Search for anomalies in the neutrino sector with muon spectrometers and large LArTPC imaging detectors at CERN

ICARUS - NESSiE Collaborations

1. INFN, Sezione di Bari, 70126 Bari, Italy
2. Dipartimento di Fisica dell’Università di Bari, 70126 Bari, Italy
3. INFN, Sezione di Bologna, 40127 Bologna, Italy
4. Dipartimento di Fisica dell’Università di Bologna, 40127 Bologna, Italy
5. CERN, Geneva, Switzerland
6. Laboratori Nazionali di Frascati dell’INFN, 00044 Frascati (Roma), Italy
7. INFN, Sezione di Genova, 16146 Genova, Italy
8. Dipartimento di Fisica dell’Università di Genova, 16146 Genova, Italy
9. Laboratori Nazionali del Gran Sasso, INFN, 67010 Assergi (L’Aquila), Italy
10. Institute of Physics, University of Silesia, Katowice, Poland
11. Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy Science, Krakw, Poland
12. INFN, Sezione di Lecce, 73100 Lecce, Italy
13. Dipartimento di Matematica e Fisica dell’Università del Salento, 73100 Lecce, Italy
14. Dipartimento di Ingegneria dell’Innovazione dell’Università del Salento, 73100 Lecce, Italy
15. Los Alamos National Laboratory, New Mexico, USA
16. Department of Physics and Astronomy, University of California, Los Angeles, USA
17. INFN, Sezione di Milano Bicocca, Dipartimento di Fisica G. Occhialini, 20126 Milano, Italy
18. INFN, Sezione di Milano e Politecnico, 20133 Milano, Italy
19. INR-RAS, Moscow, Russia
20. INFN, Sezione di Napoli, 80126 Napoli, Italy
21. Dipartimento di Scienze Fisiche, Università Federico II, 80126 Napoli, Italy
22. INFN, Sezione di Padova, 35131 Padova, Italy
23. Dipartimento di Fisica e Astronomia dell’Università di Padova, 35131 Padova, Italy
24. INFN, Sezione di Pavia, 27100 Pavia, Italy
25. Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, 27100 Pavia, Italy
26. Dipartimento di Fisica dell’Università di Roma “La Sapienza” and INFN, 00185 Roma, Italy
27. National Center for Nuclear Research, Warszawa, Poland
28. Institute for Radioelectronics, Warsaw University of Technology, Warsaw, Poland
* Also at Centre de Recherche en Astronomie Astrophysique et Gophysique, Alger, Algeria
Introduction

The long standing series of experimental results hinting at the hypothesis of sterile neutrinos [1] deserve in our opinion a major CERN investment to definitely clarify the underlying physics.

Over the last several years, neutrinos have been the origin of an impressive number of “surprises”. Neutrino oscillations have so far established a beautiful picture, consistent with the mixing of three physical neutrino \( \nu_e, \nu_\mu \) and \( \nu_\tau \) and mass eigenstates \( \nu_1, \nu_2 \) and \( \nu_3 \). The two observed mass differences turn out to be relatively small \( \Delta m^2_{23} \approx 2.4 \times 10^{-3} \text{ eV}^2 \) and \( \Delta m^2_{21} \approx 8 \times 10^{-5} \text{ eV}^2 \). The sum of the strengths of the \( \nu_\tau \)'s has been found very near to 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. Just a few eV neutrino mass may be the source of the dark mass.

The possible presence of oscillations into sterile neutrinos was proposed by B. Pontecorvo [2], but so far without conclusion. Two distinct classes of anomalies have been reported, although not in an entirely conclusive level, namely:

- The observation of excess \( \nu_e \) electrons originated by initial \( \nu_\mu \) beam from accelerators (LSND [3] / MiniBooNE [4]). At present the LSND experiment and the MiniBooNe experiment both claim an independent 3.8 \( \sigma \) effect from standard neutrino physics. The LSND signal with anti-neutrino oscillations from an accelerator would imply an additional mass-squared difference largely in excess of the Standard Model’s values. The LSND signal (87.9 \( \pm \) 22.4 \( \pm \) 6.0) represents a 3.8 \( \sigma \) effect at L/E values of about 0.5 \( \pm \) 1.0 meter/MeV. The recent MiniBooNe result, confirming the LSND result, indicates a neutrino oscillation signal both in neutrino and antineutrino with \( \Delta m^2_{new} \sim 0.01 \) to 1.0 eV\(^2\).

- The apparent disappearance signal in the \( \tau_e \) events detected from (a) near-by nuclear reactors and (b) from Mega-Curie k-capture sources in the solar \( \nu_e \) Gallium experiments [5]. (a) Recently a re-evaluation of all the reactor antineutrino spectra has increased the flux by about 4\% and a new value of the neutron lifetime has been reported [6]. With such a new flux evaluations, the ratio between the observed and predicted rates decreased to 0.927 \( \pm \) 0.023, leading to a deviation of 3.0 \( \sigma \) from unity (99.6 \% confidence level). Reactor experiments however generally explore distances which are far away from the perspective oscillatory region with \( \Delta m^2_{new} \simeq 2 \text{ eV}^2 \), with perhaps the exception of the ILL experiment (at \( \sim 9 \) m from the source) which had unfortunately a very modest statistical impact (68\% confidence level). (b) SAGE and GALLEX experiments recorded the calibration signal produced by intense artificial k-capture sources of \( ^{51}\text{Cr} \) and \( ^{37}\text{Ar} \). The averaged ratio between the source detected and predicted neutrino rates are consistent with each other, giving (0.86 \( \pm \) 0.05), about 2.7 \( \sigma \) from unity and a broad range of values centered around \( \Delta m^2_{new} \sim 2 \text{ eV}^2 \) and \( \sin^2 2\theta_{new} \sim 0.3 \). By combining the Gallium and the reactor anomalies the non oscillation hypothesis is disfavored at 3.6 \( \sigma \).

- The existence of additional neutrino states may be also hinted – or at least not excluded – by cosmological data [7].

All recalled “anomalies” which have accumulated an impressive number of standard deviations, may indeed hint at a unified scheme in which the values of \( \Delta m^2_{new} \) may have a common origin, the different values of \( \sin^2 2\theta_{new} \) for different channels reflecting the structure of \( U_{(4,k)} \) matrix (or even with an higher number of neutrinos) with \( k = \mu \) and \( e \).

The ultimate goal is to prove the existence of additional neutrino states and the corresponding oscillation parameters. The proposed CERN experiment may be in a unique position to be able to
investigate such oscillation scenario with high sensitivity. The direct, unambiguous measurement of an oscillation pattern requires necessarily the (simultaneous) observation at least at two different positions. It is only in this way that the new values of $\Delta m^2$ and of $\sin^2 2\theta$ can be separately identified. All other experimental non accelerator programmes under investigation will not focus with an equal sensitivity to the direct parameters of the oscillation phenomenon.

The CERN experiment with the novel development of a large mass LAr-TPC – routinely operated at CNGS over the last 2.5 years and to be moved to CERN – complemented with magnetic spectrometers for the charge determination introduces new relevant features, allowing a simultaneous clarification of all the above described “anomalies”. More precisely we will provide:

- L/E oscillation path-lengths appropriate to match to the $\Delta m^2$ window for the expected anomalies;
- “imaging” detector capable to identify unambiguously all reaction channels with a “Gargamelle class” LAr-TPC;
- magnetic spectrometers able to determine muon charge with few % mis-identification and momentum in a broad range;
- clean measure of interchangeable $\nu$ and anti-$\nu$ focused beams;
- very high event rates due to large detector masses, allowing to record relevant effects at the % level ($> 10^6 \nu_\mu$ and $\simeq 10^4 \nu_\tau$);
- initial $\nu_e$ and $\nu_\mu$ components cleanly identified.

A similar LAr-TPC accelerator experiment, MicroBooNe, has been approved at FermiLab. The experiment (widely based on ICARUS experience) should start data taking around end 2014 with one single site at about 470 m from the target and $\simeq 60$ ton fiducial mass. The average neutrino beam is about 0.8 GeV and $6 \times 10^{20}$ pot in neutrino mode from the 8 GeV Booster (2-3 year run). The expected neutrino signal events at the LSND best fit ($\Delta m^2 = 1.2 \text{ eV}^2$, $\sin^2 2\theta = 0.003$ and 475-1250 MeV) are $\sim 70$ events with an expected background of 150 events. There is apparently no immediate plan to run with anti-neutrinos, since event rates will be even lower (by a factor of 37).

The FermiLab experiment should be compared to the present proposal whose $\nu_e$ background after 2 years of neutrino run, $9.0 \times 10^{19}$ pot and $E_\nu < 6$ GeV, is about 6150 events. The expected signal for $\Delta m^2 = 2.0 \text{ eV}^2$, and the smaller value of $\sin^2 2\theta = 0.002$, is $\sim 1450$ events. The huge differences in rates are mainly associated with the much greater detector mass of the CERN proposal, its simultaneous detection in two or more positions and to the higher energy of the CERN neutrino beam. Moreover in our proposal spectrometers allow $\nu_\mu$ disappearance search thereby filling in the project physics reach and to constrain systematic errors at few %level.

A Double Liquid Argon TPC “proposal” has also been visualized for FermiLab with a second 1 kton LAr detector to be constructed, but with no muon spectrometer at least to our knowledge.

The experimental proposal

We report here on the experimental proposal [5] currently under scrutiny by CERN committees. The experiment follows the setting up of a new neutrino beam at SPS in a short time schedule. We deem mandatory that both beam and experiment be ready by December 2015, in order to be competitive with the expected flow of neutrino physics results in the international landscape.

The experiment is based on two identical LAr-TPCs [6] complemented by magnetized spectrometers [7] detecting electron and muon neutrino events at Far and Near positions, 1600 m and 300 m from the proton target, respectively (Figure 1). The project will exploit the ICARUS T600 detector, the largest LAr-TPC ever built with a size of about 600 ton of imaging mass, now running in the LNGS underground laboratory exposed to the CNGS beam, moved at the CERN Far position. An additional 1/4 of the T600 detector (T150) will be constructed and located in the Near position.
Two spectrometers will be placed downstream of the two LAr-TPC detectors to greatly complement the physics capabilities. Spectrometers will exploit a classical dipole magnetic field with iron slabs, and a new concept air-magnet, to perform charge identification and muon momentum measurements from sub-GeV to several GeV energy range, over a transverse area larger than 50 m$^2$. A 3D sketch of the detector layout at the far site is shown in Figure 2.

![Figure 1: The new SPS North Area neutrino beam layout. Main parameters are: primary beam: 100 GeV; fast extracted from SPS; target station next to TCC2, ∼11 m underground; decay pipe: 100 m, 3 m diameter; beam dump: 15 m of Fe with graphite core, followed by muon stations; neutrino beam angle: pointing upwards; at ∼3 m in the far detector ∼5 mrad slope.](image)

At the two positions the energy spectra of the $\nu_e$ beam component must coincide but for second order effects which can be reliably reproduced. In absence of oscillations, since all cross sections and experimental biases cancel out, the observed event distributions at the near and far detectors must be the same. Any difference can be ascribed to the possible existence of $\nu$-oscillations due to additional neutrinos with new mixing angles $\sin^2 2\theta_{ij}$ and mass differences $\Delta m_{ij}^2$ larger than those measured in the standard three neutrino family scheme.

The superior quality of the LAr imaging TPC, now widely experimentally demonstrated, and in particular its unique electron - $\pi^0$ discrimination allows full rejection of backgrounds and offers a lossless $\nu_e$ detection capability. The determination of the muon charge with the spectrometers allows the full separation of $\nu_\mu$ from $\overline{\nu}_\mu$ and an improved control of systematics from muon mis-identification.

Two main anomalies will be explored with both neutrino and anti-neutrino focused beams. The first anomaly, emerged in radioactive sources and reactor neutrino experiments [5], could originate from $\nu_e$ ($\overline{\nu}_e$) and/or of the $\nu_\mu$ ($\overline{\nu}_\mu$) converted into “invisible” (sterile) components, leading to observation of oscillatory, distance dependent, disappearance rates. In a second anomaly (following LSND and MiniBooNE observations [4]) some distance dependent $\nu_\mu \rightarrow \nu_e$ oscillations may be observed as a $\nu_e$ excess, especially in the antineutrino channel. The disentangling of $\nu_\mu$ from $\overline{\nu}_\mu$ will allow to exploit the interplay of the different possible oscillation scenarios, as well as the interplay between disappearance and appearance of different neutrino states and flavors. Moreover the NC/CC ratio will provide a sterile neutrino oscillation signal by itself and it will beautifully complement the normalization and the systematics studies. This experiment will offer remarkable discovery potentials, collecting a very large number of unbiased events both in the neutrino and antineutrino channels, largely adequate to definitely settle the origin of the $\nu$-related anomalies.
The new SPS neutrino facility

To explore the interesting neutrino $\Delta m^2 \sim 1 \text{ eV}^2$ region the Far distance has been chosen at 1.6 km with a central value of the on-axis neutrino beam energy spectrum around $E_\nu \sim 2 \text{ GeV}$ (Figure 3). A proton beam intensity of $4.5 \times 10^{19}$ pot/year at 100 GeV energy has been assumed as a conservative reference in order to produce high intensity $\nu$ beam and to minimize the beam related background expected at the near detector located at 300 m. A fast proton extraction from the SPS is also required for the LAr-TPC operation at surface in order to effectively separate the beam related events among the cosmic ray background.

Expected sensitivities to neutrino oscillations

A complete discussion of $\nu_\mu \rightarrow \nu_e$ oscillation search both in appearance and disappearance modes is presented in the SPSC-P345 document [9], that includes the genuine event selection and background rejection in the LAr-TPC. In particular, due to the excellent $\pi^0$ to electron separation, a $\pi^0$ rejection at $10^3$ level is obtained when requiring at least 90% electron recognition efficiency. The effects of the high-energy event tail in the event selection was carefully studied: the resulting background is negligible, of the same order of the residual NC background.

In addition to the $\nu_\mu \rightarrow \nu_e$ oscillation searches, $\nu_\mu$ oscillation studies in disappearance mode are discussed at length in the SPSC-P-343 proposal [10], by using large mass spectrometers with high capabilities in charge identification and muon momentum measurement. It is important to note that all sterile neutrino models predict large $\nu_\mu$ disappearance effects together with $\nu_e$ appearance/disappearance. To fully constrain the oscillation searches, the $\nu_\mu$ disappearance mode has to has be carefully investigated. Much higher disappearance probabilities (with relative amplitudes as large as 10%) are expected than in appearance mode. The spectrometers will allow to correctly
Figure 3: Muon (left) and electron (right) neutrino CC interaction spectra, at near and far positions.

identify about 40% of all the CC events produced in, and escaped from, the LAr-TPCs, both at the near and far sites. That will greatly increase the fraction of CC events with charge identification and momentum measurement. Therefore a complete measurement of the CC event spectra will be possible, along with the measurement of the NC/CC event ratio (in synergy with the LAr-TPC), and the associated background systematics.

The large mass of the magnets (∼3 kton) will allow an internal check of the NC/CC ratio in an extended energy range, and an independent measure of the CC oscillated events.

We are sensitive to $\sin^2 2\theta$ down to $3 \times 10^{-4}$ (for $|\Delta m^2| > 1.5 \text{ eV}^2$) and $|\Delta m^2|$ down to 0.01 eV$^2$ (for $\sin^2 2\theta = 1$) at 90% C.L. for the $\nu_\mu \rightarrow \nu_e$ transition with one year exposure ($4.5 \times 10^{19}$ pot) at the CERN-SPS $\nu_\mu$ beam (Figure 4 left). The parameter space region allowed by the LSND experiment is fully covered, except for the highest $\Delta m^2$ region. The sensitivity has been computed according to the above described particle identification efficiency and assuming a 3% systematic uncertainty in the prediction of Far to Near $\nu_e$ ratio. A further control of the overall systematics will be provided by the LAr and spectrometer combined measurement of CC spectra in the near site and over the full energy range.

In anti-neutrino focusing, twice as much exposure ($0.9 \times 10^{20}$ pot) allows to cover both the LSND region and the new MiniBooNE results (Figure 4 right) [4]. Both favoured MiniBooNE parameter sets, corresponding to two different energy regions in the MiniBooNE antineutrino analysis, fall well within the reach of this proposal.

It should be remarked that the observation of the $\nu_e$ energy distribution at two different distances offers the possibility of distinguishing both the mass difference $\Delta m^2$ and the mixing angle $\sin^2 2\theta$ independently. In Figure 5 some different oscillation parameter values are identified by the electron neutrino spectrum which appears to be extremely sensitive to the actual values of LSND like $\nu_\mu \rightarrow \nu_e$ sterile neutrino events. The presence of the intrinsic $\nu_e$ beam associated background is also shown.

In Figure 6 the sensitivity for $\nu_e$ disappearance search in the $\sin^2 2\theta$, $\Delta m^2$ plane is shown for one year data taking. The oscillation parameter region related to the anomalies from the combination of the published reactor neutrino experiments, GALLEX and SAGE calibration sources experiments [5] is completely explored.

The $\nu_\mu$ disappearance signal is well studied by the spectrometers, with a very large statistics,
Figure 4: Expected sensitivity for the proposed experiment exposed at the CERN-SPS neutrino beam (left) and anti-neutrino (right) for $4.5 \times 10^{19}$ pot (1 year) and $9.0 \times 10^{19}$ pot (2 years), respectively. The LSND allowed region is fully explored in both cases.

Figure 5: The present method, unlike LSND and MiniBooNE, determines both the mass difference and the value of the mixing angle. Very different and clearly distinguishable patterns ($\star$, 1–4) are possible, depending on the values in the $(\Delta m^2 - \sin^2 2\theta)$ plane. The intrinsic $\nu_e$ background (5) is also shown.
Figure 6: Oscillation sensitivity in $\sin^2 2\theta$ vs $\Delta m^2$ distribution for 1 year data taking. A 3\% systematic uncertainty on energy spectrum is included. Combined anomalies from reactor neutrino, Gallex and Sage experiments are also shown.

Figure 7: Sensitivity plot (at 90\% C.L.) considering 3 years of the CERN-SPS beam (2 years in anti-neutrino and 1 year in neutrino mode) from CC events fully reconstructed in NESSiE+LAr. Red line: $\nu_\mu$ exclusion limit. The three filled areas correspond to the present exclusion limits on the $\nu_\mu$ from CCFR, CDHS and SciBooNE+MiniBooNE experiments (at 90\% C.L.). Orange line: recent exclusion limits on $\nu_\mu$ from MiniBooNE alone measurement.
and disentangling of $\nu_\mu$ and $\bar{\nu}_\mu$ interplay. Figure 7 shows the sensitivity plot (at 90% C.L.) for two years negative-focusing plus one year positive-focusing. A large extension of the present limits for $\nu_\mu$ by CDHS and the recent SciBooNE+MiniBooNE will be achievable in $\sin^2 2\theta$, $\Delta m^2$.

For one year of operation, either with negative or positive polarity beam, Table 1 reports the expected interaction rates in the LAr-TPCs at the near (fiducial 119 ton) and far locations (fiducial 476 ton), and the expected rates of fully reconstructed events in the NESSiE spectrometers at the near (fiducial 241 ton) and far locations (fiducial 661 ton), with and without LAr contribution. Both $\nu_e$ and $\nu_\mu$ disappearance modes will be used to add conclusive information on the sterile mixing angles as shown in the Table 2.

| Osc. type | Neutrinos | Experiments |
|-----------|-----------|-------------|
| $\theta_{12}$ | $\nu_e$ (solar, reactors) | SNO, SK, Borexino, Kamland |
| $\theta_{23}$ | $\nu_\mu$ (atmospheric, accelerators) | SK, Minos, T2K |
| $\theta_{13}$ | $\nu_e$ (reactors) | Daya Bay, Reno, Double Chooz |
| $\theta_{14}$ | $\nu_e$ (reactors, radioactive sources) | SBL Reactors, Gallex, Sage. **This Proposal** |
| $\theta_{24}$ | $\nu_\mu$ (accelerators) | CDHS, MiniBooNE. **This Proposal** |

**Table 1:** The expected rates of interaction (LAr) and reconstructed (NESSiE) events for 1 year of operation. Values for $\Delta m^2$ around 2 eV$^2$ are reported as example.

| Osc. type | Neutrinos | Experiments |
|-----------|-----------|-------------|
| $\theta_{12}$ | $\nu_e$ (solar, reactors) | SNO, SK, Borexino, Kamland |
| $\theta_{23}$ | $\nu_\mu$ (atmospheric, accelerators) | SK, Minos, T2K |
| $\theta_{13}$ | $\nu_e$ (reactors) | Daya Bay, Reno, Double Chooz |
| $\theta_{14}$ | $\nu_e$ (reactors, radioactive sources) | SBL Reactors, Gallex, Sage. **This Proposal** |
| $\theta_{24}$ | $\nu_\mu$ (accelerators) | CDHS, MiniBooNE. **This Proposal** |

**Table 2:** Measurements of the mixing angle as provided by different experiments.
References

[1] K.N. Abazajian et al., “Light Sterile neutrinos: a White Paper”, arXiv:1204.5379.

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

[3] A. Aguilar et al. (LSND Collaboration), Phys. Rev. D 64, 112007 (2001);

[4] A. A. Aguilar-Arevalo (MiniBooNE Collaboration), Phys. Rev. Lett. 102, 101802 (2009); A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), arXiv:1007.1150
F.Mills, ICHEP 2010, Paris, France; R. Van de Water, Neutrino 2010, Athens, Greece; E.D. Zimmerman, PANIC 2011, Cambridge, U.S.A.;
A. A. Aguilar-Arevalo (MiniBooNE Collaboration), arXiv:1207.4809.

[5] J. N. Abdurashitov et al. (SAGE Collaboration), Phys. Rev. C 80, 015807 (2009); J. N. Abdurashitov et al. (SAGE Collaboration), Phys. Rev. Lett. 77, 4708 (1996); J. N. Abdurashitov et al. (SAGE Collaboration), Phys. Rev. C 59, 2246 (1999); J. N. Abdurashitov et al., Phys. Rev. C 73, 045805 (2006); F. Kaether, W. Hampel, G. Heusser, J. Kiko, and T. Kirsten, Phys. Lett. B 685, 47 (2010); P. Anselmann et al. (GALLEX Collaboration), Phys. Lett. B 342, 440 (1995); W. Hampel et al. (GALLEX Collaboration), Phys. Lett. B 420, 114 (1998).

[6] G. Mention, et al., Phys.Rev. D83 (2011) 073006 and previous references therein.
D. Lhuiller and T. Lasserre, Talks to Neutrino 2012 Conference, Kyoto (Japan).

[7] E. Komatsu et al., Astrophys. Jour. Suppl.192:18,2011; J. Dunkley et al., Astrophys. Jour., 749 (2012) 90; J. Hamann et al., Phys. Rev. Lett.105:181301,2010; Y. I. Izotov, T. X. Thuan, Astrophys. Jour. Lett. 710 (2010) L67-L71.

[8] M. Antonello et al., “Search for anomalies from neutrino and anti-neutrino oscillations at $\Delta m^2 \sim 1 \text{ eV}^2$ with muon spectrometers and large LArTPC imaging detectors”, SPSC-P-347 (2012).

[9] C. Rubbia et al., “A comprehensive search for anomalies from neutrino and anti-neutrino oscillations at large mass differences ($\Delta m^2 \sim 1 \text{ eV}^2$) with two LArTPC imaging detectors at different distances from the CERN-PS”, SPSC-P-345 (2011).
C. Rubbia et al., ICARUS/CNGS2 Collaboration, “Physics Programme for ICARUS after 2012”, SPSC-M773 (2011).

[10] P. Bernardini et al., “Prospect for Charge Current Neutrino Interactions Measurements at the CERN-PS”, SPSC-P-343 (2011).

[11] Some relevant papers are the following: J. Kopp, M. Maltoni, and T. Schwetz, Are there Sterile-Neutrinos at the eV scale?, arXiv:1103.4570 (2011); Giunti, C. and Laveder, M., 3+1 and 3+2 Sterile Neutrino Fits, arXiv:1107.1452 (hep-ph), 2011.