5 $\nu_\mu \rightarrow \nu_\tau$ Oscillation Experiments (Past and Ongoing)

The atmospheric neutrino anomaly presents a hint of possible existence of $\nu_\mu \rightarrow \nu_\tau$ oscillations with a relatively low value of Δm^2 ($\Delta m^2 << 1eV^2$). The accelerator experiments to date have not, as yet, been able to address this potentially interesting region. Rather, the focus so far has been on investigating the high Δm^2 region ($\Delta m^2 >> 1eV^2$), recently extending the reach to low values of $\sin^2 2\theta$. This chapter summarizes the current situation in this area and the prospects for the currently running experiments.

5.1 Disappearance Experiments

Three different experiments of this kind have been performed to date utilizing the CDHS, CHARM, and CCFR detectors (or their modifications). They all have very similar features, i.e.,

(a) Two detectors at different locations, the first one at 100, 100 and 400 m respectively, for the three experiments, and the second one at about 1 km away from the neutrino source.

(b) The basic measurement is a comparison of rates at the two locations.

(c) All three experiments find null results and thus can only set limits.

Because the experiments are disappearance experiments, i.e., they cannot identify the flavor of the final-state neutrino. However, because they probe the region of Δm^2-$\sin^2 2\theta$ space that has been excluded by reactor experiments (discussed below in Chapter 6) which are sensitive to the $\nu_e \rightarrow \nu_x$ oscillation mode (and hence, also the $\nu_e \rightarrow \nu_\mu$ channel) the primary interest in the results of these experiments is to see what information they can give about a possible $\nu_\mu \rightarrow \nu_\tau$ signal.

The results of these three experiments are shown in Fig. 25. The relatively small Δm^2 range investigated is a reflection of the relatively small distance between the near and far detectors. There is no sensitivity at low Δm^2 because for such values of Δm^2 the ν's did not yet have a chance to have oscillated when they arrived at the far detector. There is no sensitivity at high values of Δm^2 because for high values of that parameter the oscillations already would have occurred at the near detector. Thus, a near/far comparison would yield a null result.

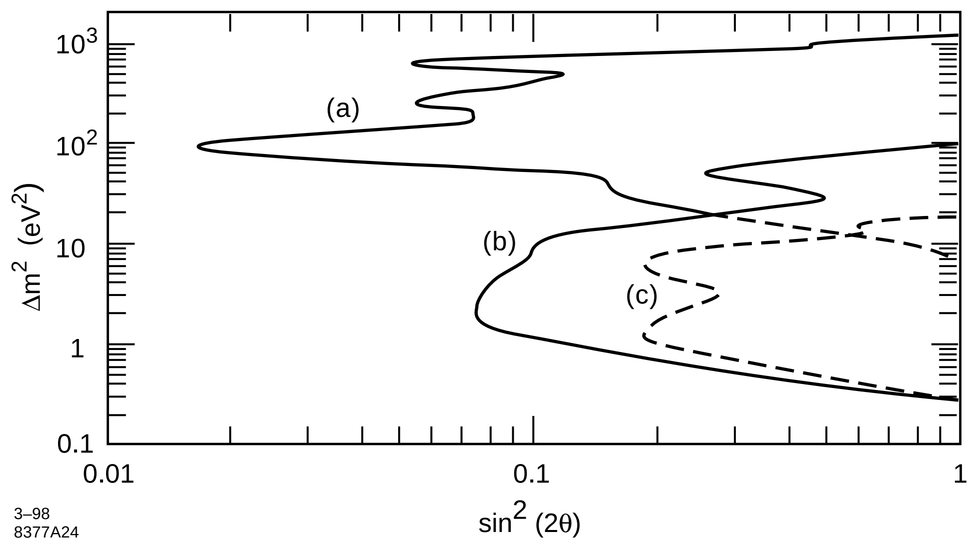

FIG. 25. Exclusion contour plots from the three early accelerator ν_μ disappearance experiments: (a) CCFR, (b) CDHS, and (c) CHARM.

The CDHS[76] and CHARM[77] experiments used the neutrino beam from the CERN PS, a beam with energy around 1 GeV. Hence, the Δm^2 region probed is lower. The CCFR[78] experiment used a much higher energy beam, from the Fermilab 400 GeV synchrotron, and thus explored a relatively higher region of Δm^2.

5.2 Completed Appearance Experiments

Up to now two $\nu_\mu \rightarrow \nu_\tau$ appearance experiments have been concluded and until very recently, they provided the best limit on possible $\sin^2 2\theta$ value for this mode of oscillations at high Δm^2.

One of these was the E531 experiment[79] at Fermilab, the first one utilizing a hybrid emulsion detector for oscillation search. It pioneered a number of general ideas subsequently used in the CHORUS experiment and which have also been proposed for the next generation of τ appearance experiments. The experiment was actually designed to study charm production by neutrinos and measure their lifetimes.[80] The $\nu_\mu \rightarrow \nu_\tau$ was a by-product, the search and potential identification of τ's being done using the same method as for the charged charm decays, i.e., looking for tracks with large kinks near the vertex. No event candidates were found.

An alternative approach was adopted by the CHARM II Collaboration[81] who searched for quasielastic τ production and subsequent decay via the exclusive mode $\tau \to \pi(K) + \nu_\tau$.

A fine-grained calorimeter was used with the plate thickness of about 1/9 of a hadronic interaction length. Thus the expected topology was a reasonably long single track, traversing many plates, followed by an interaction star. τ signatures were expected to have a large amount of energy in the star, since the pions from τ decays would be quite energetic, especially from the quasielastic ν_τ interaction.

The experiment compared the observed distributions for the required topology, both the total energy seen in the interaction and the product of that energy times the polar angle of that track (i.e., effectively the P_T of the track) with the Monte Carlo generated distributions for τ events and neutral current events as shown in Fig. 26. No τ-like excess was seen, allowing one to exclude a certain region in parameter space. The exclusion limits obtained by the E531 and CHARM II experiments are shown in Fig. 27.

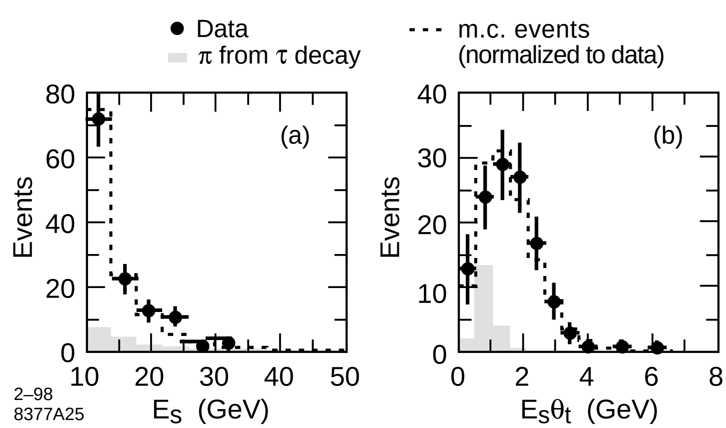

FIG. 26. CHARM II distributions of the single pion events as a function of (a) the shower energy E_s and (b) $E_s\theta_t$ for data and for Monte Carlo simulations of ν_μ N $\to \nu_\mu$ π X and ν_τ N $\to \tau$ N' with the decay $\tau \to \pi\, \nu_\tau$. Here, θ_t is the angle of the pion with respect to the direction of the incident neutrino beam.

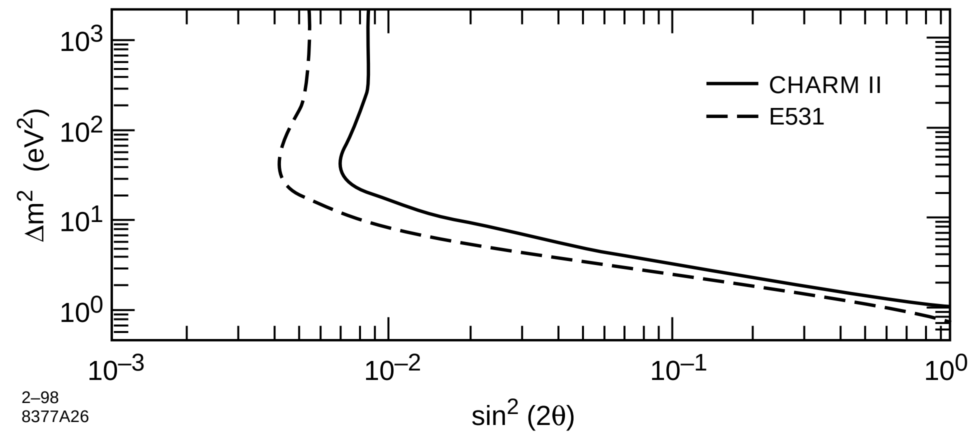

FIG. 27. Exclusion contour plots for the two $\nu_\mu \rightarrow \nu_\tau$ appearance experiments: E531 (dashed line) and CHARM II (solid line).

5.3 Statistical Analyses

Measurement of the total neutral current (NC)/charged current (CC) event ratio, as well as the differential ratio of that quantity as a function of the total hadronic energy can in principle provide us with information about the possible $\nu_\mu \rightarrow \nu_\tau$ oscillation. In practice, it is more convenient to measure the ratio of short to long events, where the division between the two is made in such a way that there is a pretty close NC/short and CC/long equivalence. If ν_μ's do oscillate into ν_τ's, then the number of ν_μ CC events, i.e., long events, will decrease. Furthermore, the majority of the ν_τ CC events will be short events because 83% of the τ decays do not have a muon in the final state. Thus, the number of short events will increase and hence the overall short/long ratio will increase. In addition, the behavior of that ratio as a function of hadronic energy can provide information about Δm^2 and $\sin^2 2\theta$ if a significant departure from the expected nonoscillated behavior is observed.

One should emphasize that such a determination of oscillation parameters can be made only on the assumption of a specific flavor oscillation made, i.e., $\nu_\mu \rightarrow \nu_\tau$ (or $\nu_\mu \rightarrow \nu_e$). The short/long ratio by itself does not allow one to determine which mode, or modes, are present and an additional measurement (or measurements) is necessary to make such a determination.

The CCFR Collaboration has performed such an analysis on their data[23] and found no evidence for any departure from the no-oscillation hypothesis expectations. Their data are shown in Fig. 28, and are compared with the expectation for the no-oscillation scenario and for two different oscillation scenarios. The sensitivity of this analysis is comparable to that obtained by the two appearance experiments discussed above, as is illustrated in Fig. 29.

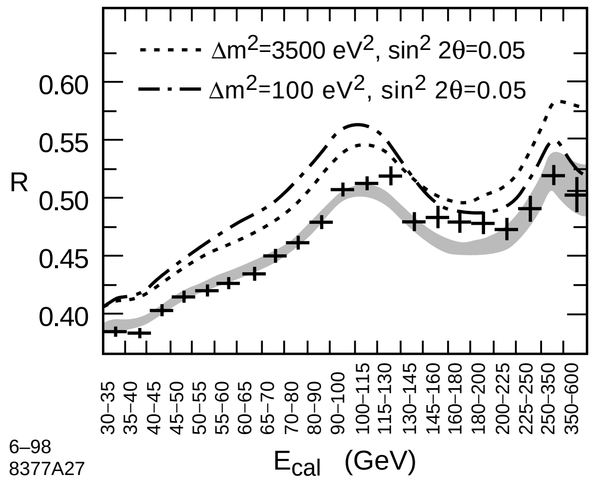

FIG. 28. Ratio of short to long events for the CCFR experiment, plotted as a function of the energy deposited in the calorimeter. The shaded band shows Monte Carlo prediction assuming no oscillations with 1 σ errors added in quadrature. The dotted and dot-dashed curves show the effect of $\nu_\mu \rightarrow \nu_\tau$ oscillations for two sets of oscillation parameters.

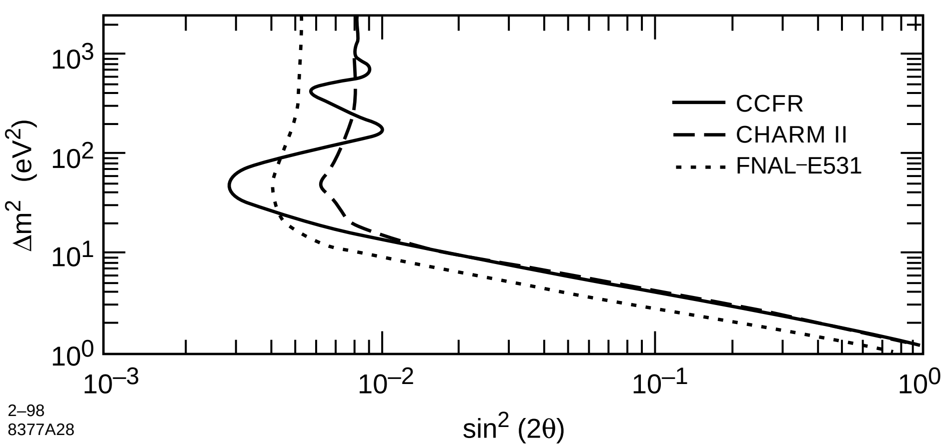

FIG. 29. Results of the CCFR experiment compared with the results from the two completed ν_τ appearance experiments.

5.4 Current Short-Baseline Program

There is currently an ongoing program to search for $\nu_\mu \rightarrow \nu_\tau$ oscillations at CERN, with two different experiments, CHORUS (CERN Hybrid Oscillation Research apparatUS) and NOMAD (Neutrino Oscillation MAgnetic Detector), attempting to push down the limits on $\sin^2 2\theta$ at high Δm^2 by another order of magnitude. This effort is motivated by a desire to explore the cosmologically interesting region in Δm^2, i.e., the region of ν masses suggested by the missing dark matter problem.[81]

Both experiments are located in the West Area of the CERN SPS,[82] in a sign-selected ν_μ beam with a mean energy of 27 GeV. The intrinsic ν_τ contamination in the beam from the D_s decay is estimated to be between 10^{-6} and 10^{-5} of the total ν flux. The ratio, averaged over the beam energy spectrum, of $\sigma_\tau^{cc} / \sigma_\mu^{cc}$ is 0.53. The length of the decay tunnel is about 300 m; the total target to detector distance is about 800 m. The experiments started in May 1994 and the expectation is that they will run through 1997, with a probable run for NOMAD also in 1998. The technique used in each experiment is quite different so we shall describe each one in turn.

The CHORUS detector, illustrated in Fig. 30, is a hybrid emulsion spectrometer, with the ν_τ interaction taking place in the emulsion target; the production of a τ is identified by a kink in the emulsion. The rest of the spectrometer is used to localize the potentially interesting events to a small region of emulsion and to measure the total hadronic energy and the direction and momentum of the muon.

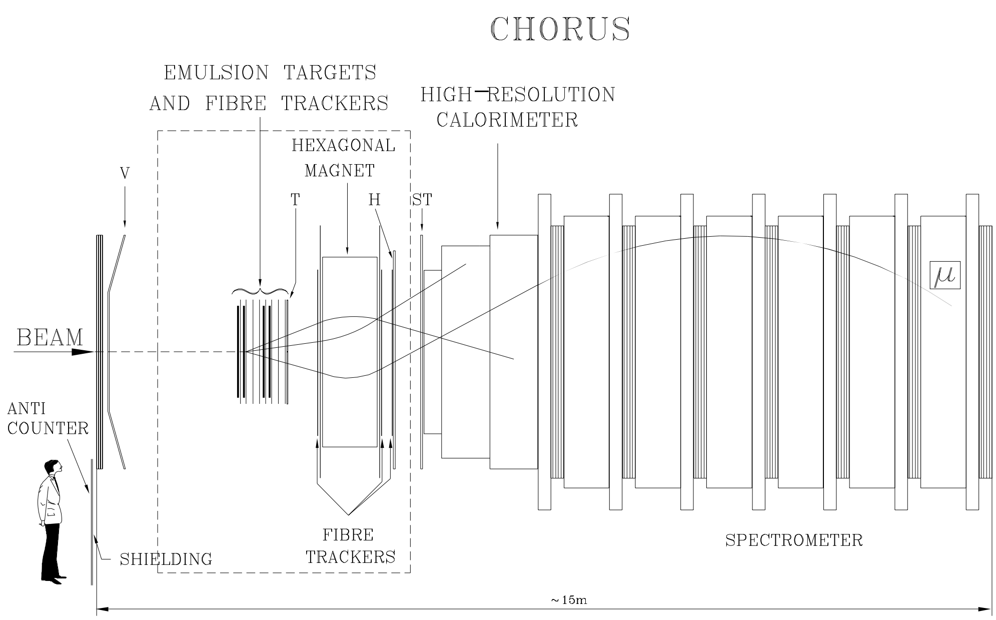

FIG. 30. The CHORUS detector.

The target region of the CHORUS detector is illustrated in Fig. 31. The downstream fiber tracking system has a spatial resolution of about 200 μm but a time resolution of 100 nsec. It is used to identify tracks that make up the neutrino interaction vertex. The changeable emulsion sheets, with spatial resolution of 1 μm, immediately upstream of the fiber tracker provide even better position and direction measurements of these tracks. They are changed every few months to aid in track finding. Finally, the bulk emulsion itself was changed twice during the run, i.e., after two years of exposure.

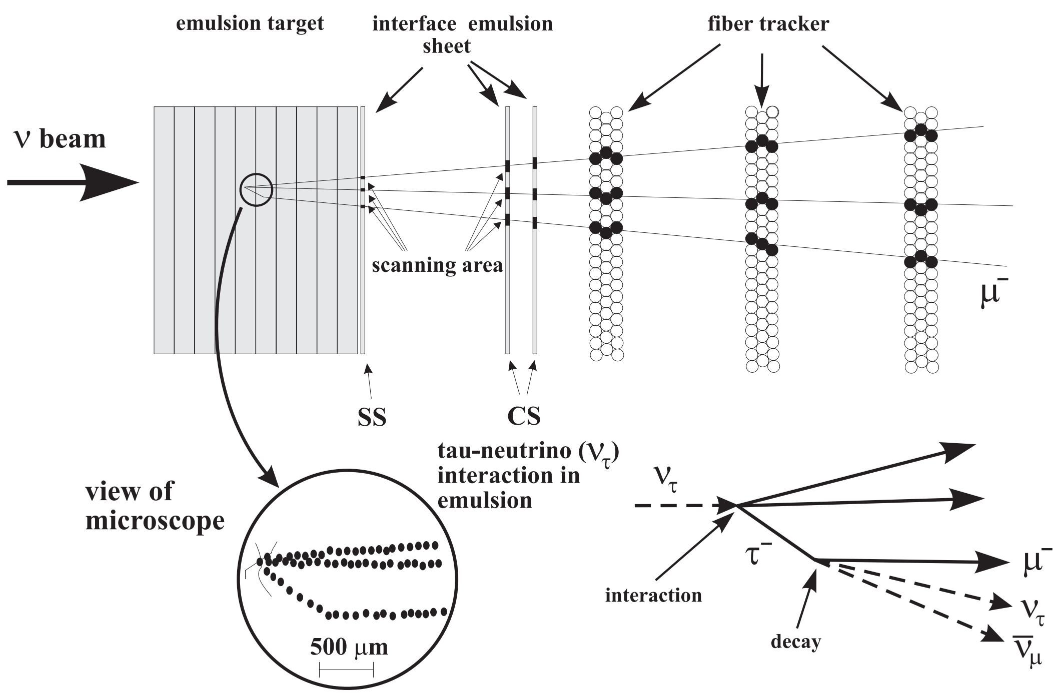

FIG. 31. The target region with an emulsion target, three interface emulsion sheets (CS and SS) and three fiber trackers is shown schematically. A ν_τ-CC interaction is shown with a "kink" structure which would be visible under the microscope is shown.

An experiment of this nature is fundamentally limited by the ability to process the data, i.e., scanning. It is important both to reduce the number of candidate events and to automate the scanning process as much as possible. The Japanese groups have made great progress in the latter area with the development of a computer-controlled automatic microscope attached to a CCD camera. Track reconstruction is done by overlapping in software the 16 frames corresponding to different z positions of the detector. The measured data are then used to obtain an impact parameter for each track reconstructed in this manner and if that value exceeds a threshold, the event is manually scanned. The distribution of the impact parameter from simulated ν_τ interactions and data is shown in Fig. 32. The manual scan checks the topology for the accepted events and rejects charm candidates, which will have an accompanying μ^- and a D^+ decay with either one positive decay daughter or with three particles. The kink is also required to have a sufficiently large P_T so as to reject the coherent scatters on a nucleus, without a visible recoil or boiloff nucleon. The observed and simulated (for ν_τ's) P_T distribution is shown in Fig. 33.

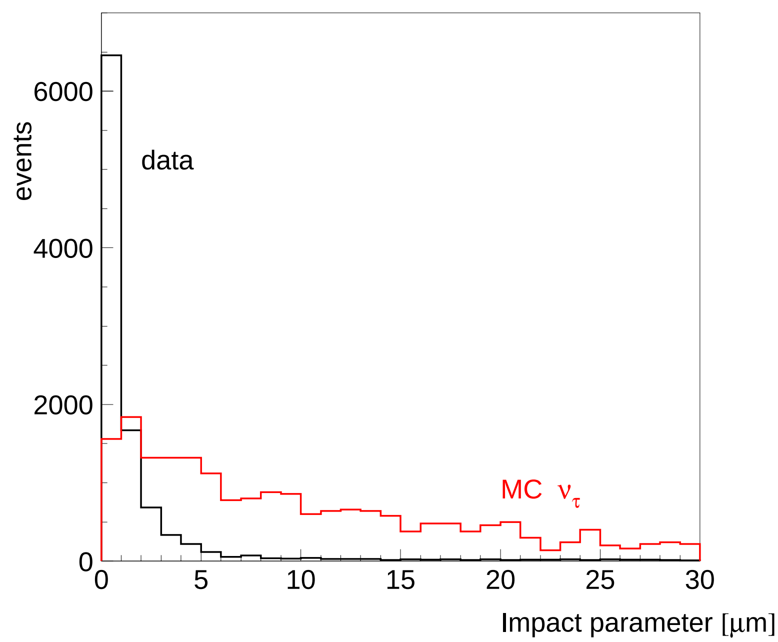

FIG. 32. Distribution of the impact parameter from simulated ν_τ interaction and data. With a cut on the impact parameter of 2--8 μm, 59% of the ν_τ interactions survive. A large fraction of data, mostly ν_μ-induced interactions, is cut.

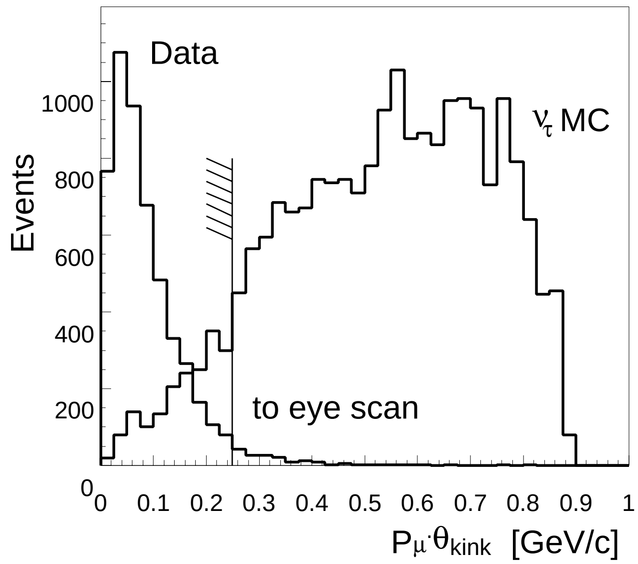

FIG. 33. Distribution of $p_\mu \cdot \theta_{kink}$ from simulated ν_τ interactions and real data. With a cut $p_\mu \cdot \theta_{kink} > 250$ MeV most of the ν_τ interactions survive.

There are expectations that all the τ decay modes will eventually be looked for, even though at this time the $\tau \to \mu$ analysis is most advanced. The efficiency for finding the $\tau \to \mu$ events is about a factor of two higher than for the other decay modes. At the time of these lectures about 10% of the potential muon decay sample was analyzed;[84] no events were found, giving a $\sin^2 2\theta$ limit of 4.5×10^{-3}. For the other decays, so far only 4% of the neutral current events have been analyzed. Three low P_T (< 250 MeV/c) kinks were found but no τ candidates. It is hoped that the full analysis of all the data can be completed by the end of 1998.

The other experiment, NOMAD, relies on a kinematical analysis to identify τ production and decay. To be able to achieve that goal, the target/detector is composed of a number of thin plane drift chambers located in a large magnetic volume, the magnet used being formerly a part of the UA1 experiment. NOMAD, like CHORUS, also hopes to have a background-free experiment. The schematic of the detector is shown in Fig. 34.

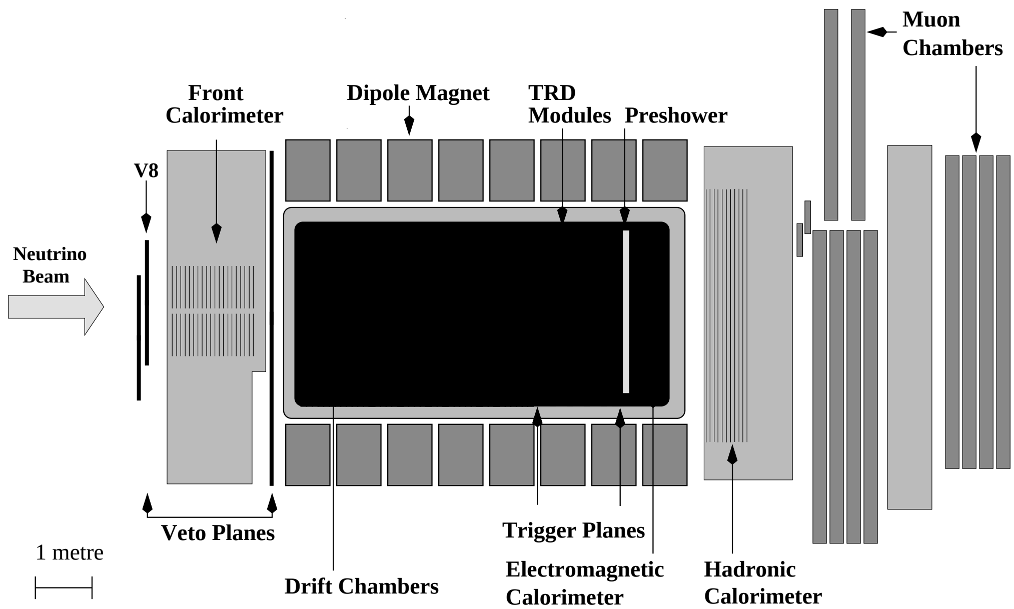

FIG. 34. Side view of the NOMAD detector.

Downstream of the 44 tracking chambers in the magnetic volume are located nine modules of transition radiation detectors (TRD's) and then an electromagnetic calorimeter, 19 radiation lengths deep, composed of lead glass Cherenkov counters. Further downstream, outside the magnet, is a hadronic calorimeter followed by muon chambers, composed of arrays of drift tubes.

The kinematical analysis used to identify the purely leptonic τ decay events relies on correlations between these vectors: P_{lepton}, P_{hadron}, and P_{miss}. For ν_μ or ν_e charged current events P_{lepton} and P_{hadron} will generally be back to back, with a relatively small P_{miss}. The last will be due to contributions from the Fermi motion in the nucleus, nuclear reabsorption and rescattering, and measurement errors (including missing particles). Thus on a two-dimensional plot, where axes are defined by the azimuthal angles between the three vectors: $\varphi_{\mu h}$ and φ_{mh}, there will be a region populated by τ events but not by μ (or e) events. This is illustrated in Fig. 35 where we show the Monte Carlo calculated scatter plots for the ν_μ events and the ν_τ CC events.

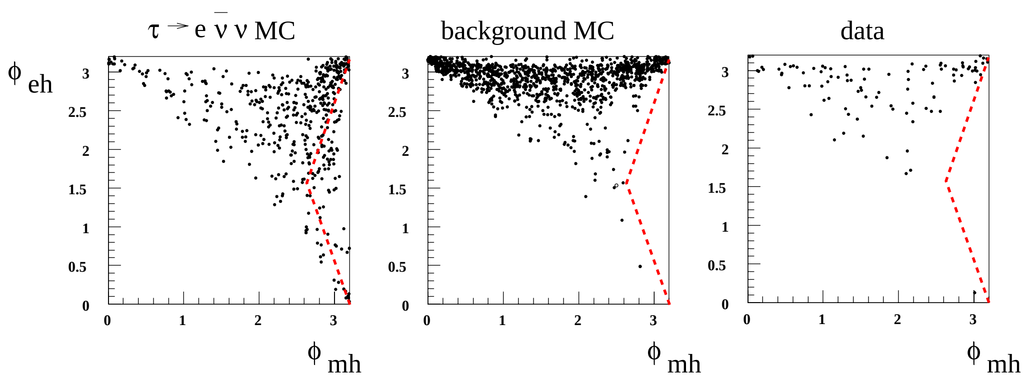

FIG. 35. Distributions of φ_{eh} vs. φ_{mh} obtained after $\tau^- \to e^- \nu_\tau \bar{\nu}_e$ selections cuts have been applied.

The initial data taken gave a measured P_T distribution for ν_μ CC events somewhat broader than what was expected from the Monte Carlo calculation: specifically one obtained $<P_T>_{meas}$ = 770 MeV vs. $<P_T>_{MC}$ = 610 MeV. The precise reasons for this discrepancy were not understood at the time of these lectures; they could be due to some neglected nuclear effects or easier reconstruction in Monte Carlo. Currently, the ν_μ data sample is used to calibrate and then correct for this discrepancy.

At the present time, based on 18% of the proposed statistics, no candidate events were observed (0.6 background events were expected).[85] This gives a limit: $\sin^2 2\theta < 3.4 \times 10^{-3}$ (90% C.L.) at high Δm^2.

There are expectations that the limit will be improved significantly by inclusion of more decay modes, increased statistics, and improved efficiency.

In summary, the three most sensitive experiments, E531, CHORUS, and NOMAD, have so far seen no candidate events for $\nu_\mu \to \nu_\tau$ oscillations. Thus, one can combine the whole data sample from all the experiments to obtain the current global limit on $\sin^2 2\theta$ of about 1.2×10^{-3}. The projected sensitivities of NOMAD and CHORUS as stated in the proposals are shown in Fig. 36 and compared there with the current limits from the published experiments. Finally, we might add that these experiments also set a limit on possible $\nu_e \to \nu_\tau$ oscillations which is about a factor of 50-100 worse than the $\nu_\mu \to \nu_\tau$ limit, reflecting the much smaller ν_e flux in the beam.

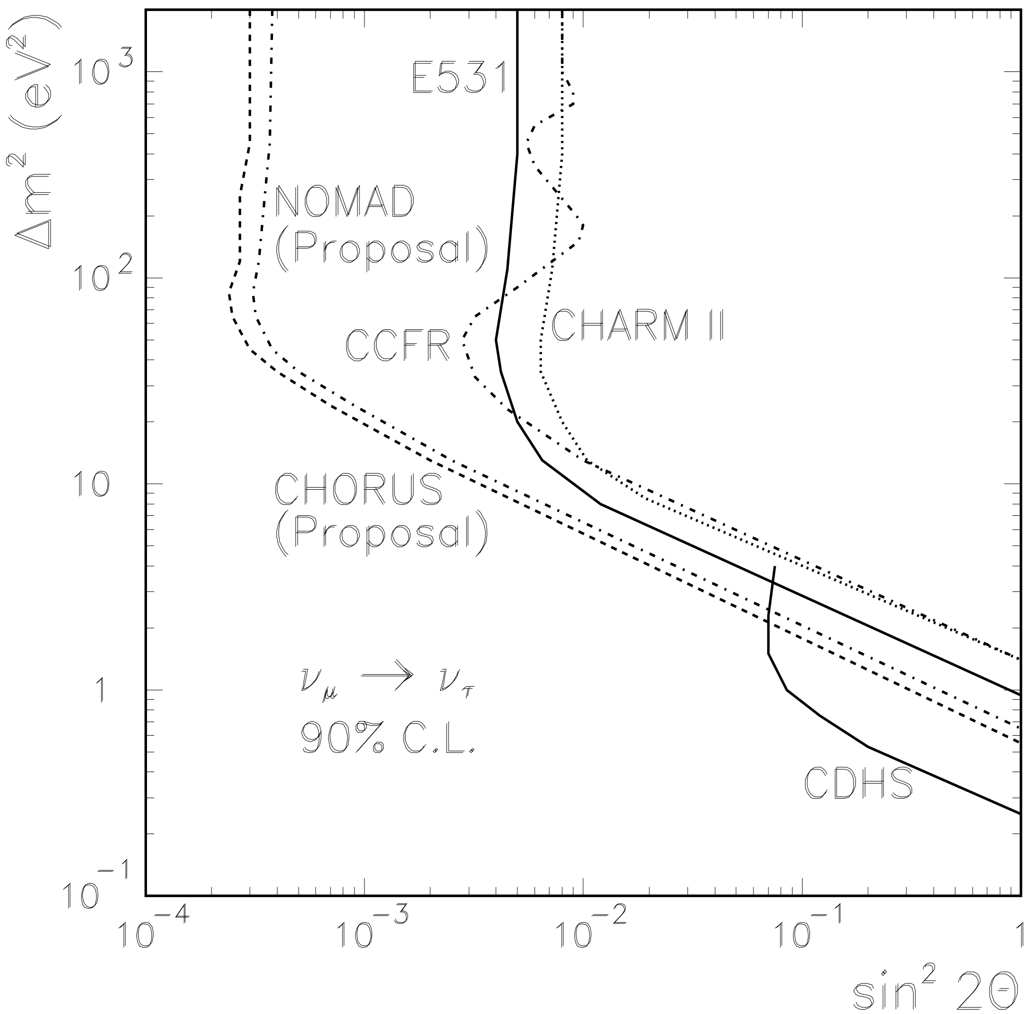

FIG. 36. Current 90% C.L. neutrino oscillation parameter limits compared to the limits achievable by the CHORUS and NOMAD experiments.