EPJ Web of Conferences **126**, 04031 (2016) DOI: 10.1051/epjconf/201612604031
ICNFP 2015

Search for sterile neutrino mixing in the $\nu_\mu \rightarrow \nu_\tau$ appearance channel with the OPERA detector

N. Mauri[1,a] on behalf of the OPERA Collaboration

[1] *INFN - Sezione di Bologna, Viale Berti Pichat 6/2, I-40127 Bologna, Italy*

Abstract. The OPERA experiment has observed muon neutrino to tau neutrino oscillations in the atmospheric sector in appearance mode. Five ν_τ candidate events have been detected, a number consistent with the expectation from the "standard" 3ν framework. Based on this result new limits on the mixing parameters of a massive sterile neutrino have been set. The analysis is performed in the 3+1 neutrino model.

1 Introduction

The discovery of neutrino oscillations established the fact that neutrinos have a non-zero mass, pointing to physics beyond the Standard Model. Since the first observation of the disappearance of atmospheric muon neutrinos in 1998, many experiments contributed to draw a coherent picture of the new "standard" 3ν framework. The oscillations are formalized by the PMNS unitary matrix U_{PMNS} through which three flavour eigenstates are mixed with three mass eigenstates [1, 2]. After less than 20 years, the three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ parameterized in U_{PMNS} are measured as well as the two squared mass differences $\Delta m^2_{21}, \Delta m^2_{32}$ determining the oscillation frequencies [3].

However, a certain number of so-called neutrino "anomalies" show tensions with this well established 3ν framework [4]. Different kinds of experiments, both in appearance and disappearance [5–8], point towards a new parameter region $\Delta m^2 \sim 1$ eV^2. Since the number of flavour-active neutrinos is bound to 3 by the coupling with the Z^0, the new squared mass difference could be accounted for by the existence of a sterile neutrino. A sterile neutrino is a neutral lepton which does not couple to $W^\pm/Z^0$ bosons. It is not an exotic particle, e.g. right-handed neutrinos are singlets under $SU(2)_L$ gauge. Sterile neutrinos can mix with the active ones and the mass scale of additional states has no strong a priori. The experimental "anomalies" hint to the existence of light $\mathcal{O}(1)$ eV steriles.

The OPERA experiment was designed to observe $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode, in order to unambiguously prove the $\nu_\mu \rightarrow \nu_\tau$ transition at the atmospheric scale in the 3ν framework. OPERA recently assessed the discovery of ν_τ appearance in the CNGS ν_μ beam with a significance of 5.1σ [9]. The number of ν_τ events detected by OPERA is compatible with the expectations from the standard 3ν framework. We can therefore set limits on the oscillations induced by a sterile neutrino, here formalized by the 3 + 1 neutrino model.

[a] e-mail: nicoletta.mauri@bo.infn.it

2 The 3+1 neutrino model

The new 3+1 model should include the well established 3ν framework. The additional sterile eigenstate can be represented through an extended 4×4 mixing matrix U which slightly perturbs the inner 3×3 U_{PMNS} and extends the mixing to a 4^{th} neutrino. In this 3+1 neutrino model, the first three mass eigenstates are mostly composed by flavour-active states with the well known mixing, while the forth mass eigenstate is almost exclusively composed by the sterile state. The 4^{th} mass term is supposed to be heavier than the other three ones, since the experimental anomalies suggest a $\Delta m^2 \sim \text{eV}^2$ and the cosmological limits on the sum of neutrino masses favour a positive Δm^2_{41} [10]. In the 3+1 model, defining $\Delta_{ij} = 1.27\, \Delta m^2_{ij}\, L/E$ (where Δm^2_{ij} is expressed in eV^2, L in km and E in GeV), the probability for $\nu_\mu \to \nu_\tau$ transitions in given by

$$\begin{aligned} P_{\nu_\mu\to\nu_\tau}(E) &= 4|U_{\mu3}|^2|U_{\tau3}|^2 \sin^2 \Delta_{31} + 4|U_{\mu4}|^2|U_{\tau4}|^2 \sin^2 \Delta_{41} \\ &+ 2\mathcal{R}[U_{\mu3}U^*_{\tau3}U^*_{\mu4}U_{\tau4}] \sin 2\Delta_{31} \sin 2\Delta_{41} \\ &- 4\mathcal{I}[U_{\mu3}U^*_{\tau3}U^*_{\mu4}U_{\tau4}] \sin^2 \Delta_{31} \sin 2\Delta_{41} \\ &+ 8\mathcal{R}[U_{\mu3}U^*_{\tau3}U^*_{\mu4}U_{\tau4}] \sin^2 \Delta_{31} \sin^2 \Delta_{41} \\ &+ 4\mathcal{I}[U_{\mu3}U^*_{\tau3}U^*_{\mu4}U_{\tau4}] \sin 2\Delta_{31} \sin^2 \Delta_{41} \end{aligned} \tag{1}$$

In the above formula, the solar-driven term is neglected due to the CNGS baseline and neutrino energy ($\Delta_{21} \approx 4 \times 10^{-3}$). In the first row of Eq. 1, the first term corresponds to the standard oscillation probability for ν_τ appearance. The second term corresponds to the oscillation purely induced by the mixing with the sterile state, with an effective mixing parameter $\sin 2\theta_{\mu\tau} = 2|U_{\mu4}||U_{\tau4}|$. The remaining four terms correspond to the interference between active and sterile neutrinos, and depending on the extra terms in the extended U matrix they can lead to an enhancement or a suppression of the expected ν_τ. These interference terms depend on the possible $CP-$violating phase $\phi_{\mu\tau} = Arg(U^*_{\mu4}U_{\tau4}U_{\mu3}U^*_{\tau3})$ and on the mass hierarchy of standard neutrinos (Normal Hierarchy, NH, $\Delta m^2_{31} > 0$, or Inverted Hierarchy, IH, $\Delta m^2_{31} < 0$).

The number of ν_τ events observed by OPERA is compared to the number of events expected from the 3+1 model as a function of the new mixing angles and squared mass difference. In Sect. 4 these numbers are used to constrain the parameters appearing in Eq. 1.

3 The OPERA experiment

OPERA is a long baseline experiment located in the underground Gran Sasso laboratory and exposed to the CNGS ν_μ beam from 2008 to 2012. The experiment was designed to perform a direct observation of ν_τ charged-current interactions on event-by-event basis, with a signal to background ratio of $O(10)$.

The topological observation of the short-lived τ decay requires an exceptional granularity integrated in a large mass. This is achieved in OPERA using Emulsion Cloud Chambers (ECC) and real-time electronic detectors with a modular structure [11]. The ECC basic unit is a “brick” composed of 57 nuclear emulsion films, providing the necessary micrometric accuracy, interleaved with 56 lead plates, providing the necessary mass. The target is a hybrid modular structure in which the bricks are arranged in vertical “walls”, transverse to the beam direction, alternated with planes of plastic scintillator strips. The detector is made of two identical Super Modules, each consisting of a target section and a muon spectrometer. The latter is a dipolar iron magnet instrumented with Resistive Plate Chambers (RPC) and high precision drift tube detectors (PT). The electronic detectors trigger the read-out and allow identifying the brick containing the neutrino interaction. If a muon track crosses the spectrometers, the RPCs and PTs are used to measure the muon charge and momentum [12]. The neutrino interaction vertex and its full topology are reconstructed in the brick with a sub-μm spatial resolution.

3.1 $\nu_\mu \rightarrow \nu_\tau$ search

In five years of data taking, from 2008 to 2012, OPERA integrated a CNGS beam luminosity corresponding to 17.97×10^{19} protons on target (p.o.t.), the 80% of the nominal design value. A total of 19505 CNGS events have been registered correspondingly. Only interactions inside the OPERA target volume are analysed for oscillation studies. These internal events are further classified by an automatic algorithm into 0μ and 1μ through the identification of a muon track [12] or the total number of fired scintillator or RPC planes.

The data set used for the $\nu_\mu \rightarrow \nu_\tau$ search is composed by internal 0μ events and 1μ events with a muon momentum below 15 GeV/c, for a total of 5408 fully analysed events in the ECCs. In this sample, after the whole scanning and decay search procedure [13], 5 ν_τ candidate events are observed. The total expected background is 0.25 ± 0.05 events. The background fluctuation probability is evaluated with two test statistics, one based on the Fisher's method and the other on the profile likelihood ratio. The background-only hypothesis is excluded with a 5.1σ significance by both methods [9].

The expected signal from the standard 3ν model, assuming $\Delta m^2_{32} = 2.44 \times 10^{-3}$ eV^2 [3] and a maximal mixing, considering all the τ decay channels, amounts to 2.64 ± 0.53 events, compatible with the observed ν_τ candidates [9].

4 Constraints on the mixing with a sterile neutrino

In this paper we interpret the OPERA results in the context of the 3+1 neutrino model, deriving limits on the oscillations induced by a massive sterile neutrino. Limits on the sterile neutrino mixing based on the observation of 4 ν_τ candidate events have been recently published by the OPERA Collaboration [14]. Here we report on the preliminary updated analysis considering the current number of 5 ν_τ events [15, 16].

The results of this analysis are given in terms of the effective mixing parameter $\sin 2\theta_{\mu\tau} = 2|U_{\mu 4}||U_{\tau 4}|$ (see Sect. 2), which is the leading mixing term at short baseline experiments, allowing a direct comparison with their results.

The number μ of expected ν_τ events in the 3+1 model is evaluated as:

$$\mu = A \int \phi_{\nu_\mu}(E)\, P_{\mu\tau}(E)\, \sigma_{\nu_\tau}(E)\, \epsilon_{\nu_\tau}(E)\, \mathrm{d}E + n_b \tag{2}$$

where A is a normalization factor taking into account the delivered p.o.t. and the target mass, ϕ_{ν_μ} is the CNGS neutrino flux, $P_{\mu\tau}$ is the oscillation probability given by Eq. 1, σ_{ν_τ} is the ν_τ CC cross section, ϵ_{ν_τ} is the ν_τ identification efficiency, and n_b is the number of expected background events.

A gaussian prior is assumed for the atmospheric squared mass difference Δm^2_{31} with parameters determined from global fits, i.e. $(2.47 \pm 0.06) \times 10^{-3}$ eV^2 for normal hierarchy and $(-2.34 \pm 0.06) \times 10^{-3}$ eV^2 for inverted hierarchy [3].

In order to derive limits on the sterile neutrino mixing, the test statistics $-2 \ln \lambda_p$ is used, where λ_p is the profile likelihood ratio. In this counting analysis, the likelihood is given by a poissonian depending on the number of expected events μ (Eq. 2) and on the number of observed events $n_{\nu_\tau} = 5$. Two independent implementations of the method give similar results. Details on the statistical treatment of both analyses can be found in [15, 16].

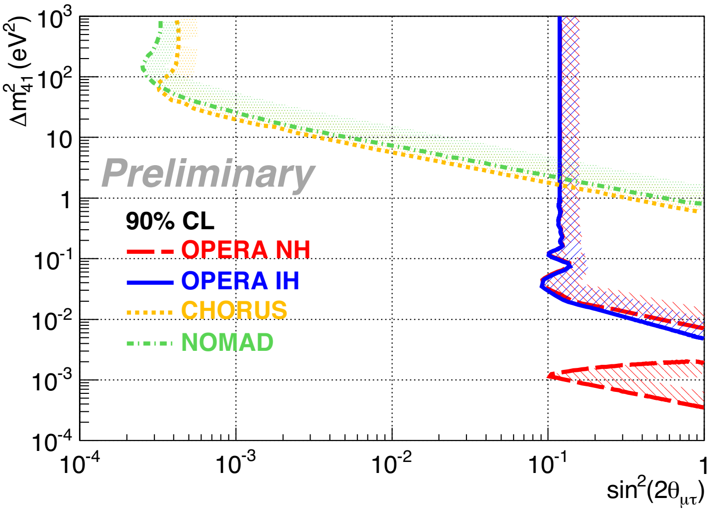

Figure 1. Limits on the sterile neutrino mixing derived from the OPERA data. Preliminary 90% C.L. exclusion limits in the Δm^2_{41} versus $\sin^2 2\theta_{\mu\tau}$ parameter space for normal (red) and inverted (blue) hierarchy. The CHORUS and NOMAD 90% C.L. excluded regions are also shown.

The limits on the sterile neutrino parameters are derived minimizing $-2 \ln \lambda_p$ and are shown in Fig. 1. The 90% C.L. exclusion regions in the $(\Delta m^2_{41}, \sin^2 2\theta_{\mu\tau})$ parameter space are obtained for both normal (NH) and inverted (IH) mass hierarchies. The OPERA results in this parameter space can be directly compared to the limits given by the CHORUS and NOMAD short baseline $\nu_\mu \to \nu_\tau$ searches [17, 18].

The OPERA sensitivity extends the limits on Δm^2_{41} to 10^{-2} eV^2 for a relatively large mixing, i.e. $\sin^2 2\theta_{\mu\tau} > 0.5$, for both hierarchies. In case of normal hierarchy, a small region at $\Delta m^2_{41} \sim 10^{-3}$ eV^2 is also excluded, since the number of expected ν_τ events in this model is lower than the number expected from the 3ν framework. The suppression is due to the interference terms in Eq. 1. As said in Sect. 2, cosmological limits on the sum of neutrino masses favour $\Delta m^2_{41} > 0$, which is the assumption of the analysis here presented. For negative values of Δm^2_{41} the exclusion plots are similar but with NH and IH regions exchanged.

At large values of Δm^2_{41} (> 1 eV^2), there is almost no correlation between Δm^2_{41} and the effective mixing parameter, and the dependence of the oscillation probability $P_{\nu_\mu \to \nu_\tau}$ on Δm^2_{41} vanishes. In this context, which is in fact the phenomenological 3+1 model, the limits are expressed in the $(\phi_{\mu\tau}, \sin^2 2\theta_{\mu\tau})$ space. In Fig. 2 the 90% C.L. exclusion regions are shown for NH and IH hierarchies. Marginalizing over the phase $\phi_{\mu\tau}$, values of $\sin^2 2\theta_{\mu\tau} > 0.119$ are excluded at 90% C.L. Given the definition of the effective mixing parameter $\sin 2\theta_{\mu\tau} = 2|U_{\mu 4}||U_{\tau 4}|$, the upper limit $\sin^2 2\theta_{\mu\tau} < 0.119$ can be translated into an exclusion curve in the $(|U_{\mu 4}|^2, |U_{\tau 4}|^2)$ space, as shown in Fig. 3 together with the unitarity bound $|U_{\mu 4}|^2 + |U_{\tau 4}|^2 \leq 1$.

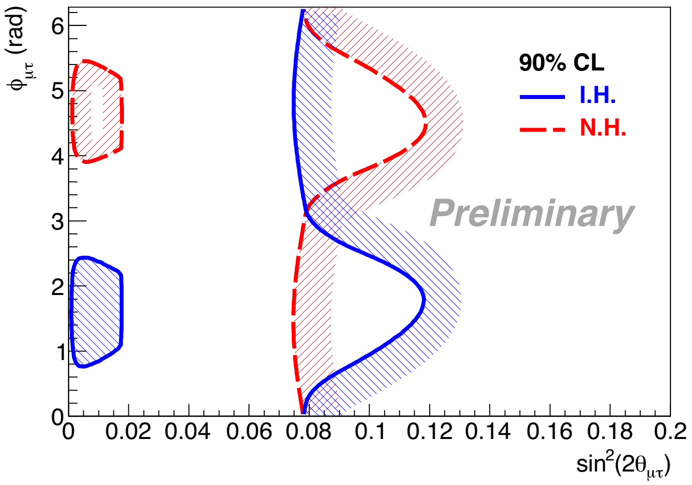

Figure 2. Preliminary 90% C.L. exclusion limits in the $\phi_{\mu\tau}$ versus $\sin^2 2\theta_{\mu\tau}$ parameter space for normal (red) and inverted (blue) hierarchy, assuming $\Delta m^2_{41} > 1$ eV^2.

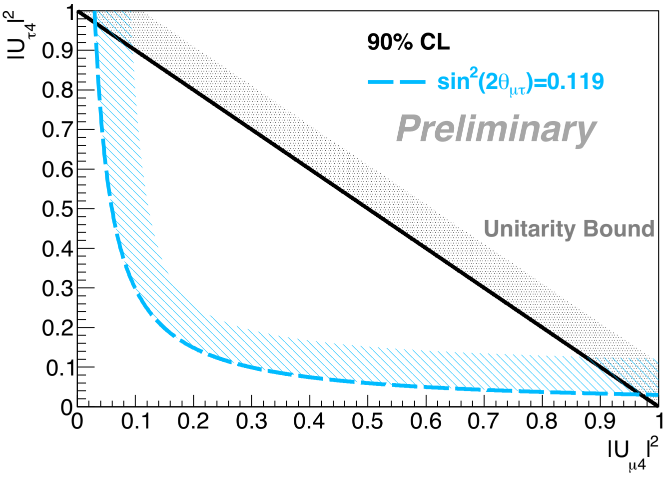

Figure 3. Preliminary 90% C.L. exclusion limits in the $|U_{\tau 4}|^2$ versus $|U_{\mu 4}|^2$ parameter space (cyan line), assuming the upper limit $\sin^2 2\theta_{\mu\tau} < 0.119$ for $\Delta m^2_{41} > 1$ eV^2. The unitarity bound is also shown (black line).

5 Conclusions

The OPERA experiment has observed $\nu_\mu \rightarrow \nu_\tau$ oscillations in the atmospheric sector in appearance mode detecting 5 ν_τ event candidates with an expected background of 0.25 events. The 5.1σ discovery of ν_τ appearance is compatible with the standar 3ν oscillation framework.

In this paper, OPERA results have been used to derive limits on the oscillations induced by a sterile neutrino, obtaining 90% C.L. exclusion regions for three different parameter spaces. The effective mixing parameter of the 3 + 1 neutrino model, for $\Delta m^2_{41} > 1$ eV^2, is constrained at 90% C.L. at $\sin^2 2\theta_{\mu\tau} < 0.119$. Based on this upper limit, constraints on $|U_{\tau 4}|^2$ and $|U_{\mu 4}|^2$ have also been set.

The OPERA sterile mixing search in appearance mode provides complementary information with respect to disappearance experiments, and the long baseline search further complements the short baseline one, providing stringent limits in the effective mixing angle.

References

[1] B. Pontecorvo, Zh. Eksp. Teor. Fiz. **33** 549 (1957); B. Pontecorvo, Zh. Eksp. Teor. Fiz. **34** 247 (1958); B. Pontecorvo, Sov. Phys. JETP **26** 984 (1968)
[2] Z. Maki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. **28** 870 (1962)
[3] K. A. Olive *et al.*, [Particle Data Group], Chin. Phys. C **38** 090001 (2014)
[4] K. N. Abazajian *et al.*, "Light sterile neutrinos: a White Paper", arXiv:1204.5379.
[5] A. Aguilar *et al.* (LSND Collaboration), Phys. Rev. D **64**, 112007 (2001)
[6] A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration) Phys. Rev. Lett. **110**, 161801 (2013)
[7] G. Mention *et al.*, Phys. Rev. D **83**, 073006 (2011)
[8] C. Giunti and M. Laveder, Phys. Rev. C **83**, 065504 (2011)
[9] N. Agafonova *et al.* (OPERA Collaboration), Phys. Rev. Lett. **115**, 121802 (2015)
[10] P. A. R. Ade *et al.* (Planck Collaboration), submitted to A&A (2015), arXiv:1502.01589
[11] R. Acquafredda *et al.* (OPERA Collaboration), JINST **4**, P04018 (2009)
[12] N. Agafonova *et al.* (OPERA Collaboration), New J. Phys. **13**, 053051 (2011)
[13] N. Agafonova *et al.* (OPERA Collaboration), Eur. Phys. J. C **74**, 2986 (2014)
[14] N. Agafonova *et al.* (OPERA Collaboration), JHEP **06**, 069 (2015)
[15] S. Dusini, G. Sirri and M. Tenti, OPERA Public Note 181 (2015)
[16] A. Longhin, A. Paoloni and F. Pupilli, OPERA Public Note 180 (2015)
[17] CHORUS Collaboration, Nucl. Phys. B **793**, 326 (2008)
[18] NOMAD Collaboration, Nucl. Phys. B **601**, 3 (2001)