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A Search for $\nu_\mu \to \nu_\tau$ Oscillation

The CHORUS Collaboration

E. Eskut, A. Kayis, G. Onengüt
Çukurova University, Adana, Turkey

R. van Dantzig, M. de Jong, J. Konijn, O. Melzer, R. G. C. Oldeman, C. A. F. J. van der Poel, J. W. E. Uiterwijk, J. L. Visschers
NIKHEF, Amsterdam, The Netherlands

A. S. Ayan, E. Pesen, M. Serin-Zeyrek, R. Sever, P. Tolun, M. T. Zeyrek
METU, Ankara, Turkey

N. Armenise, F. Cassol, M. G. Catanesi, M. T. Muciaccia, E. Radicioni, S. Simone, L. Vivolo
Università di Bari and INFN, Bari, Italy

A. Bülte, P. Lendermann, A. Meyer-Sievers, T. Patzak[1)], K. Winter
Humboldt Universität, Berlin, Germany[2)]

P. Annis[3)], M. Gruwé[9,5)], C. Mommaert[4,6)], M. Vander Donckt[5)], B. Van de Vyver[7)], P. Vilain[8)], G. Wilquet[8)]
Inter-University Institute for High Energies (ULB-VUB), Brussels, Belgium

P. Righini, B. Saitta
Università di Cagliari and INFN, Cagliari, Italy

E. Di Capua, C. Luppi, P. Zucchelli
Università di Ferrara and INFN, Ferrara, Italy

Y. Ishii, T. Kawamura, M. Kazuno, S. Ogawa, H. Shibuya
Toho University, Funabashi, Japan

R. Beyer[9)], J. Brunner, D. Cussans, J. P. Fabre, R. Ferreira[10)], W. Flegel, R. Gurin[11)], M. Litmaath, L. Ludovici[12)], D. Macina[13)], R. Meijer Drees[14)], H. Meinhard, P. Migliozzi, E. Niu, H. Øverås, J. Panman, I. M. Papadopoulos, F. Riccardi, S. Ricciardi, A. Rozanov[15)], D. Saltzberg[16)], R. Santacesaria[12)], G. Stefanini, R. Tsenov[17)], Ch. Weinheimer[18)], H. Wong[19)]
CERN, Geneva, Switzerland

J. Goldberg, K. Hoepfner[9)]
Technion, Haifa, Israel

M. Chikawa
Kinki University, Higashiosaka, Japan

E. Arik, I. Birol, A. A. Mailov
Bogazici University, Istanbul, Turkey

C. H. Hahn[20)], H. I. Jang, I. G. Park, M. S. Park, J. S. Song, C. S. Yoon
Gyeongsang National University, Jinju, Korea[21)]

K. Kodama, N. Ushida
Aichi University of Education, Kariya, Japan

S. Aoki, T. Hara
Kobe University, Kobe, Japan

G. Brooijmans[22)], D. Favart, G. Grégoire, J. Hérin[22)], V. Lemaître[9)]
Université Catholique de Louvain, Louvain-la-Neuve, Belgium

A. Artamonov, P. Gorbunov, V. Khovansky, V. Shamanov, V. Smirnitsky
Institute for Theoretical and Experimental Physics, Moscow, Russian Federation

D. Bonekämper, D. Frekers, D. Rondeshagen, T. Wolff[23)]
Westfälische Wilhelms - Universität, Münster, Germany[2)]

K. Hoshino, M. Kobayashi, Y. Kotaka, T. Kozaki, M. Miyanishi, M. Nakamura, K. Nakazawa[24)], T. Nakano, K.Niu, K. Niwa, Y. Obayashi, O. Sato, T. Toshito
Nagoya University, Nagoya, Japan

S. Buontempo, A. Cocco, N. D'Ambrosio, G. De Lellis, A. Ereditato, G. Fiorillo, F. Garufi, F. Marchetti-Stasi, M. Messina, V. Palladino, S. Sorrentino, P. Strolin
Università Federico II and INFN, Naples, Italy

K. Nakamura, T. Okusawa, T. Yoshida
Osaka City University, Osaka, Japan

A. Capone, D. De Pedis, S. Di Liberto, U. Dore, P. F. Loverre, A. Maslennikov[11)], M. A. Mazzoni, F. Meddi, G. Piredda
Università La Sapienza and INFN, Rome, Italy

A. di Bartolomeo, C. Bozza, G. Grella, G. Iovane, G. Romano, G. Rosa[25)]
Università di Salerno and INFN, Salerno, Italy

Y. Sato, I. Tezuka
Utsunomiya University, Utsunomiya, Japan

Abstract

CHORUS is an experiment searching for $\nu_\mu \to \nu_\tau$ oscillation in the CERN wide band neutrino beam with a *hybrid* setup consisting of a nuclear emulsion target followed by electronic detectors. The experiment has been taking data from 1994 through 1997. A subset of the neutrino interactions collected in 1994 and 1995 have been analyzed, looking for ν_τ charged current interactions where the τ lepton decays to $\mu\bar{\nu}_\mu\nu_\tau$. In a sample of 31,423 ν_μ charged current interactions, no ν_τ candidates were found. For large $\Delta m^2_{\mu\tau}$ values, a limit on the mixing angle of $sin^2 2\theta_{\mu\tau} < 3.5 \times 10^{-3}$ at 90% C.L. can be set, thus improving the previous best result.

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8) Fonds National de la Recherche Scientifique.
9) Now at DESY, Hamburg, Germany.
10) On leave of absence from LIP, Lisbon.
11) CASPUR, Rome, Italy.
12) On leave of absence from INFN Sezione di Roma, Rome, Italy.
13) Now at Université de Genève, Geneva, Switzerland.
14) Now at University of Washington, Seattle, USA.
15) Now at CPPM CNRS-IN2P3, Marseille, France.
16) Now at U.C.L.A., Los Angeles, USA.
17) On leave of absence from Sofia University, Bulgaria, with support from the Bogazici University, Centre for Turkish-Balkan Physics Research and Applications.
18) Now at University of Mainz, Mainz, Germany.
19) Now at Academia Sinica, Taipei, Taiwan.
20) Now at the Changwon Nat. Univ., Changwon, Korea.
21) Supported by the Korea Scince and Engineering Foundation, and the Ministry of Education through Research Fund (BSRI-97-2407), Republic of Korea.
22) Institut Interuniversitaire des Science Nucléaires.
23) Supported by a grant from Deutsche Forschungs Gemeinschaft.
24) Now at Gifu University, Gifu, Japan.
25) Now at Università La Sapienza and INFN, Rome, Italy.

1 Introduction

CHORUS is an experiment designed to search for $\nu_\mu \to \nu_\tau$ oscillation through the observation of charged current interactions ν_τ N $\to$ τ^- X, followed by the decay of the τ lepton. The experiment can probe neutrino masses difference above few eV ($\Delta m^2_{\mu\tau} \gtrsim 1$ eV^2). Massive neutrinos in this range have been proposed as candidates for the hot component of dark matter in the universe[1], and the $\nu_\mu \to \nu_\tau$ oscillation search is further motivated if one assumes a hierarchical pattern of neutrino masses.

The experiment is performed in the CERN Wide-Band Neutrino Beam, which contains mainly ν_μ with a contamination from ν_τ well below the level of sensitivity that can be reached in this experiment.

Neutrino interactions occur in a target of nuclear emulsion, whose exceptional spatial resolution (below one micrometer) and hit density (300 grains/mm along the track) allow a three dimensional "visual" reconstruction of the trajectories of the τ lepton and its decay products.

The experiment is sensitive to most of the decay channels of the τ; in this paper however we report on the results obtained with a subsample where we confined ourselves to the $\tau^- \to \mu^- \nu_\tau \overline{\nu}_\mu$ decay search. The detection of the decay topology in the nuclear emulsion, together with the reconstruction of the event kinematics in the electronic detectors, make CHORUS an essentially background free ν_τ appearance experiment.

2 The Experimental setup

2.1 The neutrino beam

The CERN wide band neutrino beam (WBB) contains dominantly muon neutrinos from π^+ and K^+ decay, with a $\overline{\nu}_\mu$ contamination of 5% , a $\nu_e, \overline{\nu}_e$ contamination at a level of 1%. The estimated ν_τ background[2] is of the order of 3.3×10^{-6} ν_τ charged current interactions per ν_μ charged current interaction, hence negligible. The ν_μ component of the beam has an average energy of 27 GeV.

2.2 The apparatus

The short decay length of the τ (1.5 mm on average, assuming that the ν_τ have the same energy spectrum as the ν_μ beam) and the large statistics needed to improve the best existing result [3] have guided the design of the apparatus, which is described in ref. [4]. The *hybrid* setup, shown in Fig. 1, is composed of an emulsion target, a scintillating fiber tracker system, trigger hodoscopes, a magnetic spectrometer, a lead-scintillator calorimeter and a muon spectrometer.

The emulsion target has a mass of 770 kg and a surface area of 1.42×1.44 m^2. It consists of four stacks of 36 plates each. Each plate has two 350 μm thick layers of nuclear emulsion on both sides of a 90 μm thick plastic base.

Downstream of each emulsion stack there are three sets of *interface emulsion* sheets of the same lateral dimensions as the emulsion target. Each interface emulsion sheet consists of a 800 μm acrylic base coated, on both sides, with a 100 μm thick emulsion layer. They are placed between each emulsion stack and the following fiber tracker module as shown in Fig. 2.

Scintillating fiber trackers locate the trajectories of charged particles produced in the neutrino interaction. The trajectories of these particles are extrapolated to the downstream face of the emulsion stack with the help of the interface emulsion sheets. The fiber tracker resolution on lateral position and direction is $\sigma = 150$ μm and $\sigma = 2$ mrad, respectively.

Downstream of the target region, a magnetic spectrometer allows the reconstruction of the charge and momentum of charged particles. The spectrometer consists of an air-core magnet of hexagonal shape and three scintillating fiber trackers, one in front and two behind the air-core magnet, which record the charged particles' trajectory and deflection.

A lead scintillating fiber calorimeter following the spectrometer measures the energy and direction of the hadronic showers and allows neutral particles detection.

The calorimeter is followed by a muon spectrometer which identifies muons and measures their charge and momentum. It is composed of magnetized iron disks and tracking devices. A momentum resolution of 19% is achieved above 7 GeV/c by magnetic field deflection. By range measurement, a 6% resolution is obtained below 7 GeV/c.

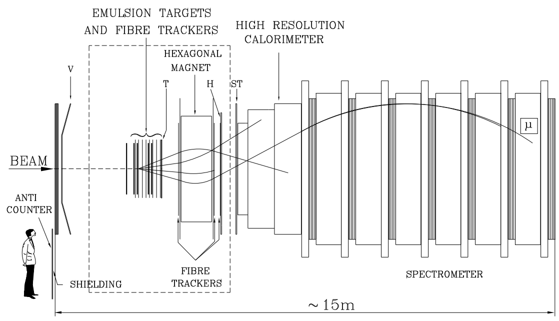

Figure 1: General layout of the detector.

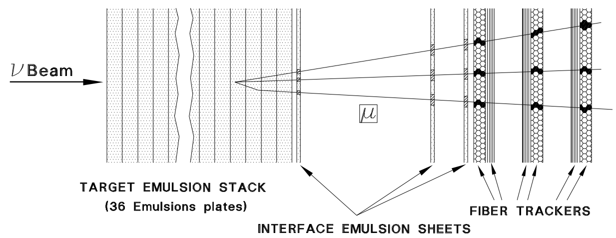

Figure 2: Layout of an emulsion stack and associated fiber trackers.

Table 1: Current status of the CHORUS $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$ search.

Year	1994	1995
Protons on target	0.81×10^{19}	1.20×10^{19}
Emulsion triggers	$422,000$	$547,000$
Charged current interactions expected	$120,000$	$200,000$
Events with one identified muon and vertex predicted in emulsions	$95,374$	$155,558$
Events with $P_\mu < 30$ GeV	$66,911$	$110,916$
Events scanned so far	$41,931$	$37,569$
Events within the fiducial cuts	$35,767$	$32,046$
Events with a vertex found in the emulsion	$16,837$	$14,586$

3 The Data Collection

The detector has been exposed to the WBB from 1994 to 1997. After a first run (1994–95), the target emulsion was replaced and the exposed emulsion developed. During this period CHORUS collected approximately 969,000 triggers, corresponding to 2.01×10^{19} protons on target. On the basis of neutrino flux estimate, trigger efficiency, cross section, dead-time correction and target mass, about $320,000$ charged current ν_μ interactions are expected to have occurred in the emulsion target. Of these $250,932$ events have been reconstructed in the electronic detectors with an identified negative muon and an interaction vertex in the emulsion.

4 The $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$ search analysis

4.1 Principles

The search for $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$ decays starts from the reconstructed events recorded in the electronic detectors. The event selection, described later, provides us with a set of events with a reconstructed muon track and a prediction for the trajectory of the muon through the interface emulsion sheets. The muon track is located in the interface emulsion sheets using automatic techniques and followed into the emulsion target in order to locate the plate where the interaction had occurred. Automatic criteria are then applied to select candidate events with the one-prong decay topology we are looking for.

If the automatic decay search does not *reject* the event, computer assisted *eye scan* of the vertex plate (and downstream plates if necessary) is performed, in order to assess the presence of a $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$ decay topology. If a candidate is found, all tracks are measured in the emulsion and connected to those found in the electronic detectors; in addition, the event kinematics can be reconstructed.

4.2 Event selection

Only events with one negative muon, of momentum $P_\mu < 30$ GeV/c, have been considered. The momentum cut reduces the number of events to be further analyzed to 177,827. Since muons from τ decay have a lower momentum, on average, than those produced in charged current interactions, this selection would reject only a small fraction of genuine ν_τ interactions (15% in the case that ν_τ have the same energy spectrum as the ν_μ beam), while reducing the ν_μ charged current interactions that would have to be scanned to 71% of the total.

So far, only 79,500 events of the 177,827 have been scanned. Since the scanning procedure requires the application of fiducial cuts on the angle and position of the muon track, the sample is further reduced to 67,813 events. The number of events at each stage of the analysis are summarized in Table 1.

4.3 The vertex location

The emulsion scanning procedure is fully automated using computer controlled microscopes equipped with CCD cameras and fast processors: this is the first time that fully automatic scanning is achieved. The processor, which is called *track-selector* [5], is capable of identifying the tracks inside the emulsion and measuring their parameters *on-line*. In the scanning procedure, these systems are used to locate the negative muon track in the interface emulsion sheets, and to follow it inside the target, plate by plate, until it disappears in two consecutive plates. The first plate where the track disappears is called the *vertex plate*. The vertex location procedure, called *scan-back*, has been successful for $31,423$ charged current events.

Once the vertex plate has been located, the decay search, described in more detail in the following section, is performed.

4.4 The decay search procedure

An event with a τ lepton is identified by the presence of a change of direction (*kink*) of the τ^- track due to the $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$ semileptonic decay, while a muon pointing to the vertex is the leading muon of a ν_μ charged current event. We consider as τ candidates events satisfying the following criteria:

- a decay signature (kink) along the μ^- track;
- no other charged leptons at the primary vertex;
- the muon transverse momentum P_t, with respect to the τ candidate direction, is larger than 250 MeV/c.

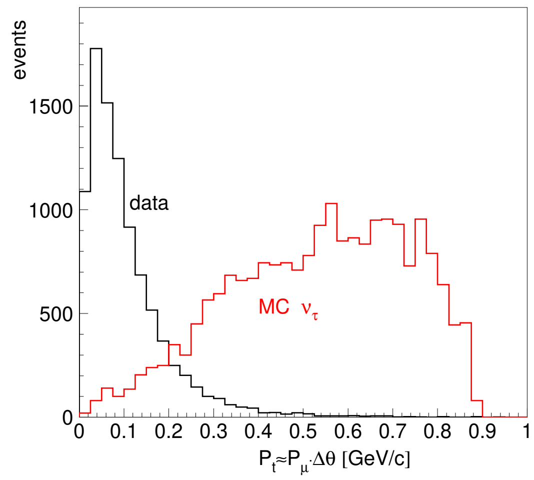

Figure 3: Transverse momentum distribution in long decay path events of data and of $\nu_\tau N \to (\tau \to \mu)X$ MC simulation.

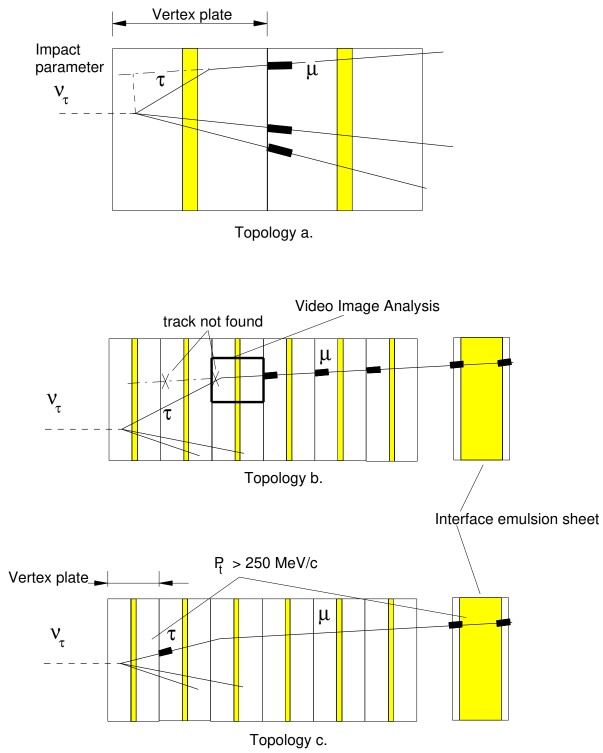

Figure 4: Search for kink topologies, as described in the text.

- the kink plate is located within 5 plates downstream of the vertex plate (corresponding to a maximum τ decay path length of 3.95 mm).

The cut on P_t eliminates the $K^- \to \mu^- \bar{\nu}_\mu$ decays, keeps the loss of efficiency for τ events small and at the same time discards the large majority of μ^- coming from ν_μ interactions at the level of automatic measurements. Figure 3 shows the P_t distribution for the collected data sample compared with the Monte Carlo distribution expected for ν_τ events. Due to the ongoing development of the automatic scanning devices and procedures, different kink search algorithms have been applied to the analysis of 1994 and 1995 data in order to optimize speed and efficiency of the decay search procedure.

4.4.1 The 1994 data analysis

The decay search is performed following two different procedures, which are applied concurrently on each event located.

i) short decay path search. This search is designed to detect decays in the vertex plate. Two different approaches are followed according to the number of tracks reconstructed by the track-selector at the upstream face of the plate following the vertex plate. If there is at least one track matched with the tracker predictions (Fig. 4, topology **a.**), the μ^- impact parameter is evaluated as the minimum distance between the muon track and any other track of the event (Fig. 5). Only events which show a large impact parameter, *i.e.* bigger than $2 - 8$ μm according to the longitudinal position inside the plate, are visually inspected and re-measured with semi-automatic techniques. For the events with no matched hadrons, digital images of the microscope fields over the whole vertex plate depth are recorded, and the search for a kink continues off-line (*video image* analysis).

ii) long decay path search. This procedure is designed to detect decays downstream of the vertex plate. The scan-back procedure follows the muon track from one plate of the target to the next one, implicitly assuming the track straightness. A 'long' decay path can thus be detected in two ways, according to its kink angle:

- If the decay angle is larger than the scan-back angular tolerance (large angle kinks), the scan-back procedure stops and the kink plate is assumed to be the vertex plate (Fig. 4, topology **b.**). Since no other emulsion tracks can be matched to the fiber trackers predictions to apply the short decay path search, the video image analysis is undertaken.
- If the kink angle is smaller than the tolerances of the scan-back (Fig. 4, topology **c.**), the vertex plate is indeed the interaction plate and decays can be detected by measuring a track direction in the plate immediately downstream of the vertex plate which is not compatible with measurements in the other detectors (emulsion plates, interface emulsions, fiber tracker). If the measured transverse momentum $P_t \approx \Delta\theta \cdot P_\mu$ is larger than 250 MeV/c, the complete event is scanned by eye in five plates downstream of the vertex plate.

4.4.2 The 1995 data analysis

Currently only the long decay path search has been performed on 1995 data, with the recently developed *"parent track"* search technique applied for large angle

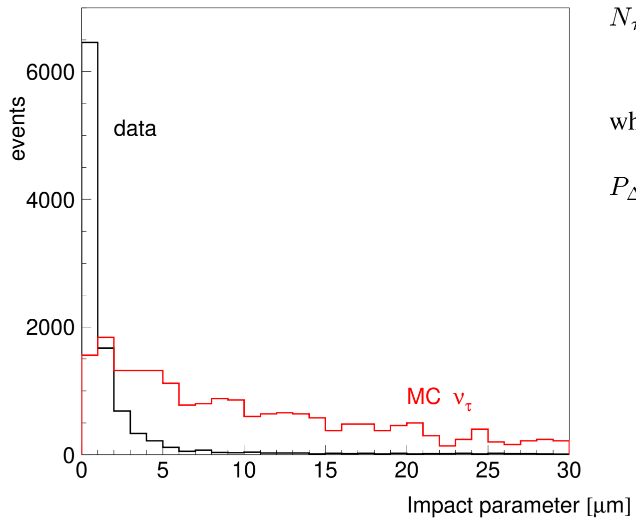

Figure 5: Impact parameter distributions in the search of *short decay path* decays of data and of $\nu_\tau N \to (\tau \to \mu)X$ MC simulation.

kink detection. As explained in the 1994 long decay path search, whenever a large angle decay is found, the kink plate is assumed to be the vertex plate (Fig. 4, topology **b**). In the *'parent track'* search technique the upstream part of the vertex plate is scanned in order to check the possibility of associating a track with the muon. If the minimal distance between a track and the muon is less than 15 μm, this track will be considered its *'parent'*. Checks are made to ensure that the parent track is not a passing-through track accidentally associated to the muon. If a parent track is found, the event is scanned by eye.

5 Analysis and Result

A total of 31,423 muonic events have been analyzed as described above, and no tau decays have been found. By evaluating the $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$ detection efficiency this *negative* result is used to exclude a significant region of the oscillation parameter space.

5.1 Oscillation sensitivity

In the two flavour mixing scheme, the result can be expressed as an exclusion plot in the parameter space $(sin^2 2\theta_{\mu\tau}, \Delta \mathrm{m}^2_{\mu\tau})$. The oscillation probability depends on the number of observed ν_τ and ν_μ events.

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

$$N_\mu = S \cdot \int \Phi_{\nu_\mu} \cdot \sigma_{\nu_\mu} \cdot A_{\nu_\mu} \cdot dE$$

and the total number of observed ν_τ interactions with a muonic τ decay is

$$\begin{aligned} N_\tau = &\quad S \cdot sin^2 2\theta_{\mu\tau} \cdot BR \cdot \int \Phi_{\nu_\mu} \cdot P_{\Delta \mathrm{m}^2_{\mu\tau}} \cdot \sigma_{\nu_\tau} \cdot A_{\nu_\tau} \cdot \epsilon_k \cdot dE \\ = &\quad S \cdot sin^2 2\theta_{\mu\tau} \cdot BR \cdot I \end{aligned}$$

where

$$P_{\Delta \mathrm{m}^2_{\mu\tau}} = \int \Psi(E,L) \cdot sin^2 \left(\frac{1.27 \cdot \Delta m^2_{\mu\tau}[\mathrm{eV}^2] \cdot L[\mathrm{km}]}{E[\mathrm{GeV}]} \right) dL$$

and

E is the incident neutrino energy;
L is the neutrino path-length to the emulsion target;
$\theta_{\mu\tau}$ is the $\nu_\mu - \nu_\tau$ mixing angle;
$\Delta \mathrm{m}^2_{\mu\tau} = m^2_{\nu_\tau} - m^2_{\nu_\mu}$;
S is a constant factor (identical for ν_μ and ν_τ interactions) that takes into account the mass of the detector and the integrated neutrino flux;
Φ_{ν_μ} is the ν_μ energy distribution;
$\Psi(E,L)$ is the ν_μ path distribution at a given neutrino energy value;
σ_{ν_μ} and σ_{ν_τ} are the charged current ν_μ and ν_τ differential cross sections;
A_{ν_μ} and A_{ν_τ} are the energy dependent acceptance and reconstruction efficiencies;
ϵ_k is the energy dependent kink detection efficiency;
BR is the $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$ branching ratio ($17.35 \pm 0.10\%$, [6]).

Since we have observed zero candidate events, we can express the 90% C.L. upper limit on $sin^2 2\theta_{\mu\tau}$ according to:

$$sin^2 2\theta_{\mu\tau} \leq \frac{2.37 \cdot \int \Phi_{\nu_\mu} \cdot \sigma_{\nu_\mu} \cdot A_{\nu_\mu} dE}{N_\mu \cdot BR \cdot I} \qquad (1)$$

In the above formula the numerical factor takes into account the total systematic error (16%) following the prescriptions given in [12].

For large $\Delta \mathrm{m}^2_{\mu\tau}$ values, $P_{\Delta \mathrm{m}^2_{\mu\tau}} = 1/2$ and so the previous formula can be simplified into

$$sin^2 2\theta_{\mu\tau} \leq \frac{2 \cdot 2.37 \cdot r_\sigma \cdot r_A}{N_\mu \cdot \langle \epsilon_k \rangle \cdot BR} = 3.5 \cdot 10^{-3} \qquad (2)$$

where

$r_\sigma = \langle \sigma(\nu_\mu) \rangle / \langle \sigma(\nu_\tau) \rangle$ is the neutrino energy weighted cross section ratio[13]. A value of $r_\sigma = 1.89 \pm 0.13$ has been used; it takes into account quasi elastic interactions, resonance production and deep inelastic reactions.
$r_A = \langle A(\nu_\mu) \rangle / \langle A(\nu_\tau) \rangle$ is the cross section weighted acceptance ratio of ν_μ and ν_τ interactions, its value has been evaluated to be 0.95 ± 0.07.
$\langle \epsilon_k \rangle$ is the average kink detection efficiency for the accepted events. Because of the different procedures, its value is 0.54 ± 0.06 for the 1994 data sample and 0.34 ± 0.04 in 1995 where only the long decay path search has been performed.

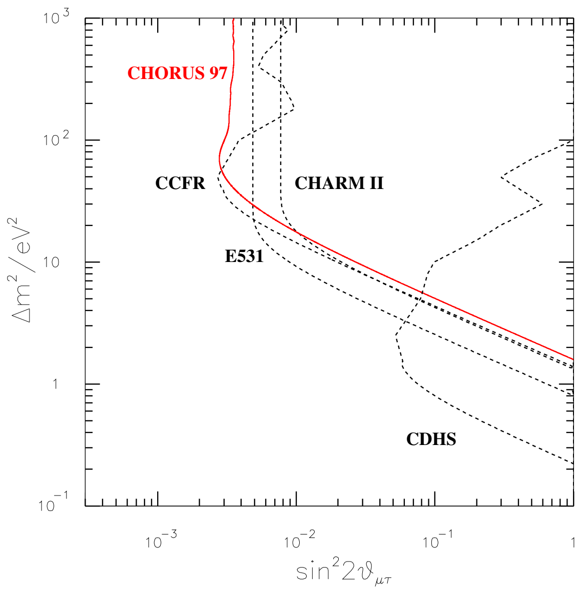

Figure 6: Present result and previous limits from CCFR [8], CDHS [9], CHARM II [10] and E531 [3].

A graphical representation of the oscillation parameter region excluded with the current data is shown in Fig. 6. Maximum mixing between ν_μ and ν_τ is excluded at 90% C.L. if $\Delta m^2_{\mu\tau} > 1.5$ eV^2.

5.2 The τ identification efficiency.

The computation of the exclusion plot in the oscillation parameter space requires the knowledge of the acceptance and reconstruction efficiencies A_{ν_τ} and A_{ν_μ} and of the kink detection efficiency. These efficiencies have been estimated by Monte Carlo simulation of the detector and of the scanning procedure. The scanning procedure and hence A_{ν_τ} and A_{ν_μ} have evolved in the course of the analysis. Several approaches have been used in computing the above quantities so we can estimate a systematic error of 7%.

The kink detection efficiency ϵ_k has been evaluated by Monte Carlo simulation and has been averaged over the different kink search procedures described previously. The relative systematic error has been evaluated to be 10%.

Since we expect D^+ production in ν_μ induced interactions[7]

$$\nu_\mu \, N \rightarrow \mu^- \, D^+ \, X$$

we can check experimentally the estimated kink finding efficiency on one-prong muonic charm decays

$$D^+ \rightarrow \mu^+ X^0 \nu_\mu$$

These events have two muons of opposite charge in the final state (*dimuons*) and – except for the particle charges – the topology of the muonic charm decay is the same as that of the τ decay. A sample of positive muons from dimuon events has been scanned to estimate the kink detection capability. A first sample consisting of 10 dimuon events with a decay kink was selected by eye and the automatic τ kink search applied. The kink finding efficiency of the automatic procedure is consistent with our estimates by Monte Carlo simulation. In an enlarged sample of 17 events, including three prong decays, the distribution of flight path length is in good agreement with that obtained from the Monte Carlo simulation of the automatic scanning procedure. Although the number of events is too low to draw quantitative conclusions, we can take these results as a qualitative check of the simulation of the automatic scanning procedure.

5.3 Backgrounds estimate

The main sources of potential background are charm production and the ν_τ contamination of the beam.

We expect less than 0.05 charm events in the current sample from the anti-neutrino components of the beam:

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

followed by

$$D^- \rightarrow \mu^- \, X^0$$

in which the μ^+ (e^+) escapes detection or is mis-identified.

Taking into account cross sections, branching ratio and kink detection efficiency, we expect the current sample to contain less than 0.01 events due to direct ν_τ contamination of the beam[2].

6 Conclusions

We have presented limits on $\nu_\mu \rightarrow \nu_\tau$ oscillation parameters based on the muonic decay channel of the τ using a fraction of the data collected by the CHORUS experiment. The limit on $sin^2 2\theta_{\mu\tau}$ for large $\Delta m^2_{\mu\tau}$ values is $sin^2 2\theta_{\mu\tau} < 3.5 \times 10^{-3}$ at 90% C.L., and improves the best previous result. A search for hadronic τ decays using the sample of events without a muon is in progress and results from partial statistics have been reported in [11]. By improving the efficiencies, by increasing the number of τ decay channels searched for and by enlarging the ν_τ search to the complete set of data we expect to reach the design sensitivity of the experiment. If no candidates are found this corresponds to a limit of $sin^2 2\theta_{\mu\tau} < 2 \times 10^{-4}$ for large $\Delta m^2_{\mu\tau}$ values.

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