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Ideas for a Long-Baseline Neutrino Detector

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Disclaimer

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1 Introduction

The Atmospheric Neutrino Deficit defines a region in Δm^2–$\sin^2 2\theta$ space which ought to be conclusively tested in a long-baseline experiment. This talk sets out a region to cover (which may change as more data is analyzed) and translates that region into an L/E. I present exclusion curves for different experiments based on their distance and their precision; I conclude that an experiment which can detect oscillations down to 1% located at 1200 km will cleanly test the allowed region from Kamioka and IMB. I then describe the techniques which can perform such a measurement and outline both a detector capable of performing such an experiment and some of the systematic problems we might expect.

2 Where Do We Look?

Fig. 1 shows the approximate region allowed by the Atmospheric Neutrino Deficit after regions excluded by other experiments have been taken into account.[1] Very roughly, we would like to exclude from $\Delta m^2 \approx 10^{-3}$ and $\sin^2 2\theta > 30\%$. An analysis of upwards-going muons from IMB may cut off the lower portion of Δm^2; in that case, the desired baseline will become shorter.[2] However, the discussion of potential techniques and the demands on the detector will remain much the same.

3 What Is the Necessary Baseline?

It is a straightforward problem to compute the exclusion curves parameterized by (1) the Main Injector energy spectrum, (2) a response function of the detector, (3) a baseline distance, and (4) a minimum measureable oscillation probability ϵ. Parke and I performed such an analysis and I reproduce and extend some of the results here.[3] Fig. 2 shows the power of a search which can measure $\mathcal{P}(\nu_\mu \leftrightarrow \nu_\tau)$ to 1% with the Main Injector beam for three distances: 100, 300, and 1000 km. The detector was taken to be capable of identifying

† Based on talk presented at Long-Baseline Neutrino Oscillation Workshop, Batavia IL 17–20 November 1991.

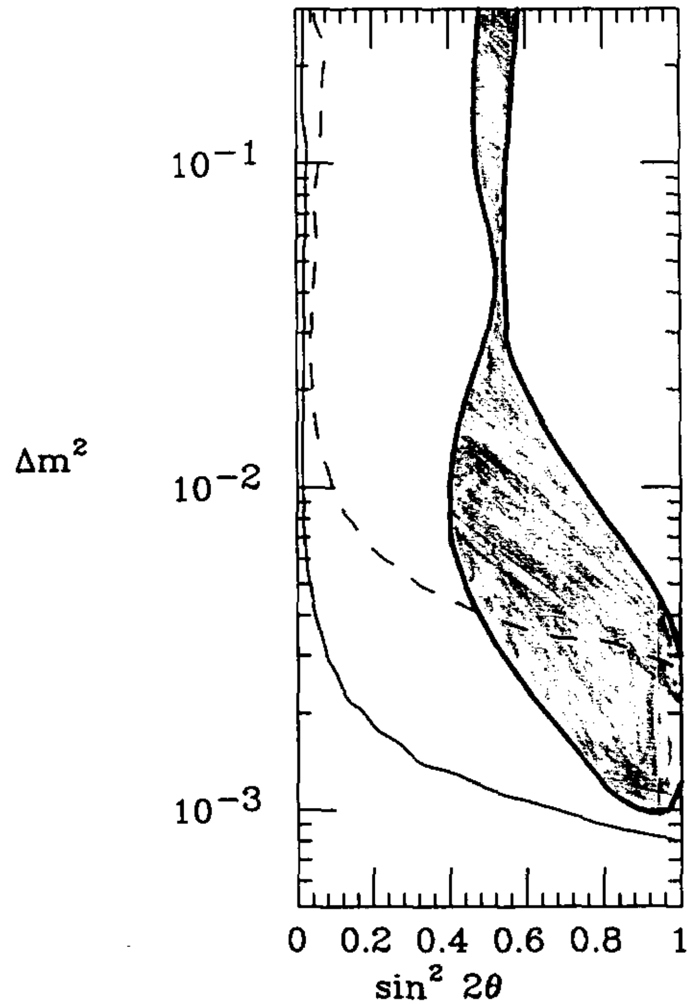


Figure 1: Regions of parameter space allowed by one Kamioka analysis for $\nu_\mu \leftrightarrow \nu_\tau$(shaded region). The region is compared to limit regions from an experiment which could perform a search to $\mathcal{P} < 1\%$ at 600 (dashed curve) and 1200 km (solid curve).

muons with momenta above 5 GeV/c; below that threshold, they were considered lost and were not used in detecting oscillations.

The reach in Δm^2 is only approximate and depends on the details of the muon acceptance; the results are good to within a factor of two when applied to a particular detector. With the acceptance as shown, only the 1000 km distance probes the entire region and even this is somewhat short. This argues against baselines shorter than 600 km and indicates that in order to definitively address the problem, the longer the baseline the better, so long as we achieve a small ϵ. This is why the upward-going muon analysis from IMB is the most important unfinished study; ruling out the lower end will change the required baseline distance and radically change the mass (and cost) of the detector. Whether or not a detector at the IMB/Soudan distance can cover the region can only be determined by a detailed simulation of the individual detector.

4 How Can We Achieve a 1% Measurement?

There are two techniques that have been proposed for performing the oscillation search. I conclude that only a measurement of the neutral current (NC) to charged current (CC) ratio can achieve the desired precision.

4.1 Entering Muons

The sketch in Fig. 3 depicts two variations of the technique. In the first, the number of entering muons from charged-current events is normalized to the total number of neutrino interactions which occur in the fiducial volume of the detector. The second variation uses a rate measured in an upstream detector to calculate the neutrino flux; the entering muon rate in the downstream detector is compared to the prediction from the upstream detector.

If N_μ is the number of observed muons, and

$$f_{\nu_\mu} = N_\mu / A_\mu \tag{1}$$

then gives the ν_μ content of the beam. We can either normalize to contained events in the downstream detector or to the neutrino flux in the upstream detector.

The systematic errors limit the achievable ϵ. Calculating A_μ requires:

1. Knowledge of the neutrino spectrum in order to calculate the muon spectrum.
2. Knowledge of the acceptance for a muon created in the surroundings to pass through and trigger the detector.

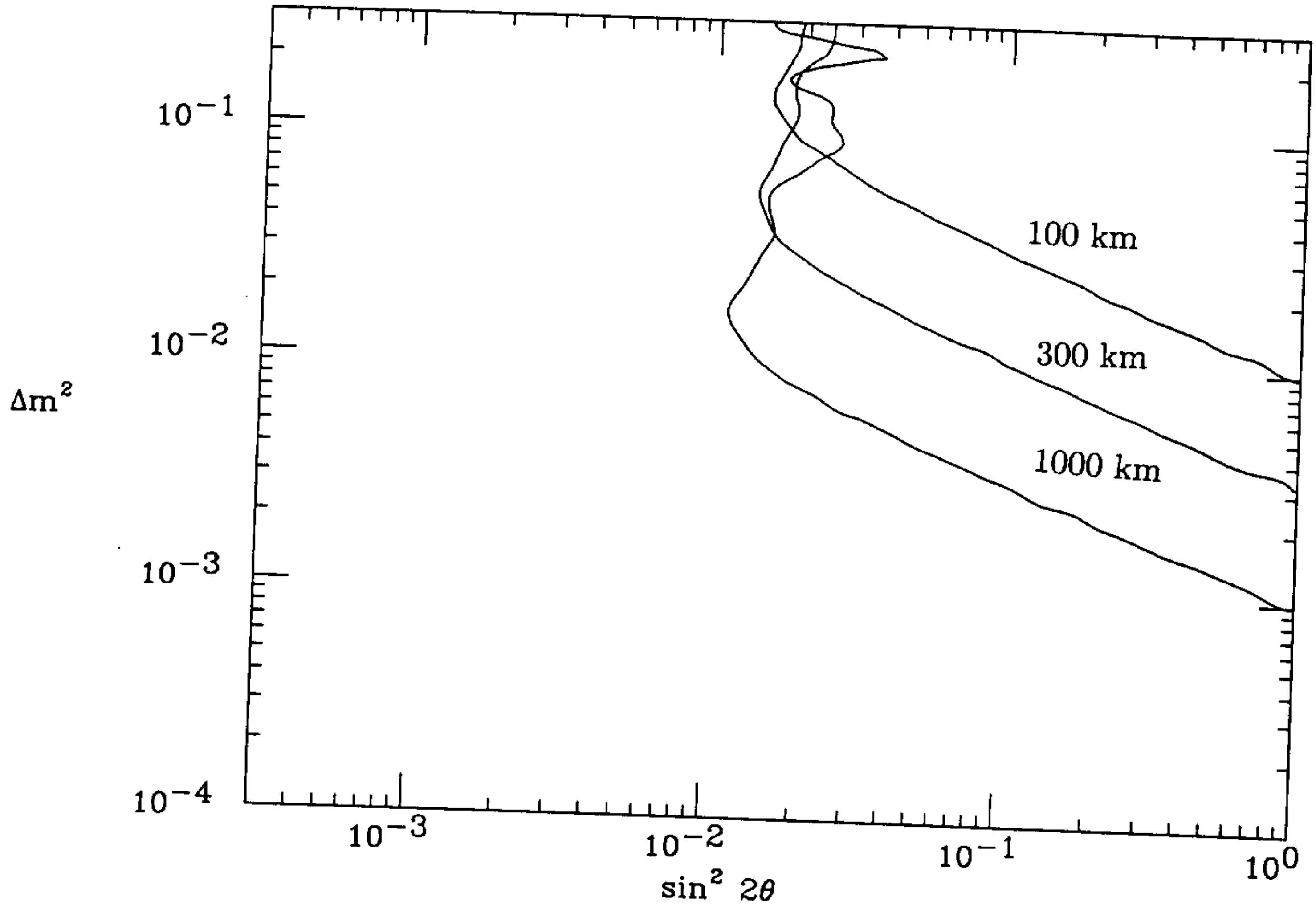


Figure 2: Exclusion Curves for Oscillation Experiments at 100, 300, and 1000 km. The Main Injector spectrum is used; the acceptance for muons is taken to be a step-function at 5 GeV/c.

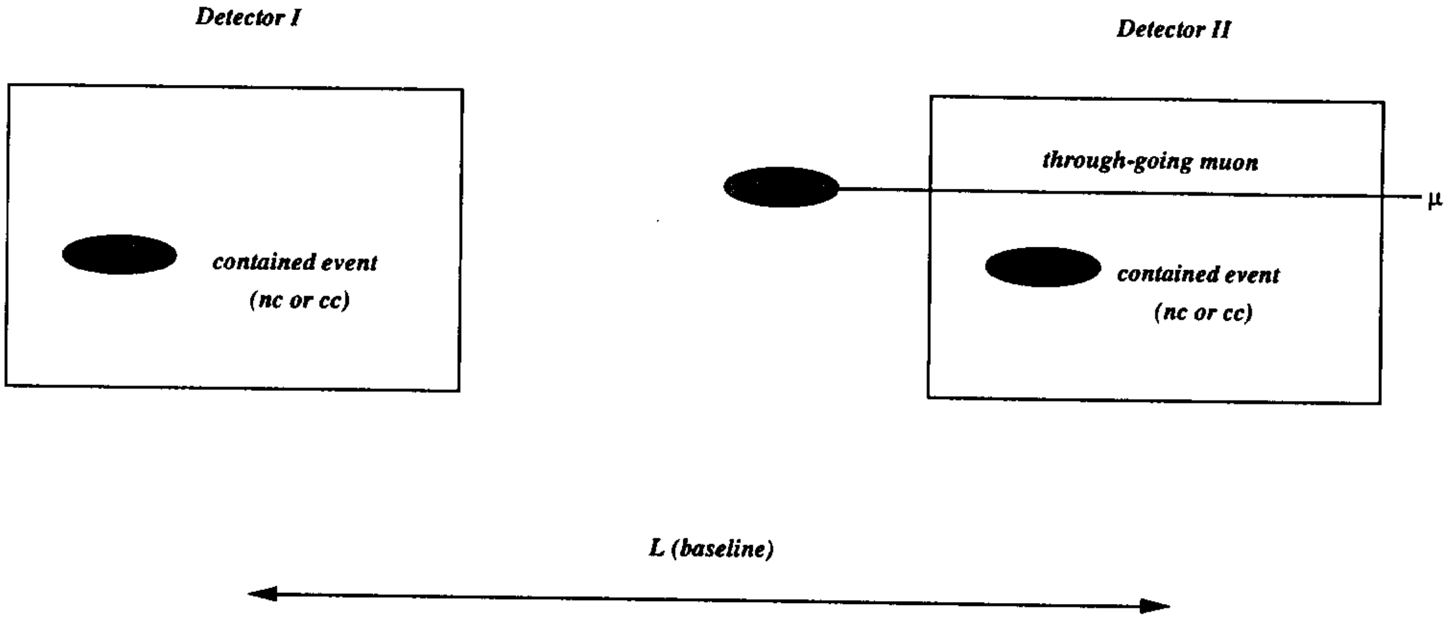


Figure 3: Methods of measuring the muon flux at a downstream detector. In one method, the ratio of contained events to through-going muons gives the ν_μ fraction of the beam, compared to the rate predicted by the upstream detector. In the second method, the absolute flux of muons through the second detector is predicted from the rate in the first detector.

3. Accurate beam pointing, if we normalize to an upstream detector. We are also then sensitive to small changes in the spectrum between the two locations and must model them accurately.

I suspect (2) is the most difficult to obtain. There is no obvious way to check a simulation of the acceptance, making the task still more difficult. Setting a limit is always possible, but establishing a signal under such uncertain circumstances is effectively impossible (unless we are lucky and the signal is huge, but we should not count on that.)

4.2 NC/CC Tests

This seems the systematically most clean method; it suffers statistically relative to through-going muons, and so larger and more costly detectors are required.

"Neutral" current in this context does not imply interactions mediated by Z-exchange, but refers to all events without a visible muon at the event vertex. All ν_e, and most ν_τ interactions, will appear to be neutral current. Hence an excess of neutral current events over the Standard Model prediction will be a signal for neutrino oscillations.

For all but the most finely grained detectors, all ν_e will look like neutral currents, since the e from a charged current ν_e interaction will be obscured in the hadronic shower. Similarly, since the branching fraction of τ into muons is 14%, 86% of all τ interactions appear as NC. R_ν = NC/CC has been measured in deep-inelastic scattering at 400–800 GeV (50–150 GeV neutrinos) in order to measure the Weinberg angle; the techniques are mature and will work at Main Injector energies. Hence by measuring R_ν we can detect oscillations from ν_μ to either ν_e or ν_τ. Furthermore, since the charged currents from all ν_e and 86% of ν_τ appear as neutral currents, the sensitivity to oscillations is enhanced by a factor $1 + 1/R_\nu \approx 4$.

The full expression for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations is

$$R_\nu^{\rm obs} = \frac{R_\nu^{\rm true} + \eta\mathcal{P} - \eta B_\mu \mathcal{P}}{1 - \mathcal{P} + \eta B_\mu \mathcal{P}} \qquad (2)$$

where $\eta \approx 0.25$ reflects the kinematic suppression for τ production, B_μ is the $\tau \rightarrow \mu$ branching fraction, and $\mathcal{P}$ is the oscillation probability.

If we could perform a 1% measurement of R_ν ($\sigma = \pm 0.003$), Eq. 2 can be inverted to tell us the significance of the result for a fixed oscillation probability.[4] In the $\nu_\mu \leftrightarrow \nu_e$ case, the factor of four enhancement $(1 + 1/R_\nu)$ produces a ratio $\sigma/\mathcal{P} \approx 3.3$. After including the ν_τ cross-section suppression $\eta \approx 0.25$ for $\nu_\mu \leftrightarrow \nu_\tau$, we find $\sigma/\mathcal{P} \approx 1.1$.[1] Hence a definitive discovery at the 1% level will be difficult if we are systematics limited at 1%. Thus I would

[1] I have included a factor 1.29 for the 90%CL limit for a one-sided Poisson distribution.

conclude that these experiments could set limits at 1%, but the discovery potential of the NC/CC method is limited to a few percent. The larger values favored by the Atmospheric Deficit would produce huge results (but in fairness, so would almost any method!)

The experiment requires two nearly identical detectors located at two distances along the beam; one near and one far. The first detector would measure an initial NC/CC rate to be compared to the downstream measurement. This comparison makes it unnecessary to calculate R_ν expected from first principles and significantly lessens the dependence on a detailed model of the apparatus.

The principle behind the measurement is simple. Hadronic showers die out after $< 10\lambda_I$; muons lose energy through dE/dx and hence travel much further before ranging out. In Fe detectors such as CCFR, a 50 GeV shower ceases to deposit significant energy after approximately 2 meters of Fe; this is the same length is traversed by a 3 GeV muon. Crosstalk from CC $\rightarrow$ NC arises from muons which range-out or escape the apparatus before exiting downstream of the hadron shower.

Fig. 4 is a representation of the measurement. If we plot the length of observed events, we obtain a distribution like that in Fig. 5, taken from CCFR data. The overlaid simulation of the charged current events shows the excellent level of understanding that has been achieved. The error on R_ν from the CC$\rightarrow$NC crosstalk is already down to 1%; in theory, this error will be irrelevant when we compare the ratio in two identical detectors up to two effects discussed below.

The measurement may be further sharpened by comparing R_ν as a function of the observed hadronic energy $E_{\rm HAD}$ because the beam spectra will differ between the two locations. The observed R_ν will then shift because the charged current contamination is a function of beam energy. If we measure R_ν as a function of hadronic energy, the change in the charged-current subtraction from the beam spectrum will cancel up to resolution smearing.

Beam divergence will also change the ν_e fraction from the upstream to downstream detector. We expect this contamination to be small, and have only a small change ($\nu_e/\nu_\mu \approx$ 1%), but this may be a limiting systematic error at the 1% level.

5 Apparatus

I begin with an approximate rule of thumb:

$$\frac{\rm NC}{\rm run} = 800 \times M({\rm kton}) \times \left(\frac{600}{L({\rm km})}\right)^2$$

where one run is taken to have 2×10^{20} protons on target.

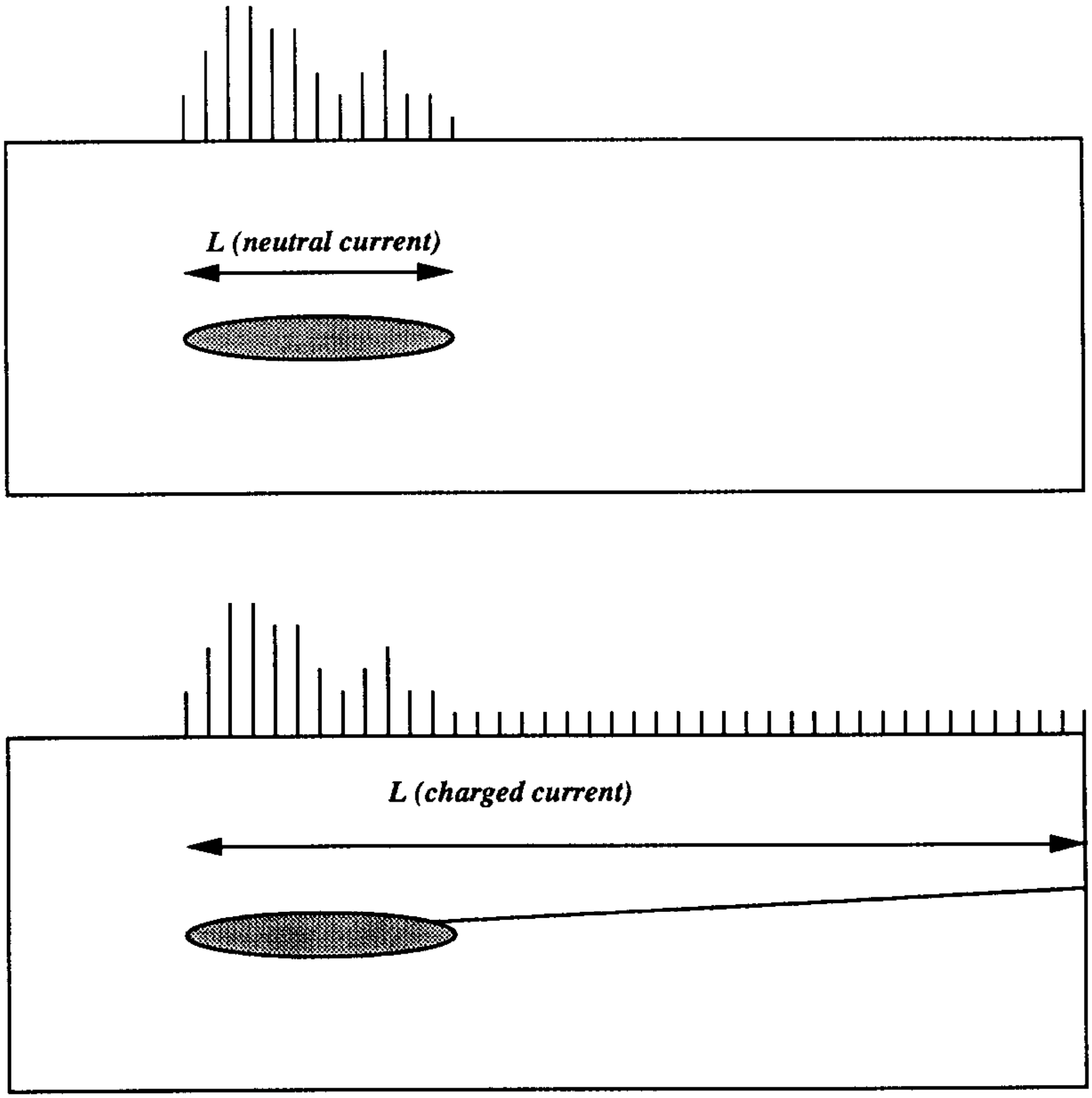
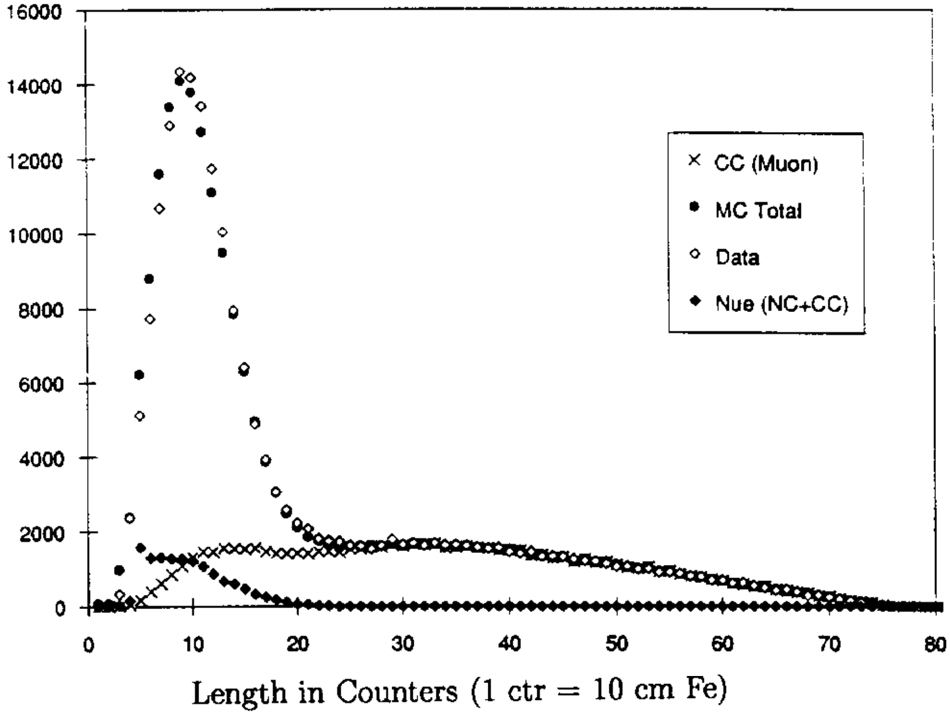


Figure 4: NC/CC Separation Technique, described in the Text. The ν is incident from the left. The shaded region represents a hadronic shower; the height of the vertical bars on top of the Apparatus indicate the amount of energy deposited as a function of depth in the calorimeter for a representative shower. We see the beginning and end of the hadronic shower in the neutral current event, defining a length; in the charged current, the muon deposits a constant dE/dx for a much longer length.



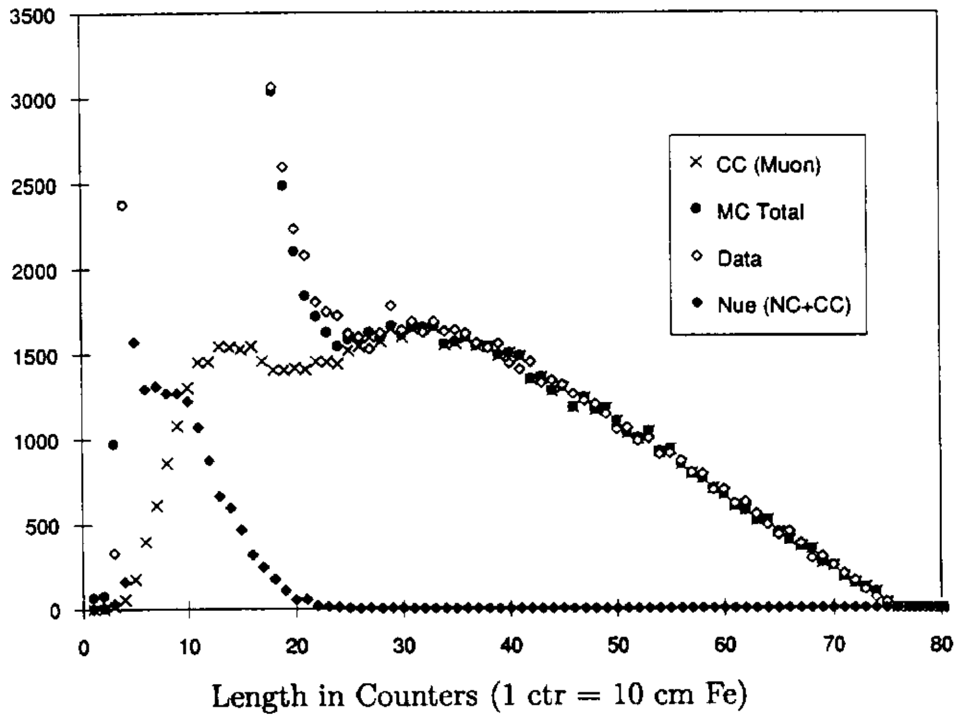


Figure 5: Length Distribution of ν events in Tevatron Experiment E770; the data and a simulation, including hadronic showers and electromagnetic showers from ν_e, is shown. The top plot shows the entire distribution; the bottom shows the data and simulation near the NC/CC crossover region.

Suppose we demand 10K neutral current events/run; then we can write down the following Table:

L (km)	M(kton)
300	3
600	12.5
1200	50

We saw in the first Figure that a distance in the range of 600–1200 km was required. Let's examine a 30 kton detector with the NC/CC test and see (1) what is required, and (2) what it would cost.

5.1 Detector

Our 30 kton detector will require 2 runs. It would be located approximately 1200 km away (BNL is a natural choice!) and would be under a 30 ft dirt shield. I presume it would be made of concrete, which is relatively cheap and a good density for NC/CC separation in the 5–20 GeV region. The FMMF detector (sand/shot) certainly has the appropriate power and the density would be about the same.[5]

For this mass, the detector would have a size of 10 m $\times$ 10 m $\times$ 100 m. With an interaction length in concrete of 40 cm, sampling once every 30 cm would provide the same sampling frequency as CCFR's Fe detector. Although I have not written a simulation, this frequency should suffice for NC/CC separation. Let us use 20 cm sampling as a benchmark.

The detector must be a sampling calorimeter with $1/\sqrt{E}$ resolution. It needs to measure E_H as well as determine whether the shower is NC or CC. The CCFR calorimeter has performed an NC/CC separation at $\approx$ 100 GeV E_ν with less than 1% errors. It has a measured resolution (with scintillators) of $0.8/\sqrt{E_\nu}$ and roughly the same value with FADC's attached to drift chambers. The $0.8/\sqrt{E_\nu}$ resolution is sufficient to perform the measurement.

5.2 What Would It Cost?

Concrete costs approximately \$75/yd^3; if we double this, for supports, stands, construction, *etc.* we find \$2.0 M.

If we sample five times per meter, and sample every 10 cm transverse to the beam, with an x and y measuring location at each station, we find 100K channels. At \$200/channel, a typical cost, we find \$20.0M.

The chambers themselves could be resistive plate chambers, with $\Delta t \approx 1$ nsec and resolutions of ≈ 1 mm. An approximate price is $70/m^2. The total area is 100K m^2 for a total cost of $7.0M.

The sum is $29M, which does not include installation, cosmic ray vetoes, and miscellaneous expenses. Clearly the most expensive item is the electronics and work here would have significant payoffs.

5.3 Cosmic Ray Flux

Such a detector could go deep underground, but there is no convenient location 1200 km away. What would be the cosmic ray flux through a surface detector and how would it compare to the rate?

Recall that we can always measure the rate to high accuracy off-spill; only the statistical fluctuation in the final rate matters. If there are 10^4 cosmic rays and 10^4 neutral currents in the final sample, then the fluctuations from cosmic rays will be ± 100 events, or 1%, which is the hoped-for precision. Let us posit a desirable goal to be 1000 cosmic ray events; the resultant fluctuations will then be small on the scale of the errors.

S. Werkema has studied the effects.[6] He concluded that the primary source of background are high-energy (> 500 GeV) muons which deposit energy in the detector by catastrophic processes where the muons themselves pass through a detector plane. Werkema's estimate implied that after a 4 msec gate cut is applied the total is 15×10^8 events. If we assume a veto which is 99% efficient we would find 15×10^6 events, still to be compared to the 10K sample.

Finding an additional factor of 1500 will be difficult. Software cuts distinguishing the topology of cosmic ray interactions from neutrino interactions will need to be made; a factor of 100 seems reasonable, bringing the fluctuations in the rate to $\approx \pm 120$ events, or 1.2% of the 10K NC sample. Placing the detector underneath a berm will not help since most of the muons which produce these showers are high-energy (≥ 500 GeV) and will not be stopped by a few meters of dirt. Constructing the veto will be a difficult and expensive project as well.

6 Conclusions

An NC/CC test with two copies of a ionization detector is a systematically clean way to achieve a 1% measurement. Such a measurement can definitively test the allowed region for Atmospheric Neutrino Oscillations. The formidable cosmic ray flux poses problems for an above-ground detector at 1200 km.

If the detector is built underground, existing detectors at the likely sites (Soudan 2, IMB) are too close to test down to $\Delta m^2 \approx 10^{-3}$, although a larger and suitably instrumented detector could make up the difference. The NC/CC method would work well at either site. We need to wait to see what the allowed region will be after IMB has completed its analysis for a final decision.

References

[1] I have combined exclusion and signal regions shown by M. Goodman at this Conference. The region shown does not represent a simultaneous fit to all data.

[2] R. Svoboda, priv. comm.

[3] R. Bernstein and S.J. Parke, Phys.Rev. **D44**, 2069 (1991).

[4] R. Snyder and M. Goodman, this Conference.

[5] W.J. Womersley *et al.*, Nucl.Instr.Meth. **A267**,49 (1988) , ERRATUM-*ibid.* **A278**, 447 (1989).

[6] S. Werkema, this Conference.