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Limit on $\nu_e \to \nu_\tau$ oscillations from the NOMAD experiment

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Abstract

In the context of a two-flavour approximation we reinterpret the published NOMAD limit on $\nu_\mu \to \nu_\tau$ oscillations in terms of $\nu_e \to \nu_\tau$ oscillations. At 90% C.L. we obtain $\sin^2 2\theta_{e\tau} < 5.2 \times 10^{-2}$ for large Δm^2, while for $\sin^2 2\theta_{e\tau} = 1$ the confidence region includes $\Delta m^2 < 11$ eV$^2/c^4$.

Keywords: Neutrino oscillations

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1. Introduction

In a recent article [1], we have reported results from a search for $\nu_\mu \to \nu_\tau$ oscillations using the NOMAD detector to look for ν_τ appearance in the CERN wide-band neutrino beam. The detection of the potential oscillation signal relies on the identification of ν_τ charged-current (CC) interactions using kinematic criteria. The analysis described in Ref. [1] was based on data collected in the 1995, 1996 and 1997 runs, corresponding to approximately 950 000 ν_μ CC events in the detector fiducial volume. No oscillation signal was observed.

Since the beam contains a small but significant ν_e component, ν_τ's can in principle also be produced through $\nu_e \to \nu_\tau$ oscillations. This would change the rate and energy spectrum of the expected τ signal, but does not affect the background prediction. In the approximation of two-flavour oscillations, the $\nu_\mu \to \nu_\tau$ result can therefore be reinterpreted in terms of $\nu_e \to \nu_\tau$ oscillations. In this letter we evaluate the corresponding confidence region by assuming that any observed ν_τ signal should come from the ν_e component of the beam.

2. NOMAD detector

The NOMAD detector is described in Refs. [1,2]. Inside a 0.4 T magnetic field is an active target (2.7 tons) of drift chambers (DC), followed by a transition radiation detector (TRD) [3], a preshower detector (PS), and an electromagnetic calorimeter (ECAL) [4]. A hadron calorimeter (HCAL) and two muon stations are located just after the magnet coil.

The neutrino interaction trigger [5] consists of a coincidence between two planes of counters located after the active target, in the absence of a signal from a large area system of veto counters in front of the NOMAD detector.

3. Neutrino beam

This $\nu_e \to \nu_\tau$ search differs from the corresponding $\nu_\mu \to \nu_\tau$ search only in the neutrino flux estimation. A detailed study of the different beam contributions is in progress. The results presented here are based on the spectra described in Ref. [2], which were checked to be consistent with the observed CC spectra. These spectra were also used as an input for the Monte Carlo simulations of neutrino interactions in the NOMAD detector. Details of these simulations can be found in Ref. [1].

A more recent beam simulation [6] predicts a relative beam composition of $\nu_\mu : \bar{\nu}_\mu : \nu_e : \bar{\nu}_e = 1.00 : 0.061 : 0.0094 : 0.0024$, with average energies of 23.5, 19.2, 37.1, and 31.3 GeV, respectively. The analyzed data sample corresponds to about 14 000 ν_e CC interactions. The prompt ν_τ component was calculated to be negligible [7].

Dedicated comparisons [6,8] indicate that the systematic uncertainty on the relative ν_e / ν_μ flux ratio associated to the different beam predictions of Refs. [2,6] is 10% or less. This is added to the overall uncertainty on the absolute normalization given in Ref. [1].

Neutrinos are produced at an average distance of 625 m from the detector.

4. Discussion

The search for $\nu_e \to \nu_\tau$ oscillations is based on the analyses described in Ref. [1], where the identification of ν_τ charged current interactions is obtained

Table 1
Number of background and data events for all the Deep Inelastic Scattering (DIS) and the low-multiplicity (LM) analyses reported in [1]. The corresponding quantities for each of the subdivisions (sub-boxes) of the signal region is also given where applicable. The maximum number of expected signal events ($N_\tau^{\max}$), as computed from Eq. (2), is listed for each channel

Decay channel	Analysis	Sub-box #	Total bkgnd.	Data	$N_\tau^{\max}$
$\tau \to e$	DIS	I	1.19 ± 0.39	0	3.9
		II	0.42 ± 0.27	1	4.5
		III	3.01 ± 0.67	4	12.1
		IV	1.45 ± 0.50	0	10.9
		V	0.28 ± 0.24	0	23.3
$\tau \to h(n\pi^0)$	DIS	I	2.70 ± 0.90	3	12.6
		II	0.50 ± 0.50	2	4.5
		III	1.80 ± 0.70	0	20.1
$\tau \to \rho$	DIS	–	$5.0^{+1.7}_{-0.9}$	5	45.7
$\tau \to 3\pi(\pi^0)$	DIS	–	6.5 ± 1.1	5	25.9
$\tau \to e$	LM	–	$0.5^{+0.6}_{-0.2}$	0	1.8
$\tau \to \pi(\pi^0)$	LM	–	$0.1^{+0.3}_{-0.1}$	1	2.1
$\tau \to 3\pi(\pi^0)$	LM	–	$0.4^{+0.6}_{-0.4}$	0	1.8

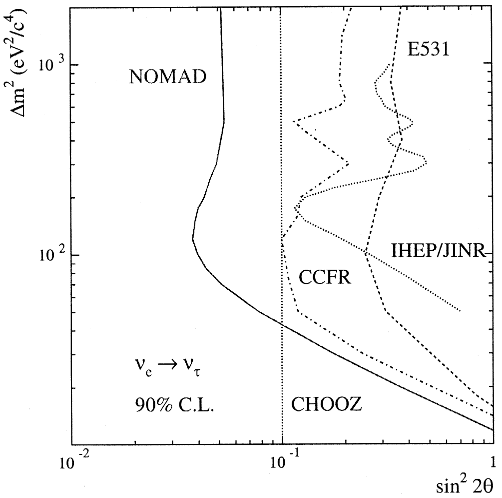

Fig. 1. The $\Delta m^2 - \sin^2 2\theta$ plane. The region excluded by NOMAD at 90% C.L. (solid line) is shown together with the ν_τ appearance and ν_e disappearance limits published by other experiments [11,12]. The curve from Ref. [11] is drawn according to the remarks in [14].

through the reconstruction of the visible secondary products of the subsequent τ decays. Since for a given analysis the expected number of background events is independent of the oscillation mode, the background estimate can be directly obtained from Ref. [1] for all the available decay channels.

In order to extract our confidence interval on the $\nu_e \to \nu_\tau$ oscillation probability we need to compute the maximal number of signal events, which is the number of expected signal events if the oscillation probability, P_{osc}, were unity. This can be done by starting from the maximal number of events under the $\nu_\mu \to \nu_\tau$ hypothesis of Ref. [1] and by appropriately weighting the simulated signal events for the relevant differences between the ν_e and ν_μ fluxes. Two main effects must then be taken into account, concerning both the absolute normalization and the spectra. Due to the small ν_e/ν_μ ratio in the beam, the expected total number of signal events from $\nu_\mu \to \nu_\tau$ oscillations must be rescaled by about two orders of magnitude. However, the actual average reduction is smaller for two reasons: i) the energy spectrum of the ν_e component is somewhat harder than the corresponding ν_μ spectrum, since the former is dominated by K decays; ii) the kinematic selection enhances the contribution from high energy ν_τ CC events. As a consequence, each simulated τ event is given a weight, w_i, which depends on the energy, E_ν, of the neutrino giving rise to it:

$$w_i = \frac{\Phi_e(E_\nu)}{\Phi_\mu(E_\nu)} \qquad (1)$$

where Φ_e and Φ_μ denote the ν_e and ν_μ fluxes. These weights should also include the radial dependence of the neutrino fluxes which is different for ν_μ and ν_e. However, we have checked, using the $\tau^- \to e^- \bar{\nu}_e \nu_\tau$ DIS channel, that including this radial dependence changes the normalization (given by $N_\tau^{\max}$, as defined below) by 1.5%. This is negligible with respect to the 10% uncertainty on the ν_e/ν_μ flux ratio quoted in Section 3.

The number of expected signal events for $P_{\mathrm{osc}} \equiv 1$ then reads:

$$N_\tau^{\max}(\nu_e \to \nu_\tau) = N_\tau^{\max}(\nu_\mu \to \nu_\tau) \times \frac{\sum_{i=1}^{n} w_i}{n} \qquad (2)$$

where the sum extends over the total number of simulated events n and the value $N_\tau^{\max}(\nu_\mu \to \nu_\tau)$ refers to the $\nu_\mu \to \nu_\tau$ hypothesis [1]. In Table 1 all the relevant quantities are listed for the different decay modes and signal bins.

The overall systematic uncertainties are estimated to be 20% for the background prediction and 15% for $N_\tau^{\max}$. This latter value, which includes the uncertainty on the relative flux prediction of Eq. (1), is negligible within the frequentist approach [9].

The final result of the measurement is expressed as a frequentist confidence interval [10] by exploiting the fact that each τ decay mode and signal bin has a different $N_\tau^{\max}$ to background ratio. The computation [1] takes into account the number of observed signal events, the expected background and its uncertainty, and the value of $N_\tau^{\max}$.

The resulting 90% C.L. upper limit on the two-flavour generation oscillation probability is:

$$P_{\mathrm{osc}}(\nu_e \to \nu_\tau) < 2.6 \times 10^{-2} \qquad (3)$$

which corresponds to $\sin^2 2\theta_{e\tau} < 5.2 \times 10^{-2}$ for large Δm^2 and to the exclusion region in the $\Delta m^2 - \sin^2 2\theta$

plane shown in Fig. 1. The result is significantly better than the existing limits [11–13] [1].

The sensitivity [10] of the experiment is $P_{\mathrm{osc}} = 4.3 \times 10^{-2}$; this is higher than the quoted confidence limit, since the number of observed events is smaller than the estimated background. In the absence of signal events, the probability to obtain an upper limit of 2.6×10^{-2} or lower is $29 \pm 2\%$.

5. Conclusions

Using events with DIS topology from the 1995, 1996, and 1997 NOMAD data sets, combined with the analyses of the low-multiplicity 1995 events, we have excluded a region of the $\nu_e \to \nu_\tau$ oscillation parameters which limits $\sin^2 2\theta_{e\tau}$ at high Δm^2 to values less than 5.2×10^{-2} at 90% C.L., and which limits Δm^2 to values less than $\Delta m^2 < 11$ eV$^2/c^4$ at $\sin^2 2\theta_{e\tau} = 1$. For large Δm^2 this result improves the existing limits by a factor of two or more.

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[1] The result quoted in [13] has been obtained from an unphysical value [14]. When treated according to the prescriptions of Ref. [10] it gives a 90% upper limit on the oscillation probability of $P_{\mathrm{osc}} < 0.14$.