New results on the $\nu_\mu \rightarrow \nu_\tau$ oscillation search with the CHORUS detector

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Abstract

The present results on the $\nu_\mu \rightarrow \nu_\tau$ oscillation search by the CHORUS experiment at CERN are summarised. A fraction of the neutrino interactions collected in 1994-1995-1996 by the CHORUS experiment has been analysed, searching for ν_τ charged current interactions followed by the τ lepton decay into a negative hadron or into a muon. A sample of 68,156 events with an identified final state muon and 7,206 events without an identified muon in the final state have been located in the emulsion target. Within the applied cuts, no ν_τ candidate has been found. This result leads to a 90% C.L. limit $P(\nu_\mu \rightarrow \nu_\tau) < 6.0 \cdot 10^{-4}$ on the mixing probability.

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The CHORUS experiment has recently reported [1, 2, 3] a limit on $\nu_\mu - \nu_\tau$ oscillation obtained by the analysis of a subsample of neutrino interactions, taken in 1994-1995, both with and without an identified μ^- in the final state. This paper contains an update of the statistics of the subsample of events with an identified μ^- in the final state.

The experimental setup and the characteristics of the CERN wide band neutrino beam are summarised in [1] and described in more details in [4].

1 The apparatus

The "*hybrid*" CHORUS apparatus combines a 770 kg nuclear emulsion target with various electronic detectors : a scintillating fibre tracker system, trigger hodoscopes, an air-core magnet, a lead/scintillator calorimeter and a muon spectrometer.

Details about the experimental setup and the performances of the sub-detectors can be found in [4].

2 Data collection and event selection

In the 1994-1997 period, CHORUS has collected 2,271,000 triggers corresponding to $5.06\ 10^{19}$ protons on target. Of these, 458,601 have a muon identified in the final state (the so called 1μ events) and 116,049 do not (the so called 0μ events) and a vertex position compatible with one of the four emulsion target stacks.

All tracks, associated to the interaction vertex, with an angle less than 0.4 rad with the beam axis and, in view of the large emulsion background of muons originating from a nearby secondary target, bigger than 0.05 rad from the direction of this target are extrapolated downstream and selected for further analysis. These tracks are searched for in the emulsion if their charge is negative and their momentum is in the range $0 \leq p_h \leq 20$ GeV/c and $0 \leq p_\mu \leq 30$ GeV/c for hadrons and muons, respectively.

It should be noted that use has not been made of the energy deposition in the calorimeter to reject electrons or unidentified muons. The contribution of the τ^- leptonic decay modes to the 0μ data sample is taken into account in the evaluation of the sensitivity.

3 Scanning procedure

3.1 Vertex location

The various steps leading to the plate containing the vertex by means of fully automatised microscopes are identical to those described in [1, 2]. They are independently applied to all the selected tracks in the event, the muon for the 1μ events, all the negative tracks for the 0μ events. A track which has been found in the interface emulsion sheets is followed upstream in the target emulsion, using track segments reconstructed in the most upstream 100 μm of each plate, until the track disappears. This plate is referred to as the vertex plate, since it should contain the primary neutrino vertex or the secondary (decay) vertex from which the track originates. The three most downstream plates of each stack are used to validate the matching with the interface emulsion sheets and are not considered as possible vertex plates. The scanning results are summarised in Table 1.

The mean efficiency of this scan-back procedure is found to be $\sim 32\%$ and $\sim 42\%$ for 0μ and 1μ events, respectively. A detailed simulation of the scanning criteria shows that the difference mainly reflects the poorer quality of the hadron track predictions at the interface emulsion sheets, because of the difficulty of reconstruction inside a dense hadronic shower and the larger multiple scattering owing to the lower average momentum.

3.2 Decay search

Once the vertex plate is defined, automatic microscope measurements are performed to select the events potentially containing a decay topology (kink). Different algorithms have been applied, as a result of the progress in the scanning procedures and of the improving performance in speed of the scanning devices. They are described in [1, 2] and briefly recalled here.

In the first procedure the event is selected either when the scan-back track has a significant impact parameter with respect to the other predicted tracks or when the change in the scan-back track direction between the vertex plate and the exit from the emulsion corresponds to an apparent transverse momentum, p_T, larger than 250 MeV/c. For the selected events and for those with only one predicted track, digital images of the vertex plate are recorded and are analysed off-line for the presence of a kink.

The second procedure is restricted to the search of *long* decay paths. In that case the vertex plate is assumed to contain the decay vertex of a charged parent particle produced in a more upstream plate. With this procedure only kink angles larger than 0.025 rad are detected.

For the events selected by either one of these procedures, a computer assisted eye-scan is performed to assess the presence of a secondary vertex and measure accurately its topology. A τ^- decay candidate must satisfy the following criteria:

1. the secondary vertex appears as a kink without black prongs, nuclear recoils, blobs or Auger electrons;
2. the transverse momentum of the decay muon (hadron) with respect to the parent direction is larger than 250 MeV/c (to eliminate decays of strange particles);
3. the kink, in the 0μ channel, occurs within 3 plates downstream from the neutrino interaction vertex plate. Because of the lower background, the kink search in the muonic decay channel was extended to 5 plates, with a gain in efficiency of about 8%.

No τ^- decay candidate has been found satisfying the selection criteria.

4 Experimental check of the kink finding efficiency

The kink finding efficiency, ϵ_{kink}, has been evaluated by Monte Carlo simulation and experimentally checked looking at hadron interactions and dimuon events.

A sample of about 55 m of hadron tracks was scanned in emulsion. In the decay search procedure, 21 neutrino interaction events with a hadron interaction have been

Table 1: *Current status of the CHORUS analysis*

	1994	1995	1996
Protons on target	$0.81 \cdot 10^{19}$	$1.20 \cdot 10^{19}$	$1.38 \cdot 10^{19}$
Emulsion triggers	422,000	547,000	617,000
1μ to be scanned	66,911	110,916	129,669
0μ to be scanned	17,731	27,841	32,548
1μ scanned so far	42,154	49,912	72,615
0μ scanned so far	8,908	12,635	-
1μ vertex located (in the 33 most upstream plates)	18,286	20,642	30,128
0μ vertex located (in the 33 most upstream plates)	3,401	3,805	0

detected. This result is in good agreement with the expected value of (24 ± 2) from Monte Carlo simulation.

Part of the dimuon sample (two muons on the final state) collected in 1995 and 1996 have been analysed searching for the reaction $\nu_\mu N \rightarrow \mu^- D^+ X$ with the subsequent muonic decay of the D^+. Assuming a charm yield of about $\sigma_{charm}/\sigma_{CC} \sim 5\%$, in the sample scanned we expect (22.8 ± 3.9) dimuon events and we found 25 events. This result shows that Monte Carlo simulation and real data are in good agreement.

Although the number of events is too low to draw quantitative conclusions, we can take these results as qualitative checks of the simulation of the automatic scanning procedure.

5 Sensitivity and backgrounds

In this section we discuss the expected background from known sources and, in absence of τ^- candidates, limits on the $\nu_\mu \rightarrow \nu_\tau$ oscillation parameters are derived. Both signal efficiencies and background estimation have been evaluated from large samples of events, generated according to the relevant processes, passed through a GEANT [5] based simulation of the detector response. The output is then processed through the same reconstruction chain as used for data. The simulated tracks in emulsion are used to estimate the efficiencies of each scanning step. Apart from the kink detection efficiency, only ratios of acceptances enter the calculation of the experimental result and most of the systematic uncertainties of the simulation cancel out.

5.1 Background estimates

Sources of background for the hadronic τ decay channel are:

- the production of negative charmed particles from the anti-neutrino components of the beam. These events constitute a background if the primary μ^+ or e^+ remains unidentified. Taking into account the appropriate cross-sections and the branching ratios, in the present sample we expect ~ 0.02 events from these sources;
- the production of positive charmed mesons in charged current interactions, if the primary lepton is not identified and the charge of the charmed particle daughter is incorrectly measured. We expect ~ 0.03 events from this source in the present sample;
- the associated charm production both in charged (when the primary muon is lost) and neutral current interactions, when one of the charmed particles is not detected. The cross-section for charm-anticharm pair production in neutral current interactions relative to the total charged current cross-section has been measured by the E531 experiment [6] to be $0.13^{+0.31}_{-0.11}\%$. The production rate of associated charm in charged current interactions is unknown, but an upper limit is available ($< 0.12\%$ [6]). In the present sample, the estimated background from this process represents $\lesssim 0.01$ events.
- the main potential background to the hadronic τ^- decays is due to so-called hadronic “white kinks”, defined as 1-prong nuclear interactions with no heavily ionising tracks (*black* and *grey* tracks in emulsion terminology) and no evidence for nuclear break up (evaporation tracks, recoils, blobs or Auger electrons). Published data allowing to determine the white kink interaction cross-section are scarce [7, 8]. In a dedicated experiment with 4 GeV pions at KEK [7], a very steep fall-off in p_T was observed and only 1 out of 58 observed kinks had a p_T larger than 300 MeV/c.
  Since the experimental information of the p_T dependence is statistically poor at large values, a Monte Carlo simulation, based on a modified version of FLUKA [9, 10], has been performed. The results of this simulation are in good agreement with the p_T dependence of the KEK measurement. An effective white kink mean free path in emulsion, $\lambda_{wk} \sim 22$ m, is obtained for a p_T cut at 250 MeV/c, using a pion energy spectrum as observed in the 0-μ sample. The above result is compatible with the observation of 4 events with $p_T > 250$ MeV/c, all at large distance from the primary vertex, along a total path of ~ 92 m of scan-back tracks, and corresponds to a background estimate

of 0.5 events within 3 plates downstream from the primary vertex plate. As the statistics will increase, this background source will be better measured using the CHORUS data. It will be possible to significantly reduce, by kinematical analysis, the effect of this background on the sensitivity to a possible oscillation signal.

The main source of potential background in the muonic τ channel is the charm production. We expect less than 0.1 events in the current sample from the anti-neutrino components of the beam:

$$\bar{\nu}_\mu(\bar{\nu}_e)M \rightarrow \mu^+(e^+)D^-X$$

followed by

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

in which the $\mu^+(e^+)$ escapes the detection or is not identified.

The prompt ν_τ contamination of the beam [11] is a background common to both the hadronic and muonic decay channels. For the present sample the expected background is much less than 0.1 events.

5.2 Oscillation sensitivity

In the usual approximation of a two-flavour mixing scheme, the probability of ν_τ appearance in an initially pure ν_μ beam can be expressed as

$$\begin{aligned} P_{\mu\tau}(E) &= sin^2 2\theta_{\mu\tau} \cdot \int \Psi(E,L) \cdot \\ &\cdot sin^2\left(\frac{1.27 \cdot \Delta m^2_{\mu\tau}(eV^2) \cdot L(km)}{E(GeV)}\right) \cdot dL \end{aligned}$$

where

- E is the incident neutrino energy;
- L is the neutrino flight length to the detector;
- $\theta_{\mu\tau}$ is the effective $\nu_\mu - \nu_\tau$ mixing angle;
- $\Delta m^2_{\mu\tau}$ is the difference of the squared masses of the two assumed mass eigenstates;
- $\Psi(E,L)$ is the fraction of ν_μ with energy E originating at a distance between L and $L + dL$ from the emulsion target.

The τ^- channels considered in the $\nu_\mu \rightarrow \nu_\tau$ oscillation search we describe in this paper are:

1) $\tau \rightarrow \mu$, 2) $\tau \rightarrow h$, 3) $\tau \rightarrow e$ and 4) $\tau \rightarrow \bar{\mu}$ (the μ is not identified) channels.

The expected number, $N_{\tau i}$ ($i = 1,2,3,4$), of observed τ^- decays into a channel of branching ratio BR_i is then given by

$$N_{\tau i} = BR_i \cdot \int \Phi_{\nu_\mu} \cdot P_{\mu\tau} \cdot \sigma_\tau \cdot A_{\tau i} \cdot \epsilon_{\tau i} \cdot dE \qquad (1)$$

with

- $BR_{(1\ or\ 4)} = BR(\tau \rightarrow \nu_\tau \bar{\nu}_\mu \mu^-) = (17.35 \pm 0.10)\%$ [12]).
- $BR_2 = BR(\tau \rightarrow \nu_\tau h^- n h^0) = (49.78 \pm 0.17)\%$ [12]);
- $BR_3 = BR(\tau \rightarrow \nu_\tau \bar{\nu}_e e^-) = (17.83 \pm 0.08)\%$ [12]);
- Φ_{ν_μ} the incident ν_μ flux spectrum;
- σ_τ the charged current ν_τ interaction cross-section;
- $A_{\tau i}$ the acceptance and reconstruction efficiency for the considered channel (up to the vertex plate location);
- $\epsilon_{\tau i}$ the corresponding efficiency of the decay search procedure;

With proper averaging (denoted by $\langle\rangle$), $N_{\tau i}$ can also be written as a function of n_i:

$$N_{\tau i} = BR_i \cdot n_i \cdot \langle P_{\mu\tau}\rangle \cdot \frac{\langle\sigma_\tau\rangle}{\langle\sigma_\mu\rangle} \cdot \frac{\langle A_{\tau i}\rangle}{\langle A_\mu\rangle} \cdot \langle\epsilon_{\tau i}\rangle \qquad (2)$$

where

- $n_1 = N_\mu$ (the number of located charged current ν_μ interactions corresponding to the considered event sample) and $n_2 = n_3 = n_4 = (N_\mu)_{0-\mu}$ (the product of N_μ and the relative fraction of the 0-μ sample for which the analysis has been completed);
- $\langle\sigma_{\mu(\tau)}\rangle = \int \frac{d\sigma_{\mu(\tau)}}{dE} \cdot \Phi_{\nu_\mu} \cdot dE$. It takes into account quasi-elastic interactions, resonance production and deep inelastic interactions ($\sigma(\frac{\langle\sigma_\tau\rangle}{\langle\sigma_\mu\rangle})_{syst} \sim 7\%$);
- $\langle A_{\mu(\tau i)}\rangle = \int \frac{d\sigma_{\mu(\tau)}}{dE} \cdot A_{\mu(\tau i)} \cdot \Phi_{\nu_\mu} \cdot dE$ ($\sigma(\frac{\langle A_{\tau i}\rangle}{\langle A_\mu\rangle})_{syst} \sim 7\%$);
- $\langle\epsilon_{\tau i}\rangle$ is the average efficiency of the decay search procedure for the accepted events ($\sigma(\langle\epsilon_{\tau i}\rangle)_{syst} \sim 10\%$);

To allow an easy combination of the results from the 1-μ and 0-μ event samples, it is useful to define the "equivalent number of muonic events" of the 0-μ sample by

$$N^{eq}_\mu = (N_\mu)_{0-\mu} \cdot \sum_{i=2}^{4} \frac{\langle A_{\tau i}\rangle}{\langle A_{\tau\mu}\rangle} \cdot \frac{\langle\epsilon_{\tau i}\rangle}{\langle\epsilon_{\tau\mu}\rangle} \cdot \frac{BR_i}{BR_\mu} \qquad (3)$$

The 90% C.L. upper limit on the oscillation probability then simplifies to

$$P_{\mu\tau} \leq \frac{2.38 \cdot r_\sigma \cdot r_A}{BR_\mu \cdot \langle\epsilon_{\tau\mu}\rangle \cdot [N_\mu + N^{eq}_\mu]} \qquad (4)$$

where $r_\sigma = \langle\sigma_\mu\rangle / \langle\sigma_\tau\rangle$ and $r_A = \langle A_\mu\rangle / \langle A_{\tau\mu}\rangle$.

In the above formula, the numerical factor 2.38 takes into account the total systematic error (17%) following the prescription given in [13]. The systematic error is mainly due to the reliability of the Monte Carlo simulation of the scanning procedures.

The estimated values of the quantities appearing in this expression are given in Table 2. No statistical errors are quoted since they are much smaller than the systematic uncertainty.

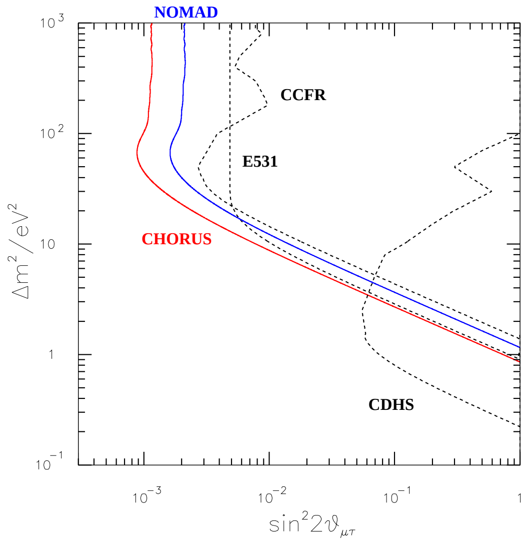

Figure 1: Present result compared with the recent NOMAD result [14] (full line) and the previous limits (dotted lines).

Using the present sample the following 90% C.L. limit is obtained

$$P_{\mu\tau} \leq 6.0 \cdot 10^{-4} \tag{5}$$

In a two flavour mixing scheme, the 90% C.L. excluded region in the $(sin^2 2\theta_{\mu\tau}, \Delta m^2_{\mu\tau})$ parameter space is shown in Figure 1. Maximum mixing between ν_μ and ν_τ is excluded at 90% C.L. for $\Delta\, m^2_{\mu\tau} \gtrsim 0.9$ eV^2; the large Δm^2 are excluded at 90% C.L. for $sin^2 2\theta_{\mu\tau} > 1.2 \cdot 10^{-3}$.

6 Conclusions

The emulsion scanning methods, previously described in [1, 2], have been applied to a fraction of the 1994-1995-1996 data. No τ^- decay candidate has been found, leading to a more stringent 90% C.L. upper limit on the $\nu_\mu \rightarrow \nu_\tau$ oscillation probability ($P_{\mu\tau} \leq 6.0 \cdot 10^{-4}$). This negative result is compatible with an estimated background of less than one event, mainly from "white kink" secondary interactions in the 0μ channel. With the large increase in statistics expected from the ongoing analysis of the data, a direct measurement of this background process will be possible and kinematical cuts are planned for its reduction. Furthermore, a second phase of the analysis (with better efficiencies, larger statistics and faster automatic emulsion scanning) has started with the aim of reaching the design sensitivity ($P_{\mu\tau} \leq 1.0 \cdot 10^{-4}$) [15].

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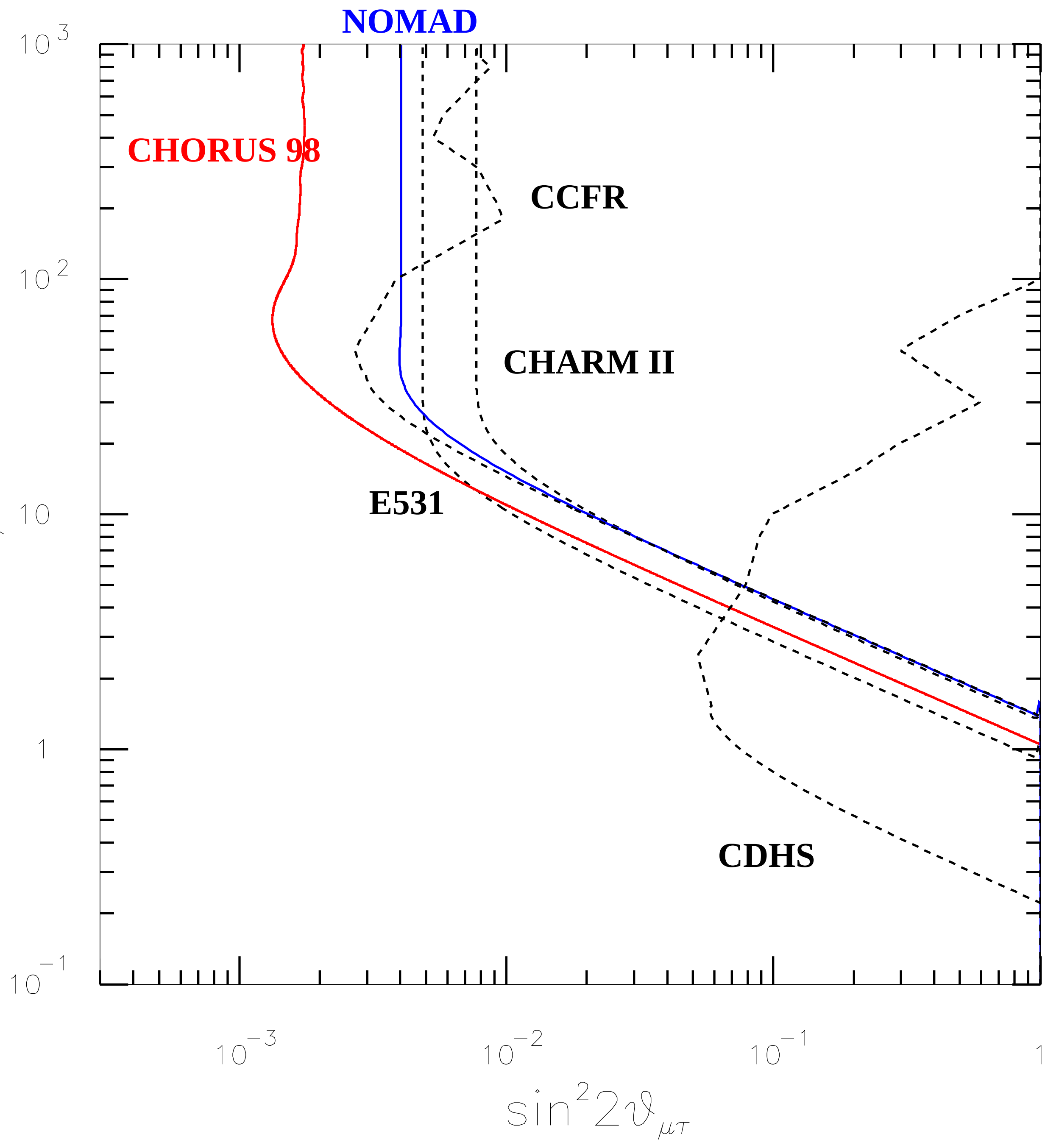
Table 2: *Quantities used in the estimation of the sensitivity*

	1994	1995	1996
N_μ	18,286	20,642	30,128
r_σ	1.89	1.89	1.89
r_A	0.93	0.93	0.93
$\langle A_{\tau\mu} \rangle$	0.39	0.39	0.39
$\langle A_{\tau h} \rangle$	0.17	0.17	-
$\langle A_{\tau e} \rangle$	0.093	0.093	-
$\langle A_{\tau\bar{\mu}} \rangle$	0.026	0.026	-
$\langle \epsilon_{\tau\mu} \rangle$	0.53	0.35	0.37
$\langle \epsilon_{\tau h} \rangle$	0.24	0.25	-
$\langle \epsilon_{\tau e} \rangle$	0.12	0.13	-
$\langle \epsilon_{\tau\bar{\mu}} \rangle$	0.22	0.23	-
N_μ^{eq}	11,987	12,743	-


NOMAD
CHORUS 98
CCFR
CHARM II
E531
CDHS
10^3
10^2
10
1
10^{-1}
$\Delta m^2/eV^2$
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\vartheta_{\mu\tau}$