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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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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 four observed ν_τ interactions are consistent with the expected number of events in the standard three neutrino framework. In this work, we interpret the results in terms of the 3 + 1 sterile neutrino model using the GLoBES software. This analysis allows to constrain the effective mixing of the sterile and the new squared mass difference.

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1. Introduction

The OPERA experiment [1] operated on the CERN Neutrinos to Gran Sasso (CNGS) beam [2]. Neutrinos were 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 [3]. So far, the OPERA experiment observed four ν_τ CC interaction candidates, consistent with 2.3 events expected in the standard three neutrino oscillations framework at the so-called atmospheric scale ($\Delta m^2_{32} \sim 2.4 \times 10^{-3}$eV^2 [4]) with close-to-maximal mixing. This result represents the first direct observation of $\nu_\mu \to \nu_\tau$ oscillations in appearance mode [5] and it adds to the consistency of the standard three neutrino oscillations framework.

Anyway, several experimental anomalies exist in neutrino oscillation data that cannot be accommodated in the standard three neutrino oscillations framework (the Gallium [6, 7] and nuclear reactor anomalies [8], the LSND [10] 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 [11, 12].

2. Analysis in the 3 + 1 Neutrino Model

The number, μ, of expected tau candidate events is evaluated using the GLoBES software [13, 14] as:

$$\mu = N_{bkg} + K \int \Phi_{\nu_\mu}(E)\, P_{\mu\tau}(E)\, \sigma_{\nu_\tau}(E)\, \varepsilon_{\nu_\tau}(E)\, dE \tag{2.1}$$

where Φ_{ν_μ} is the CNGS muon neutrino flux [15], K is a normalization constant which includes the proton on target (pot) and the detector mass averaged on the pot, while $N_{bkg} = 0.23$ is the expected number of background events [5]. The cross-section of ν_τ CC interaction on ^{208}Pb (σ_{ν_τ}) is evaluated using GENIE [16]. The ν_τ identification efficiency (ε_{ν_τ}) is estimated using the official OPERA simulation and analysis software (OpRelease). The effect of the detector energy resolution is not taken into account since the analysis is based only on the total number of the expected ν_τ events and not on their energy distribution.

In presence of a fourth neutrino with mass m$_4$, the $\nu_\mu \to \nu_\tau$ oscillation probability, $P_{\mu\tau}$, is a function of the 4 $\times$ 4 mixing matrix U and of three squared mass differences. The parameter Δm^2_{21} is fixed to 7.54×10^{-5} eV^2 and Δm^2_{31} is given a Gaussian prior with mean and sigma equal to $(2.47 \pm 0.06) \times 10^{-3}$ eV^2 for normal hierarchy of the three standard neutrinos (N.H.) and $(-2.34 \pm 0.06) \times 10^{-3}$ eV^2 for inverted hierarchy (I.H.) [4]. Matter effects are also considered, assuming a constant matter density profile (average matter density from the PREM onion shell model of the Earth [19, 20]).

The likelihood $\mathscr{L}$ is defined as:

$$\mathscr{L} = P(n|\mu) \times \pi(\Delta m^2_{31}) \tag{2.2}$$

where P is a Poissonian distribution depending on μ and n the number of observed events; π is a Gaussian prior of the nuisance parameter Δm^2_{31}. The effects of possible systematic errors are negligible because, for this analysis, results are dominated by the statistical error.

3. Analysis Results

The results of this analysis are given by additional squared mass difference, Δm^2_{41}, and effective mixing parameter $\sin 2\theta_{\mu\tau} = 2|U_{\mu 4}||U_{\tau 4}|$. Being $\sin 2\theta_{\mu\tau}$ the leading mixing term at short base line experiments, it allows a direct comparison with previous results of SBL experiment (NOMAD [17], CHORUS [18]). To extract limits on the sterile neutrino mixing parameters, we used the test statistic $-2\ln\lambda_p$, where λ_p is the profile likelihood ratio [4] defined as:

$$\lambda_p(\alpha) = \frac{\mathscr{L}\left(\alpha, \hat{\hat{\beta}}\right)}{\mathscr{L}\left(\hat{\alpha}, \hat{\beta}\right)} \tag{3.1}$$

α represents the parameters of interest (Δm^2_{41}, $\sin^2 2\theta_{\mu\tau}$), β the nuisance parameters, $\hat{\beta}$ are the maximum likelihood estimators of β and $\hat{\hat{\beta}}$ is the value of β that maximizes the likelihood for fixed α. In order to obtain an exclusion region at 90% Confidence Level (CL) in the [Δm^2_{41}, $\sin^2 2\theta_{\mu\tau}$] plane, the asymptotic χ^2 distribution of the test statistic is assumed.

The 90% CL excluded region on Δm^2_{41} extends down to 10^{-2} eV^2 for $\sin^2 2\theta_{\mu\tau} > 0.5$. For the normal hierarchy a small region is excluded also at $\Delta m^2_{41} \approx 10^{-3}$ eV^2. This stringent limit arises from the suppression of the $\nu_\mu \to \nu_\tau$ oscillation probability due to the interference with the oscillation probability terms involving sterile neutrino. The analysis was performed assuming $\Delta m^2_{41} > 0$. Present limits on the sum of neutrino masses from cosmological surveys do not exclude small negative values for Δm^2_{41}, the analysis was repeated under this assumption. The exclusion plots obtained in this way are similar to those of Fig. 1, but with hierarchies exchanged.

A separate analysis was performed by deriving an analytical expression for the oscillation probability. Indeed at the OPERA baseline (730 km) and at the average CNGS neutrino energy ($\langle E_\nu \rangle = 17$ GeV), $\left(\frac{\Delta m^2_{21} L}{4E}\right)$ is of the order of 10^{-3} therefore the dependence of $P_{\mu\tau}$ from Δm^2_{21} can be neglected. Moreover the value of Δm^2_{41}, suggested by the LSND experiment, is of the order of 1 eV^2, implying that the oscillation terms led by Δm^2_{41} can be averaged when taking into account the energy resolution of the OPERA detector (i.e in the one mass dominance approximation with an active small Δm^2_{31} [21]). The oscillation probability can then be expressed as:

$$P_{\mu\tau} = \sin^2 2\psi_{\mu\tau} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \sin 2\psi_{\mu\tau} \sin 2\theta_{\mu\tau} \cos\phi_{\mu\tau} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \frac{1}{2}\sin 2\psi_{\mu\tau} \sin 2\theta_{\mu\tau} \sin\phi_{\mu\tau} \sin\left(\frac{\Delta m^2_{31} L}{2E}\right) + \frac{1}{2}\sin^2 2\theta_{\mu\tau} \quad (3.2)$$

where $\sin 2\psi_{\mu\tau} = 2|U_{\mu 3}||U_{\tau 3}|$ is an effective angle and $\phi_{\mu\tau} = \arg\left(U^*_{\mu 3} U_{\tau 3} U_{\mu 4} U^*_{\tau 4}\right)$ is a complex phase, linked to CP violation (i.e. $\sin\phi_{\mu\tau} = J^{CP}_{\mu\tau}$, where $J^{CP}_{\mu\tau}$ is a Jarlskog invariant of the 3 + 1 mixing matrix). In order to obtain an exclusion region on the [$\phi_{\mu\tau}$, $\sin^2 2\theta_{\mu\tau}$] plane, the nuisance parameter $\sin 2\psi_{\mu\tau}$ has been profiled out, while Δm^2_{31} has been fixed to 2.43×10^{-3} eV^2 for the N.H. and to 2.38×10^{-3} eV^2 for the I.H., respectively [4]. The result is shown in Fig. 2. By profiling the likelihood also over $\phi_{\mu\tau}$, as shown in Fig. 3, an upper limit of 0.116 is obtained at 90% CL on $\sin^2 2\theta_{\mu\tau}$.

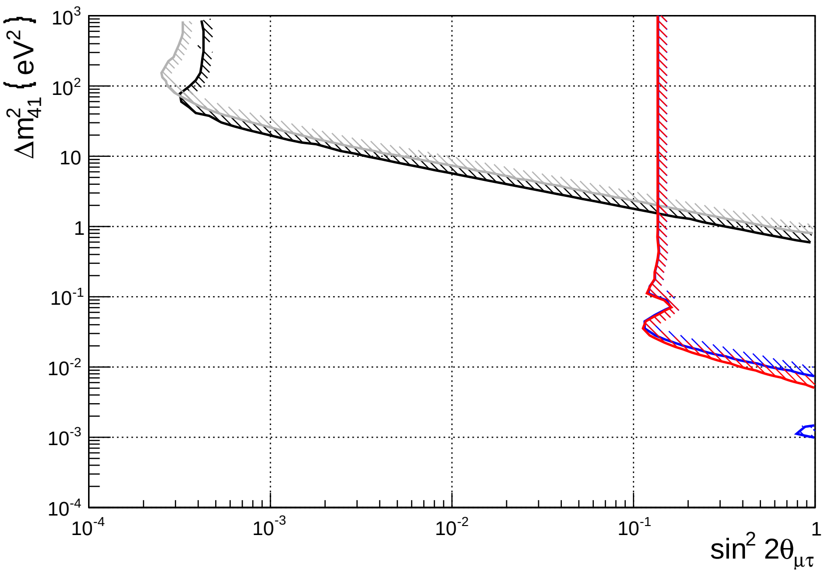

Figure 1: 90% CL excluded region in the [Δm^2_{41}, $\sin^2 2\theta_{\mu\tau}$] plane for normal (blue) and inverted (red) hierarchy. The 90% CL excluded region obtained by CHORUS (black) and NOMAD (gray) experiments are also shown.

4. Conclusion

The OPERA experiment was designed to observe $\nu_\mu \rightarrow \nu_\tau$ oscillations through ν_τ appearance at a baseline of 730 km in the CNGS beam. So far, OPERA has observed four 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 Δm^2_{41}, the measured 90% CL upper limit on the mixing term $\sin 2\theta_{\mu\tau}$ is 0.116, independent on the mass hierarchy of the three standard neutrinos. We also extend the exclusion limits on the Δm^2_{41} in the $\nu_\mu \to \nu_\tau$ appearance channel down to values of 10^{-2} eV^2 at large mixing for $\sin 2\theta_{\mu\tau} \gtrsim 0.5$.

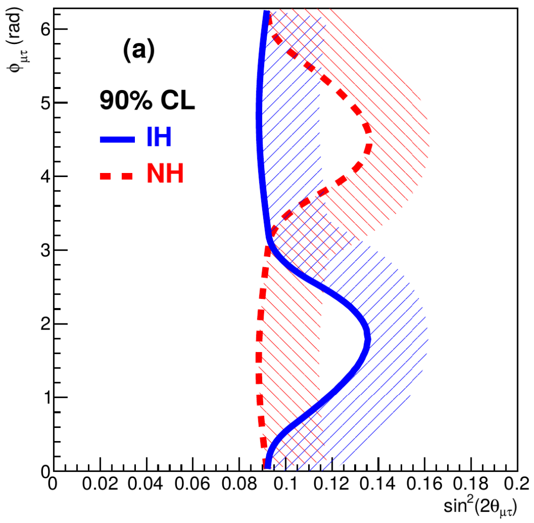

Figure 2: 90% CL exclusion region in $[\phi_{\mu\tau}, \sin^2 2\theta_{\mu\tau}]$ plane, for N.H. (dashed red) and I.H. (solid blue) in the one mass dominance approximation with an active small Δm^2_{31}.

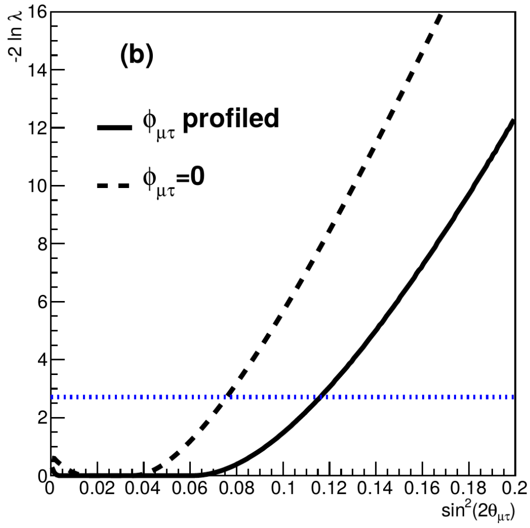

Figure 3: Log-likelihood ratio as a function of $\sin^2 2\theta_{\mu\tau}$ for $\phi_{\mu\tau} = 0$ (dashed line) and for the profile likelihood (continuous line).

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