Limits on muon-neutrino to tau-neutrino oscillations induced by a sterile neutrino state obtained by OPERA at the CNGS beam

The OPERA collaboration

E-mail: alessandro.paoloni@lnf.infn.it, alessandra.pastore@ba.infn.it

ABSTRACT: The OPERA experiment, exposed to the CERN to Gran Sasso ν_μ beam, collected data from 2008 to 2012. Four oscillated ν_τ Charged Current interaction candidates have been detected in appearance mode, which are consistent with $\nu_\mu \to \nu_\tau$ oscillations at the atmospheric Δm^2 within the "standard" three-neutrino framework. In this paper, the OPERA ν_τ appearance results are used to derive limits on the mixing parameters of a massive sterile neutrino.

Contents

1 Introduction

The OPERA experiment [1] operated in the CERN Neutrinos to Gran Sasso (CNGS) beam produced at CERN and directed towards the Gran Sasso Underground Laboratory of INFN (LNGS), 730 km away, where the detector is located. The experiment is unique in its capability to observe ν_τ appearance on an event-by-event basis. Nuclear emulsion films instrumenting the target allow the detection of the short-lived τ lepton decay, and hence the identification of ν_τ Charged Current (CC) interactions. The standard three-neutrino oscillation framework predicts $\nu_\mu \to \nu_\tau$ oscillations with close-to-maximal mixing at the so-called atmospheric scale, $\Delta m_{32}^2 \sim 2.4 \times 10^{-3}$ eV^2 [2], i.e. in the oscillation parameters region discovered by detecting atmospheric neutrinos [3]. OPERA has observed four ν_τ CC interaction candidate events [4–7], consistent with the expectation of the standard oscillation framework at this scale. This result represents the first direct evidence of $\nu_\mu \to \nu_\tau$ oscillation in appearance mode.

In the present paper, limits are derived on the existence of a massive sterile neutrino. The excess of ν_e ($\overline{\nu}_e$) observed by the LSND [8] and MiniBooNE [9] collaborations and the so-called reactor [10] and Gallium [11, 12] neutrino anomalies are also interpreted as due to the existence of a fourth sterile neutrino with mass at the eV scale. In relation to this issue, it is worth mentioning that the effective number of neutrino-like species decoupled from the primeval plasma measured by the Planck collaboration is 3.15 ± 0.23 at 95% Confidence Level (CL) [13].

Neutrino oscillations at large Δm^2 have been searched for by several short baseline experiments. The most stringent limits on $\nu_\mu \to \nu_\tau$ oscillations were set by the NOMAD [14] and CHORUS [15] experiments, with high sensitivity for Δm^2 values larger than 10 eV^2.

In the following, a short description of the OPERA experimental setup and of the procedure used to detect ν_τ interactions is given, the data analysis is described and exclusion regions in the parameter space are derived.
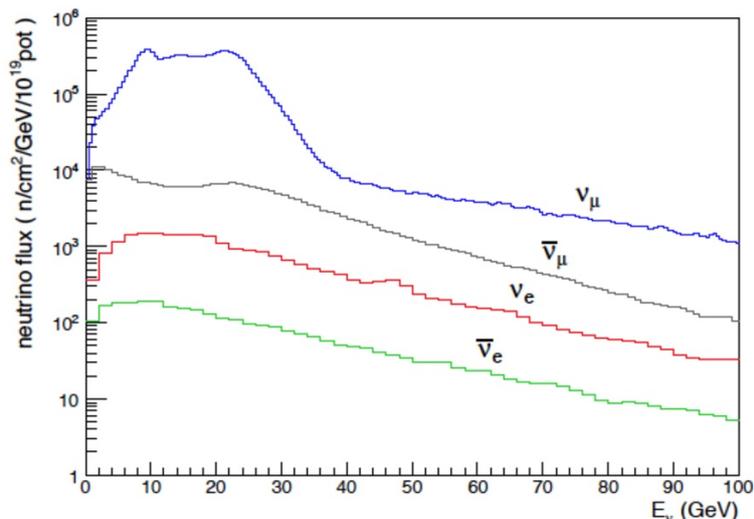
Figure 1. Fluxes of the different CNGS beam neutrino components at LNGS.

2 Detector, beam, and data sample

In OPERA, CNGS neutrinos interacted in a massive target made of lead plates interspaced with nuclear emulsion films acting as high accuracy tracking devices [16]. This kind of detector is historically called *Emulsion Cloud Chamber* (ECC). The OPERA detector is made of two identical Super Modules, each consisting of a target section and a muon magnetic spectrometer. Each target section has a mass of about 625 tons and is made of ∼75000 units called *bricks*. A target brick consists of 56 lead plates 1mm-thick interleaved with 57 nuclear emulsion films 300 μm-thick for a mass of 8.3 kg. Its total thickness along the beam direction corresponds to about 10 radiation lengths. The bricks are assembled in vertical walls instrumented with scintillator strips (*Target Tracker* detectors, TT) to trigger the read-out and locate neutrino interactions within the target.

OPERA was exposed to the CNGS ν_μ beam generated by protons from the SPS accelerator at CERN [17, 18]. The contaminations of $\overline{\nu}_\mu$, ν_e and $\overline{\nu}_e$ CC interactions at LNGS, relative to ν_μ CC interactions, are 2.1%, 0.9% and less than 0.1%, respectively. The contamination of prompt ν_τ is negligible. The average ν_μ energy is 17 GeV. The energy spectra of the four beam components at the detector site are shown in figure 1 [19].

The data taking, based on a minimum bias interaction trigger from the TT scintillators, started in 2008 and ended in December 2012. OPERA collected data corresponding to 17.97×10^{19} protons on target (pot) with 19505 recorded events. The data sample used in this analysis is defined following the selection criteria described in [5] and corresponds to about 75% of the total statistics.

3 Search for ν_τ interactions

Bricks selected as candidates to contain CNGS neutrino interactions are analysed following the procedure described in detail in [5]. Here we just recall the main steps of the analysis.

The brick where a neutrino interaction occurred is predicted by the electronic detectors and extracted from the target by an automatic brick manipulator system. Two extra low background emulsion films (*Changeable Sheets*, CS) [20] located downstream of the brick act as an interface between the brick and the electronic detectors. If the measurement of the CS yields tracks related to the neutrino interaction, the emulsion films of the brick are developed. Their analysis provides the three dimensional reconstruction of the neutrino interaction and of the possible decay vertices of short-lived particles [21] with micrometric accuracy.

This procedure has led to the detection of four ν_τ CC interaction candidates. The total expected background in the analysed sample amounts to 0.23 ± 0.05 events. The absence of a $\nu_\mu \to \nu_\tau$ oscillation signal, i.e. the hypothesis of the four events being background, is excluded with a significance of 4.2 σ [7].

4   Sterile neutrino search via $\nu_\mu \to \nu_\tau$ oscillations

In [7] the detection of four ν_τ CC events is compared to the expectation for $\nu_\mu \to \nu_\tau$ oscillations in the atmospheric sector, computed within a simplified two-flavour scheme assuming full mixing and $|\Delta m_{32}^2| = 2.32 \times 10^{-3}$ eV^2 [22]. The expected number of events is 2.30 ± 0.46 (2.21 ± 0.44) assuming normal (inverted) hierarchy of neutrino masses; the number is obtained by rescaling the value given in [7] for $|\Delta m_{32}^2| \approx |\Delta m_{31}^2| \approx |\Delta m^2| = 2.43 \times 10^{-3}$ eV^2 ($|\Delta m^2| = 2.38 \times 10^{-3}$ eV^2) [2], where Δm^2 is defined as $m_3^2 - \frac{(m_1^2 + m_2^2)}{2}$. By including the background, 2.53 ± 0.46 (2.44 ± 0.44) events are expected in total. The error, which is dominated by the uncertainty on the τ detection efficiency and on the ν_τ interaction cross section, also takes into account the experimental precision on the atmospheric oscillation parameters. The observation of four events is compatible with these expectations. Despite the limited statistics, an excess or a deficit of ν_τ interactions due to $\nu_\mu \to \nu_\tau$ oscillations induced by the mixing with a sterile neutrino can be evaluated.

In presence of a fourth sterile neutrino with mass m_4, the oscillation probability is a function of the 4×4 mixing matrix U and of the three squared mass differences. Defining $C = 2|U_{\mu 3}||U_{\tau 3}|$, $\Delta_{ij} = 1.27 \ \Delta m_{ij}^2 \ L/E$ ($i,j = 1,2,3,4$), $\phi_{\mu\tau} = \ Arg(U_{\mu 3} U_{\tau 3}^* U_{\mu 4}^* U_{\tau 4})$ and $\sin 2\theta_{\mu\tau} = 2|U_{\mu 4}||U_{\tau 4}|$, the $\nu_\mu \to \nu_\tau$ oscillation probability $P(E)$ can be parametrised as:

$$
\begin{aligned}
P(E) \ = \ & C^2 \ \sin^2 \Delta_{31} \ + \ \sin^2 2\theta_{\mu\tau} \ \sin^2 \Delta_{41} \\
& + \ \frac{1}{2} \ C \ \sin 2\theta_{\mu\tau} \ \cos \phi_{\mu\tau} \ \sin 2\Delta_{31} \ \sin 2\Delta_{41} \\
& - \ C \ \sin 2\theta_{\mu\tau} \ \sin \phi_{\mu\tau} \ \sin^2 \Delta_{31} \ \sin 2\Delta_{41} \\
& + \ 2 \ C \ \sin 2\theta_{\mu\tau} \ \cos \phi_{\mu\tau} \ \sin^2 \Delta_{31} \ \sin^2 \Delta_{41} \\
& + \ C \ \sin 2\theta_{\mu\tau} \ \sin \phi_{\mu\tau} \ \sin 2\Delta_{31} \ \sin^2 \Delta_{41}
\end{aligned}
\tag{4.1}
$$

where Δm_{31}^2 and Δm_{41}^2 are expressed in eV^2, L in km and E in GeV. Given the long baseline and the average CNGS neutrino energy, $P(E)$ is independent of Δm_{21}^2, since $\Delta_{21} \approx 4 \times 10^{-3}$. The terms proportional to $\sin \phi_{\mu\tau}$ are CP-violating, while those proportional to $\sin 2\Delta_{31}$ are sensitive to the mass hierarchy of the three standard neutrinos, normal ($\Delta m_{31}^2 > 0$) or inverted ($\Delta m_{31}^2 < 0$). Matter effects have been checked to be negligible for $\Delta m_{41}^2 > 1$ eV^2.

Observed neutrino oscillation anomalies [23], if interpreted in terms of one additional sterile neutrino, suggest $|\Delta m_{41}^2|$ values at the eV^2 scale (the so-called 3+1 model). In the following, unless stated otherwise, the analysis will be restricted only to positive Δm_{41}^2 values, since negative values are disfavoured by results on the sum of neutrino masses from cosmological surveys [13]. For $\Delta m_{41}^2 > 1$ eV^2, at the concerned domain of L/E and taking into account the finite energy resolution, $\sin 2\,\Delta_{41}$ and $\sin^2 \Delta_{41}$ average to 0 and $\frac{1}{2}$, respectively. The oscillation probability $P(E)$ can thus be approximated to [23]:

$$
\begin{aligned}
P(E) \;=\; & C^2 \; \sin^2 \Delta_{31} \;+\; \frac{1}{2} \; \sin^2 2\theta_{\mu\tau} \\
& +\; C \; \sin 2\theta_{\mu\tau} \; \cos\phi_{\mu\tau} \; \sin^2 \Delta_{31} \\
& +\; \frac{1}{2} \, C \; \sin 2\theta_{\mu\tau} \; \sin\phi_{\mu\tau} \; \sin 2\Delta_{31}.
\end{aligned}
\tag{4.2}
$$

In order to obtain an upper limit on $\sin^2 2\theta_{\mu\tau}$ at high values of Δm_{41}^2, the likelihood is defined as $L(\phi_{\mu\tau}, \sin^2 2\theta_{\mu\tau}, C^2) = e^{-\mu} \mu^n/n!$, where $n = 4$ is the number of ν_τ candidate events and μ is the expected number of events, $\mu \;=\; n_b \;+\; A \int \phi(E)P(E)\sigma(E)\epsilon(E)\, dE$. $n_b = 0.23$ is the expected number of background events [7], $\phi(E)$ is the ν_μ flux shown in figure 1, $P(E)$ is the oscillation probability given by equations (4.1) or (4.2), $\sigma(E)$ is the ν_τ CC interaction cross section, $\epsilon(E)$ is the τ detection efficiency and A is a normalisation factor proportional to the fraction of the analysed sample and to the target mass.

The analysis presented here is based on the asymptotic χ^2 distribution of the log likelihood ratio test statistics: $q \;=\; -2 \; \ln(\widetilde{L}(\phi_{\mu\tau}, \sin^2 2\theta_{\mu\tau})/L_0)$, where $L_0 = e^{-n} \, n^n/n!$ and $\widetilde{L}(\phi_{\mu\tau}, \sin^2 2\theta_{\mu\tau})$ is the profile likelihood obtained by maximising $L(\phi_{\mu\tau}, \sin^2 2\theta_{\mu\tau}, C^2)$ over C^2. By definition, C^2 ranges between 0 and 1, but for any pair of values of $\sin^2 2\theta_{\mu\tau}$ and $\phi_{\mu\tau}$, it is limited by the unitarity of the mixing matrix; the likelihood is maximised accordingly. The value of $|\Delta m_{31}^2|$ has been fixed to 2.43×10^{-3} eV^2 for the normal hierarchy and to 2.38×10^{-3} eV^2 for the inverted hierarchy of the three standard neutrinos [2].

In figure 2(a) the 90% CL exclusion limits are presented for both normal and inverted mass hierarchies in the parameter space of $\phi_{\mu\tau}$ vs $\sin^2 2\theta_{\mu\tau}$. The edge of the excluded region ranges from 0.088 to 0.136 in $\sin^2 2\theta_{\mu\tau}$ for both mass hierarchies of the three standard neutrinos. For any fixed value of $\phi_{\mu\tau}$, q is distributed according to a χ^2 statistics with one degree of freedom. Profiling the likelihood also over $\phi_{\mu\tau}$, as shown in figure 2(b), an upper limit of 0.116 is obtained at 90% CL on $\sin^2 2\theta_{\mu\tau}$, almost independently of the hierarchy of the three standard neutrino masses. A negligible difference arises from the different $|\Delta m_{31}^2|$ value used in the analysis. The $\sin^2 2\theta_{\mu\tau}$ upper limit is affected by a 20% systematic error from the uncertainties on the τ detection efficiency and ν_τ interaction cross section.

Given the definition of $\sin^2 2\theta_{\mu\tau}$ in terms of $U_{\mu4}$ and $U_{\tau4}$, it is possible to translate the upper limit on $\sin^2 2\theta_{\mu\tau}$ into an exclusion curve in the $|U_{\mu4}|^2$ vs $|U_{\tau4}|^2$ plane, as shown in figure 3 together with the unitarity bound ($|U_{\mu4}|^2 + |U_{\tau4}|^2 \leq 1$).

A review of experimental neutrino oscillation results, interpreted in terms of $|U_{\mu4}|^2$ and $|U_{\tau4}|^2$ in the range $0.1 < \Delta m_{41}^2 < 10$ eV^2 can be found in [23]; in addition, the Super-Kamiokande collaboration recently published new limits based on the analysis of atmospheric neutrinos [24]. $|U_{\mu4}|^2$ is constrained by muon (anti-)neutrino disappearance experi-
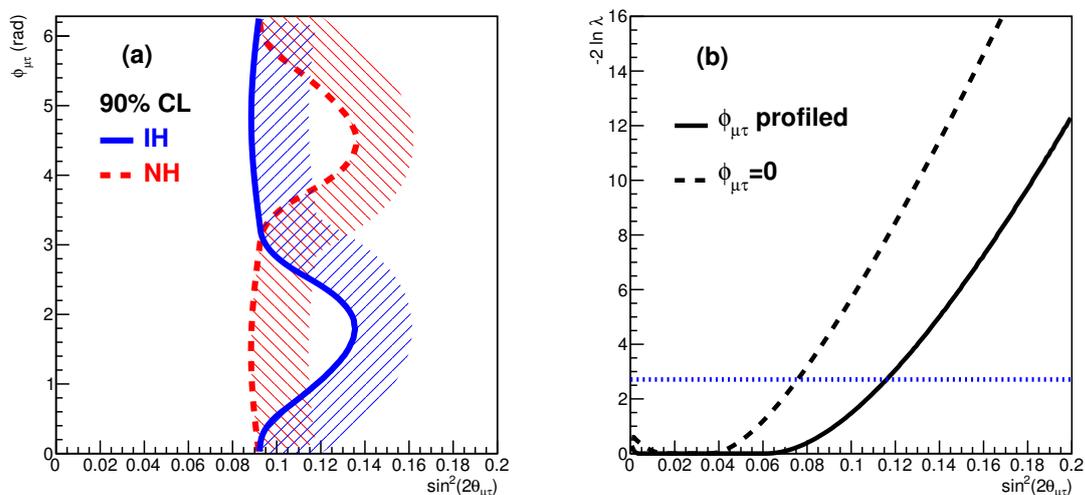
Figure 2. (a) 90% CL exclusion limits in the $\phi_{\mu\tau}$ vs $\sin^2 2\theta_{\mu\tau}$ parameter space for normal (NH, dashed red) and inverted (IH, solid blue) hierarchies assuming $\Delta m_{41}^2 > 1$ eV^2. Bands are drawn to indicate the excluded regions. (b) Log likelihood ratio as a function of $\sin^2 2\theta_{\mu\tau}$ for $\phi_{\mu\tau} = 0$ (dashed line) and for the profile likelihood (continuous line).
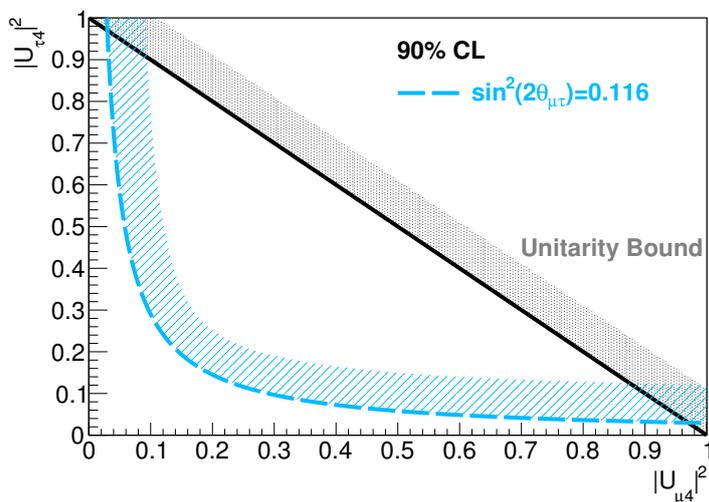
Figure 3. 90% CL exclusion limits (blue line) in the $|U_{\tau 4}|^2$ vs $|U_{\mu 4}|^2$ plane assuming $\Delta m_{41}^2 > 1$ eV^2. The unitarity bound (grey line) is also shown. Bands are drawn to indicate the excluded regions.
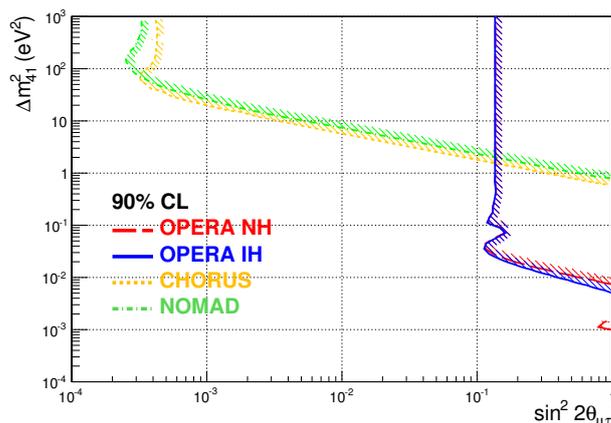
Figure 4. OPERA 90% CL exclusion limits in the Δm_{41}^2 vs $\sin^2 2\theta_{\mu\tau}$ parameter space for the normal (NH, dashed red) and inverted (IH, solid blue) hierarchy of the three standard neutrino masses. The exclusion plots by NOMAD [14] and CHORUS [15] are also shown. Bands are drawn to indicate the excluded regions.

ments: CDHS [25], CCFR [26], MiniBooNE+SciBooNE [27] and MINOS [28], as well as by Super-Kamiokande [24]. Limits on $|U_{\tau 4}|^2$ have been derived from the MINOS results on the neutral current interaction rate comparison between the near and the far detector [29] and more recently by the Super-Kamiokande analysis on matter effects for up-going atmospheric neutrinos [24]. As a consequence, for $\Delta m_{41}^2 > 0.1$ eV^2, the 90% CL limits are $\mathcal{O}(10^{-2})$ on $|U_{\mu 4}|^2$ and 0.18 on $|U_{\tau 4}|^2$, the latter being dominated by the Super-Kamiokande results.

To extend the search for a possible fourth sterile neutrino down to small Δm_{41}^2 values, the likelihood has been computed using the GLoBES software [30, 31], which takes into account the non-zero Δm_{21}^2 value and also matter effects, the Earth density being approximated by a constant value estimated with the PREM [32, 33] onion shell model. The likelihood has been profiled also on the Δm_{31}^2 value. More details on the analysis are available in [34]. In figure 4 the 90% CL exclusion plot is reported in the Δm_{41}^2 vs $\sin^2 2\theta_{\mu\tau}$ parameter space. The most stringent limits of direct searches for $\nu_\mu \to \nu_\tau$ oscillations at short-baselines obtained by the NOMAD [14] and CHORUS [15] experiments are also shown. Our analysis stretches the limits on Δm_{41}^2 down to 10^{-2} eV^2, extending the values explored with the τ appearance searches by about two orders of magnitude at large mixing, for $\sin^2 2\theta_{\mu\tau} \gtrsim 0.5$. For maximal mixing, the 90% CL excluded region extends down to $\Delta m_{41}^2 = 7.4$ (5.2) $\times 10^{-3}$ eV^2 for normal (inverted) hierarchy of the three standard neutrino masses, with a 10% systematic error deriving from the uncertainties on the τ detection efficiency and ν_τ interaction cross section.

A narrow region is excluded at 90% CL at $\Delta m_{41}^2 \approx 10^{-3}$ eV^2 for the normal hierarchy of the three standard neutrinos. It arises from a suppression of the $\nu_\mu \to \nu_\tau$ oscillation probability due to the presence of the sterile neutrino. Instead, the oscillation probability is enhanced at full mixing and high Δm_{41}^2 values. For a number of τ neutrino candidates equal to the expectation in the three neutrino framework, the excluded region at $\Delta m_{41}^2 \approx 10^{-3}$ eV^2 would disappear.

The analysis was performed assuming $\Delta m_{41}^2 > 0$. Since present limits on the sum of neutrino masses from cosmological surveys do not exclude small negative values for Δm_{41}^2, the analysis was repeated following this assumption. The exclusion plots obtained in this way are similar to those of figure 4, but with hierarchies exchanged. It is worth underlining that the results obtained in the 3+1 model, shown in figures 2 and 3, are independent of the sign of Δm_{41}^2, as is the probability in equation (4.2).

Assuming CP conservation, that implies $\sin \phi_{\mu\tau} = 0$, and neglecting terms in $\sin^2 \Delta_{31}$ in equation (4.1), of the order of 10^{-2} at CNGS energies E_{CNGS}, the oscillation probability at high values of Δm_{41}^2 approximates to that of a two-flavour model parametrised in terms of two effective mixing parameters, θ_{eff} and Δm_{eff}^2:

$$\lim_{E \to E_{CNGS}} P(E|CP \text{ conservation}) \approx \sin^2 2\theta_{\text{eff}} \cdot sin^2(1.27 \; \Delta m_{\text{eff}}^2 \; L/E)$$

In this framework, with 4 observed events and 2.53 ± 0.46 events expected from the normal hierarchy of standard oscillations, including background, the upper limit on the number of additional ν_τ events, evaluated in the Feldman-Cousins approach [35], is 6.4 at 90% CL. The upper limit on $\sin^2 2\theta_{\text{eff}}$ is 0.069, to be compared with 0.076 for $\sin^2 2\theta_{\mu\tau}$ at $\phi_{\mu\tau} = 0$ (see figure 2(b)).

5 Conclusions

The OPERA experiment was designed to observe $\nu_\mu \to \nu_\tau$ oscillations through ν_τ appearance at a baseline of 730 km in the CNGS beam. Exploiting its unique capability to identify τ neutrino interactions, OPERA has observed four ν_τ CC candidate interactions, consistent with the expected number of oscillation events in the standard three-neutrino framework, 2.30 ± 0.46 (2.21 ± 0.44), for the normal (inverted) mass hierarchy and 0.23 ± 0.05 background events.

In this paper we present limits on the existence of a sterile neutrino in the 3+1 neutrino model. At high values of Δm_{41}^2, the measured 90% CL upper limit on the mixing term $\sin^2 2\theta_{\mu\tau} = 4|U_{\mu4}|^2|U_{\tau4}|^2$ is 0.116, independently of the mass hierarchy of the three standard neutrinos. The OPERA experiment extends the exclusion limits on Δm_{41}^2 in the $\nu_\mu \to \nu_\tau$ appearance channel down to values of 10^{-2} eV^2 at large mixing for $\sin^2 2\theta_{\mu\tau} \gtrsim 0.5$.

References

[1] OPERA collaboration, R. Acquafredda et al., *The OPERA experiment in the CERN to Gran Sasso neutrino beam*, 2009 *JINST* **4** P04018 [INSPIRE].

[2] PARTICLE DATA GROUP collaboration, K.A. Olive et al., *Review of particle physics*, *Chin. Phys.* **C 38** (2014) 090001 [INSPIRE].

[3] SUPER-KAMIOKANDE collaboration, Y. Fukuda et al., *Evidence for oscillation of atmospheric neutrinos*, *Phys. Rev. Lett.* **81** (1998) 1562 [hep-ex/9807003] [INSPIRE].

[4] OPERA collaboration, N. Agafonova et al., *Observation of a first ν_τ candidate in the OPERA experiment in the CNGS beam*, *Phys. Lett.* **B 691** (2010) 138 [arXiv:1006.1623] [INSPIRE].

[5] OPERA collaboration, N. Agafonova et al., *New results on $\nu_\mu \to \nu_\tau$ appearance with the OPERA experiment in the CNGS beam*, *JHEP* **11** (2013) 036 [*Erratum ibid.* **04** (2014) 014] [arXiv:1308.2553] [INSPIRE].

[6] OPERA collaboration, N. Agafonova et al., *Evidence for $\nu_\mu \to \nu_\tau$ appearance in the CNGS neutrino beam with the OPERA experiment*, *Phys. Rev.* **D 89** (2014) 051102 [arXiv:1401.2079] [INSPIRE].

[7] OPERA collaboration, N. Agafonova et al., *Observation of τ neutrino appearance in the CNGS beam with the OPERA experiment*, *Prog. Theor. Exp. Phys.* **2014** (2014) 101C01 [arXiv:1407.3513] [INSPIRE].

[8] LSND collaboration, A. Aguilar-Arevalo et al., *Evidence for neutrino oscillations from the observation of $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam*, *Phys. Rev.* **D 64** (2001) 112007 [hep-ex/0104049] [INSPIRE].

[9] MINIBOONE collaboration, A.A. Aguilar-Arevalo et al., *Improved search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations in the MiniBooNE experiment*, *Phys. Rev. Lett.* **110** (2013) 161801 [arXiv:1207.4809] [INSPIRE].

[10] G. Mention et al., *The reactor antineutrino anomaly*, *Phys. Rev.* **D 83** (2011) 073006 [arXiv:1101.2755] [ɪɴSPIRE].

[11] M.A. Acero, C. Giunti and M. Laveder, *Limits on ν_e and $\bar{\nu}_e$ disappearance from Gallium and reactor experiments*, *Phys. Rev.* **D 78** (2008) 073009 [arXiv:0711.4222] [ɪɴSPIRE].

[12] C. Giunti and M. Laveder, *Statistical significance of the Gallium anomaly*, *Phys. Rev.* **C 83** (2011) 065504 [arXiv:1006.3244] [ɪɴSPIRE].

[13] PLANCK collaboration, P.A.R. Ade et al., *Planck 2015 results. XIII. Cosmological parameters*, [arXiv:1502.01589] [ɪɴSPIRE].

[14] NOMAD collaboration, P. Astier et al., *Final NOMAD results on $\nu_\mu \to \nu_\tau$ and $\nu_e \to \nu_\tau$ oscillations including a new search for ν_τ appearance using hadronic τ decays*, *Nucl. Phys.* **B 611** (2001) 3 [hep-ex/0106102] [ɪɴSPIRE].

[15] CHORUS collaboration, E. Eskut et al., *Final results on $\nu_\mu \to \nu_\tau$ oscillation from the CHORUS experiment*, *Nucl. Phys.* **B 793** (2008) 326 [arXiv:0710.3361] [ɪɴSPIRE].

[16] N. Agafonova et al., *The detection of neutrino interactions in the emulsion/lead target of the OPERA experiment*, 2009 *JINST* **4** P06020 [arXiv:0903.2973] [ɪɴSPIRE].

[17] K. Elsener, *The CERN neutrino beam to Gran Sasso (NGS): conceptual technical design*, CERN-98-02, CERN, Geneva Switzerland (1998) [INFN-AE-98-05].

[18] R. Bailey et al., *The CERN Neutrino beam to Gran Sasso (NGS): addendum to report no. CERN-98-02, INFN-AE-98-05*, CERN-SL-99-034(DI), CERN, Geneva Switzerland (1999) [INFN-AE-99-05].

[19] *CNGS neutrino flux calculations webpage*, http://www.mi.infn.it/∼psala/Icarus/cngs.html.

[20] OPERA collaboration, A. Anokhina et al., *Emulsion sheet doublets as interface trackers for the OPERA experiment*, 2008 *JINST* **3** P07005 [arXiv:0804.1985] [ɪɴSPIRE].

[21] OPERA collaboration, N. Agafonova et al., *Procedure for short-lived particle detection in the OPERA experiment and its application to charm decays*, *Eur. Phys. J.* **C 74** (2014) 2986 [arXiv:1404.4357] [ɪɴSPIRE].

[22] PARTICLE DATA GROUP collaboration, J. Beringer et al., *Review of particle physics (RPP)*, *Phys. Rev.* **D 86** (2012) 010001 [ɪɴSPIRE].

[23] J. Kopp, P.A.N. Machado, M. Maltoni and T. Schwetz, *Sterile neutrino oscillations: the global picture*, *JHEP* **05** (2013) 050 [arXiv:1303.3011] [ɪɴSPIRE].

[24] SUPER-KAMIOKANDE collaboration, K. Abe et al., *Limits on sterile neutrino mixing using atmospheric neutrinos in Super-Kamiokande*, *Phys. Rev.* **D 91** (2015) 052019 [arXiv:1410.2008] [ɪɴSPIRE].

[25] F. Dydak et al., *A search for ν_μ oscillations in the Δm^2 range $0.3\,\mathrm{eV}^2$ to $90\,\mathrm{eV}^2$*, *Phys. Lett.* **B 134** (1984) 281 [ɪɴSPIRE].

[26] I.E. Stockdale et al., *Limits on muon neutrino oscillations in the mass range $55\,\mathrm{eV}^2 < \Delta m^2 < 800\,\mathrm{eV}^2$*, *Phys. Rev. Lett.* **52** (1984) 1384 [ɪɴSPIRE].

[27] MINIBOONE and SCIBOONE collaborations, G. Cheng et al., *Dual baseline search for muon antineutrino disappearance at $0.1\,\mathrm{eV}^2 < \Delta m^2 < 100\,\mathrm{eV}^2$*, *Phys. Rev.* **D 86** (2012) 052009 [arXiv:1208.0322] [ɪɴSPIRE].

[28] MINOS collaboration, P. Adamson et al., *Search for sterile neutrino mixing in the MINOS long baseline experiment*, *Phys. Rev.* **D 81** (2010) 052004 [arXiv:1001.0336] [ɪɴSPIRE].

[29] MINOS collaboration, P. Adamson et al., *Active to sterile neutrino mixing limits from neutral-current interactions in MINOS*, *Phys. Rev. Lett.* **107** (2011) 011802 [arXiv:1104.3922] [INSPIRE].

[30] P. Huber, M. Lindner and W. Winter, *Simulation of long-baseline neutrino oscillation experiments with GLoBES (General Long Baseline Experiment Simulator)*, *Comput. Phys. Commun.* **167** (2005) 195 [hep-ph/0407333] [INSPIRE].

[31] P. Huber, J. Kopp, M. Lindner, M. Rolinec and W. Winter, *New features in the simulation of neutrino oscillation experiments with GLoBES 3.0: General Long Baseline Experiment Simulator*, *Comput. Phys. Commun.* **177** (2007) 432 [hep-ph/0701187] [INSPIRE].

[32] A.M. Dziewonski and D.L. Anderson, *Preliminary reference earth model*, *Phys. Earth Planet. Interiors* **25** (1981) 297 [INSPIRE].

[33] F.D. Stacey, *Physics of the earth*, 2nd ed., Wiley, U.S.A. (1977).

[34] S. Dusini et al., *Search for sterile neutrino mixing in the $\nu_\mu \to \nu_\tau$ appearance channel with the OPERA detector*, http://operaweb.lngs.infn.it/Opera/publicnotes/OPERA-public-note-175.pdf.

[35] G.J. Feldman and R.D. Cousins, *A unified approach to the classical statistical analysis of small signals*, *Phys. Rev.* **D 57** (1998) 3873 [physics/9711021] [INSPIRE].

The OPERA collaboration

N. Agafonova,[a] A. Aleksandrov,[b] A. Anokhina,[c] S. Aoki,[d] A. Ariga,[e] T. Ariga,[e] D. Bender,[f]
A. Bertolin,[g] I. Bodnarchuk,[h] C. Bozza,[i] R. Brugnera,[g,j] A. Buonaura,[b,k] S. Buontempo,[b]
B. Büttner,[l] M. Chernyavsky,[m] A. Chukanov,[h] L. Consiglio,[b] N. D'Ambrosio,[n] G. De Lellis,[b,k]
M. De Serio,[o,p] P. Del Amo Sanchez,[q] A. Di Crescenzo,[b] D. Di Ferdinando,[r] N. Di Marco,[n]
S. Dmitrievski,[h] M. Dracos,[s] D. Duchesneau,[q] S. Dusini,[g] T. Dzhatdoev,[c] J. Ebert,[l]
A. Ereditato,[e] R. A. Fini,[p] T. Fukuda,[t] G. Galati,[b,k] A. Garfagnini,[i] J. Goldberg,[v]
Y. Gornushkin,[h] G. Grella,[i] A.M. Guler,[f] C. Gustavino,[w] C. Hagner,[l] T. Hara,[d]
A. Hollnagel,[l] B. Hosseini,[b,k] K. Ishiguro,[x] K. Jakovcic,[y] C. Jollet,[s] C. Kamiscioglu,[f]
M. Kamiscioglu,[f] J. H. Kim[z] S. H. Kim, [z,1] N. Kitagawa,[x] B. Klicek,[y] K. Kodama,[aa]
M. Komatsu,[x] U. Kose, [g,2] I. Kreslo,[e] A. Lauria,[b,k] A. Ljubicic,[y] A. Longhin,[ab] A. Malgin,[a]
M. Malenica,[y] G. Mandrioli,[r] T. Matsuo,[t] V. Matveev,[a] N. Mauri,[r,u] E. Medinaceli,[g,j]
A. Meregaglia,[s] S. Mikado,[ad] P. Monacelli,[w] M. C. Montesi,[b,k] K. Morishima,[x]
M. T. Muciaccia,[o,p] N. Naganawa,[x] T. Naka,[x] M. Nakamura,[x] T. Nakano,[x] Y. Nakatsuka,[x]
K. Niwa,[x] S. Ogawa,[t] T. Omura,[x] K. Ozaki,[d] A. Paoloni,[ab,*] L. Paparella,[o,p] B. D. Park, [z,3]
I. G. Park,[z] L. Pasqualini,[r,u] A. Pastore,[p,*] L. Patrizii,[r] H. Pessard,[q] D. Podgrudkov,[c]
N. Polukhina,[m] M. Pozzato,[r,u] F. Pupilli,[n] M. Roda,[g,j] T. Roganova,[c] H. Rokujo,[x]
G. Rosa,[w,ac] O. Ryazhskaya,[a] O. Sato,[x] A. Schembri,[n] I. Shakirianova,[a] T. Shchedrina,[b]
A. Sheshukov,[h] H. Shibuya,[t] T. Shiraishi,[x] G. Shoziyoev,[c] S. Simone,[o,p] M. Sioli,[r,u]
C. Sirignano,[g,j] G. Sirri,[r] M. Spinetti,[ab] L. Stanco,[g] N. Starkov,[m] S. M. Stellacci,[i]
M. Stipcevic,[y] P. Strolin,[b,k] S. Takahashi,[d] M. Tenti,[r] F. Terranova,[ab,ae] V. Tioukov,[b]
S. Tufanli,[e] P. Vilain,[af] M. Vladymyrov,[m] L. Votano,[ab] J. L. Vuilleumier,[e] G. Wilquet,[af]
B. Wonsak,[l] C. S. Yoon,[z] S. Zemskova[h]

[a] *INR - Institute for Nuclear Research of the Russian Academy of Sciences, RUS-117312 Moscow, Russia*
[b] *INFN Sezione di Napoli, 80125 Napoli, Italy*
[c] *SINP MSU - Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, RUS-119991 Moscow, Russia*
[d] *Kobe University, J-657-8501 Kobe, Japan*
[e] *Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics (LHEP), University of Bern, CH-3012 Bern, Switzerland*
[f] *METU - Middle East Technical University, TR-06531 Ankara, Turkey*
[g] *INFN Sezione di Padova, I-35131 Padova, Italy*
[h] *JINR - Joint Institute for Nuclear Research, RUS-141980 Dubna, Russia*
[i] *Dipartimento di Fisica dell'Università di Salerno and "Gruppo Collegato" INFN, I-84084 Fisciano (Salerno), Italy*
[j] *Dipartimento di Fisica e Astronomia dell'Università di Padova, I-35131 Padova, Italy*
[k] *Dipartimento di Fisica dell'Università Federico II di Napoli, I-80125 Napoli, Italy*
[l] *Hamburg University, D-22761 Hamburg, Germany*
[m] *LPI - Lebedev Physical Institute of the Russian Academy of Sciences, RUS-119991 Moscow, Russia*
[n] *INFN - Laboratori Nazionali del Gran Sasso, I-67010 Assergi (L'Aquila), Italy*
[o] *Dipartimento di Fisica dell'Università di Bari, I-70126 Bari, Italy*
[p] *INFN Sezione di Bari, I-70126 Bari, Italy*
[q] *LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy-le-Vieux, France*
[r] *INFN Sezione di Bologna, I-40127 Bologna, Italy*

---

[1]Now at Kyungpook National University, Daegu, Korea.
[2]Now at CERN, Geneva, Switzerland.
[3]Now at Samsung Changwon Hospital, SKKU, Changwon, Korea.

[s] *IPHC, Université de Strasbourg, CNRS/IN2P3, F-67037 Strasbourg, France*

[t] *Toho University, J-274-8510 Funabashi, Japan*

[u] *Dipartimento di Fisica e Astronomia dell'Università di Bologna, I-40127 Bologna, Italy*

[v] *Department of Physics, Technion, IL-32000 Haifa, Israel*

[w] *INFN Sezione di Roma, I-00185 Roma, Italy*

[x] *Nagoya University, J-464-8602 Nagoya, Japan*

[y] *IRB - Rudjer Boskovic Institute, HR-10002 Zagreb, Croatia*

[z] *Gyeongsang National University, 900 Gazwa-dong, Jinju 660-701, Korea*

[aa] *Aichi University of Education, J-448-8542 Kariya (Aichi-Ken), Japan*

[ab] *INFN - Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati (Roma), Italy*

[ac] *Dipartimento di Fisica dell'Università di Roma "La Sapienza", I-00185 Roma, Italy*

[ad] *Nihon University, J-275-8576 Narashino, Chiba, Japan*

[ae] *Dipartimento di Fisica dell'Università di Milano-Bicocca, I-20126 Milano, Italy*

[af] *IIHE, Université Libre de Bruxelles, B-1050 Brussels, Belgium*