THE CHORUS EXPERIMENT: A STATUS REPORT

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The search for $\nu_\mu \to \nu_\tau$ oscillations in CHORUS is in progress and the 1994-1995 (Run I) data sample is being analyzed. Automatic emulsion scanning looking for τ^- decay topology is in a very active phase. A first result ($sin^2 2\theta_{\mu\tau} \leq 3 \cdot 10^{-2}$ for large Δm^2), based on a sample of 2622 fully analyzed 1 μ^- events, has been presented, confirming that the CHORUS proposal sensitivity for Run I ($sin^2 2\theta_{\mu\tau} \leq 3 \cdot 10^{-4}$) is reachable.

1 Introduction

Neutrinos are among the most mysterious of all known elementary particles. Questions as: are they massive? are they stable? are they Dirac or Majorana particles? are the 3 weak interaction eigenstates (ν_e, ν_μ, ν_τ) mass eigenstates? etc, fundamental for Particle Physics as well as for Astrophysics and Cosmology, are still without answer.

The CHORUS experiment is aiming at a progress in the knowledge of neutrino physics by searching for $\nu_\mu \to \nu_\tau$ oscillations, throught the ν_τ appearance in the nearly pure ν_μ beam at CERN.

Flavour oscillations may only occur if the weak interaction eigenstates are not mass eigenstates, rather a superposition of them, and if the mass eigenvalues are not equal. In a simplified model with two neutrino flavours, in this case ν_μ and ν_τ, only one parameter (the mixing angle $\theta_{\mu\tau}$) is needed to express the flavour eigenstates in terms of the mass eigenstates, ν_1 and ν_2:

$$\begin{aligned} \nu_\mu &= \nu_1 \cdot cos(\theta_{\mu\tau}) + \nu_2 \cdot sin(\theta_{\mu\tau}) \\ \nu_\tau &= -\nu_1 \cdot sin(\theta_{\mu\tau}) + \nu_2 \cdot cos(\theta_{\mu\tau}). \end{aligned}$$

Hence, the oscillation probability can be written as

$$\mathrm{P}(\nu_\mu \to \nu_\tau) = sin^2(2\theta_{\mu\tau}) sin^2 \left(\frac{|m_1^2 - m_2^2| L}{4E_\nu} \right)$$

where m_1 and m_2 are the ν_1's and ν_2's masses, E_ν the neutrino energy and L the source-detector distance.

If CHORUS succeeds in its search:

1. a ν_τ charge current (CC) interaction will be observed for the first time;

2. a proof that neutrinos have nonzero mass and that they mix will be given;
3. an extension of the Standard Model will be necessary;
4. the explanation in terms of neutrino oscillations of the solar neutrino problem and of the atmospheric neutrino anomaly will be reinforced;
5. the ν_μ and mainly the ν_τ will be the best candidates for hot dark matter [1].

2 The CHORUS experiment

2.1 Conceptual design

The CHORUS experiment aims to detect ν_τs produced by ν_μ oscillations through the inclusive CC interaction

$$\nu_\tau + N \to \tau^- + X \tag{1}$$

in a nuclear emulsion target. The detection of the process (1) is based on the identification of the τ^-, that, due to its very short lifetime ($(295.6 \pm 3.1) \cdot 10^{-15}$ s) and to the Lorentz boost, decays after a mean fly path of about 0.75 mm, producing an event topologically different from the background due to ν_μ interactions. The high spatial resolution ($\leq 1\mu m$) of the nuclear emulsions and their capability to provide tridimensional images, allows the detailed reconstruction of the searched events to be performed. Events (1) in emulsion are visible under microscope and appear as primary vertices without incoming charged particles and with one of the secondary particles - the τ^-- that decays close to the vertex into one (giving rise to an apparent *kink* in the trajectory - see figure 1) or more prongs.

The decay channels used to detect the τ^- in CHORUS are the following:

$$\begin{array}{ll} \tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau & BR = 17.8\% \\ \tau^- \to h^-(n\pi^0)\nu_\tau & BR = 50.4\% \\ \tau^- \to \pi^-\pi^+\pi^-(n\pi^0)\nu_\tau & BR = 13.8\% \end{array} \tag{2}$$

The undetected decay neutrinos create an unbalance in the measured transverse momentum, that can be used for the kinematical preselection of τ candidates.

The location of events in emulsion, their preselection and their complete interpretation, is made with the help of electronic detectors placed immediately behind the target.

The topological study and the accurate measurement of the kinematical quantities of the secondaries, event by event, allows CHORUS to be a practically background free experiment whose sensitivity increases almost linearly with

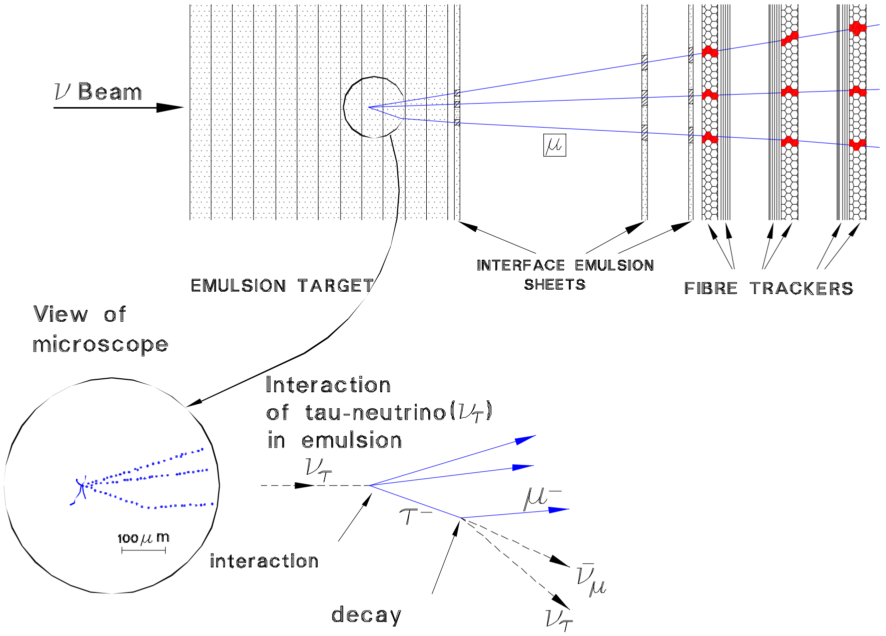

Figure 1: A fraction of the target region consisting of one emulsion stack, the three interface emulsion sheets further downstream (s.s. and c.s.) and three scintillating fiber trackers, each composed by 4 planes with differently oriented fibers. A τ-kink from a ν_τ CC interaction is illustrated, which would be only visible under the microscope.

statistics.
In 4 years of data taking a sensitivity up to values of $\sin^2(2\theta_{\mu\tau}) \sim 1.5 \cdot 10^{-4}$ for large δm^2 is expected (see figure 4). This measurement would constitute an improvement of more than a factor of 20 over the existing best limit[2].

2.2 The CERN wide-band ν_μ beam

The CERN SPS neutrino wide-band beam[3] is produced by 450 GeV protons hitting a beryllium target with a cycle of 14.4 s. The intensity delivered is about $2 \cdot 10^{13}$ protons per cycle. The positive secondaries, mostly pions and kaons, are focused by magnetic lenses in a 300 m vacuum tunnel, where they decay into μ^+ and ν_μ. Muons are then absorbed in 400 m iron and earth shield, while neutrinos reach the experimental area.
The mean distance between source and detector is 600 m.

The beam is mainly composed of ν_μ with an average energy of 27 GeV. The $\bar{\nu}_\mu$ contamination amounts to a few per cent, the fraction of $\nu_{\rm e}$ and $\bar{\nu}_{\rm e}$ is of the order of 1 %. The contamination of prompt ν_τ[a], due to decays of D_s mesons produced in the beryllium target, gives rise to a fraction of ν_τ CC interactions $< 0.5 \cdot 10^{-6}$ relative to ν_μ .

2.3 The detector

The CHORUS detector is shown in figure 2.

The *emulsion target* has a total volume of 206 liters and a mass of 770 kg. It is divided into 4 stacks, each of $1.4 \times 1.4\,m^2$ surface area and 2.8 cm thickness ($\sim$ 1 radiation length). Each stack is further subdivided in 8 sectors ($0.71 \times 0.36\,m^2$), each consisting of 36 emulsion plates, composed of a 100 μm thick plastic base with 350 μm thick emulsion layer on both sides.

Since the emulsion plates are exposed perpendicular to the beam and particles originating from neutrino interaction are nearly parallel to it, fast semi-automatic and automatic scanning[4] is possible.

In order to locate ν interactions in emulsion, 8 *scintillating fiber trackers*[5] are installed between and downstream of the 4 stacks (see figure 1). Each tracker is made of 4 planes of parallel fibers, 500 μm in diameter and orthogonal to the beam, which provide 4 projections (horizontal, vertical and skew, $\pm 8^o$).

The link between emulsion stack and tracker is ensured by 3 *interface emulsion sheets* (ss and cs). These sheets have the same transversal dimensions of the plates, but are obtained by double-coating thin emulsion layers ($\sim 100\mu m$) on a thick acrylic base ($\sim 800\mu m$). The track extrapolation from trackers to the nearest interface sheet is performed with an accuracy of $\sigma_x \simeq 200\mu m$ and $\sigma_\theta \simeq 3mrad$. Tracks found in the cs are followed back in the ss and then in the stack plates using in each extrapolation the precise measurements in emulsion performed in the previous steps.

The measurement of the charge and of the momentum of particles is provided by a *magnetic spectrometer*[6] constituted by a toroidal air core magnet instrumented in front and behind with fiber tracker planes[5]. It allows to determine sign and momentum of charged particles with $\Delta p/p \simeq 3.5\% \cdot p(GeV/c) \oplus 0.22$.

The CHORUS *calorimeter*[7] is the first large scale application of the technique of embedding scintillating fibers into a lead matrix (the "spaghetti" technique), in order to obtain fine-grained energy sampling and e/π compensation. The calorimeter provides a measurement of shower direction and energy with a resolution $\Delta E/E \simeq 14\%/\sqrt{E\,(GeV)}$ for electrons and $\Delta E/E \simeq 32\%/\sqrt{E\,(GeV)}$ for hadrons. It is the key element for the kinematical preselection of the events.

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[a] Obviously a background for the study of oscillations

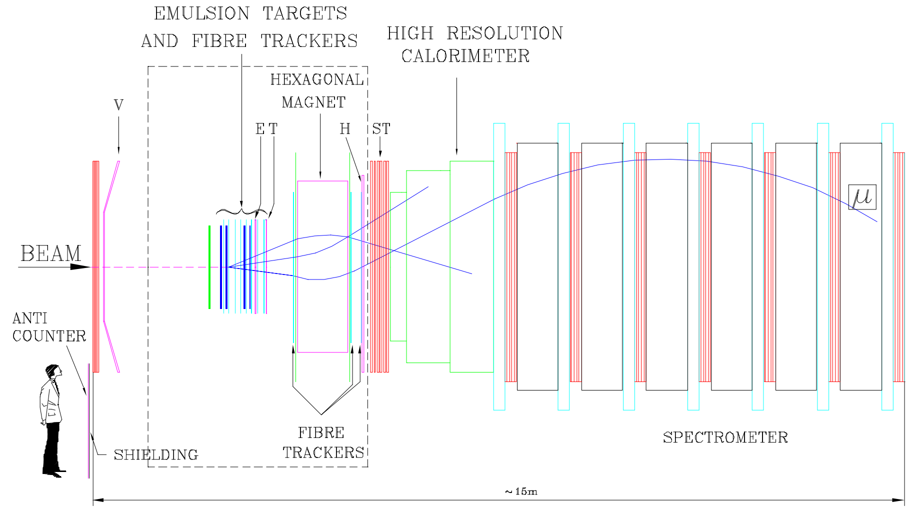

Figure 2: The CHORUS hybrid detector

The role of the *muon spectrometer*, downstream of the calorimeter, is to identify muons and to determine their trajectory, momentum and charge. It consists of six circular magnetized iron modules, each one included between two tracking sections. Its momentum resolution is $\Delta p/p \simeq 10 \div 15\%$ for muons with p$\geq$5 GeV crossing several modules [b].

2.4 Status of the experiment

CHORUS Run I consisted of data taken from April to October of 1994 and 1995, corresponding to about 120 000 and 200 000 ν_μ CC events in the emulsions. After the first year of running, emulsion stack 4 was removed (and replaced) in order to start as soon as possible the scanning and to tune methods and techniques. The analysis of part of the stack 4 data is the “pilot analysis” described below.

At the moment the scanning of the emulsion interface sheets for Run I is almost complete and the scanning of the stacks is in progress. The analysis of all the 94-95 data sample is expected to finish by the end of 1997.

CHORUS Run II was started in April 1996 with four new emulsion stacks and

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[b] The momentum of stopping muons can be measured from the range with an accuracy of about 5%.

some detector improvements. The first year of Run II, recently finished, gave 225 000 ν_μ CC events.

3 The pilot analysis

A pilot analysis has been applied on a small, almost unbiased data sample with a negative muon (1 μ^- sample) in the final state. The idea was to refine the analysis technique on the cleanest channel, $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$, whose signature is a kink resulting in a μ^- after a very small distance from the vertex. For this channel the background, mainly from muonic decays of charmed particles produced by $\bar{\nu}_\mu$ and $\bar{\nu}_\mathrm{e}$ is estimated to be a few times 10^{-6} and can therefore be neglected.
The analysis steps are the following:

1. Event reconstruction
   Events are reconstructed using data from the electronic part of the detector. Tracks are identified, measured and linked between the different subdetectors. The target trackers, in particular, predict track angles and impact points on the most downstream interface emulsion sheets (cs).

2. Event selection
   Reconstructed events are selected by requiring: i) vertex inside the stack; ii) a μ^- track pointing to the vertex; iii) a measured muon momentum $p_\mu \leq 30$ GeV/c; iv) no other lepton in the event.
   The cut on p_μ removes 10% of the signal and about 25% of the ν_μ background interactions.

3. Vertex location
   When possible, up to 3 predicted tracks per event are searched in the cs and ss. Among the found ones, at least one track (usually the muon) is followed upstream in the stack, by searching its entry points at the upstream surface of the successive plates. The ν interaction vertex is searched in the first plate (the so called "vertex plate") where the back followed track is not found. The vertex position inside the vertex plate is obtained by looking for all other tracks predicted by the target tracker at the entry points of the previous plate (see figure 3).
   The whole scanning procedure is performed with computer driven optical microscopes in a fully automatic way: tracks are recognized by requiring grain coincidence between several tomographic images at different depths in the emulsion[4].

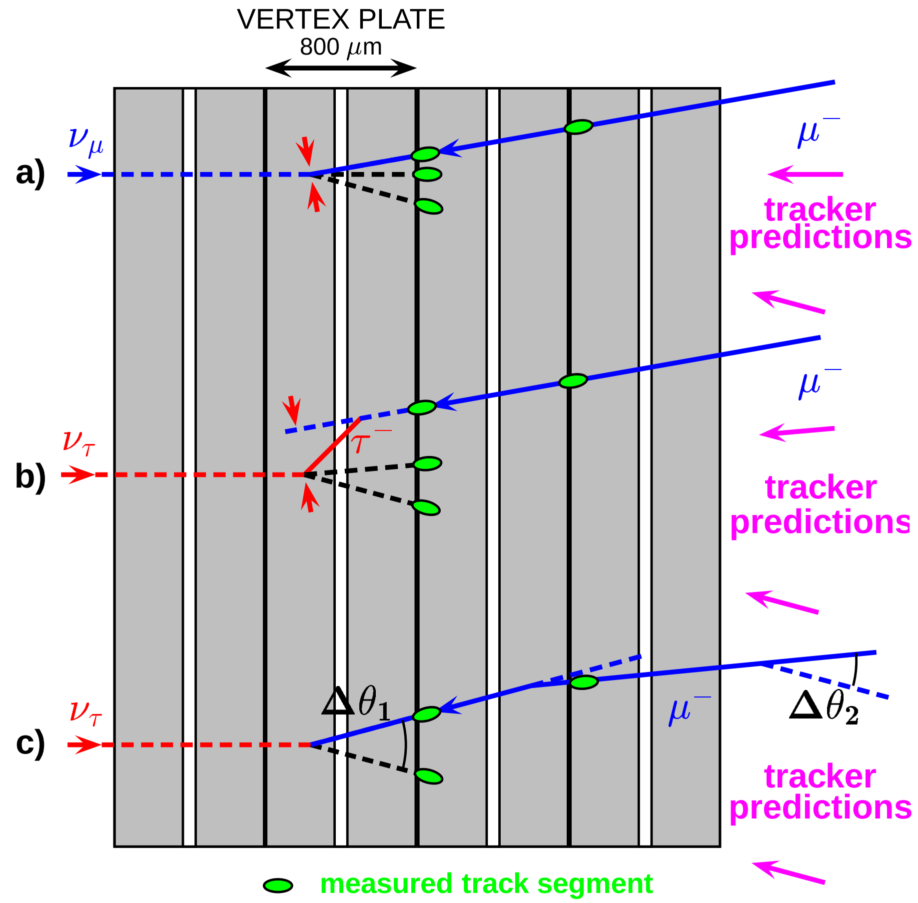

Figure 3: (a) normal ν_μ CC event, (b) ν_τ interactions with τ decay inside the primary vertex plate ("short decay length"), and (c) τ decay further downstream ("long decay length"). The track followed upstream to the vertex is assumed to be the μ^- in all 3 cases.

4. Kink analysis

   For each event two possibilities are checked: the kink is within the vertex plate (*short kink*); the kink is in the first 5 plates downstream of the vertex plate (*long kink*)[c].

   The short kink search (figure 3) is based on the automatic measurement of the impact parameter of the muon, i.e. of its spatial distance from the vertex. Events with large impact parameter ($\geq 2 \div 8$ μm[d]), are checked by semiautomatic scanning under human control. The same holds for events where the vertex cannot be validated, because no other track is predicted or found.

   If a kink is detected, the track angles upstream and downstream of the kink are measured to define the muon momentum in the plane transverse to the kink track, $p_T^{kink} = p_\mu \cdot sin|\theta_{downst.} - \theta_{upst.}|$. An event becomes a ν_τ interaction candidate if $p_T^{kink} \geq 250$ MeV/c[e].

   The long decay search, as illustrated in figure 3, is performed automatically by measuring the angle difference $\Delta\theta$ between the muon and a reference track near the vertex and in the emulsion interface sheet ss (or in the tracker) to evaluate the p_T^{kink}. Events with $p_T^{kink} \geq 250$ MeV/c, as well as events for which vertex cannot be validated by a second matching track, are rescanned under operator control and, in the case of kink, the p_T^{kink} is remeasured more precisely before applying the 250 MeV/c cut.

5. Results

   The pilot analysis is based on almost 10 000 reconstructed and $\sim$ 7500 selected events. Among these, 2622 events passed the automatic phase of the pilot analysis ($\sim$ 15% overcame the short kink analysis and 20% the long kink search). Human check has excluded for these events the presence of a τ and therefore of ν_τ CC interactions.

   For large values of the squared mass difference ($\Delta m^2 = |m_1^2 - m_2^2| >> (4 \cdot E_\nu)/L$), by averaging on L and E_ν, the oscillation probability can be simplified to:

$$\mathrm{P}(\nu_\mu \to \nu_\tau) = \frac{1}{2} \cdot \sin^2(2\theta_{\mu\tau}) \qquad (3)$$

   $\mathrm{P}(\nu_\mu \to \nu_\tau)$ is determined from the ratio of the observed ν_τ CC events, $N_{\nu_\tau}^{obs}$, and the ν_μ CC events, $N_{\nu_\mu}^{obs}$. The average cross section ratio

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[c] The probability to have a τ^- decay at a distance greater than 4 mm is less than 1%.

[d] The actual value of the cut depends on the longitudinal position of the vertex inside the vertex plate

[e] This cut is applied to eliminate or reduce topological background events due to $\pi^- \to \mu^-\nu_\mu$ and $K^- \to \mu^-\nu_\mu$ decays. The cut efficiency is $\sim 87\%$

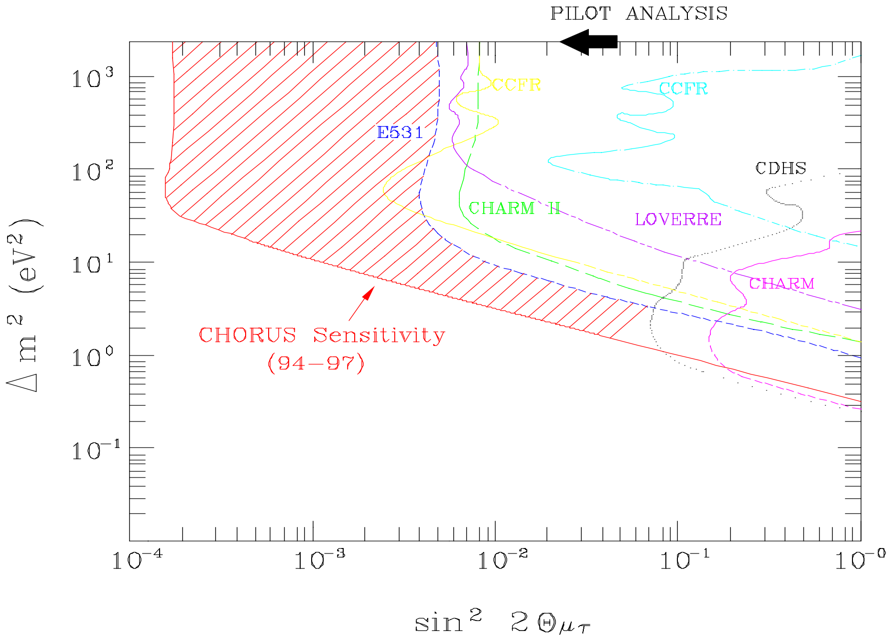

Figure 4: Exclusion plot in the Δm^2-sin$^2(2\theta_{\mu\tau})$- plane for $\nu_\mu \rightarrow \nu_\tau$ oscillation searches by various experiments, the chorus pilot analysis and the CHORUS Run I and II

$< \sigma\nu_\mu > / < \sigma\nu_\tau > \simeq 1.89$, the average detection, reconstruction, selection and scanning efficiency ratio, $A_\mu/A_\tau \simeq 0.93$, the muonic decay branching ratio and the kink finding efficiency $< \eta_{kink} > \simeq 0.61$[f] have been taken into account. P$(\nu_\mu \rightarrow \nu_\tau)$ can therefore be expressed by

$$\mathrm{P}(\nu_\mu \rightarrow \nu_\tau) = \frac{\mathrm{N}^{\mathrm{obs}}_{\nu_\tau}}{\mathrm{N}^{\mathrm{obs}}_{\nu_\mu}} \cdot \frac{< \sigma\nu_\mu >}{< \sigma\nu_\tau >} \cdot \frac{< \mathrm{A}\nu_\mu >}{< \mathrm{A}\nu_\tau >} \cdot \frac{1}{\mathrm{BR}} \cdot \frac{1}{< \eta_{\mathrm{kink}} >} \qquad (4)$$

By using (3) and (4), substitution of numerical values leads to an upper limit

$$\sin^2(2\theta_{\mu\tau}) \leq 3 \cdot 10^{-2} \qquad (90\%\ c.l.). \qquad (5)$$

This limit is illustrated by the arrow in figure 4, showing the exclusion curves of previous experiments and the region that will be explored by CHORUS after 4 years of data taking.

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[f] The values of the efficiencies have been obtained from a MC study.

analysis step	stat. improvement
statistics	$\geq$20
hadronic decay modes	4.5
efficiencies	≥ 1.5
kinematical preselection	$\simeq 0.7$
total	~ 100

Table 1: Estimated improvements of the signal statistics for the analysis of whole run I (94/95) data with the assumption that the analysis of the hadronic decay channels has the same efficiency as the muonic decay channel.

4 Outlook

Result (5) has been obtained by using slightly more than 10% of the 1994 1 μ^- sample. This pilot analysis will be applied, with some changes, to the whole 1 μ^- sample of the '94 data taking. By considering only the statistics increase, the analysis of 1 μ^- 94 data would lead CHORUS to a limit better than E531 for large Δm^2 ($\sin^2(2\theta_{\mu\tau})$ $\sim 3 \cdot 10^{-3}$).

The analysis of the whole 94/95 sample, with all channels and a reasonable efficiency gain (see table 4), would result in an improvement of a factor of about 100 on the limit here presented. This limit can be achieved by scanning about 200 000 events, as foreseen in the CHORUS proposal. With the 10 automatic scanning systems, already working in CHORUS[g], the scanning work would be completed in about 1 year. Therefore the sensitivity for large Δm^2, estimated in the CHORUS proposal for run I ($\sin^2(2\theta_{\mu\tau})$ $\leq 3 \cdot 10^{-4}$), seems to be reachable within 1 year.

CHORUS Run II will at least double the statistics and the sensitivity.

References

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[g] At least 4 other scanning systems will be ready next year.