Results on $\nu_\mu \to \nu_\tau$ oscillations from the CHORUS experiment

The CHORUS Collaboration.

Çukurova University, Turkey - NIKHEF, The Netherlands - METU, Turkey - Università di Bari and INFN, Italy - Humboldt Universität, Germany - Università di Cagliari and INFN, Italy - Inter-University Institute for High Energies (ULB-VUB), Belgium - Università di Ferrara and INFN, Italy - Toho University, Japan - CERN, Switzerland - Technion, Israel - Kinki University, Japan - Bogazici University, Turkey - Gyeongsang National University, Korea - Aichi University of Education, Japan - Kobe University, Japan - Université Catholique de Louvain, Belgium - ITEP, Russian Federation - Westfälische Wilhelms-Universität, Germany - Nagoya University, Japan - Università di Napoli "Federico II" and INFN, Italy - Osaka City University, Japan - Università di Roma "La Sapienza" and INFN, Italy - Università di Salerno and INFN, Italy - Utsunomiya University, Japan

The events collected in the 1994 CHORUS data-taking have been partially analysed. Reconstructed neutrino events have been located in the emulsion target and a search for $\tau \to \mu\nu_\tau\bar{\nu_\mu}$ and $\tau \to h^-(nh^0)\nu_\tau$ decay has been performed. No candidates for ν_τ interactions have been found leading to a limit on the mixing angle $sin^2 2\theta_{\mu\tau} < 4.5\times10^{-3}$ at 90% $C.L.$

I. INTRODUCTION

The CHORUS experiment was designed [1,2] to search for $\nu_\mu \to \nu_\tau$ oscillation through the observation of the decay of the τ lepton produced in charged-current interactions ν_τ+N $\to \tau^-$+X. The experiment uses the CERN wide-band neutrino beam, which is characterised by a ν_τ contamination well below the sensitivity level.

The τ lepton is identified by the direct observation of its decay topology in nuclear emulsions: their spatial resolution, of the order of few μm, allowing observation of the short decay path of the τ and study of the properties of the *kink* produced in its subsequent decay.

The experiment is sensitive to most of the decay channels of the τ. In this paper we restrict ourselves to the result obtained with a partial sample of data where we looked for τ decays into a muon or a single charged hadron only. The detection of the decay topology, together with the measurement of the event kinematics, provides an essentially background free appearance experiment. The neutrino masses that the CHORUS experiment can probe are particularly interesting for the validation of models considering massive neutrinos as a significant component of the possible dark matter of the universe [3,4].

II. THE EXPERIMENT

A. The apparatus

The short decay length of the τ and the high statistics needed to improve the best existing limits [5] have guided the design of the apparatus [1,2]. The neutrino target and the decay vertex detector consists of 800 kg nuclear emulsions.

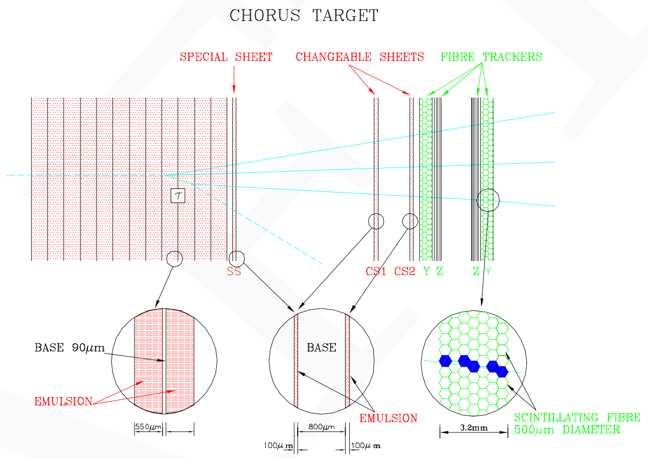

FIG. 1. Schematic side view of emulsion target and fibre trackers.

Fig. 1 shows a schematic view of the emulsion target region and of the associated electronic trackers. The target is subdivided in four stacks consisting of 36 emulsion plates each. A plate is made of a 90 μm plastic base supporting a 350 μm emulsion layer on both sides. There are a total of eight planes of fibre trackers in between and behind the emulsion stacks. Each plane is constructed from 7 layers of 500 μm diameter scintillating fibres. For a better connection of the tracks reconstructed in the scintillating-fibres tracker to those recorded inside each stack, three interface emulsion sheets (called *Special Sheet* and *Changeable Sheets*) are placed between them. The interface emulsions have a wide base supporting a thin emulsion layer, so that they provide highly accurate spatial and angular measurements.

The emulsions are kept at 4°C in a temperature-controlled environment, in order to prevent the emulsions from fading during the two years' exposure, and also to reduce misalignments due to the thermal expansion of the materials.

An air core spectrometer, an electromagnetic and hadronic calorimeter and a muon spectrometer complete the apparatus to allow a kinematical reconstruction of the events.

B. The neutrino beam

The CERN Wide Band neutrino Beam (WBB) consists mainly of ν_μ from π^+ decay, with a $\overline{\nu}_\mu$ contamination of a few percent, and a ν_e,$\overline{\nu}_e$ contamination less than 1%. The prompt ν_τ background is such that a ratio $3.3 \cdot 10^{-6}$ in the ν_τ/ν_μ charged current interaction is expected [7]. The main component of the beam has an average momentum of 27 GeV/c.

III. SCANNING PROCEDURE

After development, the events recorded inside the emulsions are measured in the scanning laboratories by using fully automatic microscopes [6]. Tracks which are candidate for a τ decay (negative muon with $p_\mu < 30\ GeV/c$ or negative hadron with $1 < p_h < 20\ GeV/c$) are selected for the following steps:

- automatic location in the interface emulsions of the tracks corresponding to the target tracker predictions, and accurate measurement of the track parameters. These values are used for the track search on the surface of the emulsion target.
- automatic vertex location: *scan-back* of tracks up to the plate where the the track disappears. This plate is called *vertex plate*;
- automatic kink search (see later), to retain candidates;
- complete semi-automatic analysis of the τ candidate events by *follow-down* of all tracks connected to the vertex. The emulsion tracks are linked to those reconstructed by the electronic detectors for kinematical reconstruction.

IV. THE DATA COLLECTION

The experiment has taken data since 1994 and the emulsions used in the first run (1994-1995) have been developed. The analysis described here refers to data collected in 1994, when 120000 charged current ν_μ events in the emulsion target were recorded by the electronic detectors. These events have been reconstructed, giving predictions of the vertex position and the locations and directions of the tracks in the interface emulsions. These predictions are used in laboratories equipped with automatic scanning systems to find tracks and vertices in the emulsions.

V. THE $\tau \to \mu\nu_\tau\bar{\nu_\mu}$ SEARCH ANALYSIS

Here we report on the search of ν_τ interactions with the subsequent muonic decay of the τ lepton. The events with a muon with less than 30 GeV/c momentum were selected. The μ track is automatically followed in the emulsions until the neutrino interaction vertex is reached.

The decay search is done in sequence in two different ways, as shown graphically in Fig. 2.

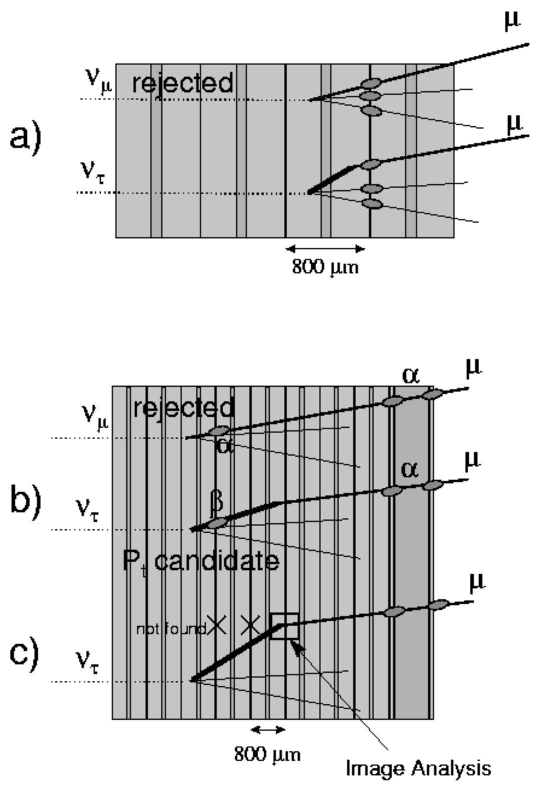

FIG. 2. Short and long decay searches

- *short decay search.*

  Inside the plate where the interaction took place (Fig. 2a), the μ^- impact parameter is evaluated as the minimum distance between the muon track and any other track of the event. Events which show a large impact parameter, *i.e.* bigger than $2 - 8\ \mu m$ according to the longitudinal position inside the plate (Fig. 3), are remeasured using semi-automatic techniques, with human intervention. Using simulation, we expect 27% of the tau decays to be in the vertex plate, and of these 59% survive to the impact parameter cut.

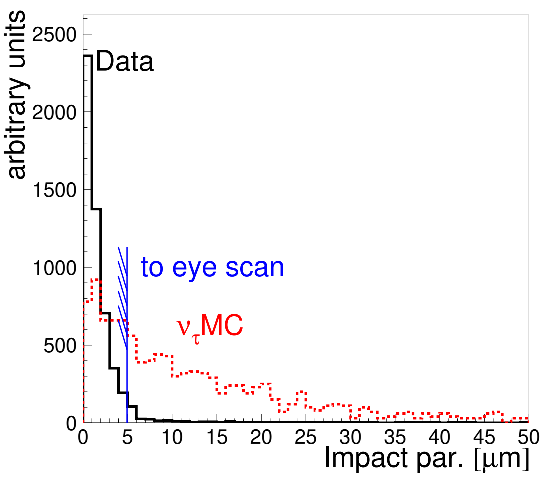

FIG. 3. Impact parameter distribution.

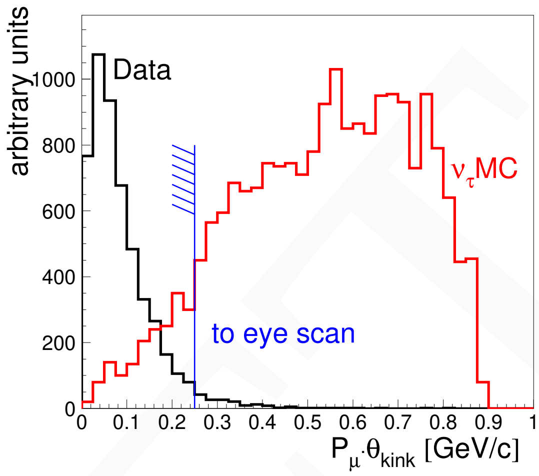

FIG. 4. Transverse momentum distribution in long decays

- *long decay search.*

  A possible decay further downstream of the vertex plate (*long decay*) can be detected in two ways, according to its kink angle:

  - by losing the track in the plate "upstream" the kink plate because of a large deviation (Fig.2c); in this case the vertex plate is the kink plate. In this case, a dedicated *image analysis* is undertaken on video pictures taken at the vertex plate. The events which still show a kink signature are fully re-measured with semi-automatic computer-assisted microscopes. The simulation shows that 61% of the τ decays are in this category.
  - when the kink angle is smaller than the tolerances of the measurements (Fig.2b), the vertex plate is assumed to be the interaction plate. In this case, the direction of the muon measured in the plate downstream of the interaction plate is compared with the one measured by the scintillating fibre tracker. If the measured transverse momentum $P_t \approx \Delta\theta \cdot P_\mu$ is larger than 250 MeV/c the event is measured manually in five plates downstream of the vertex plate (Fig. 4).

  The value of the cut is such that the τ detection efficiency is reasonably high (85% of the decays with $P_t > 250 MeV/c$), the background from π and K decay is eliminated and the manual scanning load due to multiple scattering is contained.

  For all the decays studied, those events

  - with a decay signature (kink);
  - a decay P_t larger than 250 MeV/c;
  - a kink distance from the production vertex less than 5 plates (4 mm).

  will be considered as τ candidates

Out of 120000 charged current ν_μ events recorded by the electronic detectors in the emulsion target in 1994, 63% (10% of the full expected statistics) have been analysed. After all cuts and scanning efficiencies 14897 events have been located and analysed at the vertex. No ν_τ interaction candidates have been found.

In the muon channel 0.05 background events are expected at the level of present statistics. After the prompt ν_τ production the most important source of background is given by charm production from the anti-neutrino component of the beam:

$$\overline{\nu}_\mu(\overline{\nu}_e)\ N \to \mu^+(e^+)\ +\ D^-\ + X$$

followed by

$$D^- \to \mu^- + X'$$

with the $\mu^+(e^+)$ escaping detection or mis-identified.

VI. THE $\tau \to \mathrm{h}^-(\mathrm{nh}^0)\nu_\tau$ SEARCH ANALYSIS

This decay channel has a branching ratio of 50%. A first sample of 1336 muon-less events (4% of the full expected statistics) has been analysed using the procedure outlined in section V for the $\tau \to \mu\nu_\tau\bar{\nu_\mu}$ channel and replacing the muon by the reconstructed negative-hadron tracks with $1 < p_h < 20\ GeV/c$.

With the present statistics we expect $\sim 10^{-2}$ background events from charm production and ~ 0.1 events from kinks due to recoilless elastic scattering of an hadron on nuclei *(white kinks)*. A kinematical analysis at the event vertex, considering the track segment before the kink, would allow to further reduce this background.

VII. EFFICIENCIES AND RESULT

The total number of observed charged current ν_μ interactions is given by

$$N_{CC}(\nu_\mu) = S \cdot \int\int \Phi(\nu_\mu, E, L) \cdot \sigma(\nu_\mu, E) \cdot A(\nu_\mu, E) \cdot dE\ dL$$

The total number of observed ν_τ interactions with a muonic decay is instead

$$N_{CC}(\nu_\tau) = S \cdot \int\int \Phi(\nu_\mu, E, L) \cdot P_{osc}(E) \cdot \sigma(\nu_\tau, E) \quad (1)$$
$$\cdot \sum_i^{\mu,h} A_i(\nu_\tau, E) \cdot \epsilon_i(kink) \cdot BR_i \cdot dE\ dL$$

where

$$P_{osc}(E) = sin^2 2\theta_{\mu\tau} \cdot sin^2(\frac{1.27 \cdot \Delta m^2_{\mu\tau}[eV^2] \cdot L[km]}{E[GeV]})$$

and

- E is the incident neutrino energy;
- S is a normalisation factor (identical for ν_μ and ν_τ interactions);
- $\Phi(\nu_\mu, E, L)$ is the measured ν_μ energy distribution;
- $\sigma(\nu_\mu)$ and $\sigma(\nu_\tau)$ are the charged current ν_μ and ν_τ cross-sections;
- BR_i are the branching ratios $\tau \to \mu\nu_\tau\bar{\nu_\mu}$ and $\tau \to \mathrm{h}^-(\mathrm{nh}^0)\nu_\tau$;
- $A(\nu_\mu)$ and $A_i(\nu_\tau)$ are the acceptance and reconstruction efficiencies, as obtained by detector simulation;
- $\epsilon_i(kink)$ is the overall kink detection efficiency as determined by the weighted efficiency of the kink search algorithms, previously described.

In case of large Δm^2, the mixing angle can be written as

$$sin^2 2\theta_{\mu\tau} = 2 \cdot P_{osc}(E)$$

where in terms of experimental variables

$$P_{osc}(E) = \frac{N^{obs}_{\nu_\tau}}{N^{obs}_{\nu_\mu}} \cdot \frac{\langle\sigma(\nu_\mu)\rangle}{\langle\sigma(\nu_\tau)\rangle} \cdot \frac{1}{C}$$

and

$$C = \sum_i \frac{\langle A_i(\nu_\tau, E)\rangle}{\langle A(\nu_\mu, E)\rangle} \cdot BR_i \cdot \epsilon_i(kink) \cdot r_{sc_i}$$

$$\frac{\langle\sigma(\nu_\mu)\rangle}{\langle\sigma(\nu_\tau)\rangle} = 1.89$$

r_{sc_i} accounts for the fact that the total sample selected for 0μ analysis refers only to 44% of the total sample used for 1μ analysis. The computed values are given in table I.

Since we have observed no candidate events, we can derive the 90% $C.L.$ upper limit on $sin^2 2\theta_{\mu\tau}$, for large Δm^2 as:

$$sin^2 2\theta_{\mu\tau} < 4.5 \times 10^{-3}$$

A graphical representation of the oscillation parameters space explored by this analysis is reported in Fig. 5, in the so called exclusion plot.

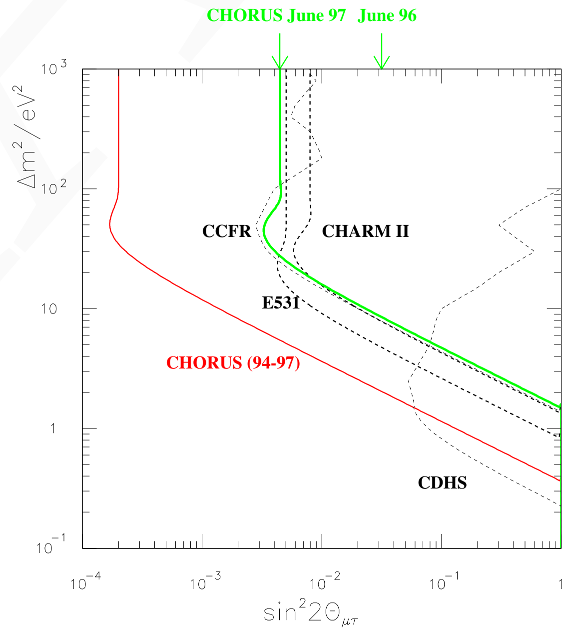

FIG. 5. Exclusion Plot.

VIII. CONCLUSIONS

We have presented the results of an experimental search for $\nu_\mu \to \nu_\tau$ oscillation parameters. This study is based on the muonic and single prong decay channel of the τ and on a small fraction of the expected statistics of the CHORUS experiment. The limit $sin^2 2\theta_{\mu\tau} < 4.5 \times 10^{-3}$ for large $\Delta m^2_{\mu\tau}$ of is already better than the best previous result [5]. The full data sample of the experiment and the concurrent development of automatic measuring devices will make it possible to reach a sensitivity of $sin^2 2\theta_{\mu\tau} < 2 \times 10^{-4}$ in a few years.

TABLE I. Parameters assumed in the τ detection efficiency estimate.

decay mode	$\frac{A_i(\nu_\tau,E)}{A(\nu_\mu,E)}$	BR	$\epsilon_i(kink)$	r_{sc_i}
$\tau \rightarrow \mu\nu_\tau\bar{\nu_\mu}$	1.07	0.17	0.55	1
$\tau \rightarrow h^-(nh^0)\nu_\tau$	0.36	0.50	0.26	0.44

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