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A Search for Neutrino Oscillations with $\Delta m^2 > 10\ \mathrm{eV}^2$

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Abstract

We propose an experiment to search for neutrino oscillations with $\Delta m^2 > 10$ eV^2. Experimental and theoretical hints suggest this may be a natural region to expect oscillations. The experiment uses two similar detectors located at the Wonder Bldg. and Lab E, along the N0 beam line. These detectors measure the change in neutrino flux with distance by detecting the number of charged current events over neutrino energies from 30 to 230 GeV. A measurement with 5×10^{18} protons on target would be sensitive to neutrino oscillations with $10 < \Delta M^2 < 1300$ eV^2 and $\sin^2(2\alpha) > .04$. The detectors are composed mostly of existing hardware which this group has used previously for measurements of neutrino cross sections. With this simple design, the two detectors can be built quickly and initial data taken during the Fall 81 running cycle. Subsequent running with the Tevatron/Saver would extend the mass and mixing angle region covered by the initial data.

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I. Introduction

In the past year, much attention has been focused on the possibility of neutrino oscillations, in which a neutrino of one type (ν_μ, for example) oscillates into a neutrino of a different type (e.g., ν_e, ν_τ, $\bar{\nu}_\mu$, or an as yet undiscovered neutrino). In its simplest form, this kind of oscillation is analogous to the K^o oscillation $K_L{}^o \rightarrow K_s{}^o$, and takes the form:

$$\text{Probability}(\nu_\mu \rightarrow \nu_x) = \sin^2(2\alpha)\sin^2(1.27\ \Delta m^2 L/E_\nu) \qquad (1)$$

where:

α = the mixing angle between ν_μ and ν_x ;

$\Delta m^2 = |m_{\nu_\mu}{}^2 - m_{\nu_x}{}^2|$ (eV^2);

L = distance from the source (kilometers);

E_ν = energy of the neutrino (GeV).

In order for oscillations to occur, there must be a mass difference between two neutrino types, so at least one of the neutrinos must have a non-zero mass. In addition, a coupling must exist between the two types so that lepton number is not exactly conserved. If these two conditions exist, then neutrinos oscillate. The recent high interest in neutrino oscillations is due in part to recent experiments, but perhaps due more to a realization that these two conditions are consistent with previous data and can be incorporated easily and naturally into a theoretical picture of neutrinos.

Experiments to detect neutrino oscillations have for the most part yielded negative or ambiguous results. This could be because there are no oscillations, of course; but it could also be that previous experiments have not looked in the right region, and indeed have not looked in the most natural region. Cosmological estimates based on the clustering of galaxies and the missing mass in the universe suggest neutrino masses of 10-100 eV. A recent measurement of the electron neutrino mass by a Russian group also favors this mass range. Neutrino oscillations are governed by the difference in mass squared between the two neutrino states,

$$\Delta m^2 = m_1{}^2 - m_2{}^2 \quad . \tag{2}$$

If the neutrino mass scale is ~ 30 eV, then

$$\Delta m^2 = 2m\,\Delta m = (60\text{ eV})(\Delta m) \tag{3}$$

which for mass differences of a few eV predicts Δm^2 in the 100 eV^2 region. Previous oscillation measurements and proposals do not explore this important region.

Experimental searches for neutrino oscillations can be divided into two classes: 1) Exclusive searches, which look for specific oscillations, such as $\nu_\mu \rightarrow \nu_e$ or $\nu_\mu \rightarrow \nu_\tau$, and 2) inclusive searches, which look for a decrease in the apparent cross section caused by muon neutrinos oscillating into other states. A positive signal in an exclusive search would indicate the probability of ν_μ going into another neutrino is non-zero, whereas in an inclusive experiment, a positve signal indicates that the probability for ν_μ to remain ν_μ is not one.

Exclusive searches for ν_e interactions in a ν_μ beam are sensitive to ν_μ oscillations into either ν_e or ν_τ. These experiments are ultimately limited by the ν_e contamination in the ν_μ beam. Experiment 53A, using the 15-ft bubble chamber, has set a limit of about .5 eV^2 for the ν_e channel. The ν_τ channel has been investigated by the emulsion experiment in the Wonder Building, Exp. 531. They have set a limit of 3 eV^2, although this is somewhat dependent on threshold assumptions. But both of these experiments are clearly not sensitive to $\nu_\mu \rightarrow \nu_x$, if ν_x does not interact and give a charged lepton.

The advantage of an inclusive experiment can be made clear through some examples. Suppose there is a fourth flavor of charged lepton h, which is presumably heavier than the 15-18 GeV limits set by Petra experiments. Then oscillations of the type, $\nu_\mu \rightarrow \nu_h$, are no less likely than other neutrino oscillations; but the cross section for $\nu_h N \rightarrow h^- X$ would be either completely below threshold or greatly reduced by limited phase space at Fermilab energies. However, the oscillations of $\nu_\mu \rightarrow \nu_h$ would reduce the apparent charged current cross section and be observable in an inclusive experiment. Another indication of this type of oscillation would come from the measured ratio of neutral current to charged current events. If ν_h couples in the standard manner, its neutral current cross section would remain unchanged, and thus the ratio to charged currents would show oscillatory behavior. However, since the neutral currents have smaller statistics and worse systematic errors, the greatest sensitivity to any oscillations comes by comparing σ_{CC}^{total} at different distances.

Another kind of oscillation uniquely probed by an inclusive experiment involves the mixing of a muon neutrino with a non-interacting type of neutrino. An example of such a sterile neutrino would be a left-handed muon anti-neutrino. If right-handed leptonic couplings exist, then oscillations of the type, $\nu_\mu \rightarrow \bar{\nu}_\mu$, are possible. In this case, there would be an apparent reduction in both the charged and neutral current cross sections with the ratio, σ_{NC}/σ_{CC}, remaining unaffected.

An inclusive oscillation experiment at Fermilab is unique in two ways. First, the neutrino energies available (50-250 GeV), the distance between source and detector (500-1000 meters), and the length of the neutrino source (decay pipe = 342 meters) are optimal for observing oscillations in the mass range of 20-1000 eV^2. As will be shown in the next section, inclusive type experiments must have detectors within three to four oscillation lengths from the neutrino source and have source sizes that are significantly less than an oscillation length. With these restrictions, lower energy experiments at reactors, LAMPF, BNL or the CERN PS, cannot reach Δm^2 values greater than 10 eV^2. Second, the cross section for neutrino interactions at Fermilab is larger than lower energy machines and experiments with 50,000-100,000 events are possible. The sensitivity of an inclusive experiment to small mixing angles is directly related to the size of the event sample. An experiment at Fermilab could in principle reach values for $\sin^2(2\alpha)$ of .01.

Inclusive searches for oscillations are difficult because they must either compare measurements of $\sigma_{\nu_\mu}^{total}$ at different energies or at different distances from the neutrino source (decay pipe). The former method (comparing different energies) is severely limited by systematic uncertainties in the calculated neutrino flux as a function of energy and time. These uncertainties ultimately limit the accuracy of total cross section measurements. At present, there are two high statistics measurements of the neutrino and anti-neutrino total cross section, CFRR at Fermilab and CDHS at CERN. These experiments quote systematic flux errors of 5-10% which limit the observation of changes in the cross section with energy. The published total cross sections for the two experiments do differ by 16% for neutrinos and 28% for anti-neutrinos. With the quoted errors, these results correspond to 12% and 1% confidence levels that the two experiments are measuring the same underlying cross section. The two experiments are at two different distances from the neutrino source (500 m for CDHS and 1080 m for CFRR) and, therefore, the difference could be interpreted in terms of oscillations. But the normalization question makes any definitive statement impossible.

We believe that the only reliable method of searching for oscillations in an inclusive sense is to simultaneously measure the interaction rate in two similar detectors located at two different distances from the decay pipe. Since the two detectors are exposed to the same neutrino beam at the same time, systematic uncertainties are minimized. For a two detector setup at Fermilab using the narrow band beam, the systematic errors should be below 1% and the ultimate sensitivity should be statistics limited only. The experiment we propose would be sensitive to oscillations of a type which would not be seen in exclusive experiments, and to an important mass and mixing angle range, inaccessible to lower energy accelerators ($10 < \Delta m^2 < 1300$ eV^2, $.04 < \mathrm{sm}^2(2\alpha) < 1.0$).

II. Method and Systematic Errors

The experiment proposed in this document involves detecting a change in the ν_μ flux at two different distances by comparing the rates of charged and neutral current events in two similar detectors. The accuracy with which this comparison can be made depends both on the statistical errors of the data sample and on systematic effects inherent in the experimental setup.

The two detectors are described in Sec. III and consist of the existing neutrino target/toroid system in Lab E, along with a new detector installed in the Wonder Building. Neutrinos will be produced using the existing dichromatic beam and decay pipe. The relevant distances (see Fig. 1) for calculating sensitivities to neutrino oscillations are:

Length of decay pipe = 342 meters,
Distance to Wonder Bldg. = 743 meters (from decay pipe center)
Distance to Lab E = 1080 meters, (from decay pipe center).

The standard oscillation formula for ν_μ going into one other neutrino is:

$$\begin{pmatrix}\nu_\mu \text{ Flux at a}\\ \text{Distance } L\\ \text{From the Source}\end{pmatrix} = \begin{pmatrix}\nu_\mu \text{ Flux}\\ \text{at the}\\ \text{Source}\end{pmatrix} (1-\sin^2(2\alpha)\sin^2(1.27\Delta m^2 L/E)) \tag{4}$$

With the above distances, this formula predicts an event ratio for the two detectors as shown in Fig. 2. The first significant maximum in the ratio occurs where the argument for the sin term is $3\pi/2$ (not $\pi/2$); the first minimum occurs at π. This behavior is a consequence of the distance ratio of the two detector being .70.

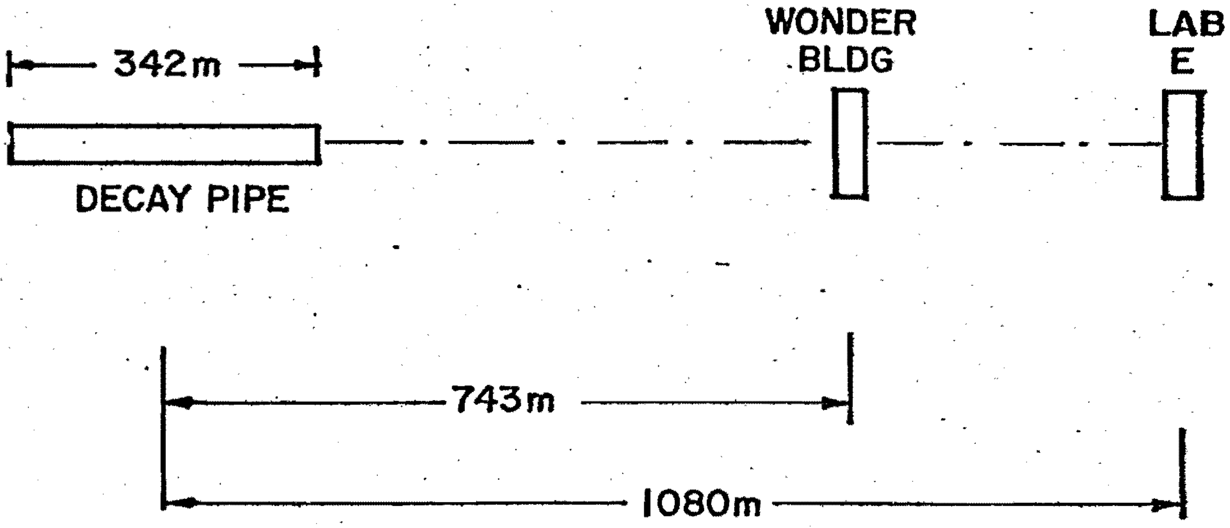


Fig. 1

Experimental Setup

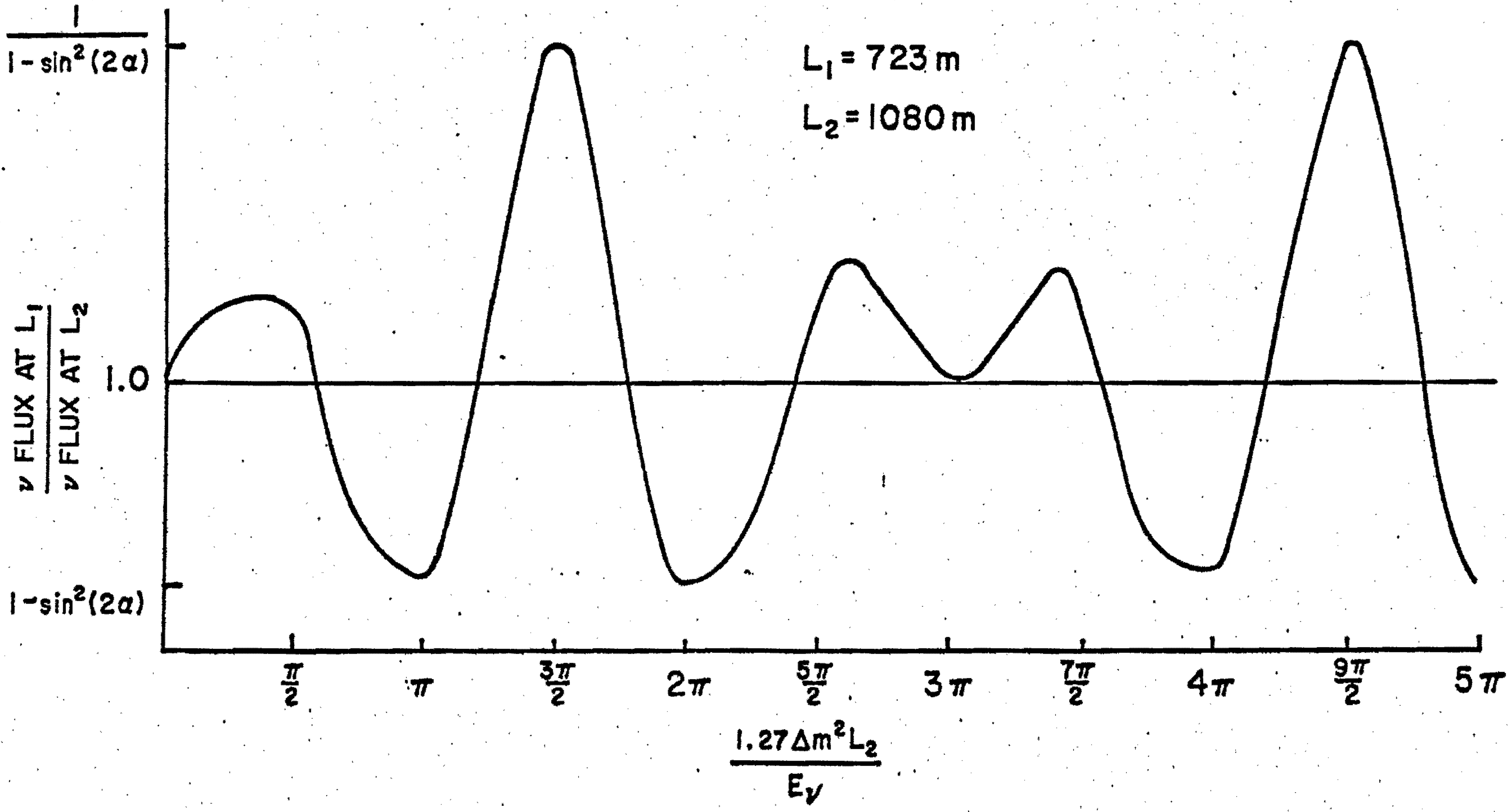


Fig. 2: Ratio of neutrino flux at the two detectors versus the argument in the sin term for Detector 2.

In a real experiment, the neutrino energy, E_ν, is known to the length of the source and detector. These errors in E_ν and L tend to reduce the changes in rate expected from Eq. (4). For example, if two monoenergetic neutrino beams have energies that differ by 20%, then after three oscillation lengths the lower energy has a maximum when the higher has a minimum (see Fig. 3). To keep the smearing of the oscillating behavior less than .2 oscillation lengths, the energy resolution must be:

$$\Delta E_\nu / E_\nu < .2/(\text{number of oscillation lengths to the detector}) \quad . \qquad (5)$$

For an experiment with energy resolution of 10%, Eq. (5) implies that the detectors are sensitive to rate changes in the one to three oscillation length region. In subsequent sections of this proposal, we investigate the limits imposed by finite energy resolution and conclude that the experiment is sensitive to the region with Δm^2 from 10 to 1300 eV^2.

The finite length of the decay pipe also reduces the measured flux differences between the two detectors especially when the oscillation length is comparable with the decay pipe length. The oscillation length defined as the distance in which the argument of the sin term in Eq. (4) changes by π is given by:

$$L_{osc}(\text{meters}) = 2.47 \times 10^3 * E_\nu(\text{GeV})/\Delta m^2(\text{eV}^2) \quad .$$

For an experiment using 400 GeV protons incident on the secondary production target, the maximum neutrino energy is about 230 GeV and, thus, the maximum Δm^2 probed is 1300 eV^2.

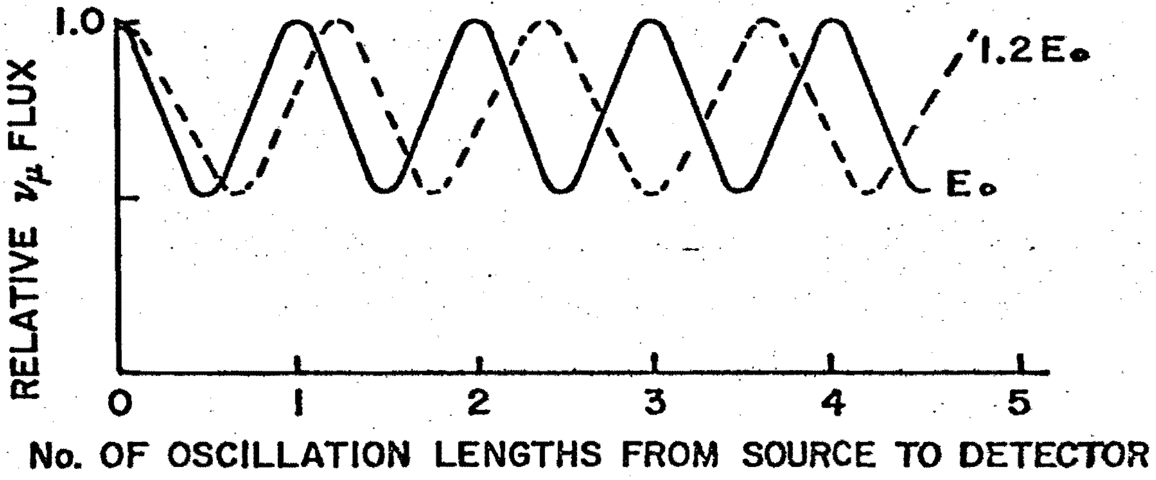


Fig. 3

Example of oscillations for two energies that differ by 20%.

At the Tevatron, 1000 GeV protons will provide neutrinos up to energies of 700 GeV and raise the maximum Δm^2 to over 3000 eV^2.

We plan to use two methods in comparing the event rates in the two detectors. First, the events can be separated into bins of measured energy and a ratio computed for each bin. For the second method, each detector is divided into radial bins around the beam center and event yields in corresponding bins are compared. The size of the bins are scaled by the distance of the given detector from the center of the decay pipe.

Bin in Detector 1		Bin in Detector 2
$R_1 < R < R_2$	corresponds to	$R_1(L_2/L_1) < R < R_2(L_2/L_1)$

where:

$L_{1(2)}$ = Distance of detector from decay pipe center.

These two methods are somewhat complimentary, each having certain advantages and systematic shortcomings.

For the radial bin method, the neutrino energy and spread in a given bin is inferred from the energy distribution of pions and kaons in the decay pipe. The observed events in a radial bin are separated into those induced by neutrinos from either pion or kaon decay. This separation is accomplished using a procedure developed for measuring total cross sections. With this procedure, all observed events are included independent of whether or not the muon energy is measured in the toroidal spectrometer. The energy resolution or spread in a certain radial bin depends on three factors: 1) the width in energy of the secondary pion/kaon beam, 2) the angular divergence and transverse size of the secondary beam, and 3) the size of the radial bin. For neutrinos from kaon decay, the energy spread in a radial bin is dominated by the spread in secondary energy which is about 9%. On the other hand, pion neutrinos have sizable contributions from beam divergence and radial bin size giving an energy spread larger than 10%. For this reason, the energy binning method in which the detector resolution is 10% is more accurate for pion neutrinos. For kaon neutrino events, there are small corrections to the raw event ratio due to: 1) the secondary beam shape coupled with the finite decay pipe length, 2) errors in the measured beam center at each detector, and 3) errors in the relative position of the decay pipe with respect to the detectors. Figure 4 shows an estimate of the error introduced by these three effects. For this estimate, we assume a secondary beam with $\sigma_\theta = .14$ mr and $\sigma_x = 2.5$ in., an error in the relative beam centers of 1 in. and in the decay pipe position of 1 m. (The beam center at the detector can be measured by fitting the spatial distribution of pion neutrino events; using this technique in Exp. 616, we have been able to determine the center to better than .5 inches.) As shown in the figure, the errors introduced by these effects are small and with corrections can be reduced to below 1%.

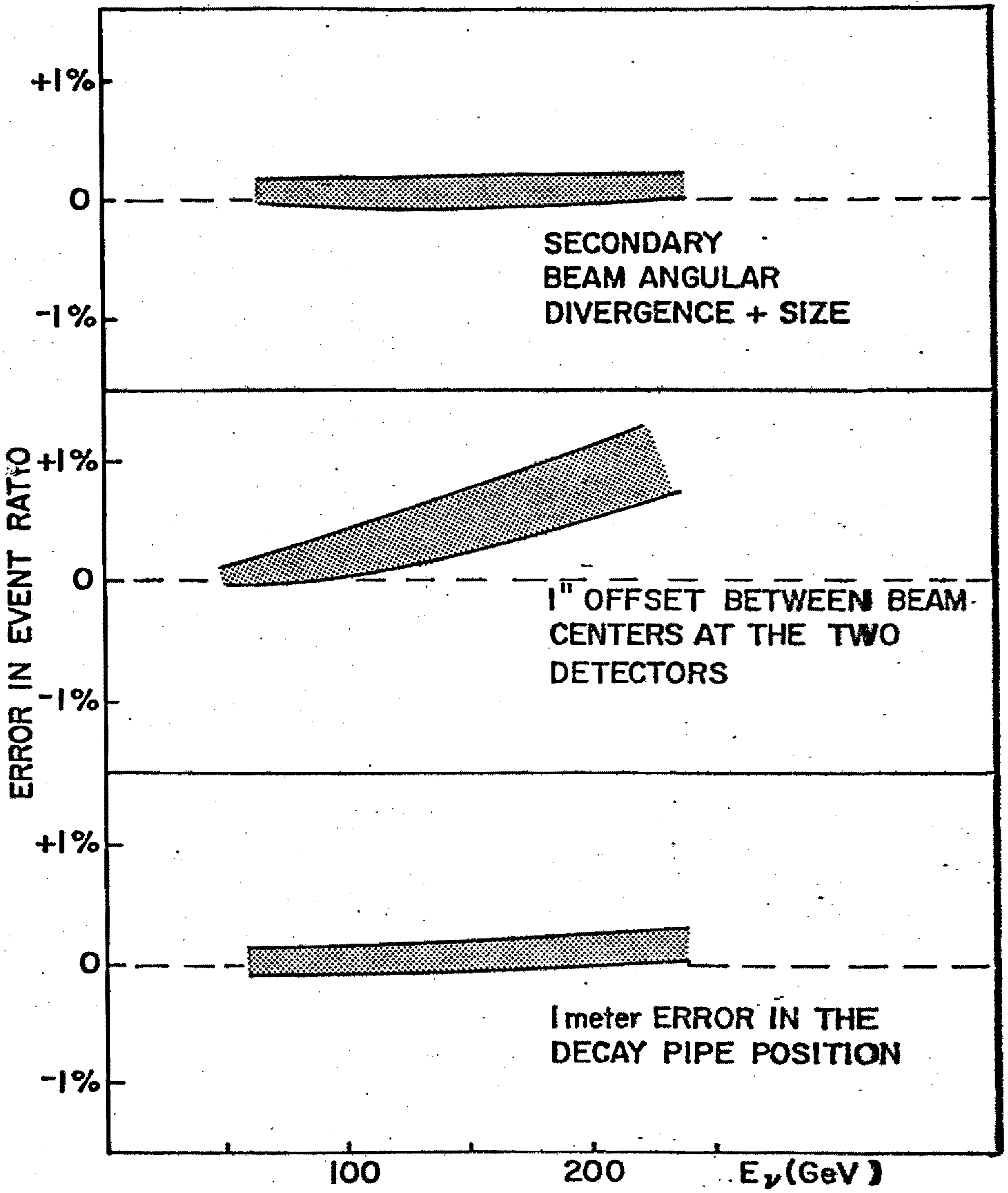


Fig. 4

Systematic errors introduced by three sources to the ratio of events observed in corresponding radial bins of the two detectors.

With the energy bin method, the energy spread within a bin is related to measurement errors for the muon momentum, P_μ, and hadronic energy E_{Had}. For our detectors, these resolutions are:

$$\left(\frac{\Delta E_\nu}{E_\nu}\right)^2 = (1-y)^2 \left(\frac{\Delta P_\mu}{P_\mu}\right)^2 + y^2 \left(\frac{\Delta E_{Had}}{E_{Had}}\right)^2$$

$$\frac{\Delta P_\mu}{P_\mu} = \begin{cases} .114 \text{ Lab E} \\ .160 \text{ Wonder Bldg.} \end{cases} \qquad \frac{\Delta E_{Had}}{E_{Had}} = \frac{.9}{\sqrt{E_{Had}}} .$$

At small y, the neutrino energy resolution is about 10% for Lab E and 13% for the Wonder Bldg. For pion neutrino events, this resolution is substantially smaller than the radial binning method. In addition, the number of events within a given energy bin is independent of the secondary beam size and divergence. One disadvantage of the energy binning method is that the comparison between the detectors is dependent on the relative energy calibration. This relative calibration can be determined directly from the data by comparing the mean energy in corresponding radial bins in the two detectors for kaon neutrino events. The 10% energy spread in a typical bin would allow this cross calibration to be made to better than 2%. With the energy binning method, there is also some loss of pion neutrino events since only those events for which the muon momentum is measured can be included. This restriction reduces the pion neutrino data sample by about 25%.

We conclude that by using a combination of the above two methods, we can measure the event ratio between the two detectors over the full energy range covered by pion and kaon neutrinos. The systematic errors introduced by the geometrical setup and the detector resolutions should be below 1%.

III. Detectors

As described earlier, we propose to compare neutrino cross sections which will be measured simultaneously at two locations. The systematic errors in the neutrino fluxes cancel in such a comparison. We propose to use the Lab E detector and build an additional detector in the Wonder Bldg. The Wonder Bldg. detector will make use of the old E 21 steel plates which still exist. The construction of the detector can be divided into two phases. During the first phase, we would make use of mostly existing equipment in order to build a Wonder Bldg. detector that can be operational within the next six months. Our aim is to obtain data during the next neutrino narrow band running period (i.e. the Fall 81 - Spring 82 cycle). Possibly more data can be obtained if a following 400 GeV run were scheduled by the laboratory. At this time, we seek approval for construction of the Phase 1 detector and for running it during the next neutrino narrow band cycle. The detector can be upgraded to run in the Saver and the Tevatron beams at a later stage without much difficulty in a similar manner to the Tevatron upgrade of the Lab E detector (E 652). That kind of upgrade is referred to as Phase II in the description below.

A. Phase 1 Detector

We propose to construct the Wonder Bldg. detector using fifty-six 5 ft x 5 ft x 4 in. steel plates from the original 80 plates of Expt. 21. We can operate two detectors by a redistribution of spark chambers from Lab E for use in the Wonder Bldg. The only new pieces of equipment to be constructed are the Wonder Bldg. neutrino target calorimetry and trigger counters (to be provided by the experimenters) and a 10 ft diameter toroid muon spectrometer (to be constructed by the laboratory).

The Wonder Bldg. detector target can be 5 ft x 5 ft in transverse dimension. This is because neutrinos which traverse near the 5 ft edge in the Wonder Bldg. end up near the 10 ft edge of the target in Lab E. We intend to make fiducial cuts in both detectors in order to compare regions of the target for which identical neutrino fluxes are subtended. The muon spectrometer in the Wonder Bldg. needs to be of similar size to the Lab E spectrometer because the kinematics of the muon angle in neutrino interactions does not change between the two detectors.

The present Lab E detector is shown in Fig. 5a. It consists of six neutrino target carts, each consisting of the equivalent of fourteen steel plates 10 ft x 10 ft x 4 in. which are interspersed with fourteen 10 ft x 10 ft liquid scintillation counters and six 10 ft x 10 ft spark chambers with magnetorestrictive readout. The target is followed by three 11 1/2 ft diameter toroids constructed from magnetized steel washers which are interspersed with twenty-four planes of acrylic scintillation counters, three planes of trigger counters and eighteen planes of spark chambers which are constructed from a combination of 10 ft x 10 ft spark chambers and 5 ft x 10 ft spark chambers.

Since the proposed Phase 1 run involves only neutrino running (as opposed to antineutrino running) for which the event rate is high, we can afford to reduce the available instrumented target tonnage in Lab E by 30% and utilize the chambers for use in the Lab E toroids. Since one 10 ft x 10 ft chamber from the target can replace two 5 ft x 10 ft chambers in the toroids, we can remove all the thirty-seven 5 ft x 10 ft chambers and use them to fully instrument the 5 ft x 5 ft Wonder Bldg. experiment. We presently have available forty-two 10 ft x 10 ft chambers and thirty-seven 5 ft x 10 ft chambers (in addition, we have twelve 5 ft x 5 ft chambers that can be used as spare replacements for 5 ft x 10 ft chambers thay may need repair during the run). We summarize our proposed detector arrangement below.

Lab E Detector for Neutrino Oscillations

1. Target (instrumented part)

12 1/2 ft x 25 ft veto wall (exists in place)
Fifty-six 10 ft x 10 ft x 4 in. steel plates (exist in place)
Fifty-six 10 ft x 10 ft liquid scintillation counters(")
Twenty-six 10 ft x 10 ft spark chambers (exist in place)

(Uninstrumented i.e., no chambers)

Twenty-four 10 ft x 10 ft x 4 in. steel plates (exist in place)
Twenty-four 10 ft x 10 ft liquid scintillation counters(")
Hadron Energy Resolution = $90\%/\sqrt{E_{Had}}$.

2. Toroids (instrumented)

Three 11 1/2 ft diameter toroids each with 64 in. of magnetized steel in the z direction (exist in place)

Twenty-four acrylic counter planes 10 ft x 10 ft (exist in place)

Three 10 ft x 10 ft trigger counter planes (exist in place)

Sixteen 10 ft x 10 ft spark chambers (all exist, some in place)

Total P_t kick of toroids = 2.4 GeV/c

Momentum resolution for muons = 11%.

Wonder Building Detector for Neutrino Oscillations

1. Target

10 ft x 10 ft veto wall (exists)

Fifty-six 5 ft x 5 ft x 4 in. steel plates (exist)

Seventeen 5 ft x 10 ft spark chambers (exist)

Forty-six 5 ft x 5 ft x 1 in. acrylic scintillation counters (to be constructed by the experimenters)

Hadron Energy Resolution = $90\%/\sqrt{E_{Had}}$.

2. Toroid

One 10 ft diameter steel toroid 96 in. in length (to be provided by the laboratory)

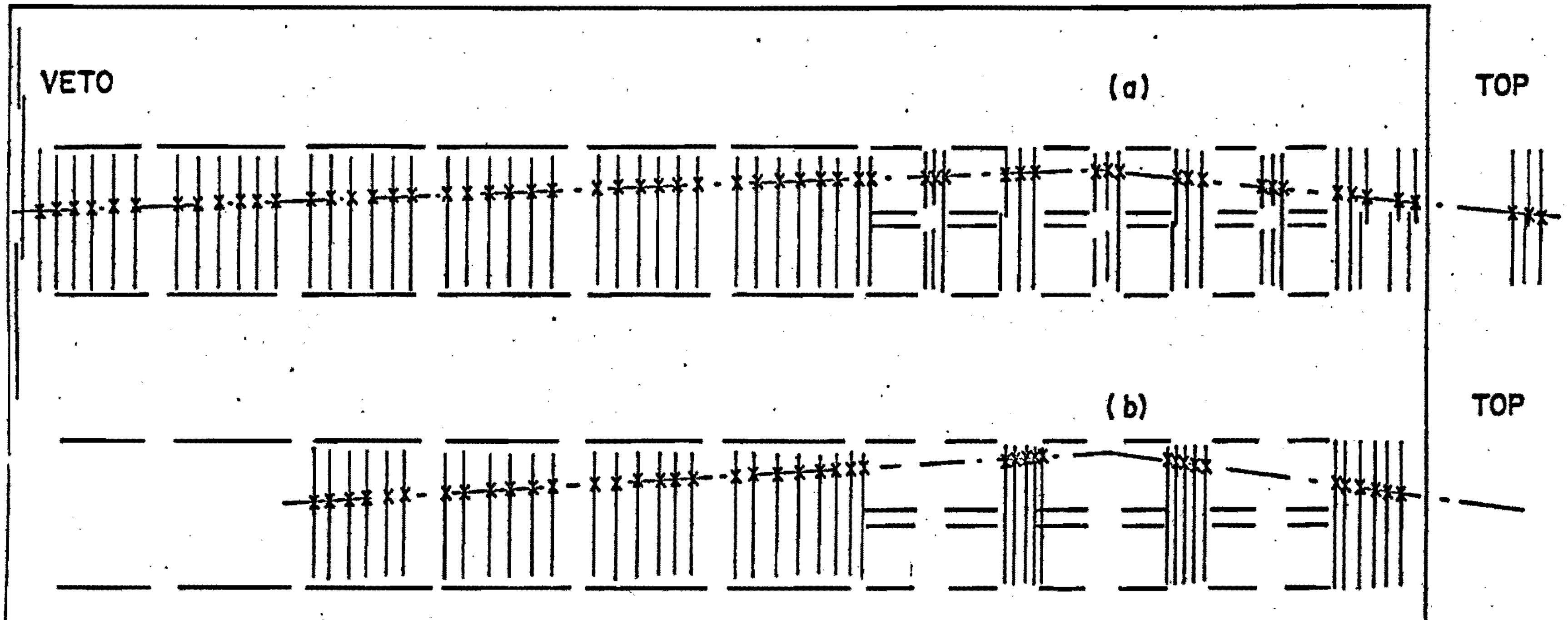
Twenty 5 ft x 10 ft spark chambers (exist)

Three 10 ft x 10 ft trigger counter planes (to be constructed by the experimenters)

P_t kick = 1.2 GeV/c

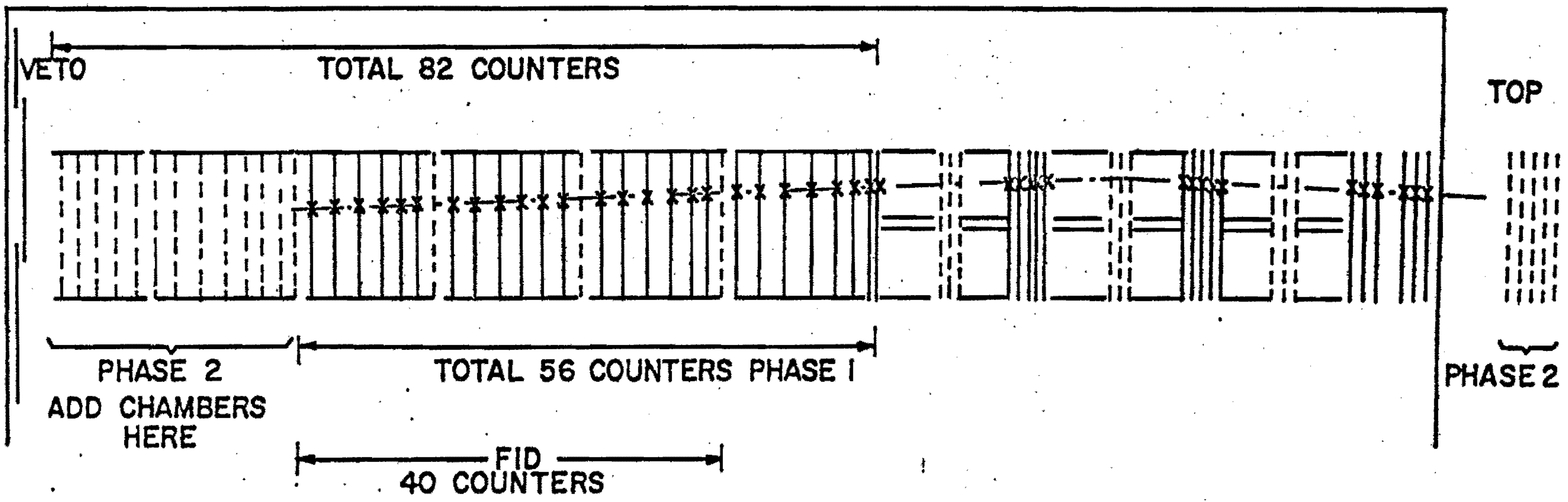
Momentum resolution = 16%.

The Phase 1 Lab E detector is shown in Figs. 5b and 6; the Phase 1 Wonder Bldg. detector is shown in Fig. 7a.



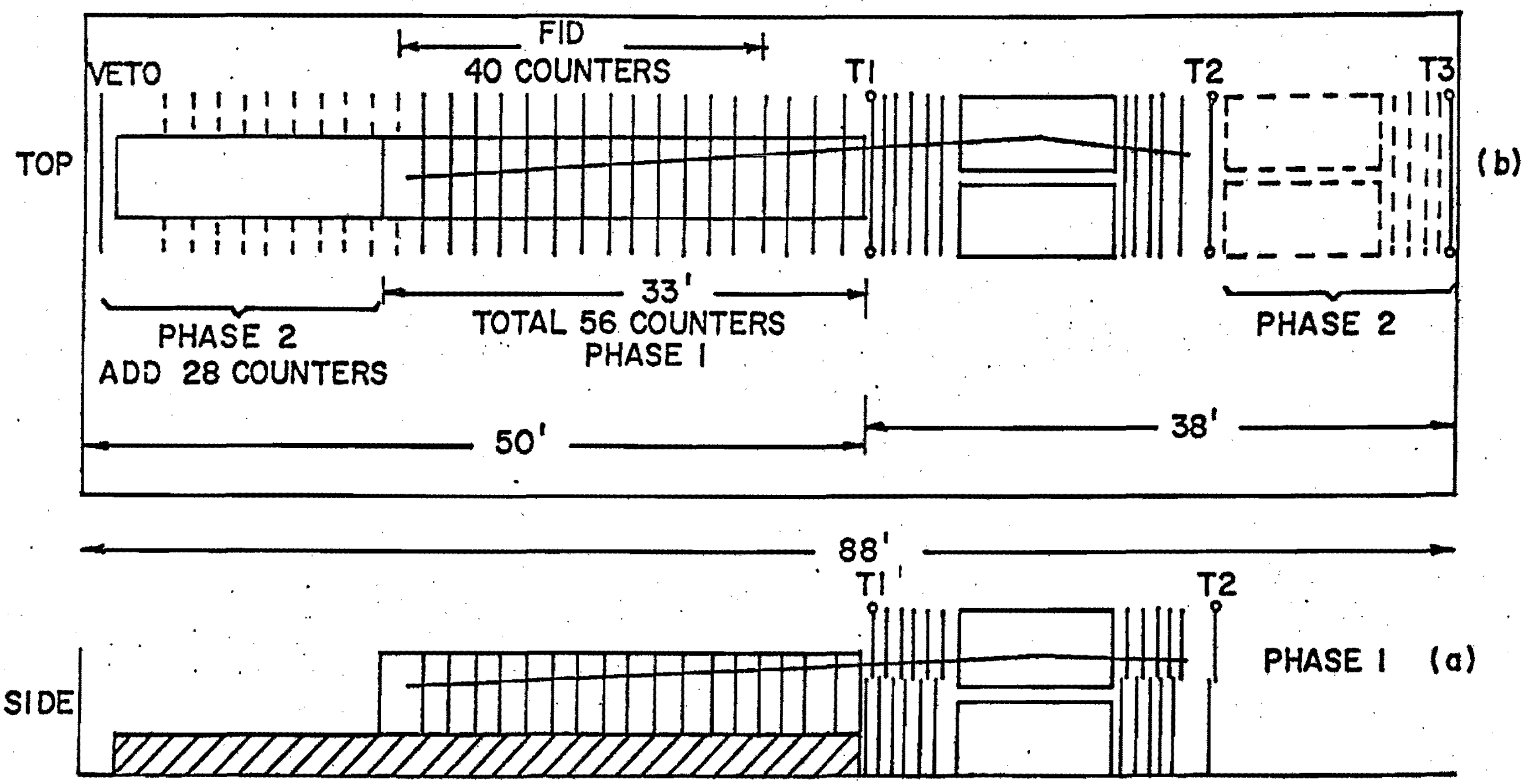
a) PRESENT LAB E ARRANGEMENT
b) LAB E AFTER CHAMBER REARRANGEMENT

Fig. 5



SOLID LINE PHASE I
DASHED LINE PHASE 2 ADDITIONS

Fig. 6
Proposed Lab E setup for the oscillation experiment.



a) SOLID LINE PHASE I WONDER BLDG DETECTOR
b) DASHED LINE PHASE 2 ADDITIONS

Fig. 7
Proposed Wonder Bldg. setup for the oscillation experiment.

B. Phase 2 Detector

The upgrade of the Lab E detector for operation with the Tevatron/Saver (Expt. E 652) involves the replacement of all the Lab E spark chambers with drift chambers. This is necessary in order to be able to accumulate several events per pulse during the Tevatron/Saver fast spill extracted beam. A similar upgrade is envisioned in the Wonder Bldg. where all the spark chambers would be replaced with drift chambers. In addition, a second 10 ft diameter toroid is needed in the Wonder Bldg. in order to measure the momentum of the higher energy muons during Tevatron/Saver operation. We also anticipate expanding the Wonder Bldg. fiducial target tonnage by 70% in order accumulate more data during the lower rate antineutrino running. The proposed Phase 2 detectors are shown in Figs. 6 and 7b for the Lab E and Wonder Bldg. configurations respectively.

IV. Rates and Data Sample

Sensitivity to a wide range of Δm^2 requires measurements covering many energies. In addition, overlap in energy of events from pion and kaon neutrinos allows further systematic checks of the two binning methods described previously.

For the initial running of the proposed experiment, we plan to concentrate on neutrino running only because the kaon event rate is substantially higher with neutrinos over antineutrinos. The neutrino charged current event yield versus secondary beam setting is shown in Fig. 8. At any secondary setting, both pion and kaon neutrino events are recorded. The number of pion events is always greater than or equal to those from kaon neutrinos and, therefore, the running time necessary to achieve a certain data sample is determined by the desired kaon neutrino statistics. The run plan given in Table I is constructed to uniformly cover the range between 40 and 230 GeV with good statistical precision, a minimum number of secondary energy settings, and approximately 5×10^{18} protons on target. Reducing the number of secondary settings below seven produces gaps in the energy coverage above 100 GeV and would result in less sensitivity for certain Δm^2 values.

These event yields are reduced by three factors: 1) spark chamber deadtime, 2) fiducial cuts, and 3) detection efficiency. We plan to run the experiment with the standard 2 ms fast spill with approximately 10^{13} protons per pulse. The spark chamber system is capable of recording one event per spill which gives an average deadtime loss of 30%. A fiducial cut of ± 25 in. for the proposed Wonder Bldg. detector corresponds to a ± 37.5 in. at Lab E. These limits reduce the kaon neutrino events by 35% but leave the pion events unaffected. As mentioned previously, the pion events are binned by measured energy for which the muon momentum must be measured. This restriction reduces the pion neutrino event sample by about 25%. With the above losses included, Table II lists the expected data sample.

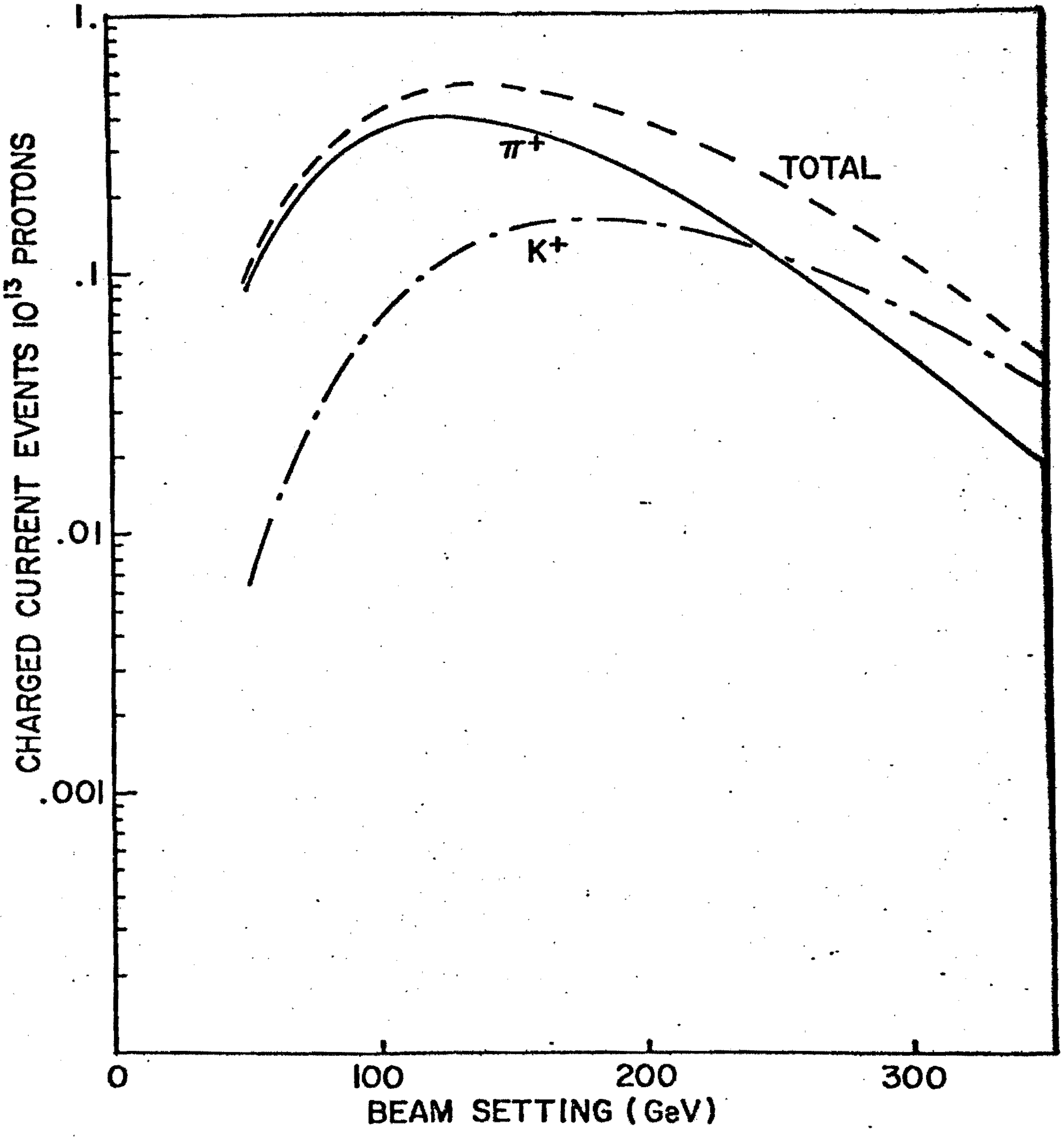


Fig. 8

Total charged current event rate per incident proton vs. secondary beam setting. (These rates are for a forty counter (~ 4m steel) fiducial volume for radii less than 67 in. at the Lab E detector.)

Table I: Run Plan

Secondary Beam Setting (GeV)	Number of Protons on Target
+ 250	13.3×10^{17}
+ 190	7.2×10^{17}
+ 160	5.2×10^{17}
+ 140	6.0×10^{17}
+ 120	7.9×10^{17}
+ 100	6.1×10^{17}
+ 80	6.7×10^{17}
Total	5.2×10^{18}

Table II: Final Data Sample Including Deadtime and Detection Efficiency Losses

Neutrino Energy (GeV)	No. of Charged Current Events	Neutrino Energy (GeV)	No. of Charged Current Events
221	3500	76	3194
200	2864	68	1240
171	3500	61	2497
157	1971	58	4009
145	3011	52	3279
136	598	47	4926
126	3500	43	4032
110	3500	39	3894
94	3899	35	3500
Total			83617

V. Sensitivity

We have made a Monte Carlo study of the expected sensitivity with the data sample of Table II. (A systematic error of 1% is added to each data point.) Figure 9 shows the 90% confidence level limit for data assuming no oscillations ($\sin^2(2\alpha) = 0$). For full mixing, the measurement covers from 10 to 1300 eV^2. The mixing angle limit for the region $50 < \Delta m^2 < 500$ eV^2 averages about $\sin^2(2\alpha) = .06$. These limits are substantially smaller than other inclusive measurements proposed and reflect the large statistics available in a Fermilab experiment.

Of course, we hope the experiment will do more than just set limits on oscillations. If an effect exists, the proposed experiment has the potential to measure the parameters involved very well. Simulated data (with the event sample of Table II) for $\Delta m^2 = 380$ eV^2 and $\sin^2(2\alpha) = .2$ is shown in Fig. 10. The data show a definite change in the events ratio versus energy. Fitting this data to Eq. (4) yields measurements of (see Fig. 11):

$$\Delta m^2 = 380 \pm 11 \text{ eV}^2$$

$$\sin^2(2\alpha) = .20 \pm .02 \quad .$$

(A fit assuming zero mixing yields a confidence level below 10^{-8}.)

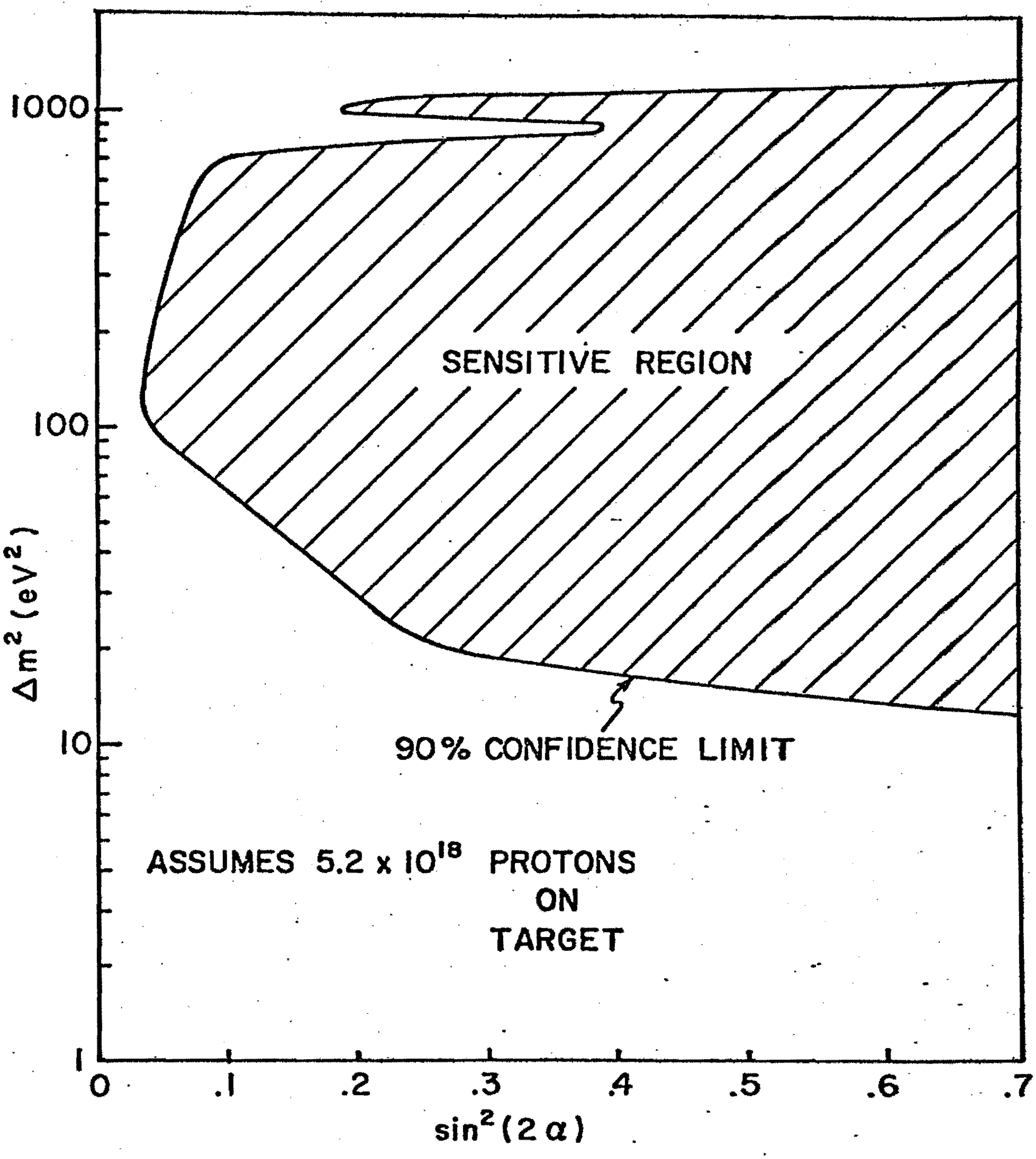


Fig. 9

Sensitivity vs. Δm^2 and $\sin^2(2\alpha)$ for the data sample of Table II.

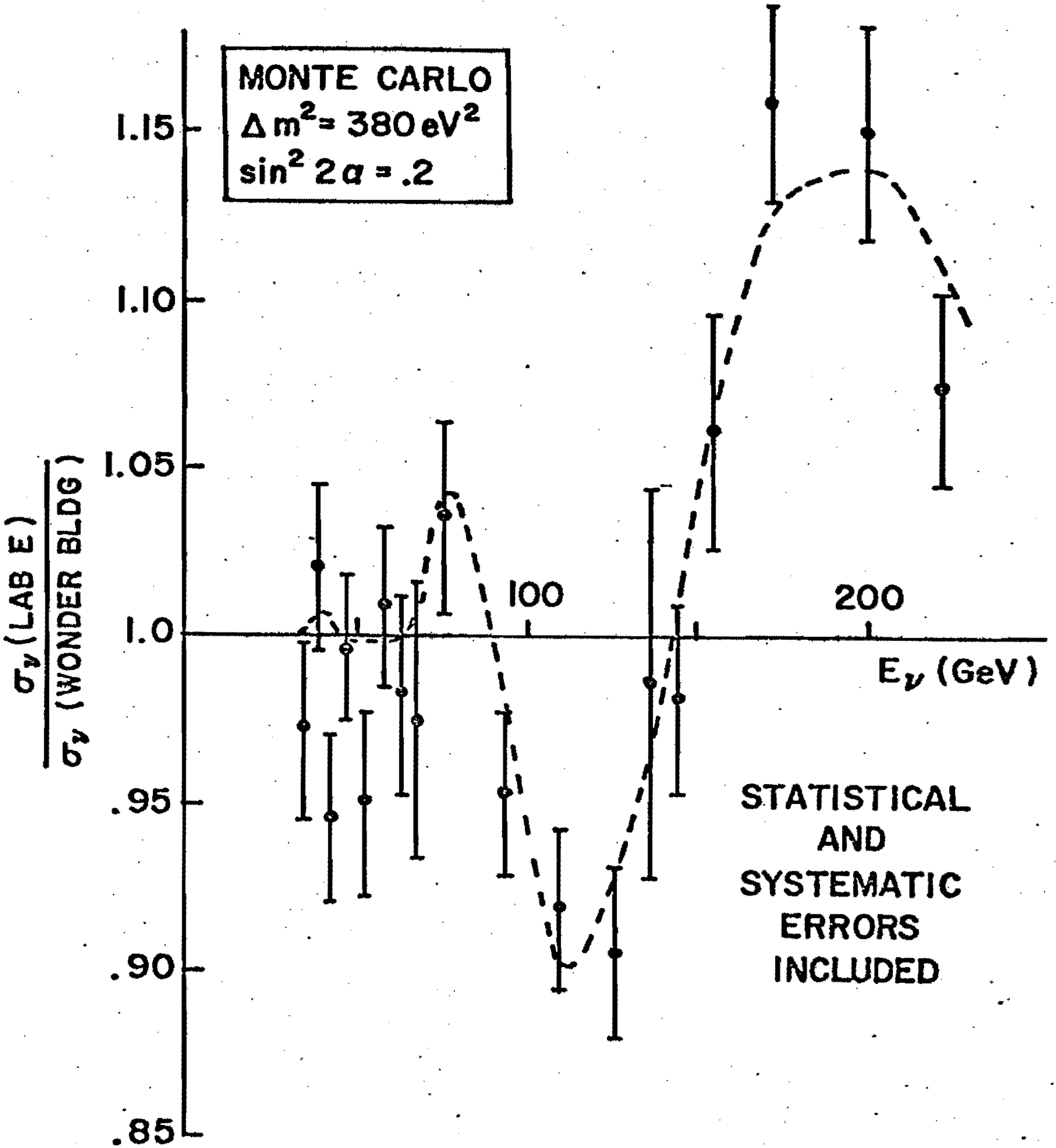


Fig. 10

Monte Carlo "fake" data for the hypothesis $\Delta m^2 = 380\ eV^2$ and $\sin^2(2\alpha) = .2$ for the data sample of Table II.

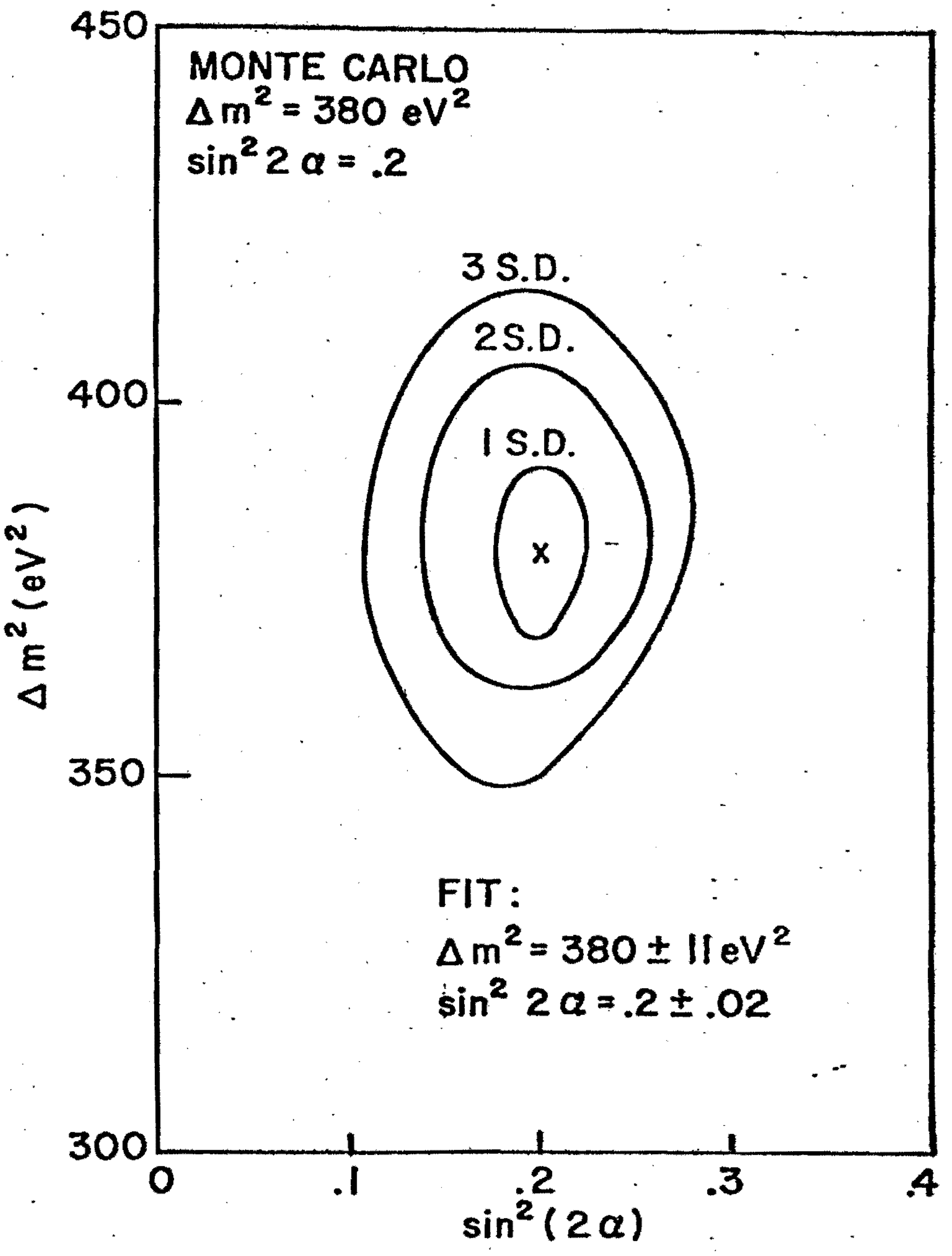


Fig. 11

Results of a fit to Eq. (4) of the data in Fig. 10. The contours are for 1, 2, and 3 standard deviations.

The present dichromatic beam was built to transmit secondary beams at energies up to 350 GeV. This means that the solid angle acceptance (10 μstrad) seriously compromises the rates at lower energies. We are investigating a very promising design for the Tevatron dichromatic beam which permits optimization of the solid angle acceptance for the specific energy range in which the beam will operate. The CERN dichromatic beam already incorporates this feature. Figures 12 and 13 show the total rates for pion and kaon neutrino events, respectively, using the Lab E detector with the present beam (a). The rates with a beam optimized in solid angle acceptance at the particular setting is also shown (b), again using 400 GeV protons. Substantial improvement is available in the energy range of interest. Operation of the same beam with 800 GeV incident protons gives the upper curves (c). Overall, these curves indicate that an order of magnitude increase in rate is conceivable. With practical factors taken into account, this increase will be more like a factor of five, matching the average rate available with present repetition rates.

Other rate improvements, such as removal of deadtime effects with our use of drift chambers, and an increase in neutrino target length in the Wonder Bldg. to match Lab E, indicate that Saver operation should be very competitive with present rates for the proposed experiment. In addition, Tevatron operation with higher energy secondaries will permit exploration of a mass region considerably higher than accessible presently.

It should be noted that exploitation of this physics with the Saver requires more than Saver operation. It also requires completion of our drift chamber upgrade on an appropriate time scale and completion of the Tevatron dichromatic beam on the same time scale. We see this as at least two, and probably three, years away. We emphasize that the largest, and possibly most important, region can be explored now with lower energy operation, either here or elsewhere. This underlies the urgency of the timing which we have outlined.

In our group deliberations, we have seriously considered the possibility that we may be compromising a better experiment to be done later by building the experiment on the proposed time scale. After penetrating deliberations, we have unanimously concluded that we will not seriously compromise the long term physics by constructing the target as proposed here.

The second target to be built in the Wonder Bldg. is not identical to that in Lab E. There is no need for it to be identical; indeed, it is preferred that it not be identical. Neutrinos passing through a certain fiducial area in Lab E pass through a fiducial area in the Wonder Bldg. that is smaller, so it is not possible to make the situations identical. The targets must be capable of identifying with high efficiency neutrino events that are in some common region, but not necessarily all regions, of the kinematic variables. Comparisons of event rates in two targets are different from total cross section measurements. In the latter case, the absolute cross section requires the use of efficiencies calculated from azimuthal rotation of events (typically about 90%) and corrections for lost regions in muon angle (typically about 97%). Target rate comparisons require only a comparison of numbers of events in kinematic regions where the acceptances of the two targets overlap. It is important that the two targets be similar for such comparison, but it is not essential that they be identical.

One technique for analysis of the data is to take events in one target and transpose the events to the other target (in the computer) to determine if they would have been accepted. Only events acceptable to both targets would be used for rate comparison. If this is done in concert with hard cuts on muon angle and momentum in both targets, the comparison can be made independently of any physics assumptions, including the physics of the primary interaction, multiple scattering, or muon energy loss. We conclude that the comparisons of flux in two targets, even though the targets are slightly different, can be made unambiguously. The effect of small apparatus differences is to compromise slightly the number of events to be used in the comparison.

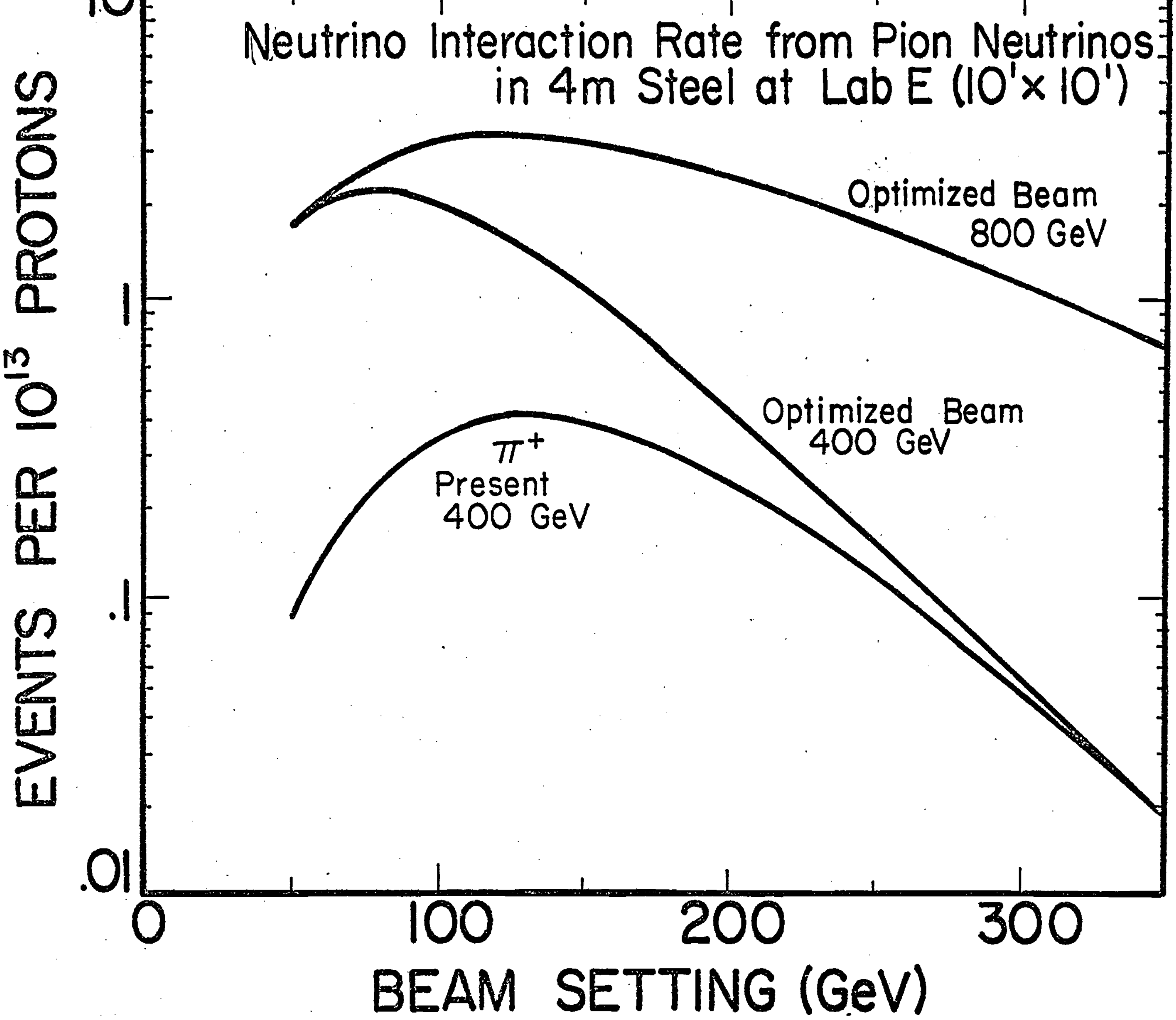

Neutrino Interaction Rate from Pion Neutrinos
in 4m Steel at Lab E (10'× 10')
Optimized Beam
800 GeV
Optimized Beam
400 GeV
π^+
Present
400 GeV
EVENTS PER 10^{13} PROTONS
10
1
.1
.01
0
100
200
300
BEAM SETTING (GeV)

Figure 12

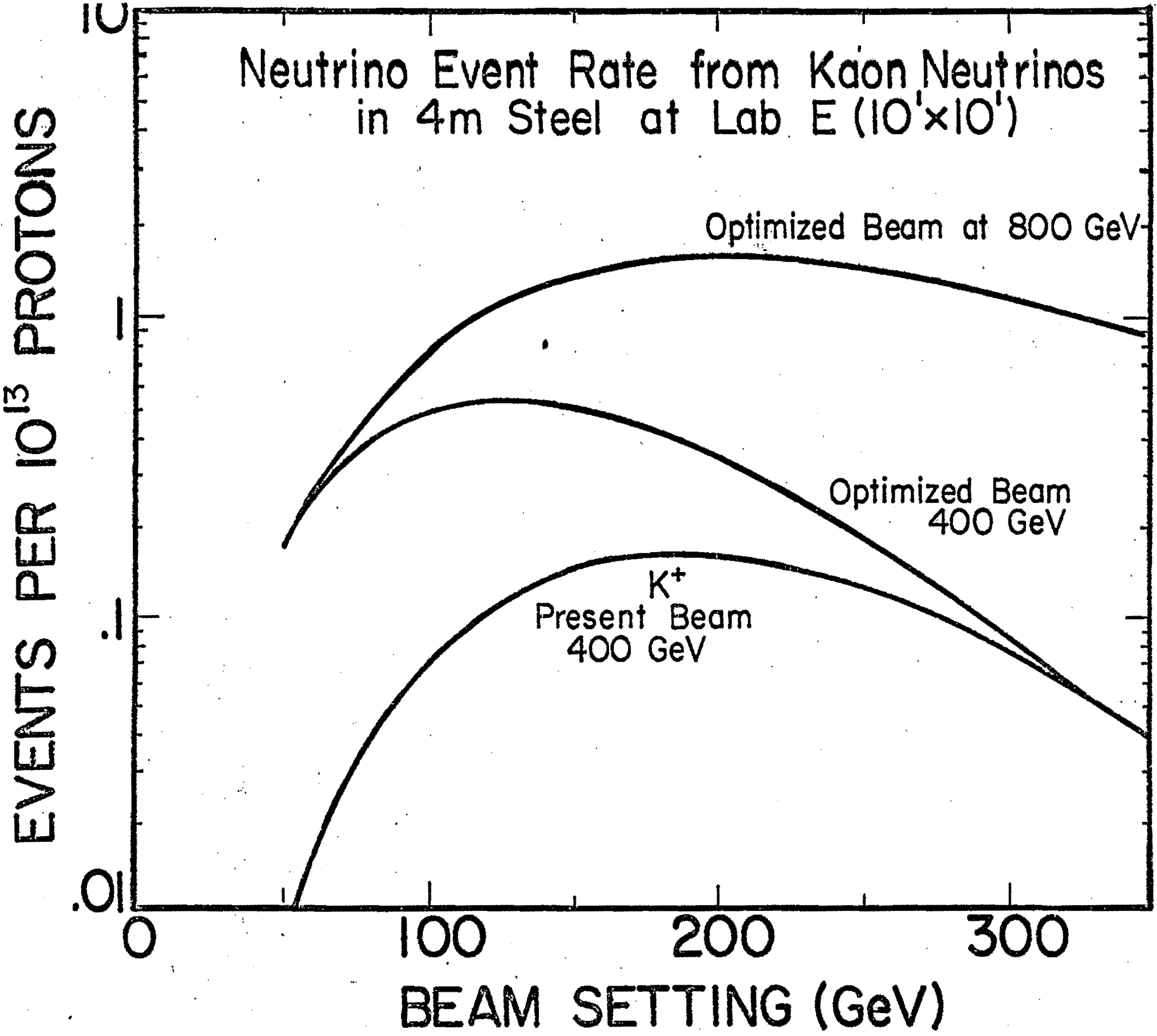

Neutrino Event Rate from Kaon Neutrinos
in 4m Steel at Lab E (10'×10')
Optimized Beam at 800 GeV
Optimized Beam
400 GeV
K+
Present Beam
400 GeV
EVENTS PER 10^13 PROTONS
10
1
.1
.01
0
100
200
300
BEAM SETTING (GeV)

Figure 13

The only compromise made with the Wonder Bldg. apparatus design are those of transverse target size and toroid diameter. The optimal size of the Wonder Bldg. target is 6.5 ft x 6.5 ft. The 5 ft x 5 ft target to be built reduces the comparable rate by about 35% for kaon neutrinos, but reduces the comparable pion neutrino rate not at all. The transverse toroid size (10 ft diameter) does not quite match the 11.5 ft diameter Lab E toroid. This reduces the comparable pion neutrino rate by about 10% (i.e., muon angle less than 87 mrad instead of 100 mrad), but has little effect on kaon neutrinos. We see a method of increasing rate in the future by increasing neutrino target longitudinally as superior to a scheme with more transverse target. The practical advantages of the smaller transverse dimensions outweigh the small rate compromises.

VII. Conclusions and Requests

A definitive measurement of neutrino oscillations in the large Δm^2 region is needed at this time. There are both experimental and theoretical hints that neutrino masses may be larger than 5 eV and that the region with $\Delta m^2 > 50\ \mathrm{eV}^2$ may be a natural place to expect neutrino oscillations. This region can be uniquely probed by experiments at Fermilab.

The experiment we propose has many advantages for this investigation: 1) The method in which two detectors are exposed simultaneously to a common neutrino beam is practically free from systematic biases and is sensitive to oscillations of ν_μ into any other neutrino type. 2) The two detectors are composed mostly of existing well understood apparatus allowing a quick turn-on date for the experiment. 3) The group involved has a broad background and much expertise in using these detectors to measure neutrino interactions. 4) With a modest run of 5×10^{18} protons, the experiment would be sensitive to ν_μ oscillations with $10 < \Delta m^2 < 1300\ \mathrm{eV}^2$ and mixings with $\sin^2(2\alpha) > .04$.

We believe that this measurement should be done as soon as possible both for compelling physics reasons and possible competition. To this end, we have designed the experiment to minimize the requests from Fermilab and allow for fast construction. The specific requirements are listed in the next section with the major requests of Fermilab being the mounting of the steel target in the Wonder Bldg. and the construction of a new 10 ft diameter steel toroid.

With some help from Fermilab, we feel strongly that the experiment can be ready for the Fall 81 running period and we would request a data taking run of 5×10^{18} protons at that time. Subsequent running with the Tevatron/Saver would extend the mass and mixing angle region covered by the initial data.

VIII. Requirements

A. Requirements from the Laboratory

1. Construct a 10 ft diameter x 96 in. long steel toroid, possibly using existing steel. Fabrication cost: $40,000; steel replacement costs: about $40,000.
2. Remove existing experiments from the Wonder Bldg. after they are completed.
3. Rig in and mount fifty-six 5 ft x 5 ft x 4 in. steel plates (using existing old E 21 steel) on the concrete pad in the Wonder Bldg.
4. Transport thirty-seven 5 ft x 10 ft spark chambers from Lab E to the Wonder Bldg. Move 10 ft x 10 ft chambers from the Lab E target into new mounts in the Lab E toroid assembly.
5. Provide one PDP 11/50 computer for online data taking and monitoring. Lab E software can be used.
6. It is the intention of the experimenters to utilize as much of the Lab E PREP equipment by temporarily borrowing items such as ADC's from the Lab E facility. (ADC's can be borrowed temporarily from the two upstream target carts from which spark chambers have been removed.) We estimate the amount of additional PREP electronics to be about $115,000.
7. After the data taking period, provide a calibration beam with momentum selected low energy hadrons and muons for the Wonder Bldg. detector. Conversations with R. Stefanski

from the Neutrino Dept. indicate that such a beam can be readily made available via the N1 line by installing a beam pipe in the berm.

B. Requirements from the Experimenters

1. Provide and construct fifty-six 5 ft x 5 ft x 1 in. calorimetry counters (solid acrylic scintillator) with wave shifter readout and with phototubes and bases. These will be used in the Wonder Bldg. target. Estimated cost: about $125,000 (see Appendix A).
2. Provide and construct three 10 ft x 10 ft trigger counter planes and one 10 ft x 10 ft veto counter plane in the Wonder Bldg. Estimated cost: about $25,000 (see Appendix A).
3. Assemble and rig into the steel the fifty-six counters, the trigger counters, and the thirty-seven 5 ft x 10 ft spark chambers in the Wonder Bldg.

Appendix A

APPENDIX A: Acrylic calorimetery counters and NE114 trigger counters.

We have constructed a large number of 5'x5'x1.5" acrylic calorimetery counters for the toroid system in lab E. We have also constructed a large number of 10'x10' liquid scintillator counters and NE114[2] 2.5'x10'x1" trigger counters. The light collection system that was developed[1] for all the lab E counters consisted of acrylic wave shifter bars doped with BBQ (90 mg/liter). This has proved to work very well and we plan to continue using the same process for the Wonder building counters.

Acrylic counters for the wonder building.

The present the lab E 5'x5'x1.5" acrylic counters yield about 5 photoelectrons per minimum ionizing particle. They have a yield of about 30% of the light output of NE110[2] and an attenuation length of about 1 meter. They were constructed about 5 years ago using scintillator cast by Polytech Inc.[3]. The formula[1] used was: acrylic base (PMMA 96%) with 3% Naphtalene, 1% PPO and 0.01% POPOP. In the last two years, acrylic scintillators with more light output and longer attenuation length have been developed[4,5] utilizing a larger concentration of ultra pure Naphtalene. We intend to use thiner counters (5'x5'x1") and use the higher light output formula. A formula[5] consisting of 83.99% PMMA acrylic, 15% Naphtalene, 1% Butyl PBD and 0.01% BBOT yields[5] about 70% of the light output of NE110[2]. We have found two commercial suppliers in the USA[3,6] who will cast this formula. The 56 counters can be cast by either supplier and delivered within 12 weeks of ordering. The BBQ bars are not very expensive and can be supplied by three manufacturers[3,4,7] Figure 14a illustrates the counter in its frame with light collection BBQ bars and two 2" phototubes(RCA6342A).

Trigger counters

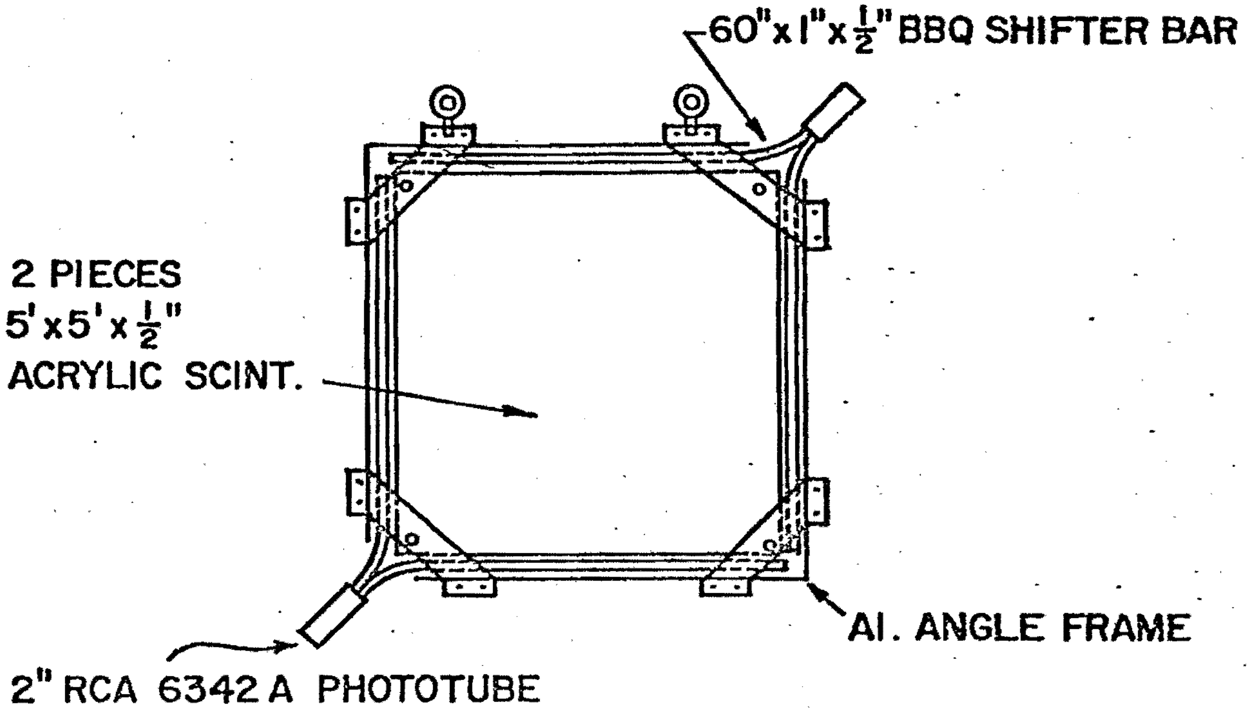
We plan to construct the trigger counters in an identical fashion to those used for the lab E veto wall system. Such counters are constructed from 2.5'x10'x1" NE114[2] PVT plastic scintillator which has 70% the light output of NE110[2]. The BBQ acrylic bars are 1" wide 0.5" thick and go into two 2" tubes (56AVP). We expect a delivery schedule of about 8 weeks for the trigger counters. Figure 14b illustrates the present veto wall counters which are used in lab E.

Appendix A, References

1. B. C. Barish et al, " Very large area scintillation counters for hadron calorimetery" IEEE Transactions on Nuclear Science NS-25 (1978) 532.

2. Nuclear Enterprises, San Carlos, California 94070.
3. Polytech Inc., Owensville Missouri 65066.
4. National Diagnostics, Somerville, New Jersy 08876
5. C. Aurouet et al, Nucl. Inst. and Meth. 169 (1980) 57. in particular the ALTUSTIPE blue scintillator made by ALTULOR Tour Gan, 92082, Paris La Defence, France
6. Polycast Inc., Stamford Conn., 06902
7. Rohm, GMBH Chemische Fabrik, Darmstadt, Germany

(a) ACRYLIC 5'x5' COUNTER



(b) 2½' x 10' TRIGGER OR VETO COUNTER

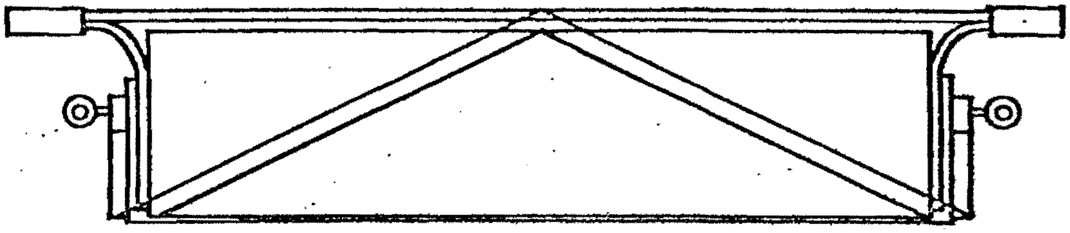


Fig. 14

a) A Wonder Bldg. target/calorimetry counter.
b) A Wonder Bldg. trigger counter. (Four of these counters make one 10 ft x 10 ft plane.)