Limit on $\nu_e \rightarrow \nu_\tau$ Oscillations from the NOMAD experiment

NOMAD Collaboration

P. Astier $^n$ D. Autiero $^h$ A. Baldissere $^r$ M. Baldo-Ceolin $^m$
G. Ballocchi $^h$ M. Banner $^n$ G. Bassompierre $^a$ K. Benslama $^i$
N. Besson $^r$ I. Bird $^{hi}$ B. Blumenfeld $^b$ F. Bobisut $^m$ J. Bouchez $^r$
S. Boyd $^i$ A. Bueno $^{cx}$ S. Bunyatov $^f$ L. Camilleri $^h$ A. Cardini $^j$
P.W. Cattaneo $^o$ V. Cavasinni $^p$ A. Cervera-Villanueva $^{hv}$
G. Collazuol $^m$ G. Conforto $^{hu}$ C. Conta $^o$ M. Contalbrigo $^m$
R. Cousins $^j$ D. Daniels $^c$ H. Degaudenzi $^i$ T. Del Prete $^p$
A. De Santo $^{hp}$ T. Dignan $^c$ L. Di Lella $^h$ E. do Couto e Silva $^h$
J. Dumarchez $^n$ M. Ellis $^t$ G.J. Feldman $^c$ R. Ferrari $^o$ D. Ferrère $^h$
V. Flaminio $^p$ M. Fraternali $^o$ J.-M. Gaillard $^a$ E. Gangler $^{hn}$
A. Geiser $^{ah}$ D. Geppert $^o$ D. Gbin $^s$ S. Gninenko $^{h, f}$ A. Godley $^t$
J.-J. Gomez-Cadenas $^{hv}$ J. Gosset $^r$ C. Gößling $^c$ M. Gouanère $^a$
A. Grant $^h$ G. Graziani $^g$ A. Guglielmi $^m$ C. Hagner $^r$
J. Hernando $^v$ D. Hubbard $^c$ P. Hurst $^c$ N. Hyett $^k$ E. Iacopini $^g$
C. Joseph $^i$ F. Juget $^i$ M. Kirsanov $^f$ O. Klimov $^f$ J. Kokkonen $^h$
A. Kovzelev $^{t, o}$ A. Krasnoperov $^{a, f}$ V.E. Kuznetsov $^{f, h}$
S. Lacaprara $^m$ C. Lachaud $^n$ B. Lakić $^w$ A. Lanza $^o$
L. La Rotonda $^q$ M. Laveder $^m$ A. Letessier-Selvon $^a$ J.-M. Levy $^n$
L. Linssen $^h$ A. Ljubičić $^w$ J. Long $^b$ A. Lupi $^g$ A. Marchionni $^g$
F. Martelli $^u$ X. Méchain $^r$ J.-P. Mendiburu $^o$ J.-P. Meyer $^r$
M. Mezzetto $^m$ S.R. Mishra $^{cs}$ G.F. Moorhead $^k$ P. Nédélec $^a$
Yu. Nefedov $^f$ C. Nguyen-Mau $^i$ D. Orestano $^q$ F. Pastore $^q$
L.S. Peak $^t$ E. Pennacchio $^u$ H. Pessard $^a$ R. Petti $^{ho}$ A. Placci $^h$
A. Pluquet $^r$ A. Polayrsh $^t$ G. Polesello $^o$ D. Pollmann $^o$
B. Popov $^{t, n}$ C. Poulsen $^k$ P. Rathouit $^r$ J. Rico $^x$ P. Riemann $^e$

(Accepted for publication on Phys. Lett. B)

*LAPP, Annecy, France
* Johns Hopkins Univ., Baltimore, MD, USA
* Harvard Univ., Cambridge, MA, USA
* Univ. of Calabria and INFN, Cosenza, Italy
* Dortmund Univ., Dortmund, Germany
* JINR, Dubna, Russia
* Univ. of Florence and INFN, Florence, Italy
* CERN, Geneva, Switzerland
* University of Lausanne, Lausanne, Switzerland
* UCLA, Los Angeles, CA, USA
* University of Melbourne, Melbourne, Australia
* Inst. Nucl. Research, INR Moscow, Russia
* Univ. of Padova and INFN, Padova, Italy
* LPNHE, Univ. of Paris VI and VII, Paris, France
* Univ. of Pavia and INFN, Pavia, Italy
* Univ. of Pisa and INFN, Pisa, Italy
* Roma Tre University and INFN, Rome, Italy
* DAPNIA, CEA Saclay, France
* Univ. of South Carolina, Columbia, SC, USA
* Univ. of Sydney, Sydney, Australia
* Univ. of Urbino, Urbino, and INFN Florence, Italy
* IFIC, Valencia, Spain
* Rudjer Bošković Institute, Zagreb, Croatia
* ETH Zürich, Zürich, Switzerland
Abstract

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

Key words: neutrino oscillations

1 Introduction

In a recent article [1], we have reported results from a search for $\nu_\mu \rightarrow \nu_\tau$ oscillations using the NOMAD detector to look for $\nu_\tau$ appearance in the CERN wide-band neutrino beam. The detection of the potential oscillation signal relies on the identification of $\nu_\tau$ 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 $\nu_\mu$ CC events in the detector fiducial volume. No oscillation signal was observed.

Since the beam contains a small but significant $\nu_e$ component, $\nu_\tau$'s can in principle also be produced through $\nu_e \rightarrow \nu_\tau$ oscillations. This would change the rate and energy spectrum of the expected $\tau$ signal, but does not affect the background prediction. In the approximation of two-flavour oscillations, the $\nu_\mu \rightarrow \nu_\tau$ result can therefore be reinterpreted in terms of $\nu_e \rightarrow \nu_\tau$ oscillations. In this letter we evaluate the corresponding confidence region by assuming that any observed $\nu_\tau$ signal should come from the $\nu_e$ 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 $\nu_e \rightarrow \nu_\tau$ search differs from the corresponding $\nu_\mu \rightarrow \nu_\tau$ 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 $\nu_e$ CC interactions. The prompt $\nu_\tau$ component was calculated to be negligible [7].

Dedicated comparisons [6][8] indicate that the systematic uncertainty on the relative $\nu_e/\nu_\mu$ flux ratio associated to the different beam predictions of Ref. [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 $\nu_e \rightarrow \nu_\tau$ oscillations is based on the analyses described in Ref. [1], where the identification of $\nu_\tau$ charged current interactions is obtained through the reconstruction of the visible secondary products of the subsequent $\tau$ 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 $\nu_e \rightarrow \nu_\tau$ oscillation probability we need to compute the maximal number of signal events, which is the number of expected signal events if the oscillation probability, $P_{\text{osc}}$, were unity. This can be done by starting from the maximal number of events under the $\nu_\mu \rightarrow \nu_\tau$ hypothesis of Ref. [1] and by appropriately weighting the simulated signal events for the relevant differences between the $\nu_e$ and $\nu_\mu$ fluxes. Two main effects must then be taken into account, concerning both the absolute normalization and the spectra. Due to the small $\nu_e/\nu_\mu$ ratio in the beam, the expected total number of signal events from $\nu_\mu \rightarrow \nu_\tau$ oscillations must be rescaled by about two orders of magnitude. However, the actual average re-
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 ($N_{\tau}^\text{max}$), as computed from Eq. (2), is listed for each channel.

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Sub-box #</th>
<th>Total Bkgrd.</th>
<th>Data</th>
<th>$N_{\tau}^\text{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \to e$</td>
<td>DIS</td>
<td>I</td>
<td>1.19 ± 0.39</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>II</td>
<td>0.42 ± 0.27</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>III</td>
<td>3.01 ± 0.67</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IV</td>
<td>1.45 ± 0.50</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>V</td>
<td>0.28 ± 0.24</td>
<td>0</td>
</tr>
<tr>
<td>$\tau \to h(n\pi^0)$</td>
<td>DIS</td>
<td>I</td>
<td>2.70 ± 0.90</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>II</td>
<td>0.50 ± 0.50</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>III</td>
<td>1.80 ± 0.70</td>
<td>0</td>
</tr>
<tr>
<td>$\tau \to \rho$</td>
<td>DIS</td>
<td>–</td>
<td>$5.0^{+1.7}_{-0.9}$</td>
<td>5</td>
</tr>
<tr>
<td>$\tau \to 3\pi(\pi^0)$</td>
<td>DIS</td>
<td>–</td>
<td>$6.5 \pm 1.1$</td>
<td>5</td>
</tr>
<tr>
<td>$\tau \to e$</td>
<td>LM</td>
<td>–</td>
<td>$0.5^{+0.6}_{-0.2}$</td>
<td>0</td>
</tr>
<tr>
<td>$\tau \to \pi(\pi^0)$</td>
<td>LM</td>
<td>–</td>
<td>$0.1^{+0.3}_{-0.1}$</td>
<td>1</td>
</tr>
<tr>
<td>$\tau \to 3\pi(\pi^0)$</td>
<td>LM</td>
<td>–</td>
<td>$0.4^{+0.6}_{-0.4}$</td>
<td>0</td>
</tr>
</tbody>
</table>

Production is smaller for two reasons: i) the energy spectrum of the $\nu_e$ component is somewhat harder than the corresponding $\nu_\mu$ spectrum, since the former is dominated by $K$ decays; ii) the kinematic selection enhances the contribution from high energy $\nu_\tau$ CC events. As a consequence, each simulated $\tau$ event is given a weight, $w_i$, which depends on the energy, $E_\nu$, of the neutrino giving rise to it:

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

(1)

where $\Phi_\nu$ and $\Phi_{\mu}$ denote the $\nu_e$ and $\nu_\mu$ fluxes. These weights should also include the radial dependence of the neutrino fluxes which is different for $\nu_\mu$ and $\nu_e$. 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 $N_{\tau}^\text{max}$, as defined
below) by 1.5%. This is negligible with respect to the 10% uncertainty on the \( \nu_e/\nu_\mu \) flux ratio quoted in Sec. 3.

The number of expected signal events for \( P_{\text{osc}} \equiv 1 \) then reads:

\[
N_{\tau}^{\text{max}}(\nu_e \rightarrow \nu_\tau) = N_{\tau}^{\text{max}}(\nu_\mu \rightarrow \nu_\tau) \times \frac{\sum_{i=1}^{n} w_i}{n}
\]  

(2)

where the sum extends over the total number of simulated events \( n \) and the value \( N_{\tau}^{\text{max}}(\nu_\mu \rightarrow \nu_\tau) \) refers to the \( \nu_\mu \rightarrow \nu_\tau \) 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 \( N_{\tau}^{\text{max}} \). 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 \( \tau \) decay mode and signal bin has a different \( N_{\tau}^{\text{max}} \) 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 \( N_{\tau}^{\text{max}} \).

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

\[
P_{\text{osc}}(\nu_e \rightarrow \nu_\tau) < 2.6 \times 10^{-2}
\]  

(3)

which corresponds to \( \sin^2 2\theta_{e\tau} < 5.2 \times 10^{-2} \) for large \( \Delta m^2 \) and to the exclusion region in the \( \Delta m^2 - \sin^2 2\theta \) plane shown in Figure 1. The result is significantly better than the existing limits [11][12][13]\(^1\).

The sensitivity [10] of the experiment is \( P_{\text{osc}} = 4.3 \times 10^{-2} \); 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 \( 2.6 \times 10^{-2} \) or lower is 29 \pm 2%.

\(^1\) 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 \( P_{\text{osc}} < 0.14 \).
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 $\nu_e$ appearance and $\nu_e$ disappearance limits published by other experiments [11,12]. The curve from Ref.[11] is drawn according to the remarks in [14].

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 $\nu_e \rightarrow \nu_\tau$ oscillation parameters which limits $\sin^2 2\theta_{\nu_e\nu_\tau}$ at high $\Delta m^2$ to values less than $5.2 \times 10^{-2}$ at 90% C.L., and which limits $\Delta m^2$ to values less than $\Delta m^2 < 11$ eV$^2$/c$^4$ at $\sin^2 2\theta_{\nu_e\nu_\tau} = 1$. For large $\Delta m^2$, this result improves the existing limits by a factor of two or more.

Acknowledgements

We thank the management and staff of CERN and of all participating institutes for their vigorous support of the experiment. Particular thanks are due
to the CERN accelerator and beam-line staff for the magnificent performance of the neutrino beam. The following funding agencies have contributed to this experiment: Australian Research Council (ARC) and Department of Industry, Science, and Resources (DISR), Australia; Institut National de Physique Nucléaire et Physique des Particules (IN2P3), Commissariat à l’Energie Atomique (CEA), Ministère de l’Education Nationale, de l’Enseignement Supérieur et de la Recherche, France; Bundesministerium für Bildung und Forschung (BMBF, contract 05 6DO52), Germany; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Russian Foundation for Basic Research, Institute for Nuclear Research of the Russian Academy of Sciences, Russia; Fonds National Suisse de la Recherche Scientifique, Switzerland; Department of Energy, National Science Foundation (grant PHY-9526278), the Sloan and the Cottrell Foundations, USA. F.J.P. Soler is supported by a TMR Fellowship from the European Commission.

We also thank our secretarial staff, Jane Barney, Marie-Anne Huber, Rachel Phillips and Mabel Richtering, and the following people who have worked with the collaboration on the preparation and the data collection stages of NOMAD: M. Anfreville, M. Authier, G. Barichello, A. Beer, V. Bonaiti, A. Castella, A. Cavestro, O. Cloué, C. Détraz, L. Dumps, C. Engster, G. Fumagalli, G. Gallay, W. Huia, E. Lessmann, J. Mulon, J.P. Passerieux, P. Petitpas, J. Poinsignon, C. Sobczynski, S. Soulié, L. Visentin, P. Wicht.

References


[12] CHOOZ Collaboration, M. Apollonio et al., hep-ex/9907037;
