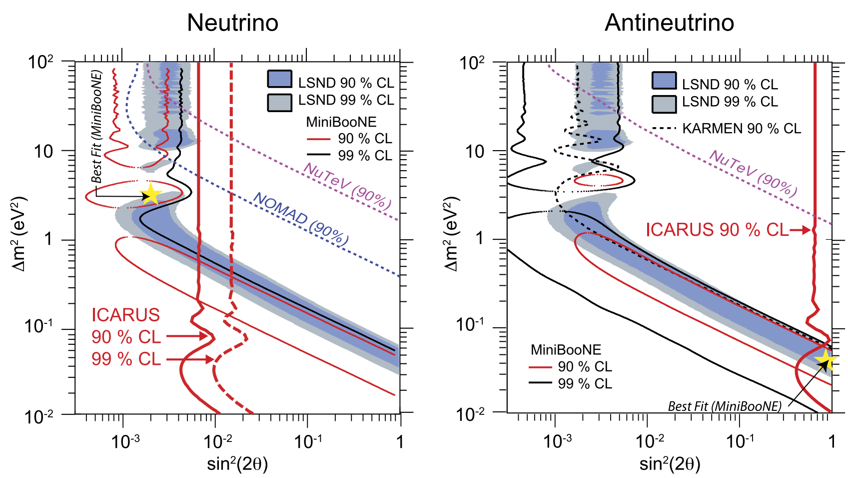

Fig. 3 Neutrino (*left*) and antineutrino (*right*) with Δm^2 as a function of $\sin^2(2\theta)$ for the main experiments sensitive to the $\overline{\nu}_\mu \to \overline{\nu}_e$ and $\nu_\mu \to \nu_e$ anomalies [7, 8, 22–24] and for the present result (*continuous red lines*). The yellow stars mark the best fit points of MiniBooNE [8]. The ICARUS limits on the oscillation probability for $\nu_\mu \to \nu_e$ are $\langle P(\nu_\mu \to \nu_e)\rangle \le 3.4 \times 10^{-3}$ and $\langle P(\nu_\mu \to \nu_e)\rangle \le 7.6 \times 10^{-3}$ at 90 % and 99 % CL, corresponding to $\sin^2(2\theta_{new}) < 6.8 \times 10^{-3}$ and $\sin^2(2\theta_{new}) < 1.5 \times 10^{-2}$ respectively. The ICARUS limit on the $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillation probability is $\langle P(\overline{\nu}_\mu \to \overline{\nu}_e)\rangle \le 0.32$ at 90 % CL, corresponding to $\sin^2(2\theta_{new}) \le 0.64$

the electron transverse momentum of 3.5 ± 0.9 GeV/c and 1.2 ± 0.2 GeV/c, respectively.

Our previously published result [6] is therefore extended with an almost doubled event statistics. At statistical confidence levels of 90 % and 99 % and taking into account the revised detection efficiency η, the limits are, respectively, 3.7 and 8.3 events [20]. The corresponding new limits on the oscillation probability are $\langle P(\nu_\mu \to \nu_e)\rangle \le 3.4 \times 10^{-3}$ and $\langle P(\nu_\mu \to \nu_e)\rangle \le 7.6 \times 10^{-3}$, respectively.

The new exclusion area of the ICARUS experiment referred to neutrino-like events is shown in Fig. 3, in terms of the two dimensional plot of $\sin^2(2\theta_{new})$ and Δm^2_{new}. In the interval $\Delta m^2_{new} \simeq 0.1$ to > 10 eV^2 the exclusion area is independent of Δm^2_{new} with $\sin^2(2\theta_{new}) = 2.0\langle P(\nu_\mu \to \nu_e)\rangle$. In the Δm^2_{new} interval from 0.1 to $\sim$0.01 eV^2, the oscillation is progressively growing and averages to about the above value of twice $\langle P(\nu_\mu \to \nu_e)\rangle$. For even lower values of Δm^2_{new}, the longer baseline strongly enhances the oscillation probability with respect to the one of the previous short baseline experiments.

The LSND result [7] was based on antineutrino events. A small $\sim$2 % antineutrino event contamination is also present in the CNGS beam as experimentally observed [21]. According to a detailed neutrino beam calculation, the $\overline{\nu}_\mu$ CC event rate is (1.2 ± 0.25) % for $E_\nu < 30$ GeV, where a 20 % uncertainty has been conservatively assumed. In the limiting case in which the whole effect is due to $\overline{\nu}_\mu \to \overline{\nu}_e$, the absence of an anomalous signal gives a limit of 4.2 events at 90 % CL. The corresponding limit on the oscillation probability is $\langle P(\overline{\nu}_\mu \to \overline{\nu}_e)\rangle \le 0.32$. The resulting (small) exclusion area is shown in Fig. 3.

As shown in Fig. 3, a major fraction of the initial two dimensional plot $(\Delta m^2, \sin^2(2\theta_{new}))$ of the main published experiments sensitive to the anomaly [7, 8, 22–24] is now excluded by the present result.

The MiniBooNE experiment has recorded both antineutrino and neutrino data [8]. The LSND result relates to the antineutrino signal and it is statistically significant only for $E_\nu/L > 1$ MeV/m, corresponding in the MiniBooNE conditions to $E_\nu^{QE} > 475$ MeV. In this energy region, a significant LSND-like effect is still observed for antineutrino while a much weaker evidence, compatible with the absence of a signal is apparent in the neutrino data. This incompatibility has been explained in Ref. [8] as caused by a number of possible reasons, like expanded oscillation models with more than one sterile neutrinos, CP violating effects and so on or by unpredicted systematic uncertainties and backgrounds. Therefore there is tension and the compatibility between the MiniBooNE antineutrino and neutrino data is low, at least in a simple two-neutrino oscillation model as in [8].

In the MiniBooNE region $200 < E_\nu^{QE} < 475$ MeV—below the sensitive E_ν/L region of LSND—a *new effect* and a significant additional anomaly has been reported [8] both for neutrino and antineutrino data. The neutrino result may be compared with the present experiment.

The present experiment has observed electron events at much larger values of L/E_ν, centered around $L/E_\nu \simeq 36.5$ m/MeV. In order to compare the results with LSND and MiniBooNE, the values of the oscillation probability have to be projected to lower values of L/E_ν. The two-neutrino model $P = \sin^2(2\theta)\sin^2(1.27\Delta m^2_{41} L/E_\nu)$ has been used to calculate the $\nu_\mu \to \nu_e$ oscillation probability as a function of the neutrino energy E_ν from the observed number of excess events/MeV of Fig. 2 in Ref. [8]. The conversion has been extracted directly from the above graph of

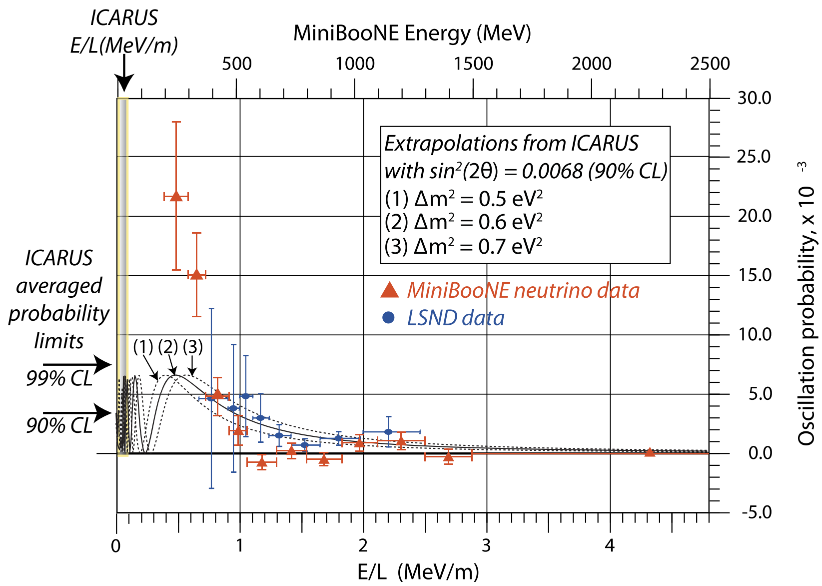

Fig. 4 Oscillation probability limits coming from the present experiment compared with corresponding data from neutrinos in MiniBooNE [8] as a function of the energy E_ν. Figure 2 in Ref. [8] has been used in order to convert the observed number of excess events/MeV to their corresponding oscillation probabilities. In order to perform the conversion, the values $\sin^2(2\theta) = 0.2$ and $\Delta m^2_{41} = 0.1\ \mathrm{eV}^2$ from Fig. 2 of Ref. [8] have been used. The resulting oscillation probability distribution for neutrino and for $E_\nu > 475$ MeV (corresponding to $E/L > 0.9$ MeV/m) appears compatible with the absence of antineutrino LNSD effect. For the $200 < E_\nu^{\mathrm{QE}} < 475$ MeV region—below the sensitive E/L region of LSND—the new MiniBooNE effect is widely incompatible with the averaged upper probability limit to anomalies from the present paper and from OPERA [25] on $\sin^2(2\theta_{\mathrm{new}})$ in their E_ν/L regions. An extrapolation from ICARUS to larger values of E_ν/L for two-neutrino oscillation parameters simultaneously compatible with LSND, MiniBooNE and Karmen is also shown as guidance

Ref. [8], converting the ratio of the excess events/MeV to the oscillation probability using their (also plotted) example of the two-neutrino model case with $\sin^2(2\theta) = 0.2$ and $\Delta m^2_{41} = 0.1\ \mathrm{eV}^2$ from Fig. 2 of [8].

The result is shown in Fig. 4. There is tension between the limits of $\sin^2(2\theta_{\mathrm{new}}) < 6.8 \times 10^{-3}$ at 90 % CL and $< 1.52 \times 10^{-2}$ at 99 % CL of the present experiment and the neutrino lowest energy points of MiniBooNE with $200 < E_\nu^{\mathrm{QE}} < 475$ MeV, suggesting an instrumental or otherwise unexplained nature of the low energy signal of Ref. [8]. Recently a similar search performed at the same CNGS beam by the OPERA experiment has confirmed our finding and the absence of anomalous oscillations with an independent limit $\sin^2(2\theta_{\mathrm{new}}) < 7.2 \times 10^{-3}$ [25].

As a conclusion, the LSND anomaly appears to be still alive and further experimental efforts are required to prove the possible existence of sterile neutrinos. The recently proposed ICARUS/NESSiE experiment at the CERN-SPS neutrino beam [26], based on two identical LAr-TPC detectors, complemented with magnetized muon spectrometers and placed at two different distances from proton target, has been designed to definitely settle the origin of these ν-related anomalies.

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