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Prospects for Long Baseline Neutrino Oscillation Experiments*

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ABSTRACT

Several recent developments have motivated consideration of neutrino experiments located hundreds or thousands of kilometers from an accelerator. The motivations and experimental challenges for such experiments are examined. Three proposals for using the Fermilab Main Injector are compared. The requirements on mass, distance and resolution for an "ideal" detector for such an experiment are considered.

1 Introduction

This paper is divided roughly into three sections. In the first section I want to review some of the experimental situation that has motivated the idea of neutrino oscillation experiments located a long distance from accelerators. In particular the solar neutrino deficit and the atmospheric neutrino deficit will be considered. Next is a discussion of some specific proposals for long baseline neutrino oscillation experiments. The discussion will focus on three proposals before Fermilab to use a neutrino beam from the Main Injector and aim at the existing or already planned detectors. The three proposals are from IMB (P805), Soudan 2 (P822) and DUMAND (P824). These proposals served to motivate the workshop on Long Baseline Neutrino Oscillations that we have just finished.

The second part of the paper is meant to review some of the physics issues discussed at the workshop. Chapter 4 discusses the physics signatures for neutrino oscillations that could be found. Chapter 5 looks at the issue of what is the best distance to place a detector in order to look for neutrino oscillations. Chapter 6 covers some of the systematic effects which might limit an experiment.

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The last part of the paper focuses on some ideas of what an "ideal" detector for a Long Baseline Neutrino Experiment might consist of. No unique answer to this question has emerged from this workshop. However two possible yet distinct directions have crystallized, and I go down each road a bit. In one point of view, there will be limited resources for this kind of experiment, but a focused experiment on the region of parameter space for $\nu_\mu \rightarrow \nu_\tau$ which is suggested by the atmospheric neutrino deficit is considered. In the second point of view, larger resources are assumed, and an experiment which can look for oscillations with lower $\sin^2 2\theta$ and lower Δm^2 is considered. I close with some personal thoughts on how advocates for these experiments should proceed in the near term future.

2 Motivations for Long Baseline Neutrino Oscillation Searches

2.1 Neutrino Mass and the solar neutrino deficit

Although there is no firm evidence for neutrino mass, it is possible to imagine a lepton sector with all three neutrinos having nonzero mass, and the existence of a weak CKM mixing matrix analogous to the quark CKM matrix. One consequence of this scenario would be neutrino oscillations, and a large number of searches for neutrino oscillations have been done using neutrinos from reactors and accelerators. Two "hints" will be discussed below using atmospheric and solar neutrinos, but no unambiguous evidence for neutrino mass presently exists. If neutrino mass does exist, it seems to be theoretically preferred, though by no means mandatory, that the usual generation hierarchy exist; this would imply

$$m_{\nu_\tau} > m_{\nu_\mu} > m_{\nu_e} \tag{1}$$

and mixing angles would be largest for adjacent generations, so that $\nu_e \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_\tau$ would be more likely than $\nu_e \rightarrow \nu_\tau$. Reactor experiments only address ν_e modes, and the best limits on $\nu_\mu \rightarrow \nu_\tau$ come from only two experiments.[1, 2]

An elegant solution to the solar neutrino problem [3] is the MSW solution [4], which requires $\nu_e \rightarrow \nu_\mu$ oscillations with vacuum parameters $\sin^2 2\theta \sim 10^{-2}$ and $\Delta m^2 \sim 10^{-6} eV^2$. Equation 1 and the existing limits would then imply that the ν_τ mass should be between .001 and 1 eV. This is just the region that is accessible to contemplated Long Baseline Experiments.

2.2 Atmospheric neutrino flavor ratio

Further motivation for this same region of parameter space comes from the atmospheric neutrino problem, first pointed out by Kamioka and IMB. [5] [6] With a total of 13 kt-year, these two Water Čerenkov detectors measure 40% fewer ν_μ events than would be expected based on the number ν_e events that they see. This is parameterized as a ratio of the measured flavor ratio to the expected ratio

$$r \equiv \frac{(\nu_\mu/\nu_e)_{measured}}{(\nu_\mu/\nu_e)_{predicted}} \tag{2}$$

This possible shortage of ν_μ events was first noticed by IMB [7], but publicly discussed as a possible manifestation of neutrino oscillations after Kamioka presented 3.4 kt-year worth of data. Now the effect is seen in 6.4 kt-year from Kamioka and 7 kt-year from IMB. [8, 9] Each experiment measures a value for r of about 0.6 ± 0.1.

If one interprets this atmospheric ν_μ deficit as due to neutrino oscillations, one can determine the probability of oscillation. In addition to the flavor ratio, one measures the energy distribution and the angular distribution of the atmospheric events. If Δm^2 is much below 10^{-2}, the oscillation length for many atmospheric neutrinos would be roughly the radius of the earth. Then one would expect a variation in the atmospheric neutrino ratio as a function of energy and angle. If Δm^2 is above 10^{-2}, most all of the atmospheric neutrinos will be fully mixed by the time they are measured in an underground detector. In that case, one would expect a flat angular distribution and a ratio which is independent of energy. Within statistics, this is what is seen. Kamioka fits the neutrino oscillation hypothesis with the ratio and the E/L distribution and gets a "best fit" point of $\sin^2 2\theta = 0.6$ and $\Delta m^2 \approx 0.9 \times 10^{-2} eV^2$. It should be kept in mind that all higher masses with that mixing angle are almost as likely with the present data.

The Frejus experiment, with 1.56 kt-year appears to measure the expected atmospheric neutrino ratio [10, 11]. However they measure a different ratio with their contained and uncontained events. Independent of any calculated ratio or other experiment, these two measurements of Frejus are inconsistent with themselves at the 3 sigma level. In any case, taking the Frejus limit at face value eliminates some, but not all of the parameter space suggested by the IMB and Kamioka deficit.

Given the flavor ratio, it is straightforward to do a neutrino oscillation analysis. The ratio could be explained by either $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_e$, but $\nu_\mu \rightarrow \nu_\tau$ is preferred for two reasons; the parameters are different than those required to explain the solar neutrino deficit, and much more of this region for $\nu_\mu \rightarrow \nu_e$ has been ruled out at accelerators and reactors. A $\nu_\mu \rightarrow \nu_\tau$ analysis has been done in figure 1 [13]. Shown are the limits from the Frejus, IMB up/down analysis, and accelerator data for $\nu_\mu \rightarrow \nu_\tau$. Two lines are shown from Kamioka, and the area between these lines is to be interpreted as the *allowed* region at the 90% confidence level. Thus the shaded region is allowed by all experiments at 90% confidence level. A full interpretation of this curve, however, requires a discussion of the following points:

- Best fit point. The flavor ratio is sensitive to the probability of oscillation. In order to extract two parameters, another variable must be used. This is done looking at the energy and angle dependence of the ratio. Both IMB and Kamioka state that their energy and angle distributions are consistent with the distributions expected without oscillations. The best fit point, therefore, should be viewed as bottom of a valley in chi-squared which goes up in Δm^2 at fixed $\sin^2 2\theta$ with a very flat slope.

- Allowed region. It is more meaningful to look at the entire area of parameter space allowed by this result, than to focus on a single point. This is done in figure 1. The choice of confidence level affects the appearance of these plots. A higher confidence level, such as 99%, would lead to all limits moving to the right, while the allowed region would grow in all four directions.

- Newer Kamioka analysis. The graph shown is based on an analysis of 3.4 kt-year of

Kamioka data in a thesis by Takita.[13] A more recent analysis of the same Kamioka data has been shown with a smaller allowed region.[15] The difference is due to the handling of systematic errors on the flavor ratio. Since the references with the more restrictive limits do not discuss these systematic errors, the conservative thing to do is use the larger region as allowed.

- More data. Figure 1 is based on 3.4 kt-year of data, and there is now 13 kt-year of data from IMB and Kamioka combined. To the extent that the region in figure 1 is statistical, more data with the same ratio will shrink the allowed region of $\sin^2 2\theta$ from both directions. To the extent that the energy and angle distributions which are measured continue to match the expected distribution within statistics, the lower region of Δm^2 is ruled out. Since the IMB and Kamioka flavor ratio agree, it would be interesting to analyze the combined data sample for any evidence of energy or angle deviations.

- Potential conflict with upward muon result. The only strong evidence against a neutrino oscillation hypothesis of the atmospheric flavor ratio is the upward muon flux limits presented at this conference.[14] That result was that the measured flux of upward going muons at IMB agrees with the expected rate without oscillations. The upward going muons are due to neutrinos interacting in the earth just outside of the detector. Similar results have been reported previously by Kamioka and Baksan [16, 17]. These limits depend critically on an absolute knowledge of the atmospheric neutrino flux. A convincing case that the absolute atmospheric neutrino flux is well understood systematically, and that it agrees with these experiments, would weaken the case for long baseline experiments somewhat.

2.3 Δm^2 Sensitivity of Atmospheric and Long Baseline Experiments

The atmospheric neutrino flavor ratio is sensitive for Δm^2 from 5.0 $10^{-4} eV^2$ to above $1 eV^2$, where accelerator limits exist.[1, 2] There is an important qualitative difference in atmospheric neutrino phenomenology for Δm^2 above and below $10^{-2} eV^2$. This break at $10^{-2} eV^2$ provides a fortuitous circumstance for neutrino oscillation searches. If the hint from the atmospheric neutrino sector is correct, there are two distinct scenarios: Δm^2 is above $10^{-2} eV^2$ and Δm^2 is below $10^{-2} eV^2$. The phenomenology of neutrino oscillations above and below this value changes for both the flavor ratio of atmospheric neutrinos and for the proposed long baseline neutrino oscillation searches.

2.3.1 $\nu_\mu \rightarrow \nu_\tau$ oscillations with $\Delta m^2 < 10^{-2} eV^2$

At the lowest values of Δm^2, atmospheric experiments should see not only an anomalous flavor ratio, but also a ratio which depends on energy and the angle of the beam. Kamioka and IMB cannot rule out ratios which are flat in both of these variables. However, given the consistency of their flavor ratios, an analysis should be done with the combined data from both experiments, and the flavor ratio should be plotted as a function of E/L. (The $\cos\theta$ distribution reflects the L which the neutrino traversed.) If this distribution is flat, then the lower values of Δm^2 in figure 1 can be ruled out. If it goes down at low values of E/L, then there is evidence that the effect is at these low values of Δm^2. Figure 2 shows the effect in the angular distribution alone that would be expected with a 5 year run from Superkamiokande at the best fit point. The size of this effect would grow rapidly as one goes down in Δm^2.

At $10^{-2} eV^2$, both there would be this small effect in the atmospheric E/L distribution, and long baseline experiments would be sensitive. At lower Δm^2, where atmospheric experiments would see large E/L effects, long baseline experiments lose their sensitivity. Most of the neutrinos will not have yet reached a full oscillation length, and so the proposed experiments will measure only the unoscillated beam.

2.3.2 $\nu_\mu \rightarrow \nu_\tau$ oscillations with $\Delta m^2 > 10^{-2} eV^2$

In this region of parameter space, neutrino mixing with large mixing angle explains the atmospheric neutrino flavor ratio. However, the atmospheric neutrinos arriving at the underground detectors are fully mixed from all directions and to the lowest energies in the atmospheric spectrum. Thus for the forseeable future, underground experiments would see an anomalous flavor ratio, but the ratio would not depend on angle or neutrino energy.

This is just the region of parameter space where all of the proposed long baseline experiments are sensitive, and should be able to confirm or deny neutrino mixing with many standard deviations.

In summary, the combination of long baseline experiments, and continued running of underground detectors, could unambiguously cover the whole region of parameter space suggested by atmospheric neutrinos. Either Δm^2 is high, in which case long baseline experiments have a specific prediction of the effects to look for, or Δm^2 is low, and long baseline experiments will see little or no effects, while the atmospheric neutrino flavor ratio will have a specific and noticeable dependence on E/L.

3 The Three Proposals for the Fermilab Main Injector

In the last 15 years, a large number of suggestions have been made for long baseline neutrino experiments. Table 1 is an attempt to list some of the suggestions. Many have made it to the proposal stage at a number of accelerators around the world, but none has yet been approved.

Three groups have recently submitted proposals to use existing or already planned detectors as a target for a long baseline neutrino experiment from Fermilab. They represent a range of opportunities to study neutrino oscillations without the added expense of a new detector. They do require the building of a new beam in a particular direction, but a group at Fermilab studying this issue determined that a new beam would need to be built anyway.[18] In order to do the short baseline experiment, P803, a new double horn beam needed to be built, and the present double horn beam area seemed unable to meet the groundwater protection requirements for the intense beams that the Main Injector was capable of producing. What follows is a short discussion of the neutrino beam design and the three proposals to use it. The neutrino oscillation tests which are referred to are discussed more thoroughly in Section 4.

3.1 The Double Horn Beam at the Fermilab Main Injector

A new beamline has been designed for use with the new Fermilab Main Injector taking into consideration the following objectives[18]:

- Full utilization of the 120 GeV Main Injector proton beam with a flux up to 4×10^{13}ppp with a cycle time of 1.9 sec and a spill time of 1 msec. A cycle time of 1.5 sec has been used for target heating and stresses as a safety margin.
- Maximization of the neutrino flux for both a short baseline experiment and a long baseline experiment by focussing the optimum number of pions and kaons from the target into the decay region.
- Minimizing the cost by shortening the decay tunnel from previous designs.
- Satisfying radiation safety and groundwater activation requirements.

The elements of the beam consist of a proton beam transport system, a proton target followed by a horn and considerable steel shielding. There is a long decay pipe for secondaries and the charged particle beam ends at a steel dump. The neutrino beam continues to short baseline detectors and the long baseline detector.

The beam utilizes a conventional double horn focusing system. The shapes, current and spacing between the horns have been designed in order to optimize the transport of $\pi's$ and $K's$ with $p_{\perp} = 0.9\ GeV/c$ into the decay tunnel. An important element of the design is to make the inner conductor large enough so that the proton beam is unlikely to strike and melt it, and the walls thick enough so that they can withstand the axial magnetic pressure. At the same time, it is the goal to minimize the material in the way of the charged particle beam so that a minimum of absorbtion takes place.

The use of the beam for a long baseline experiment raises certain civil construction issues in the construction of the beam. The distance from the beginning of the proton transport to the dump is about 500 m. The beam must be aimed down into the ground in order to reach a long baseline experiment. For a detector from 500 - 1000 km, the angle is $2 - 4°$. This means the dump must be 15-30 m underground. A short baseline detector 200 m downstream is even deeper. The Fermilab Conceptual Design Report identified ground water protection and the digging of the beam as major costs involved in the construction of the facility. Many of the details were worked out in the report. However choice of a particular long baseline target, and hence angle of the beam will dictate whether the beamline will be dug out or built within a slurry wall. A very long baseline experiment, such as the DUMAND proposal, would likely necessitate the use of a tunnel for the beam.

3.2 P805 using the IMB detector

3.2.1 Features of the Detector

The IMB detector is located in the Morton Salt mine near Cleveland, Ohio about 600 m below the surface and 570 km from Fermilab. A beam aimed towards the detector points almost due east and downward with an angle of about 45 mr with respect to the horizon.

The detector consists of a rectangular volume (17 m $\times$ 17.5 m $\times$ 23 m) of highly purified water, viewed by 2048 photomultipliers augmented with waveshifter plates. A schematic of the detector is shown in figure 3. It has operated with high reliability since 1982, and has set significant limits on proton decay, measured properties of atmospheric neutrinos, and detected the burst of neutrinos from SuperNova SN1987A. The detector resolves the patterns of Čerenkov light from muons entering the detector and from individual products of neutrino interactions in the detector volume. The detector has the capability of resolving showering (e, π^0) from nonshowering $(\mu, \pi^\pm)$ tracks and can resolve electrons from π^0's with energies below 500 MeV.

The detector trigger threshold of 10 MeV is far below the requirements of the proposed oscillation experiment. The 2.7 Hz rate of cosmic ray muons passing through the detector produces only 1% dead time. Assuming that the Main Injector will provide 3×10^{13} protons of 120 GeV energy with the repetition time of 2 sec, one can expect that IMB would record 2.6 neutrino interactions in the detector volume and 5.2 muon tracks entering the detector per hour associated with the beam. A signal of this size would result in 1.3% statistical accuracy after half a year of data collection for the sample of contained events. The background to this signal due to interactions of atmospheric neutrinos is of the order of 10^{-6}.

3.3 $R_{\mu/\nu}$ test analysis

The experiment would measure the rate of neutrino interactions in the detector volume associated with the beam and the rate of tracks entering the detector. Since the rock surrounding the IMB detector has density about 3 times larger than water, the contamination of other than muon tracks in this sample is expected to be only about 4%.

Using the $R_{\mu/\nu}$ test described in section 4, IMB can collect in a half year enough contained events so that their statistical accuracy will be 1.3%, much smaller than the systematic error.

A significant component of the systematic uncertainty of Long Baseline experiments is due to the variations of the beam characteristics with an angle with respect to the beam axis, and the accuracy with which the beam is pointed towards the detector. The IMB group helped coordinate the effort to design a beam with minimum energy variation as a function of angle. The mean energy of the beam described varies only 1% over 0.5 mr. [18] Since this variation is directly proportional to the error of the expected ratio, the beam pointing precision of $\pm$ 0.2 mr assures the experimental precision better than 1%. The potential 90% CL upper limit that IMB can set in the 6 month run is given in curve B in figure 4.

3.3.1 ν_e appearance

In the IMB detector, one can resolve patterns of Čerenkov light from electron and muon tracks, but high energy π^0's are similar to electron showers. However, for the neutrino beam considered in this document, the probability of producing a π^0 with energy above 20 GeV is only about 5% of that of leptons. Thus an observation of more showers with energies above 20 GeV than the expected π^0 background and the contamination of the beam by ν_e (about 1% in this energy region) would indicate $\nu_\mu \rightarrow \nu_e$ oscillation. The region of sensitivity to Δm^2-$\sin^2 2\theta$ of this experiment is similar to that of the $R_{\mu/\nu}$ test analysis. This region seems to be well above the region considered in the explanation of solar neutrino puzzle but it has never been tested in well controlled accelerator conditions. Again, the potential 90% CL upper limit that IMB can set in a 6 month run in the absence of oscillations in this mode is shown in curve A in figure 4. An important systematic check available to IMB in this mode would be agreement between the excess electron events above 20GeV and a ratio of contained to entering events consistent with the $\nu_\mu \rightarrow \nu_e$ hypothesis.

The IMB detector will also have the capability of measuring the neutral current to charged current ratio on a subsample of their data using the fact that an exiting muon leaves a hot spot in the tube closest to the exit point. It may be possible to reconfigure part of the IMB detector to take advantage of this fact.[20]

3.4 P822 using the Soudan 2 detector

3.4.1 Description of the detector

The Soudan 2 detector (P822) is located in an iron mine in Northern Minnesota, 800 km from Fermilab. It will be an 1100 ton fine grained calorimeter (700 tons are currently in operation), consisting of 256 modules which each contain 7560 1.4-cm radius 1-m long drift tubes. A diagram of the detector is shown in figure 5. Its spatial resolution and related properties are similar to those of "standard" neutrino detectors (Fermilab E594, the CHARM detector at CERN, ...). It could measure the muon rate from the Main Injector ν_μ beam both in the detector (5m × 8m × 16m) and in its proportional counter shield (11m × 14m × 24m) and normalize to the contained vertex events.

3.4.2 $R_{\mu/\nu}$ test analysis

Due to its larger distance and smaller size, the Soudan event rates for entering muons and contained events would be lower than IMB's by a factor of 1.8 and 9.7 respectively. The limits that Soudan 2 could obtain based on a similar $R_{\mu/\nu}$ test analysis are shown in curve C of figure 6.

3.4.3 ν_τ Appearance Experiment

In addition, Soudan 2 could also do a ν_τ appearance experiment by looking for a deviation from the expected NC/CC ratio,

$$\frac{N_{nc}}{N_{cc}} = \frac{R_{nc/cc} + \eta(1-B)P}{1 - P + \eta BP} \tag{3}$$

where B is the branching fraction for $\tau^- \rightarrow \mu^- X$, and η is the ratio of the ν_τ charged current cross section to the ν_μ charged current cross section. Integrated over the energy distribution from the main injector, $\eta \sim .25$. $R_{nc/cc} = .31 \pm .01$ is the expected ratio in the absence of oscillations and depends only on knowledge of the Weinberg angle. The limit that can be obtained in the absence of oscillations is shown in curve B of figure 6. Both tests independently cover much of the region of parameter space suggested by the Kamioka results using atmospheric neutrinos. If neutrino oscillations actually are found to exist, there is an advantage to measure them simultaneously with different methods and to check for consistency between the two results. Other capabilities of Soudan 2 include a measurement of the rate of stopping muons, which gives added sensitivity at low Δm^2, and, with a high enough flux, the possible identification of single ν_τ quasi-elastic events.

The p822 proposal includes a calculation of the statistical precision with which signals would emerge for a selection of oscillation probabilities. That table has been updated in this workshop.[21] The proposal discusses in some detail the performance of the Soudan 2 modules as measured in a low energy calibration beam. An attractive feature of the Soudan calorimeter is the ability to calibrate it using Fermilab test beams which could match the hadron and muon energies of relevance to the long baseline experiment.

3.5 P824 using the DUMAND detector

3.5.1 Description of the detector

The DUMAND detector will measure the Čerenkov light in ocean water from charged particles produced by neutrino interactions. The array is being constructed in a subsidence basin at a depth of 4.8 km, 30 km west of Keahole Point, Hawaii. The array consists of nine strings, one at the center and at each of the vertices of an octagon 40m on a side. This is shown in figure 7. Each string supports 24 phototubes, 15 inches in diameter and spaced 10 m apart vertically. The spherical tubes are oriented with the photo cathode pointing downward and have a sensitivity which falls linearly with the cosine of the angle between the most sensitive direction and the direction of the incident light. A cable from shore supplies electrical power to the array and has an optical fiber for data transmission from each string. For upward muons, the signal is almost entirely due to neutrino interactions beneath the array, and the effective area of the array is 2×10^4 m^2. The location deep in the ocean provides a huge reduction in the flux of downward muons. In the upward going hemisphere, the isotropic background from neutrinos which are due to cosmic ray interactions in the atmosphere is 1/3 event per bin of angular resolution size per year.

A prototype detector[22] has been used to measure[23] the downward flux of muons in the deep ocean (4 km) and the construction is proceeding with one third of the detector elements scheduled for installation by the end of 1992 and the remainder by the end of 1993.

3.5.2 $R_{\mu/\nu}$ test

Neutrinos from a Fermilab beam would intersect the DUMAND array at an angle 30° below the horizontal, well within the region of best acceptance and low background. The large size of the array approximately compensates for the decrease of flux with large distance, and the solid angle subtended is roughly the same for all the long baseline detectors. Monte Carlo calculations show detection and reconstruction efficiencies which are equivalent to a target mass of approximately 10^6 metric tons (half the contained volume) for muons from interactions of 20 GeV neutrinos. For interactions in the contained volume, these Monte

Carlo calculations give a 41% trigger efficiency for interactions of ν_e and 51% for ν_μ with the energy distribution expected for a neutrino beam from the Main Injector. A typical trigger rate in the Main Injector beam is about 5 events per hour or 17,000 neutrino triggers in a typical 8 month run with 100 useful hours per week. Triggering and reconstruction are clearly adequate and the detection efficiencies are sufficiently similar that the sum can be used for flux normalization. Techniques for demonstrating a small signal of ν_e in a much larger ν_μ sample are discussed elsewhere in this proceedings.[19]

The array is readily expandable. A modest addition of four additional strings inside this array would enhance the efficiency for low energy events. The cost of such an enhancement is very roughly $2.5M. If evidence for the existence of neutrino oscillations is found, it would be straightforward to increase the event rate by adding strings of phototubes outside the planned array.

3.5.3 Matter Enhanced $\nu_\mu \rightarrow \nu_e$ Oscillations

The DUMAND array is ten times as far from FNAL as the other proposed long-baseline detectors. This long path of the neutrinos provides room for longer wavelength oscillations of all flavors, and, because it is through the Earth, it also provides sufficient integrated electron density to induce flavor changes to or from ν_e, thus substantially increasing the sensitivity of this detector for small mixing angles with ν_e through the MSW effect. This possibility has been studied by Pantaleone and by Parke[24, 25, 26] for ν_μ to ν_e oscillations. Similar oscillation enhancements are expected for full three flavor mixings. For example a ν_μ-ν_e mass difference as small as that suggested by the MSW explanation of the solar neutrino deficit ($\approx 10^{-7}$ eV^2) would be very difficult to detect in a laboratory the size of the Earth, but leads one to expect a much larger ν_μ–ν_τ mass difference with a corresponding decrease in oscillation length. Matter mixing of ν_τ and ν_e may then produce a signal which is much easier to detect. The limits that DUMAND expects to achieve are given elsewhere in this proceedings.[27]

4 Physics signatures for neutrino oscillations

The signatures for neutrino oscillations have been touched on in the three previous sections. Here we address the issues in a more comprehensive way. We concentrate on the mode $\nu_\mu \rightarrow \nu_\tau$ which we consider to be of most interest. We wish to point out a difference in the common use of the terms "appearance" experiments and "disappearance" experiments. We distinguish these two types by whether the interactions of the neutrino into which the oscillation is occurring, in our case the ν_τ, plays a role. Some other authors restrict the term "appearance" to the case where a single event can be unambiguously identified, of a flavor of neutrino which was not originally in the beam.

4.1 $R_{nc/cc}$ test

If $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_e$ oscillations exist, the number of apparent charged current events would go down relative to the number of neutral current events. Equation 3 is repeated here:

$$\frac{N_{nc}}{N_{cc}} = \frac{R_{nc/cc} + \eta(1-B)P}{1 - P + \eta BP} \tag{4}$$

Examination of this equation shows several processes that are taking place.

- Whether or not the neutrino oscillates, the rate of real neutral current events is expected to stay the same.
- Most charged current ν_τ events will not have a muon after the τ decay, so they will be lost from the charged current sample and added to the neutral current sample.
- A small fraction B (17%) of the τ decays do have a muon and will stay in the charged current sample.
- The ν_τ charged current cross section is significantly smaller than the ν_μ or ν_e charged current cross section due to the τ mass. This is significant throughout the energy range of this beam [28]. Thus the loss of events from the charged current sample exceeds the gain of events in the neutral current sample.

The use of $R_{nc/cc}$ to study neutrino oscillations is affected by how well the expected ratio is known as a function of energy, neutral and charged current misidentification, and various beam systematics which are to a great extent energy dependent. These systematic effects will be discussed in further detail in Chapter 6. Note here, however, that up to corrections due to quasi-elastic events, the ratio is expected to be independent of neutrino energy, and thus most effects from unknown beam parameters cancel out.

4.2 $R_{\mu/\nu}$ test

The muons from the rock are a measure of ν_μ charged current interactions. In the presence of neutrino oscillations, a lower rate of rock muons is expected. One can normalize the expectation to the number of neutrino vertex events seen. This is the $R_{\mu/\nu}$ test. All three proposals include a variation of this test in order to measure neutrino oscillations. At first glance, it seems undesirable to rely on muons coming from rock or material outside of a detector, because the rate of muons produced is sensitive to the density which is not directly measured. However the density also affects the range in the same way, and to first order, the flux of muons entering the detector does not depend on the density of material upstream. The three proposals are in mines or the deep ocean, where the density of target material outside the detector is very well known in any case.

In a sense, the $R_{\mu/\nu}$ test is just a variation of the $R_{nc/cc}$ test. The rock muons are counting the cc events. The contained vertex events are counting the nc+cc events. The statistics of the two sets are independent, but the idea is the same. Wojtek Gajewski has introduced the parameter ϵ as the efficiency of distinguishing neutral and charged current events. For neutrino events which occur near the back edge of a detector, ϵ is very low. Even for a detector with $\epsilon = 0$, however, one can use the $R_{\mu/\nu}$ test. Consider an experiment with $\epsilon = 1$ using the nc/cc test. Then the error on the number of neutral current events measured is

$$\sigma^1_{nc} = \sqrt{N_{nc}} = \sqrt{\frac{r}{r+1} N^1_{nc+cc}} \tag{5}$$

where the superscript refers to the value of ϵ. This compares to a calculation using a detector with $\epsilon = 0$ using the $R_{\mu/\nu}$ test (and assuming the effective masses are equal),

$$N_{nc} = N^0_{\nu} - N_{\mu} \tag{6}$$

so that,

$$\sigma^0_{nc} = \sqrt{N^0_{nc+cc} + N_{cc}} = \sqrt{N^0_{nc+cc}\frac{2+r}{1+r}} \tag{7}$$

$r \sim \frac{1}{3}$, so in order to have a similar sensitivity with the $R_{\mu/\nu}$ test, one needs about 7 times the statistics as the $R_{nc/cc}$ test.

In addition to its lower statistical power, the systematic effects using $R_{\mu/\nu}$ test were not as thoroughly studied at this workshop as those for the $R_{nc/cc}$ test. This is in part because the underlying neutrino energy distribution for the rate of muons and neutrinos are different. Higher energy muons are favored because their range is proportional to energy. Thus the expected value of the ratio depends on an accurate knowledge of the energy distribution within the beam. At the present time, it is not clear with what accuracy this can handled.

4.3 $R_{near/far}$ test

If neutrinos oscillate into a sterile species, then neither of the previous two tests will measure a ratio different from the expected value. Both tests rely on the fact that the ν_τ is interacting in the detector. Therefore, even though they involve the loss of ν_μ charged current events, this author prefers to call them appearance experiments. A true disappearance experiment is sensitive to the flux of neutrinos, which must be measured or inferred in another way. Using a front detector to measure the flux of the neutrino beam, one can devise such a test. Statistically, a front detector can expect millions of events per kiloton in the proposed main injector neutrino beam. Using a beam monte carlo alone, one could expect to then predict the flux at a far detector no better than 10%. However using the energy and angle distributions measured in a high quality front detector, one would expect to do better. Statistically, the $R_{near/far}$ test is the most powerful test available to a long baseline experiment. However, it is felt that a shortage of events alone at a far detector would not by itself be a strong indication of neutrino oscillations, given the uncertainties prevalent in neutrino flux calculations. If a signal is seen in the $R_{\mu/\nu}$ and $R_{nc/cc}$ test, however, one can predict the level of deficit one would expect in the $R_{near/far}$ test. Each of the three tests alone is a statistically independent test for neutrino oscillations. An indication from each of the three tests that oscillations are present, with a probability of oscillation that is mutually consistent would be powerful evidence for the existence of neutrino oscillations.

4.4 Neutral Current Energy tests

The ν neutral current cross section is proportional to $(1 - y)^2$ which implies rather low hadron energies for most events. However, the ν_τ charged current events which are counted as neutral current events would appear to be y=1. Thus we would expect not only an excess of neutral current events, but much of that excess to appear with high hadron energies. Unfortunately, there is no likely way to measure y on an event by event basis. However, the expected hadronic energy distributions are different in the two cases. In figure 8 are shown the hadron energy spectra with and without mixing for a million neutrinos. Figure 9 shows the monte carlo distribution for 1000 events. It is found that in the latter case, the fraction of neutral current events above 35 GeV can be used as a test which will give a 4 σ effect for maximal mixing. Note that the normalization of the plots is related to the the $R_{nc/cc}$ test, but the shape of the plot, which is what is being considered here is a completely independent test. The value of the energy cut to maximize the effect depends on the statistics and can be chosen before any data is selected. Any experiment which is being designed should achieve a hadronic energy resolution with this test in mind.

4.5 Charged Current Energy tests

The charged current energy distribution is mostly a measure of those neutrinos which have not oscillated. The distributions for a million neutrinos with and without maximal mixing are shown in figure 10. Even with a million events, the plots are virtually indistinguishable, and differ only by the energy distribution of the $\tau \to \mu X$ decays.

There are two possible uses of the muon momentum distributions in long baseline experiments. First, if L is close to the first oscillation for the average energy of the beam, one would see ν_μ disappearance in the muon events lower than the average energy, and that disappearance would increase towards lower energy. The statistical power of this test is not high for any of the proposed experiments.

The most valuable use for the muon energy distribution would be as a check of the energy spectrum of the beam. Both the $R_{\mu/\nu}$ test to first order, and the $R_{nc/cc}$ test to second order require knowledge of the beam energy spectrum. An active muon momentum system using toroids or other magnets would be a considerable added expense for any of the first generation experiments, however. It may be prudent to consider the addition of such a system only after further evidence for neutrino oscillation is obtained. It may also be possible that a range distribution of the lowest energy muons will provide much of the same information.

4.6 ν_τ event identification

A number of schemes to identify individual ν_τ events were discussed at the workshop.[19] No compelling method was presented. However the value of cleanly identifying a ν_τ in an experiment would be considerable, so further effort in this regard is justified. Possible avenues that are being explored include the tau leptonic decays, the fact that τ's have a low multiplicity in their decay, and the missing energy. Quasi-elastic tau interactions may be the cleanest way to look for this, but they represent only a small fraction of the cross section.

5 Distance considerations

5.1 What we're maximizing

A key question for the long baseline experiment designer is where to put the detector. The flux of neutrinos falls off as $\frac{1}{r^2}$ beyond several kilometers from the beam position. However the probability of oscillation increases until it reaches unity at an optimum distance for a fixed energy. If neutrino oscillations exist, the probability (P) of oscillation is:

$$P_{\nu_a \to \nu_b} = \sin^2 2\theta \, \sin^2(1.27\,\Delta m^2 \,\frac{L}{E_\nu}) = P_{max} \sin^2(1.27\,\Delta m^2 \,\frac{L}{E_\nu}) \tag{8}$$

with Δm^2 in eV^2, L in km and E_ν in GeV. $\Delta m^2 = |m^2_{\nu_a} - m^2_{\nu_b}|$ and θ is the mixing angle of ν_a and ν_b neutrinos. $P_{max} \equiv \sin^2 2\theta$ can be viewed as the maximum mixing fraction for a monoenergetic beam. As an example, if we consider a 16 GeV beam, and $\Delta m^2 = 0.02\ eV^2$, P(L) is shown in figure 11. The probability of oscillation is highest at 1000 km and oscillates at much large distances. The effect of putting in the double horn beam spectrum is shown in figure 12. The probability is still highest at 1000 km, and asymptotically approaches $P_{max}/2$ at large distances. However in either case, the placement of a fixed size detector depends on the goals and ability of the experiment, due to the falling flux, which figures 11 and 12 do not reflect. Three distinct cases are considered:

1. Zero background. Maximize $N(\nu_\tau)$
2. Study oscillations with background. Maximize $N(\nu_\tau)/N(\nu_\mu)$.
3. Discover oscillations with background. Maximize $N(\nu_\tau)/\sqrt{N(\nu_\mu)}$.

5.2 A zero background detector

One can imagine a detector which could unambiguously measure $\nu_\tau' s$, such as a super P803. One wants to maximize $N(\nu_\tau)$, the number of ν_τ events, $\propto \phi \times P$, where ϕ is the flux. The surprising result is that the best detector position is as close to the beam as possible (i.e. at Fermilab). The number of ν_τ events goes as the flux times the probability of oscillation. As long as the second term in equation 8 above is low, the length terms cancels out of this equation. Farther away, the lowest energy events begin to saturate the sin term, and the number of ν_τ events falls, even though the probability of oscillation is increasing. (Very close to the beam, the flux no longer increases as $\frac{1}{L^2}$, and the optimum distance is chosen based on the beam size and muon flux backgrounds, as P803 was.) The number of ν_τ events is plotted in figure 13 from which it is seen that a close detector is more than six times better than a detector located at L corresponding to P_{max}.

5.3 Measuring Neutrino Oscillations

In an experiment to study the properties of neutrino oscillations, one wants to maximize the ratio of to the signal to background. In this case one puts the detector at

$$L = (\frac{\pi}{2})\frac{E}{1.27\Delta m^2} \tag{9}$$

or at 1000 km in the above example. Knowing the parameters of oscillation, one wants to put the detector where the oscillation effects are the biggest. At this location, one can look at the effect as a function of energy, and determine whether the quantities which are measured match a neutrino oscillation hypothesis. This region is often called the nose because it is also the region where the exclusion plot has a reach to smaller $\sin^2 2\theta$, due to a sensitivity for P between P_{max} and $P_{max}/2$. At a closer distance, most neutrinos haven't oscillated, and at a further distance, the energy spectrum washes out the second sin term in equation 8 to be $\frac{1}{2}$.

5.4 The discovery of oscillations with background

Until neutrino oscillations are actually discovered, the goal will be to maximize the statistical significance of any possible signal. This is proportional to $N(\nu_\tau)/\sqrt{N(\nu_\mu)}$. This is the situation that an experiment designer currently confronts. We do not know the L for P_{max} If we did, the significance would peak at a closer L. How much closer will depend on the amount of background. This depends on a detector size, the value of P_{max} and the nature of any backgrounds for a signal. The beam cost increases roughly as $A + BL^2$, where the second term dominates above 1000 km due to digging. From 200 - 1000 km, the costs of a beam are comparable to additional detector costs, so for a fixed cost project, another tradeoff is introduced. The optimum location generated some controversy at this workshop. A discussion of some of the issues is given in section 7.

6 Systematic effects

The ability to discover neutrino oscillations with a particular test, such as $R_{nc/cc}$, depends on the ability to believe that a systematic effect will not cause a spurious signal, or distort the effect being measured. There is a consensus from the workshop that this problem is solvable at the required accuracy for the $R_{nc/cc}$ test. Four steps seem to be required in order to reliably understand systematic effects for this test.

Step 1 The detector needs the ability to distinguish neutral current and charged current events. This depends on the granularity of the detector, but one does the best one can using track length, extrapolation of the longest track to the vertex, and other kinematic criteria. For a large fraction of the events, this separation is relatively easy. A neutral current and charged current event from the P822 proposal are shown in figure 14

Step 2 At high y, or low muon energy, some fraction of the cc events will look like neutral current events. π decay in nc showers can give some events that go the other way. It is necessary to monte carlo the nc and cc events in a given detector and make a correction to the nc/cc ratio based on this confusion matrix. In the P822 proposal, 5% of the cc events are high enough y to look like nc events.

Step 3 Measure the nc/cc ratio at a near detector as a check on the expected ratio. This is a very powerful check because any oscillation should cause a different ratio in the near and far detectors. There are two effects which limit this check; different acceptances for the near and far detector, and different energy spectra for the neutrino beam. The first effect is geometrical and certainly can be made using monte carlo techniques. The energy dependence is more difficult. The degree to which a neutrino in the decay pipe will decay in the forward direction is a function of energy. The spectrum at a near detector will have more high energy neutrinos in it than the far detector. This will certainly affect any y dependant corrections that need to be made.

Step 4 This difference in energy spectrum between the near and far detector can be addressed by using a monte carlo to model the beam and correcting for the difference in energy dependence at the near and far detector. In principle, this is a very difficult task, as accurate neutrino beam monte carlos have been elusive. However this task is helped by the following:

- 10% accuracy on a 5% correction is adequate for a measurement of $\frac{\sigma_r}{r}$ to 1% which is better than the statistical error that is foreseen in the near future.
- P803 will measure the beam at the close detector with very high accuracy. This will include the neutral and charged particle energy spectra, and the fraction of the beam which is ν_e and $\overline{\nu_\mu}$.
- The hadronic energy in charged current events can be measured at both the near and far detector, as an independent measure of the beam energy.
- The energy dependence of the beam should be better modeled than the absolute flux.

Thus it appears that the systematic error using the $R_{nc/cc}$ test is under control.

The range of mixing angle that can be explored in a long baseline experiment eventually may be limited by the systematic error which can be achieved. For $\nu_\mu \rightarrow \nu_\tau$ oscillations, the mixing angle limit which can be achieved at high Δm^2 is:

$$\sin^2 2\theta > \frac{2s\sigma_r}{\eta(1-B) + r(1-B\eta)} = 5.20\sigma_r \qquad (10)$$

where r is the neutral current to charged current ratio, σ_r is the error on r, B is the branching ratio of the tau to decay into a muon and η is the ratio of the ν_τ to ν_μ cross section weighted over the energy spectrum. s depends on the desired confidence level and is 1.29 for a 90% Confidence level upper limit using a one sided Gaussian distribution.[29] For $\nu_\mu \rightarrow \nu_e$ oscillations, the comparable limit is

$$\sin^2 2\theta > \frac{2s\sigma_r}{1+r} = 1.97\sigma_r \tag{11}$$

In either case, σ_r includes both statistical and systematic error. These are usually combined in quadrature:

$$\sigma_r = \sqrt{(\sigma_r^{stat})^2 + (\sigma_r^{sys})^2} \tag{12}$$

The statistical error on the neutral current to charged current ratio will be [29]

$$\sigma_r^{stat} = r\sqrt{\frac{1}{n_{cc}} + \frac{1}{n_{nc}}} \tag{13}$$

Based on experience from the Fermilab Lab E and Lab C detectors, we expect to do better than 2% in σ_r/r for the systematic error. In figure 15 we show the limit that can be obtained at 730 km based on 600 events and 14,000 events for these two modes, using the statistical error only. In figure 16 we show the effect of including 2% systematic error on those limits. It is seen that the 600 event limits do not change, while the 14,000 event limits are limited by the systematic error. These event totals were chosen to be those from a single run with the P822 proposal, and the result of 4 runs with a somewhat larger 4 kt fiducial volume detector. One implication of these curves is that the present proposals are not limited by systematic error if 2% in σ_r/r can actually be achieved. But better limits at low mixing angle will not be obtained with much larger detectors and/or statistics alone, with figure 16 giving an indication of the scale of this statement.

7 Focus on an ideal detector

A variety of views have been expressed at the workshop on the "optimum" detector for a long baseline neutrino experiment. They reflect various notions of how large an area of parameter space needs to be explored and various tradeoffs on cost versus performance and required statistical accuracy. Perhaps two extremes can be made by characterizing two points of view from presentations at this workshop. In the Bjorken view, on the one hand, we should consider a large 100 kton detector at 1000 km, and push the limits as far as possible both to low Δm^2 and $\sin^2 2\theta$. On the other hand, in the Al Mann point of view, we should focus on the region suggested by the atmospheric neutrino deficit, and feel content to design an experiment which covers that hint of a positive $\nu_\mu \rightarrow \nu_\tau$ signal.

At either of these two extremes, there is room for widely varying points of view. The extremely massive detector that Bjorken suggests can probably only be envisioned as a water detector. Unfortunately, the issue of how to deal with the systematic effects with such a detector were not seriously addressed at this workshop. Whether such a detector could achieve the required precision remains to be demonstrated, and calorimeter proponents have their doubts. Two large (30-50 kton) water detectors are being built [30], Superkamiokande and Lake Motosu, and they are conceivable targets for a beam from KEK, but the required neutrino fluxes do not seem available there. DUMAND with its very large mass is an attractive potential detector. However, its granularity makes it seem unsuited for a neutrino beam in this energy region, and the large angle of the beam from Fermilab discourages an adequate short baseline experiment, which has been identified as a crucial element of a long baseline program.

Focused experiments provide a wide range of choices. Should we prefer a 30 kton detector at 1200 km, for example to a 10 kton detector at 700 km? The atmospheric hint is certainly telling us that if $\nu_\mu \rightarrow \nu_\tau$ exist, the mixing angle is quite large. Much less information is provided, however, on the value of Δm^2. For example, the proposals P805 and P822 can cover the high mixing angle region down to $\delta m^2 \sim 3 \times 10^{-3} eV^2$. A common interpretation of the atmospheric allowed region goes down to Δm^2 of $10^{-3} eV^2$. If it was a requirement that a new experiment be sensitive to this extra region of parameter space, one would need an order of magnitude larger detector at 2000 km, or an even larger one at 1000km. This puts extra emphasis on understanding the E/L distribution from atmospheric neutrinos as discussed in section 2.3.1. Finally, the discussion in the last section emphasizes a point which is well known in principle, a large experiment whose goal is a limit at low mixing angles using a large number of events needs to understand its sy-tematic effects at the appropriate level.

7.1 A hybrid experiment

I close this section with a personal view of a realistic long baseline neutrino oscillation program. I start by arguing that if the case for neutrino oscillation in this region of parameter space remains strong, a long baseline neutrino oscillation experiment should be performed, probably at Fermilab.

Elements for this case to watch for in the near future:

1. Gallium results from SAGE and Gallex under 70 SNU.

2. Lack of confirmation for a 17 keV ν.

3. Lack of explanation of the atmospheric neutrino deficit by "nuclear effects".

4. Confirmation of the atmospheric neutrino effect at the 2σ level by 1 kt-year of Soudan 2.

5. A detailed understanding of the reliability of ν oscillation limits from Baksan, Kamioka and IMB using the upward going muon flux, and whether they are consistent with a $\nu_\mu \rightarrow \nu_\tau$ interpretation of the anomalous flavor ratio.

On the contrary, a high ν capture rate in Gallium, or a plausible explanation for the atmospheric flavor ratio by nuclear effects would weaken but not eliminate the case for a long baseline experiment. In my opinion, clear confirmation of a 17 keV ν *would* eliminate any present motivation for long baseline experiments.

Assuming that the case for neutrino oscillations remains strong, I advocate the following program:

- First Generation experiment at one of the existing detectors.

- Excellent short baseline detector such as P803 in order to measure the neutrino beam with high precision.

- An additional short baseline detector which is as similar as possible to the long baseline detector, in order to measure the neutrino beam at two vastly different locations.
- Sophisticated beam monitoring to get an accurate estimate of the beam flux.
- Capability for a Second Generation Detector.

A second generation detector should be able to make as many systematic checks as possible in order to get a consistent picture of neutrino oscillations. Thus a hybrid detector is called for, in order to measure as many different signatures of neutrino oscillations, rather than to measure the cleanest one with the highest statistical accuracy. Such a hybrid detector should have the following elements:

- Calorimetry- In order to measure the nc/cc ratio at the lowest possible hadronic energy.
- A large volume element- probably a water cerenkov counter, in order to get high statistics on the number of contained neutrino vertex events.
- A few sets of large area counters behind walls of rock, spaced a few kilometers apart. This would measure with high statistics the charged current reactions and the spatial extent of the beam.
- A muon momentum measuring system, in order to measure the neutrino energy distribution using charged current events, or see a disappearance effect which can determine Δm^2.

8 Conclusion

The workshop has addressed a number of issues regarding the motivation for and the execution of long baseline neutrino oscillation experiments. The highlights were:

- The hint of $\nu_\mu \rightarrow \nu_\tau$ oscillations in the atmospheric flavor ratio.
- Arguments that this large increase in parameter space for neutrino oscillations, which is accessible to long baseline proposals, is a good place to search independent of the atmospheric results.
- Proposals from three existing collaborations:
  1. P805 from IMB.
  2. P822 from Soudan 2.
  3. P824 from DUMAND.
- Complementarity of the long baseline proposals with the short baseline proposal P803.
- A consensus that $R_{nc/cc}$ is the best test, and that systematic effects on this measurement are reasonably understood.

- Several measurements are possible in a single detector at the same time which would give a consistent picture of neutrino oscillations. Such "redundancy" was agreed to be an attractive feature.
- An ideal distance or location was not determined. But it is important to note that the three existing Fermilab proposals all adequately cover the atmospheric hint.
- Second generation detectors which are larger or with enhanced capabilities are certainly desired if signals exist.
- A hybrid experiment with many capabilities may be an attractive choice as a second generation detector.

The neutrino continues to be a *mine* of valuable physics. The next target of opportunity for studying fundamental particle physics at accelerators, may well be in a *mine*.

Table I

Some ideas for Long Baseline Experiments

Experiment	Year proposed	$< E > (GeV)$	L (km)	reference
Cern to Jura (Charm)	~ 1981			[31]
Cern to Jura (Vanucci)	~ 1981			[32]
FNAL to Quebec	1977		1000	[33]
FNAL to Puget Sound	1977			[34]
Brookhaven to Long Island	1986	1		[35]
Brookhaven to Long Island	1988	1	10	[36]
FNAL MI to trucks throughout Michigan	1989	20 - 40	500 - 1000	[37]
FNAL MI to Sudbury	1990	17	1000	[38]
FNAL MI to Grande	1990	17	800	[39]
FNAL MI to a new water detector	1989	17		[39]
FNAL MI to IMB	1990	17	580	[48]
FNAL MI to Soudan	1990	17	730	[49]
FNAL MI to DUMAND	199[illegible]	25	6000	[50]
FNAL MI to BNL	199[illegible]	17	1200	[40]
CERN to Gran Sasso				[41]
SSC MEB to Grande	1990	30	400	[42]
SSC to moon	1990	30	2,000,000	[43]
UNK to Baikal				[44]
UNK east			20	[45]
KEK to Lake Motosu				[30]
KEK to Superkamioka				[30]

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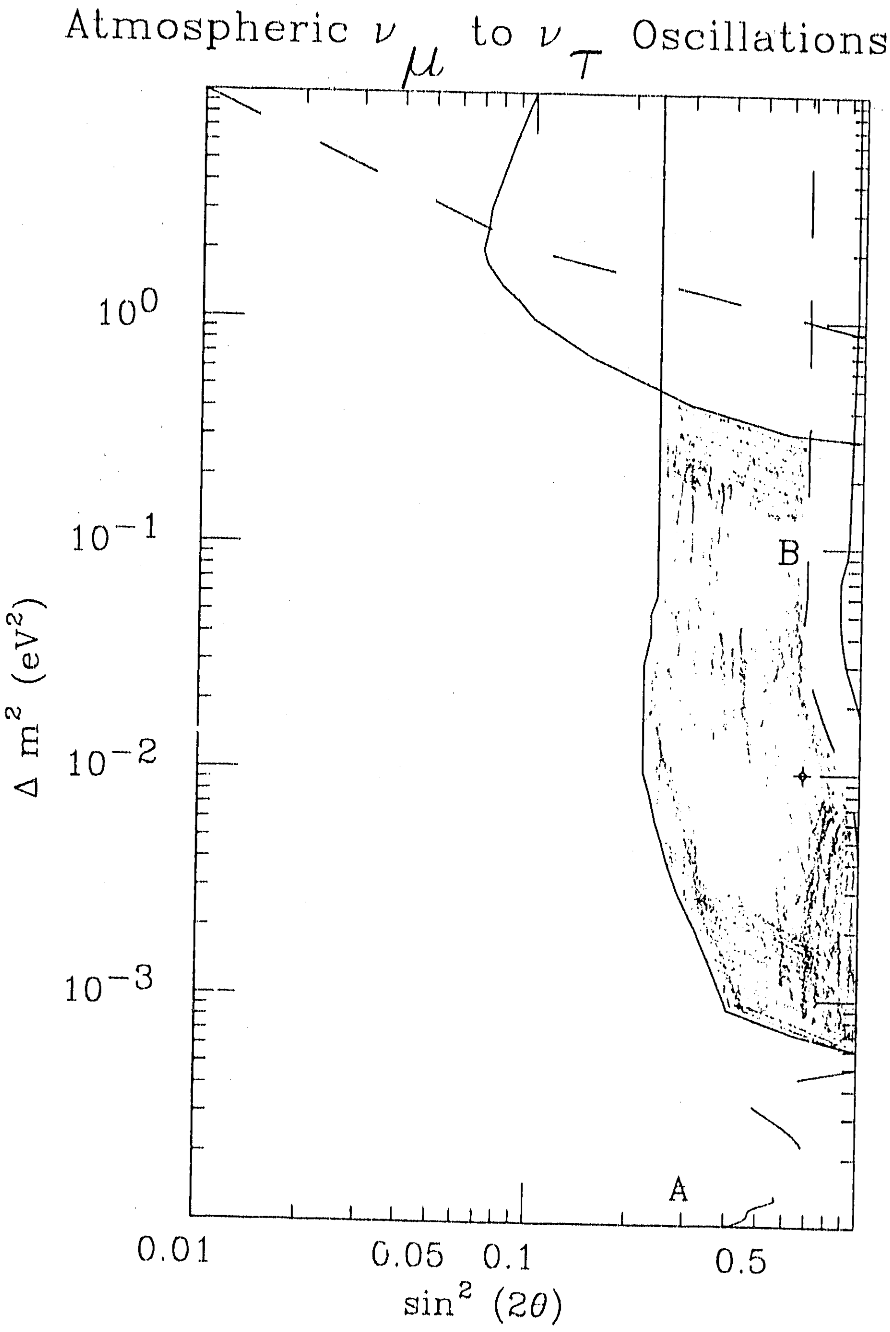

Figure 1: Neutrino oscillation analysis of the early kamioka atmospheric flavor ratio data. The shaded area is allowed by all experiments at 90% confidence level. The point is often called the "best fit" point

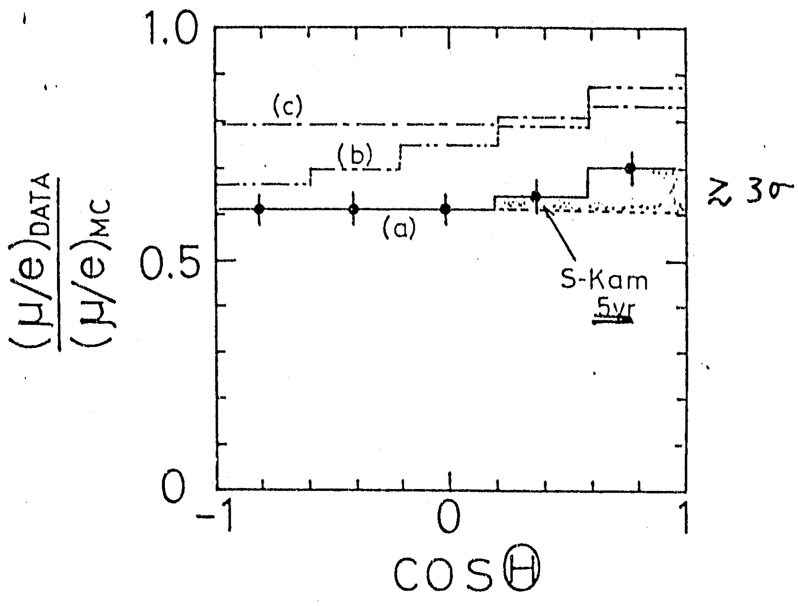

Figure 2: Angular Distribution of events from Superkamiokande expected if $\Delta m^2 \sim 10^{-2} eV^2$ after 5 years run.

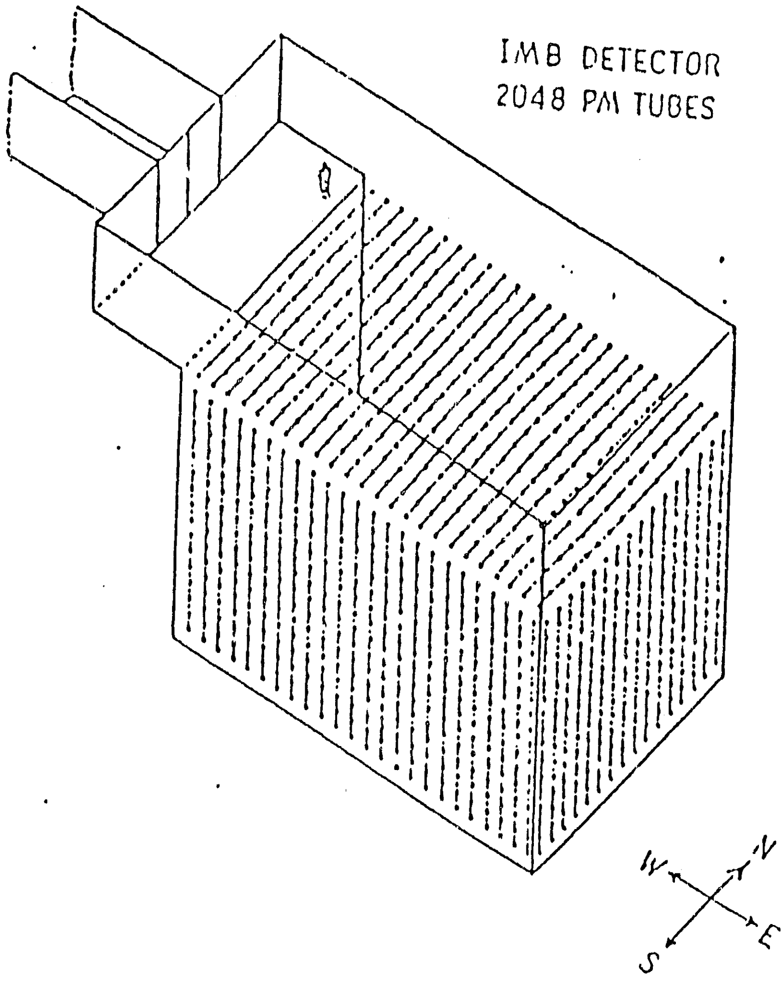

Figure 3: A diagram of the IMB detector.

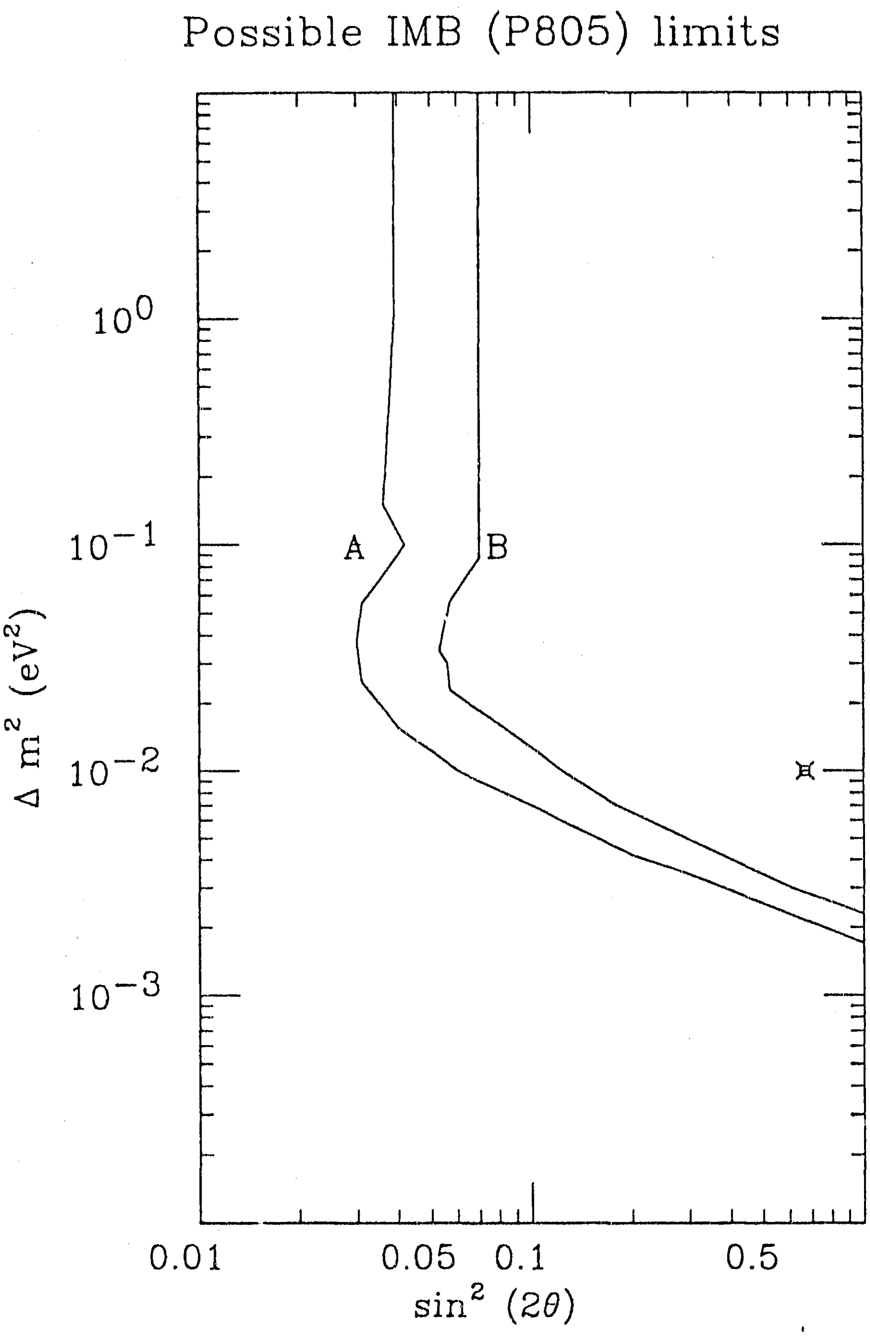

Figure 4: Region of 90% CL sensitivity to Δm^2–$\sin^2 2\theta$ of the IMB Long Baseline experiment to oscillations $\nu_\mu \rightarrow \nu_e$ (A) and $\nu_\mu \rightarrow \nu_\tau$ (B).

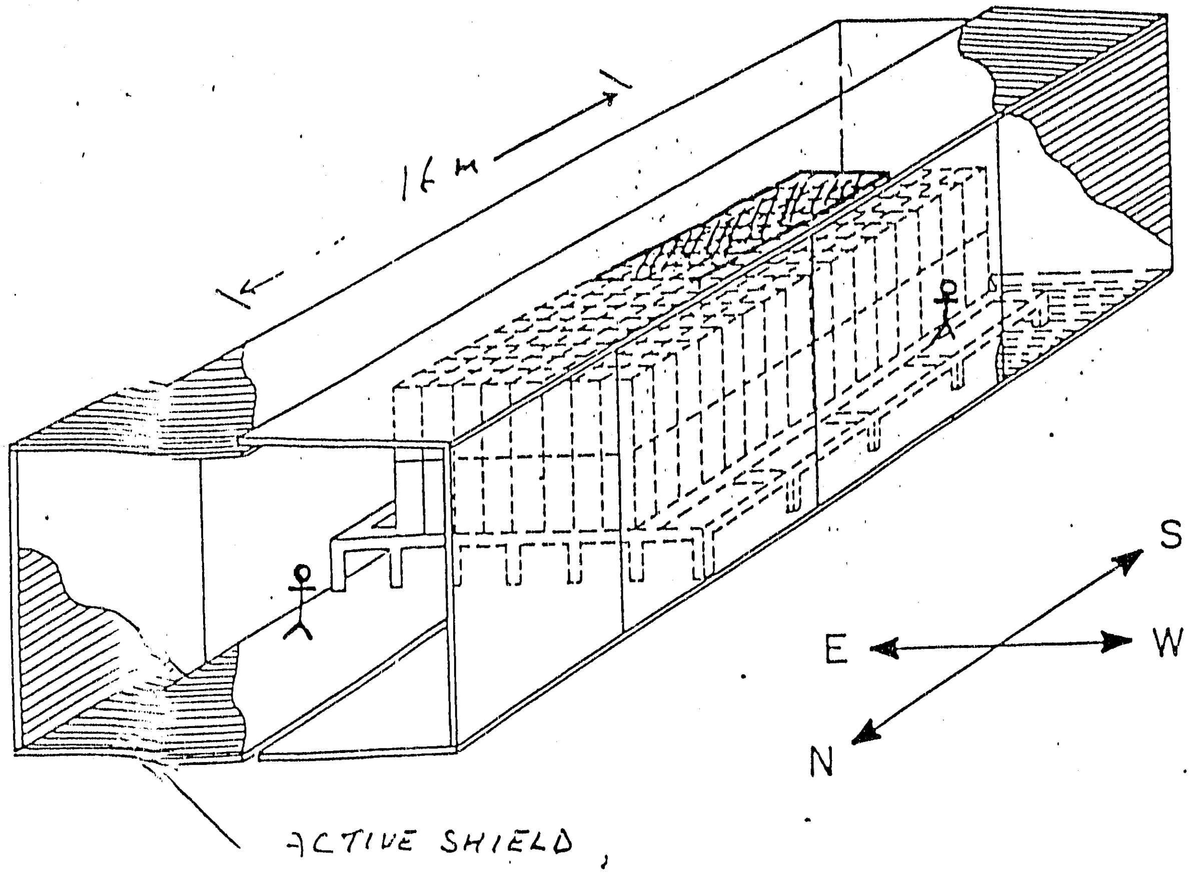

Figure 5: A diagram of the Soudan 2 Calorimeter.

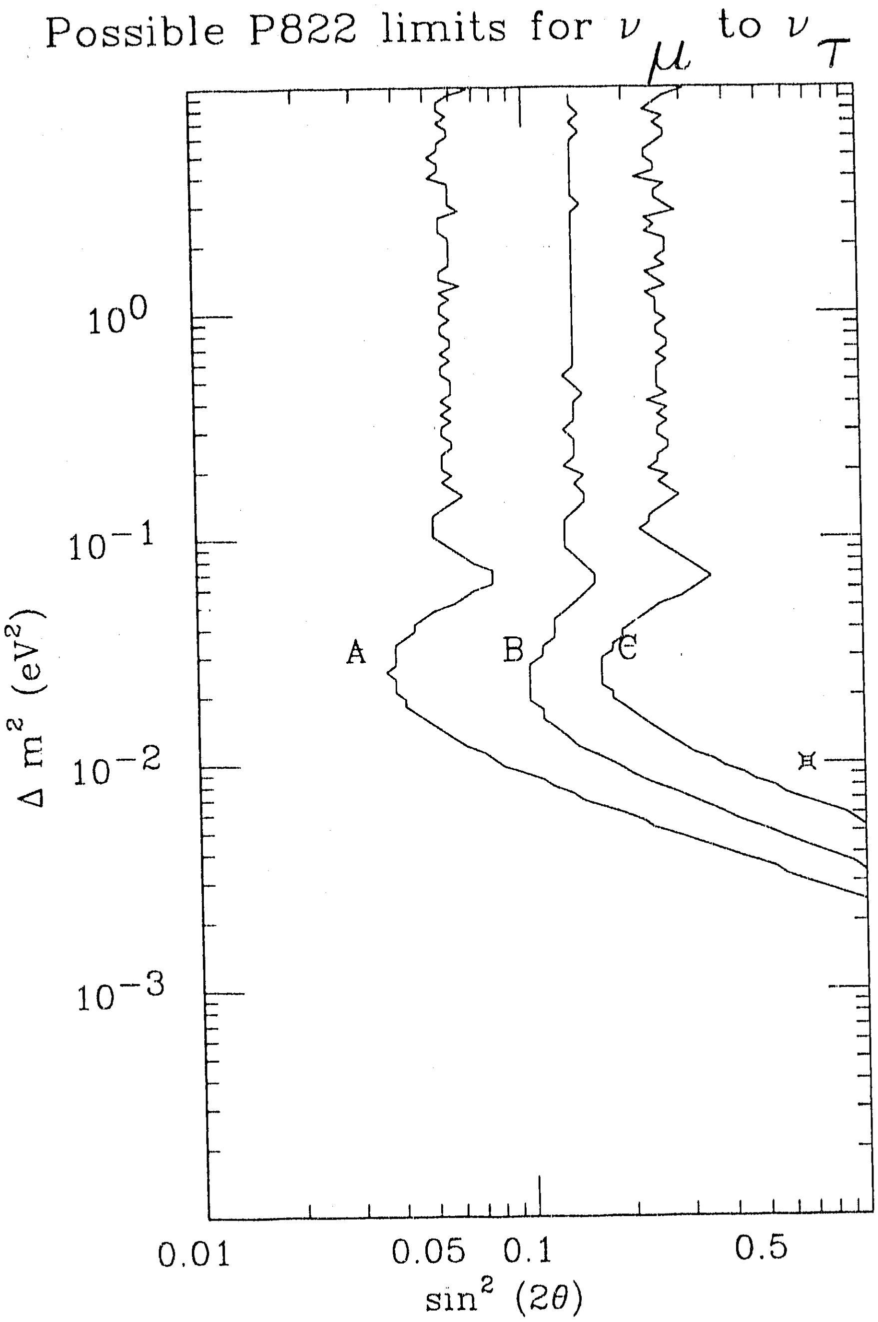

Figure 6: Limits on $\nu_\mu \rightarrow \nu_\tau$ Oscillations Attainable by Soudan. Curve A is based on the ratio of events at Soudan to that in a near detector. Curve B is based on the $R_{nc/cc}$ test, and Curve C is based on the $R_{\mu/\nu}$ test.

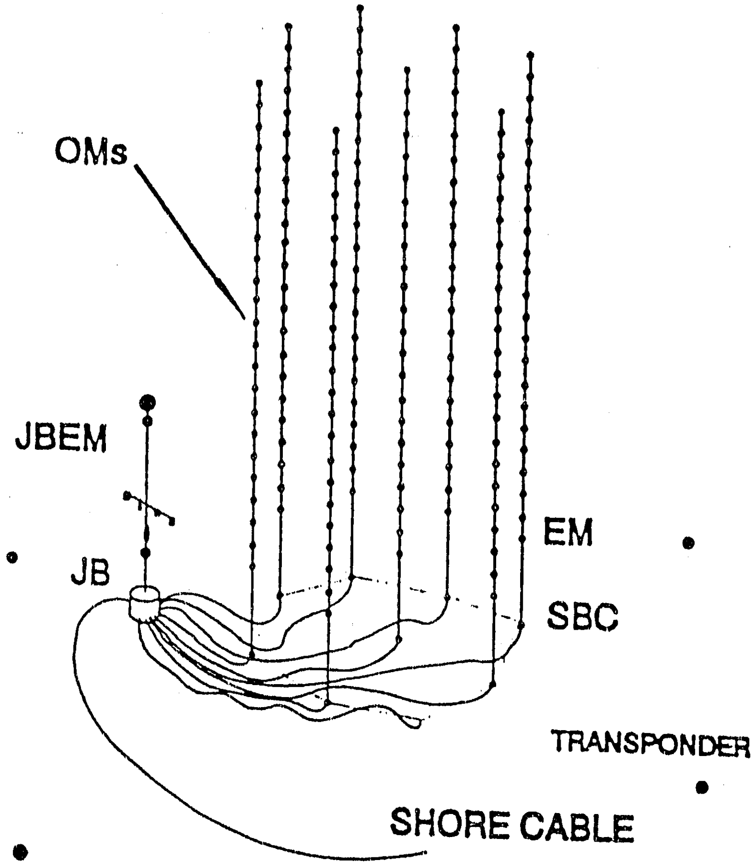

Figure 7: The DUMAND octagon array

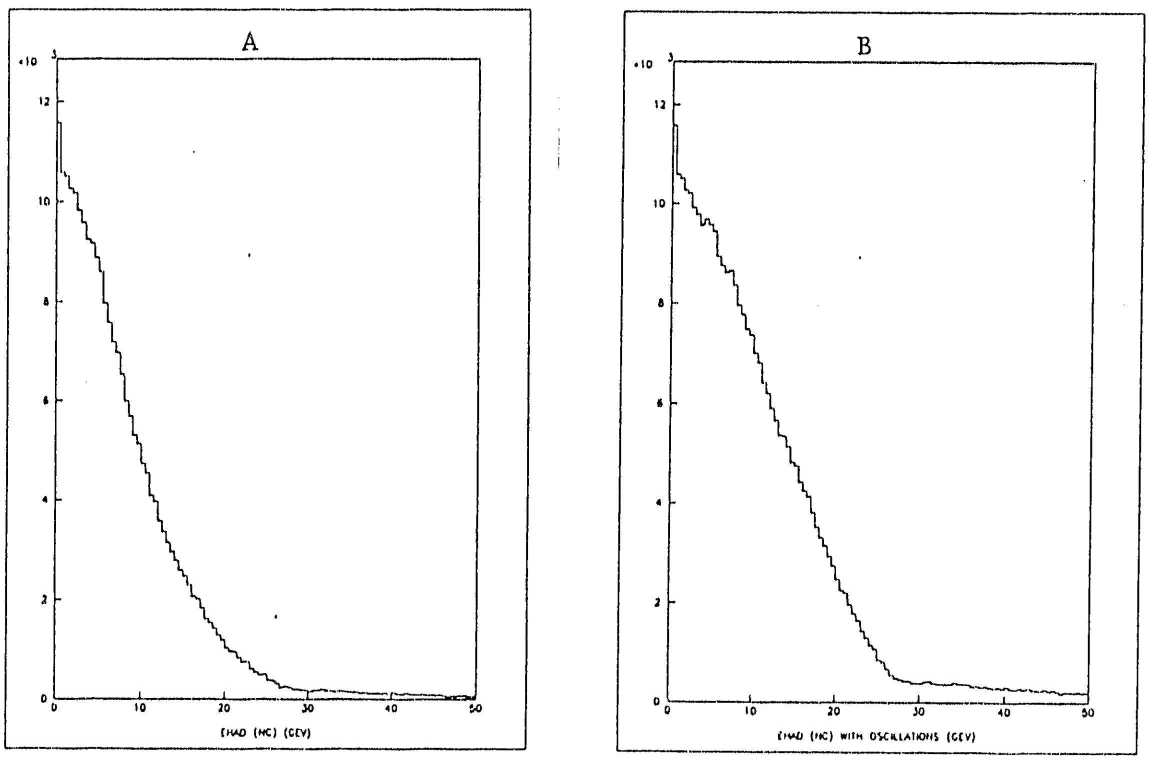

Figure 8: Hadron energy spectrum from neutral current events based on 1,000,000 neutrino events. Curve A shows the expected shape without oscillations and Curve B shows the shape with maximal mixing.

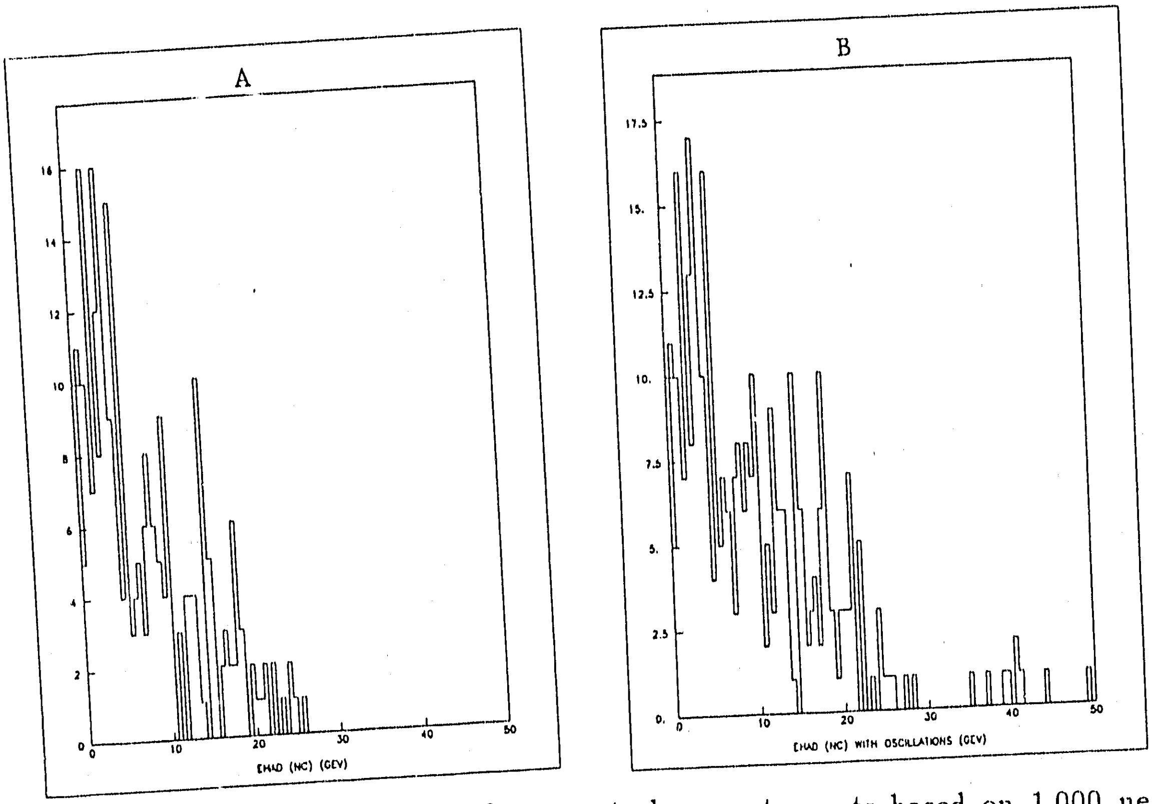

Figure 9: Hadron energy spectrum from neutral current events based on 1,000 neutrino events. Curve A shows the expected shape without oscillations and Curve B shows the shape with maximal mixing.

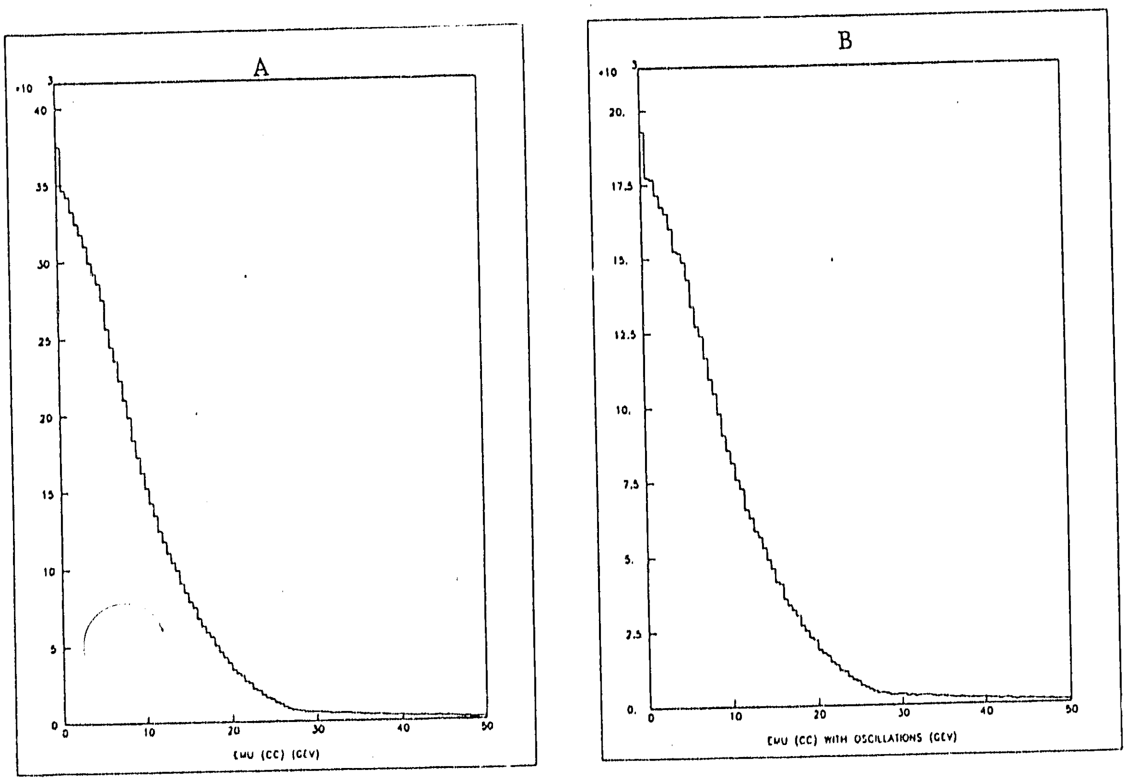

Figure 10: Muon energy spectrum from neutral current events based on 1,000,000 neutrino events. Curve A shows the expected shape without oscillations and Curve B shows the shape with maximal mixing.

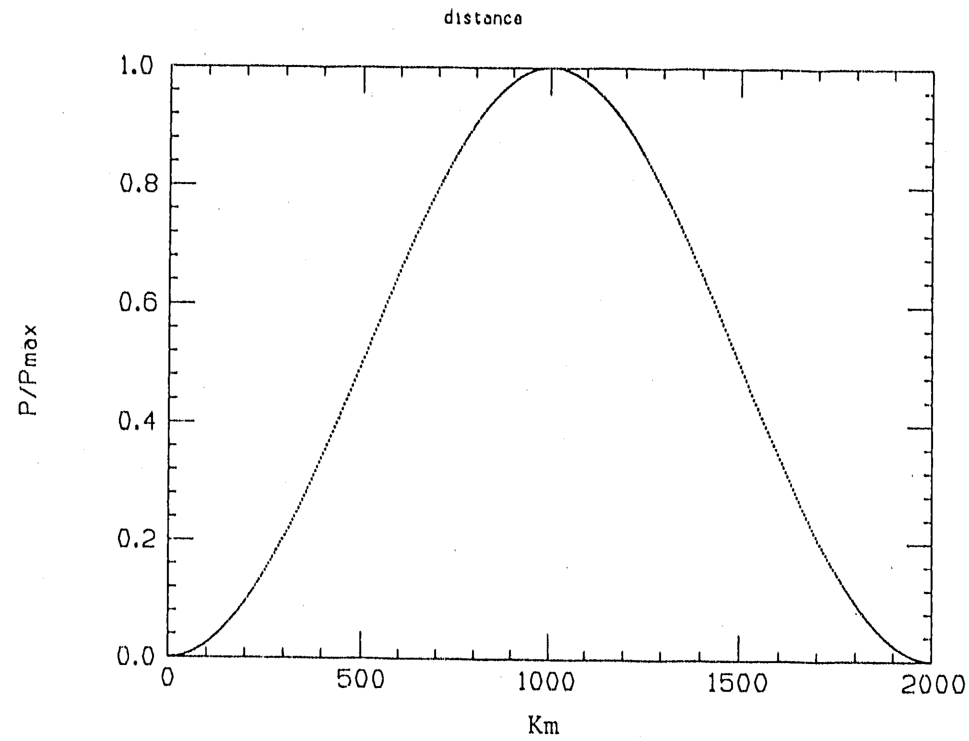

Figure 11: Oscillation probability as function of distance for a choice of parameters described in the text. A monochromatic beam is assumed.

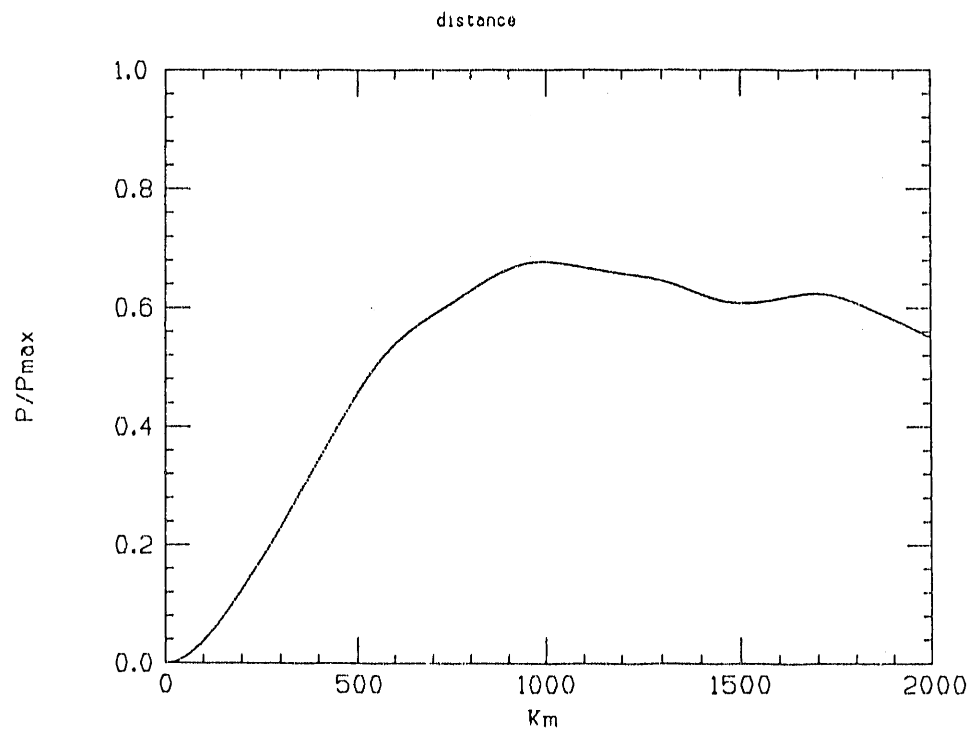

Figure 12: Oscillation probability as function of distance for a choice of parameters described in the text. The Fermilab 120 GeV horn neutrino beam energy flux is is assumed.

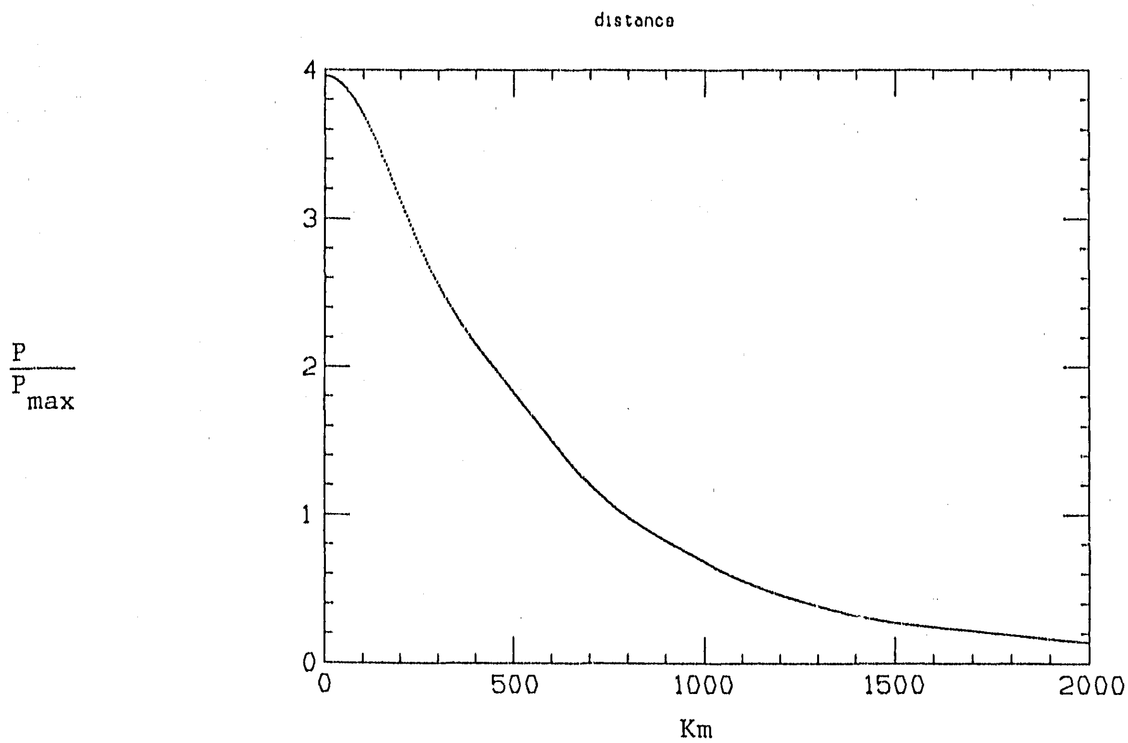

Figure 13: Relative number of ν_τ events for a fixed size detector as a function of distance for a choice of parameters described in the text. It is seen that for a zero background experiment, the detector should be placed near the accelerator.

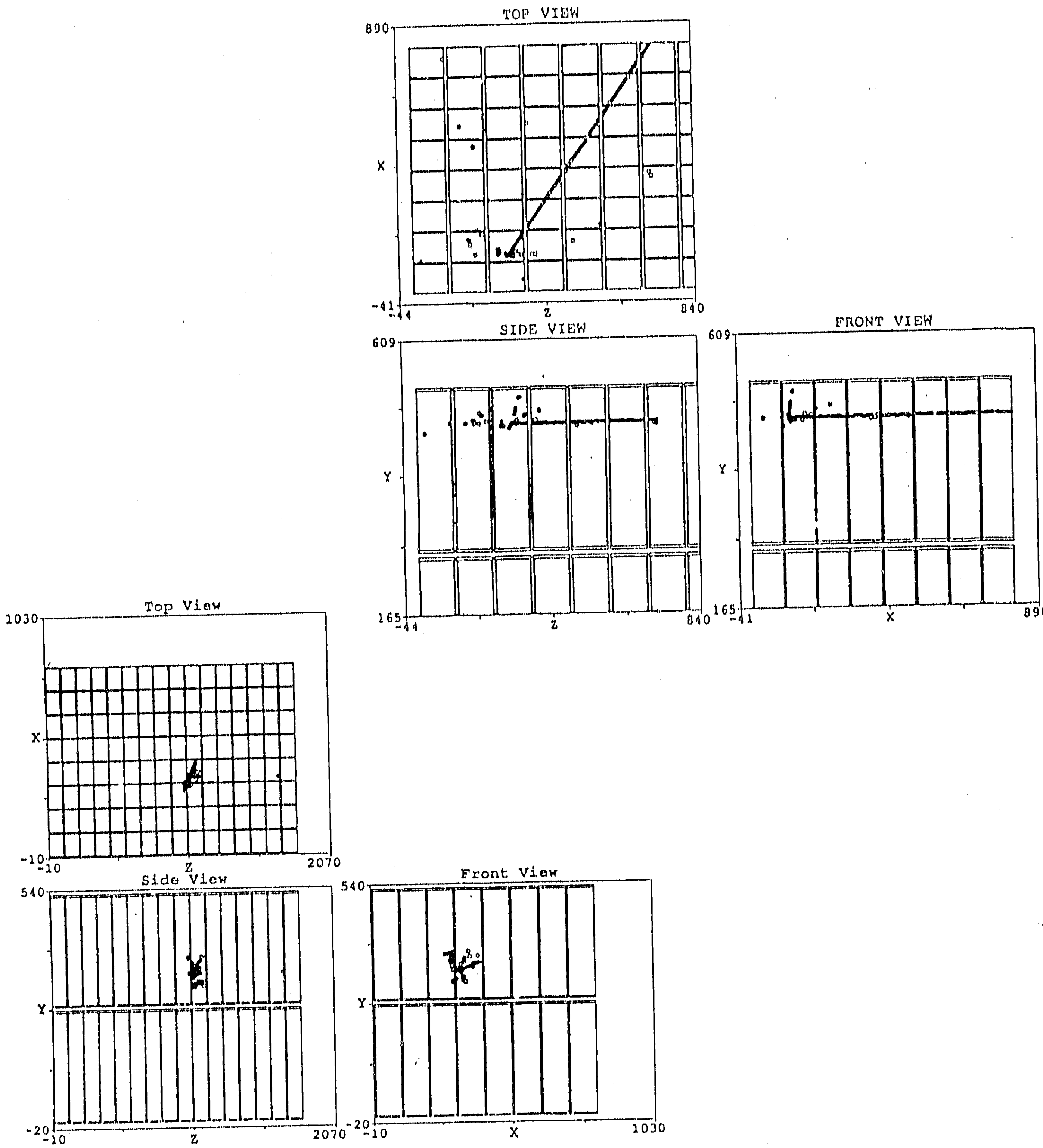

Figure 14: A charged current and neutral current monte carlo event in the P822 detector

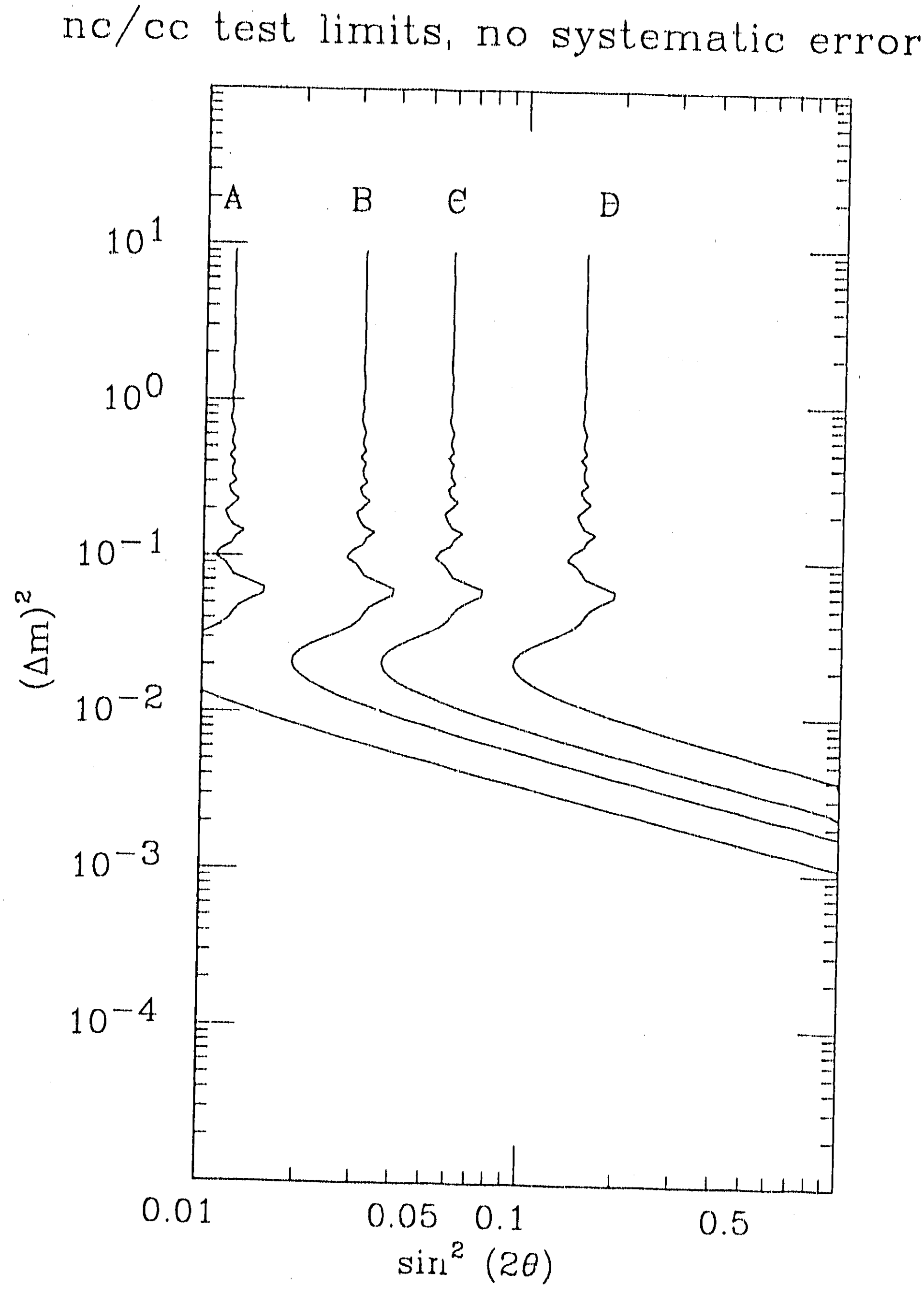

Figure 15: Curve A represents the limit using the $R_{nc/cc}$ test that could be set on $\nu_\mu \to \nu_e$ with 14,000 events. Curve B represents the limit that could be set on $\nu_\mu \to \nu_\tau$ with 14,000 events. Curve C represents the limit that could be set on $\nu_\mu \to \nu_e$ using 600 events. Curve D represents the limit that could be set on $\nu_\mu \to \nu_\tau$ using 600 events.

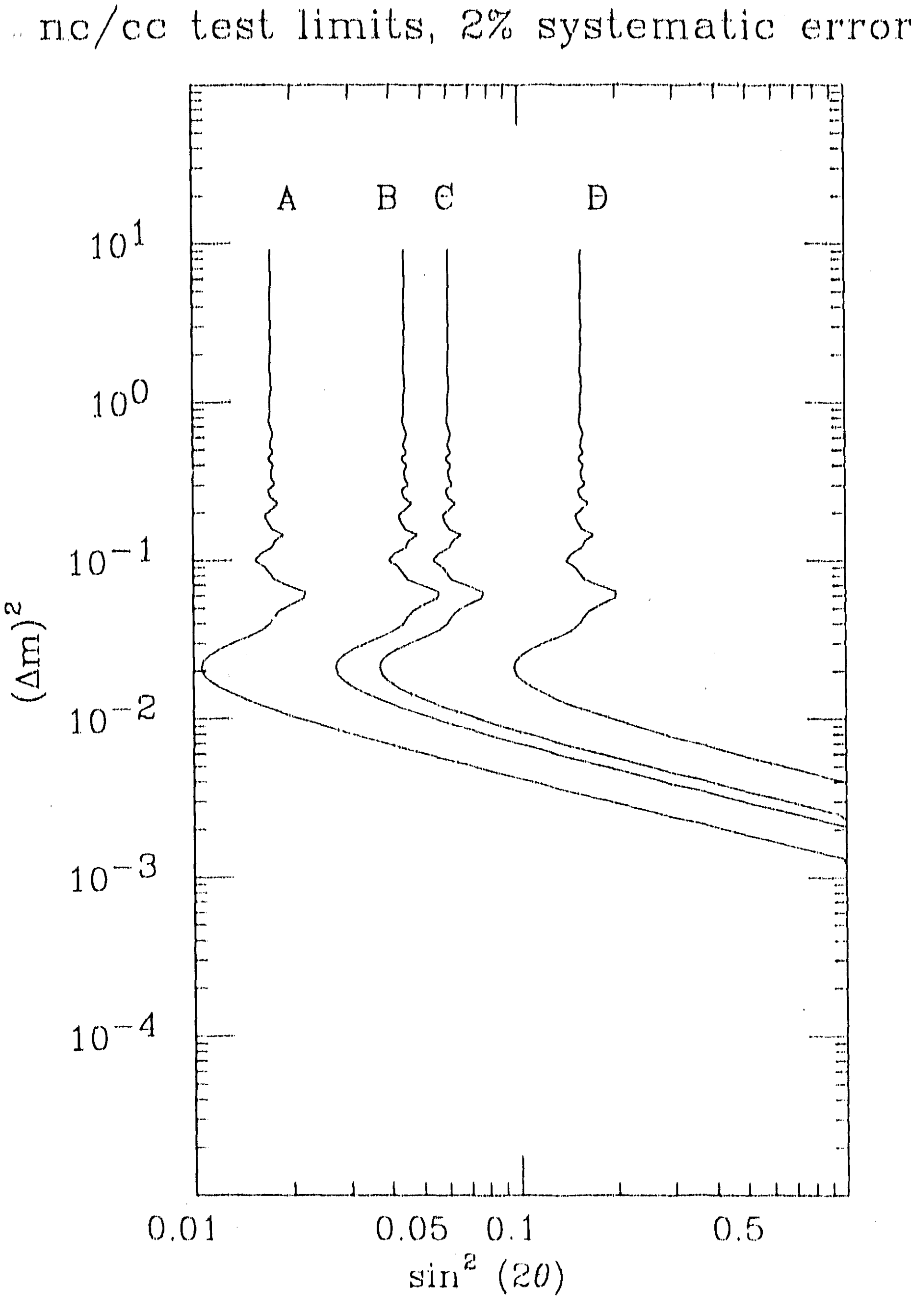

Figure 16: The labels here have the same meaning as in the last figure, but a 2% systematic error in σ_r/r has been added in quadrature with the statistical error. It is seen that the 600 event curves are not affected, but that the 14,000 event curves are limited by the systematic error.

END

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