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Search for sterile neutrino mixing in the muon neutrino to tau neutrino appearance channel with the OPERA detector

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Abstract. The OPERA experiment observed $\nu_\mu \to \nu_\tau$ oscillations in the atmospheric sector. To this purpose the hybrid OPERA detector was exposed to the CERN Neutrinos to Gran Sasso beam from 2008 to 2012, at a distance of 730 km from the neutrino source. Charged-current interactions of ν_τ were searched for through the identification of τ lepton decay topologies. The five observed ν_τ interactions are consistent with the expected number of events in the standard three neutrino framework. Based on this result, new limits on the mixing parameters of a massive sterile neutrino may be set. Preliminary results of the analysis performed in the 3+1 neutrino framework are here presented.

1. Introduction

The OPERA experiment [1] at the Gran Sasso underground Laboratory (LNGS) was designed to perform the first direct detection of $\nu_\mu \to \nu_\tau$ oscillations in the appearance mode. The direct appearance search is based on the detection of τ leptons produced in ν_τ Charged Current (CC) interactions. The neutrino beam is an almost pure ν_μ beam produced by protons accelerated in the CERN SPS and injected in the CNGS beam line [2].

So far, the OPERA experiment observed five ν_τ CC interaction candidates, consistent with 2.64 events expected in the standard three neutrino oscillations framework at the so-called atmospheric scale ($\Delta m^2_{32} = 2.44\times10^{-3}$ eV^2 [3]) with close-to-maximal mixing. This result represents the first direct observation of $\nu_\mu \to \nu_\tau$ oscillations in appearance mode [4].

Anyway, several experimental anomalies exist in neutrino oscillation data that cannot be accommodated in the standard three neutrino oscillations framework (the Gallium [5, 6] and nuclear reactor anomalies [7], the LSND [8] and MiniBooNE [9] results) that may hint to the existence of sterile neutrino(s) with a new squared mass difference (Δm^2_{41}) of the order of 1 eV^2. OPERA can test the sterile neutrino hypothesis and set limits on new effective oscillation parameters looking for deviations from the predictions of the standard three neutrino oscillations model [10].

2. The Long-Baseline scenario for sterile neutrinos

The presence of an additional sterile-state can be expressed in the extended PMNS [11, 12] mixing matrix ($U_{\alpha i}$ with $\alpha = e, \mu, \tau, s$, and $i = 1,...,4$). In this model, called 3+1 model, the neutrino mass eigenstates ν_1,...,ν_4 are labeled such that the first three states are mostly made of

active flavour states and contribute to the standard three flavour oscillations with the squared mass differences $\Delta m^2_{21} \sim 7.5 \times 10^{-5}$ eV^2 and $\Delta m^2_{31} \sim 2.4 \times 10^{-3}$ eV^2, where $\Delta m^2_{ij} = m^2_i - m^2_j$. The fourth mass eigenstate, which is mostly sterile, is assumed to be much heavier than the others, 0.1 eV$^2 < \Delta m^2_{41} <$ 10 eV^2. The opposite case in hierarchy, i.e. negative values of Δm^2_{41}, produces a similar phenomenology from the oscillation point of view but is disfavored by cosmological results on the sum of neutrino masses [13].
In a Short-Baseline experiment the oscillation effects due to Δm^2_{21} and Δm^2_{31} can be neglected since $L/E \sim$1 km/GeV. Therefore the oscillation probability depends only on Δm^2_{41} and $U_{\alpha 4}$ with $\alpha = e, \mu, \tau$. In particular the survival probability of muon neutrinos can be given by an effective two-flavour oscillation formula.
Differently when $L/E > 1$ km/GeV, that is the case for the Long-Baseline experiments, the two-flavour oscillation is not a good approximation. In the case of the CNGS beam, when studying the ν_τ oscillation rate the only valid approximations correspond to neglect the solar-driven term, i.e. $\Delta m^2_{21} \sim 0$, and to discard the ν_e component of the beam. However when the $\nu_\mu \to \nu_e$ channel is studied the intrinsic ν_e beam-component becomes a non-negligible factor [14]. Considering the $(\nu_\mu, \nu_\tau, \nu_s)$ triplet, together with the above two approximations, the most general oscillation probability $\nu_\mu \to \nu_\tau$ can be written as:

$$\begin{aligned} P_{\nu_\mu \to \nu_\tau} =& 4 \mid U_{\mu 3} \mid^2 \mid U_{\tau 3} \mid^2 \sin^2 \Delta_{31} + 4 \mid U_{\mu 4} \mid^2 \mid U_{\tau 4} \mid^2 \sin^2 \Delta_{41} \\ &+ 2\Re \mid U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3} \mid \sin 2\Delta_{31} \sin 2\Delta_{41} \\ &- \Im \mid U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3} \mid \sin^2 \Delta_{31} \sin 2\Delta_{41} \\ &+ 8\Re \mid U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3} \mid \sin^2 \Delta_{31} \sin^2 \Delta_{41} \\ &+ 4\Im \mid U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3} \mid \sin \Delta_{31} \sin^2 \frac{\Delta_{41}}{2}, \end{aligned} \tag{1}$$

using the definition $\Delta_{ij} = 1.27\Delta^2_{ij} L/E$ $(i, j = 1, 2, 3, 4)$, with Δ_{31} and Δ_{41} expressed in eV^2, L in km and E in GeV. The first term corresponds to the standard oscillation, the second one to the pure exotic oscillation, while the following four terms correspond to the interference between the standard and the sterile neutrinos. By defining $C = 2 \mid U_{\mu 3} \mid\mid U_{\tau 3} \mid$, $\phi_{\mu\tau} = Arg(U_{\mu 3} U_{\tau 3} U_{\mu 4} U_{\tau 4})$ and $\sin 2\theta_{\mu\tau} = 2 \mid U_{\mu 4} \mid\mid U_{\tau 4} \mid$ the expression can be written as

$$\begin{aligned} P(Energy) =& C^2 \sin^2 \Delta_{31} + \sin^2 2\theta_{\mu\tau} \sin^2 \Delta_{41} \\ &+ 0.5C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin 2\Delta_{31} \sin 2\Delta_{41} \\ &- C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin^2 \Delta_{31} \sin 2\Delta_{41} \\ &+ 2C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin^2 \Delta_{31} \sin^2 \Delta_{41} \\ &+ C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin 2\Delta_{31} \sin^2 \Delta_{41}, \end{aligned} \tag{2}$$

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 NH or Inverted IH). Finally, since at Long-Baseline experiments $\sin \Delta_{41} \sim 0$ and $\sin^2 \frac{\Delta_{41}}{2} \sim 0.5$, the following expression can be obtained

$$\begin{aligned} P(Energy) \simeq& C^2 \sin^2 \Delta_{31} + 0.5 \sin^2 2\theta_{\mu\tau} \\ &+ C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin^2 \Delta_{31} \\ &+ 0.5C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin 2\Delta_{31}. \end{aligned} \tag{3}$$

3. OPERA preliminary results
Results on sterile limits based on four ν_τ candidates have been very recently published by OPERA [15]. We report here the preliminary updated analysis based on the recently discovered

fifth candidate [4].
In order to obtain an upper limit on $\sin^2 2\theta_{\mu\tau}$ at high values of Δm^2_{41} a profiled likelihood method was used. In figure 1 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. Profiling the likelihood also over $\phi_{\mu\tau}$ an upper limit of 0.119 is obtained at 90% CL on $\sin^2 2\theta_{\mu\tau}$, almost independently of the hierarchy of the three standard neutrino masses.
To extend the search for a possible fourth sterile neutrino down to small Δm^2_{41} values, the likelihood has been computed using the GLoBES software [16] which takes into account the non-zero Δm^2_{21} value and also matter effects. The likelihood has been profiled also on the Δm^2_{31} value. More details on the analysis are available in [17]. In figure 2 the preliminary 90% CL exclusion plot is reported in the Δm^2_{41} 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 [18] and CHORUS [19] experiments are also shown. Our analysis stretches the limits on Δm^2_{41} 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 $\sin^2 2\theta_{\mu\tau} \leq 0.5$. For maximal mixing, the 90% CL excluded region extends down to $\Delta m^2_{41} = 7.4(5.2) \times 10^{-3}$ eV^2 for normal (inverted) hierarchy of the three standard neutrino masses.

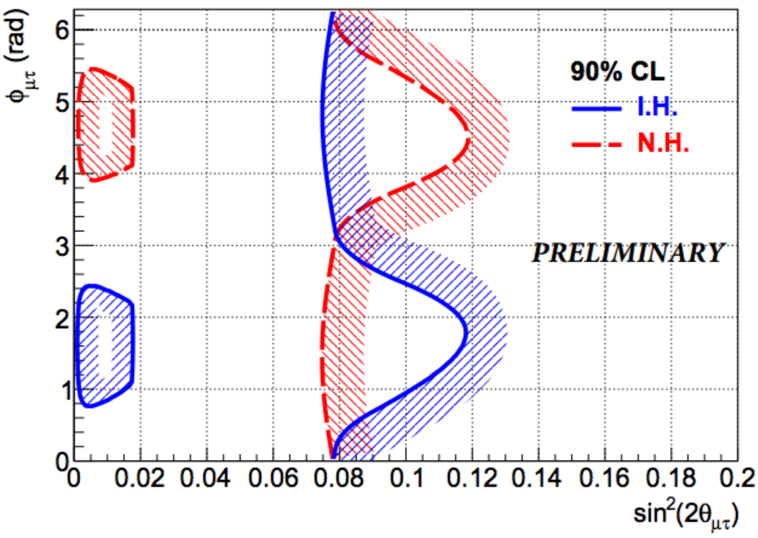

Figure 1. 90% C.L. exclusion limits in the $\phi_{\mu\tau}$ vs $\sin^2 2\theta_{\mu\tau}$ parameter space for normal (NH, dashed red) and inverted (IH, solid blue) hierarchies, and assuming $\Delta m^2_{41} > 1$ eV^2. Shaded bands are drawn to indicate the excluded regions.

4. 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. So far, OPERA has observed five ν_τ CC candidate interactions, consistent with the expected number of oscillation events in the standard three neutrino framework. In this paper we present limits on the existence of a fourth, sterile, neutrino in the 3+1 neutrino model. At high values of Δ^2_{41}, the measured 90% CL upper limit on the mixing term $\sin^2 2\theta_{\mu\tau}$ is 0.119, independent on the mass hierarchy of the three

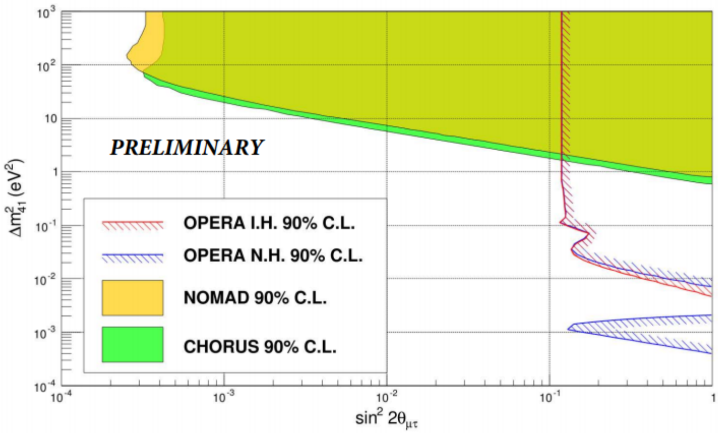

Figure 2. OPERA preliminary 90% C.L. exclusion limits in the Δm^2_{41} vs $\sin^2 2\theta_{\mu\tau}$ parameter space for the normal (NH, red) and inverted (IH, blue) hierarchy of the three standard neutrino masses. The exclusion plots by NOMAD [18] and CHORUS [19] are also shown. Shaded bands are drawn to indicate the excluded regions.

standard neutrinos. We also extend the exclusion limits on the Δ^2_{41} in the $\nu_\mu \to \nu_\tau$ appearance channel down to values of 10^{-2} eV^2 at large mixing for $\sin^2 2\theta_{\mu\tau} \leq 0.5$.

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