635

Proposal to Measure $\bar{\nu}_\mu e^-$ and $\nu_\mu e^-$ Elastic Scattering, Neutrino Oscillations, and Decays of Long-Lived Neutral Particles at The Tevatron of Fermilab

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Table of Contents

I. Introduction 1

II. Physics 5

(A) Neutrino-Electron Elastic Scattering..... 5

(B) Neutrino Masses and Neutrino Oscillations 10

(C) Decay of Long-Lived Neutral Particles 13

III. Experimental Apparatus 14

(A) The Non-Magnetic Detector 15

(1) The MWPC 15

(2) The CCD Digitizer 16

(3) The Planned Test 17

(4) The Resolutions 18

(B) The Magnetic Muon Detector 19

(C) The Neutrino Beam 20

(D) Equipment Calibration 20

(E) Beam Normalization 20

IV. Counting Rates and Backgrounds 23

(A) Counting Rate for $\nu_\mu e^-$ and $\bar{\nu}_\mu e^-$ Elastic Scattering 23

(B) Background for $\nu_\mu e^-$ and $\bar{\nu}_\mu e^-$ Elastic Scattering 24

(C) Neutrino Oscillations 26

(D) Neutral Particle Decays 27

V. Other Possibilities 28

(1) $\overset{(-)}{\nu}_e e^-$ Elastic Scattering 28

(2) Search of ν_τ 29

VI. Program of Test 31

(1) Hadron and Electron Beam 31

(2) Cosmic Ray Test 31

(3) Muon Test 31

VII. Proposal and Request 32

Appendix 1 Cost Estimate 34

Appendix 2 Manpower, Resources and Support 35

References 37

Figure Captions 40

Figures 1-11 42

I. Introduction

During the past decade, the nature of high energy neutrino experiments has changed markedly. Experiments have advanced from being of low statistics and largely qualitative to being of high statistics and quantitatively and theoretically definitive. Particularly notable among the major accomplishments of neutrino experiments during that period were the discovery of weak neutral currents[1,2], detailed information on the properties of the weak charged-currents through inelastic neutrino scattering[3,4], tests of the electroweak unifying gauge theories of Weinberg and Salam[5], and direct measurements of lepton-lepton couplings[6].

With the expected turn-on of the Tevatron within the next few years, neutrino beams of hitherto unavailable energies and fluxes will be available to physicists for further experimentation. We can anticipate that with technological improvements in detectors, the prospects for better understanding of weak interactions will be substantially enhanced.

Already, provocative questions are being generated and are capable of being answered. Among these are the following:

1. How many generations of neutrinos are there and what are their properties?
2. Do the various neutrinos have a mass and are there mass differences? If there are mass differences, is it possible to determine them through oscillations between generations in much the same way as for the K_L^o-K_S^o system?
3. What are the forms of the couplings between the leptons?

Independent of particular models such as that of Weinberg-Salam, can the vector and axial vector couplings be accurately determined?

4. What theories, alternate to the standard $SU(2)_L \times U(1)$, can provide the unification scheme of the four known forces?
5. In details, how do the weak neutral currents differ from the weak charged currents?
6. Are there long-lived objects, such as axions, which could be observed in a well instrumented neutrino detector?

The list above is only intended to be representative of fundamental questions which can be addressed using today's advanced technology. When compared to physics justification of proposals submitted in the beginning of 1970's it is clear that new directions are being emphasized.

Given the many exciting possibilities presented, it is oftentimes tempting, to design an experiment which will address all questions of interest with a single detector. We have resisted the temptation to proceed along this path in the belief that a well designed apparatus intended to answer a limited but interesting set of questions has, in the long run, a better chance to yield precise measurements which can sensitively test theoretical ideas and models. We propose, therefore, a detector about which we have developed substantial expertise and which we feel can meet the goals described above.

In our considerations, we have attempted to retain the following features for the detector:

1. The technology should be advanced state of the art capable

of yielding improved precision and information not achievable with earlier generation detectors.

2. The detector should be capable of handling high data rates to eliminate the loss of events due to equipment dead-time, since tens of neutrino events per pulse are anticipated.
3. Digitization should be performed in a manner in which the essential data can be extracted in a short time. This has two components; the first is for on-line sampling to monitor the experiment, and the second is for off-line data processing.
4. The detector should have good energy, angular, and spatial resolutions so that rare processes can be cleanly separated from backgrounds arising from more abundant processes. Also, good resolution will permit precision measurements of high rate reactions.
5. A modular design, easy to understand, maintain and operate, and for which Monte Carlo calculations will be easy to perform should be preferred. This will lead to fewer uncertainties about systematic effects which will ultimately be the limiting factor with this new generation of neutrino experiments.
6. Finally, economy in costs without major compromises in capability must be sought. In this regard, ingenuity coupled together with high technical ability are requisite.

In the following sections of this proposal, we shall attempt to define and specify a particular area of neutrino physics and to demonstrate how a unique and powerful detector we have designed is capable of address-

ing. Section II will discuss the physics of interest. Section III will describe the detector in detail. Section IV will deal with rates, backgrounds, biases, calibrations and normalizations. Section V points out the possibility of using the proposed detector on beam dump experiments. Section VI discusses the program of testing and preparation between the present and 1983 when the Tevatron program is expected to commence. Section VII will deal with the proposal and request to the Laboratory. Detailed information is provided in the appendices.

II. Physics

Among the many possibilities in the field of neutrino physics, we focus upon the study of only a few important topics which may contribute to the fundamental understanding of weak interactions. These topics include neutrino-electron elastic scattering, neutrino oscillations, and the decays of long-lived particles.

(A) Neutrino-Electron Elastic Scattering:

The reactions

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-, \text{ and} \tag{1}$$

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^- \tag{2}$$

are particularly important for the study of electroweak interactions. These reactions are particularly simple in the determination of the two parameters, ρ and $\sin^2\theta_W$, in the W-S model as no complications due to quarks are involved. These two parameters are defined by the following expression for the neutral current,

$$J_\mu^{NC} = \rho\ (I_\mu^3 - \sin^2\theta_W J_\mu^{EM}), \tag{3}$$

where ρ is the ratio of neutral to charged current; I_μ^3, the third isospin component of weak current; $\sin^2\theta_W$, the mixing parameter in W-S model; J_μ^{EM}, the electromagnetic current. The cross sections for these two reactions are given by[7]

$$\frac{d\sigma^{\nu,\bar{\nu}}}{dy} = \frac{G_V^2\, m_e\, E_{\overset{(-)}{\nu}}}{2\pi} \left[(g_V \pm g_A)^2 + (g_V \mp g_A)^2 (1-y)^2 \right], \tag{4}$$

where $y \equiv E_e/E_{\overset{(-)}{\nu}}$; E_e, the outgoing electron energy; $E_{\overset{(-)}{\nu}}$, the energy of incoming ν_μ (or $\bar{\nu}_\mu$); $G_V \approx 10^{-5}/M_p^2$, the Fermi coupling constant; M_p and m_e, the mass of proton and electron; g_V and g_A, the vector and axial-vector coupling constants; and the upper signs inside the brackets are for ν_μ, while the lower ones for $\bar{\nu}_\mu$. Equation (4) is the most general expression for neutrino-electron scattering, and it requires only the existence of leptonic neutral currents. We can integrate this expression between experimental limits in electron energy, E_e, to obtain the total cross section. Using the toal cross sections, $\sigma(\nu_\mu e^-)$ and $\sigma(\bar{\nu}_\mu e^-)$, the leptonic coupling constants, g_V and g_A, can be empirically determined independent of any theoretical model. Alternatively, we can use the $\overset{(-)}{\nu}_\mu e^-$ cross sections to determine the two independent parameters, ρ and $\sin^2\theta_W$, in the W-S model. It should be recalled that there exists also in the W-S model the condition

$$\rho \equiv \left| \frac{M_Z}{M_W \cos\theta_W} \right|^2 = 1, \tag{5}$$

where M_Z and M_W are the masses of the intermediate vector bosons, Z° and $W^\pm$, respectively. Under such circumstances, g_A is definitely predicted to be

$$g_A = -1/2, \tag{6}$$

and g_V is related to the single remaining parameter, $\sin^2\theta_W$, by the relationship

$$g_V = 2\sin^2\theta_W - 1/2. \tag{7}$$

There exist theoretical models, e.g., the symmetric left-right gauge models $SU(2)_L \times SU(2)_R \times U_{B-L}(1)$ and $U_L(2) \times U_R(2)$[8], or the graded gauge model $SU(2/1)$[9], in which the value of $\sin^2\theta_W$ can be calculated, rather than leaving it as an experimental parameter. They all predict $\sin^2\theta_W = 1/4$, which is equivalent to $g_V = 0$ and $g_A = -1/2$. This prediction implies that, in purely leptonic weak interactions, the electron current is a purely axial vector. The left-handed and the right-handed couplings are equal in magnitudes, but opposite in sign. However, some of the grand unification schemes, such as SU(5), call for $\sin^2\theta_W \lesssim 0.19$[10]. It is imperative to resolve this issue by an $\overset{(-)}{\nu}_\mu e$ elastic scattering experiment of good statistics.

During the past years, substantial progress has been made in the measurement of $\overset{(-)}{\nu}_\mu e^-$ elastic scattering. The results are summarized in Table 1.

Table 1

Experiment	Experimental Group	No. of Events
$\nu_\mu + e^- \to \nu_\mu + e^-$	GGM[11]	<0.7
	Aachen-Padova[12]	11.5
	BNL-Columbia[13]	11.0
	GGM[14]	3.6
	CHARM[15]	6.5
	E-253 (Fermilab)[16]	34.0
$\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$	GGM[17]	3.0
	Aachen-Padova[18]	9.6
$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	Savannah River[19]	-460*

*See footnote in reference 19.

These purely leptonic scattering experiments can provide definitive results, free from hadronic complications; but they lack adequate statistics. Also, the prediction of $g_A = -1/2$ in the standard $SU(2)_L \times U(1)$ model of W-S has not been critically tested in these reactions. Further, the ambiguity in $g_V \rightleftarrows g_A$ cannot be resolved by the study of $\overset{(-)}{\nu}_\mu e^-$ elastic scattering alone. Because Eq.(4) is an expression quadratic in g_V and g_A, its plot in the g_V - g_A plane is an ellipse. The intersections of the two ellipses, corresponding to $\nu_\mu e^-$ and $\bar{\nu}_\mu e^-$ elastic scattering, yield four pairs of solutions on g_V and g_A. This four-fold ambiguity can be resolved if we include also the following two reactions:

$$\nu_e + e^- \rightarrow \nu_e + e^- \tag{8}$$

and

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-. \tag{9}$$

In these two reactions, both charged and neutral current contribute. Their cross sections can also be calculated by Eq.(4) with the substitutions $g_V \rightarrow 1 + g_V$ and $g_A \rightarrow 1 + g_A$. Without doing all four purely leptonic scattering experiments, the uniqueness of the solution for g_V and g_A can only be obtained by using the interference term between the electromagnetic and weak interaction currents in the experiment of $e^+ + e^- \rightarrow \mu^+ + \mu^-$; or by the factorization relationship[20] together with the data from polarized eD scattering[21] and $\overset{(-)}{\nu}$ N reactions[22]. Summary of the present status is shown in Figure 1.

Within the context of the standard $SU(2)_L \times U(1)$ theory of W-S, with spontaneous symmetry breaking being induced by Higgs doublets, or alternatively with a γ-W^o interference scheme a la Sakurai, the value of $\rho \equiv |\frac{m_W}{m_Z \cos\theta_W}|^2$ can be unity. However, higher order radiative corrections[23], which are calculable and finite in the gauge theory, could cause a finite value for $(\rho-1)$. For instance, the loop corrections to the $W^\pm$ propagator can be different from those to the Z^o propagator as shown in figure 2. As $q^2 \rightarrow 0$, the $W^\pm$ and Z^o self energy parts will differ, and we will have

$$\rho = 1 + 8\pi^2 G_V^2 \, m_f^2 + (\text{logarithmic terms}), \tag{10}$$

where m_f refers to the mass of the fermion which circulates in the loop. If we use the presently available value for ρ from the $\overset{(-)}{\nu}$ N experiments:

$$\rho = 1.01 \pm 0.03^{(24)} \tag{11}$$

then we obtain $m_f \lesssim 500$ GeV. A better limit on ρ would therefore improve the upper bound on the mass of the heaviest quark allowed.

The new experiment we plan to perform at Fermilab on the Tevatron anticipate obtaining $\gtrsim 1{,}000$ $\nu_\mu e^-$ and $\gtrsim 200$ $\bar{\nu}_\mu e^-$ events. This should allow us to determine both ρ and $\sin^2\theta_W$ to an accuracy of ± 0.01, or alternatively g_A and g_V to an accuracy of about ± 0.02. Results of such an accuracy will allow us to make definitive comparisons with the predictions of various gauge models, e.g., $g_A = -1/2$ in the standard model, $\sin^2\theta_W \lesssim 0.19$ in SU(5), $\sin^2\theta_W = 0.25$ in the left-right symmetric models; and to establish better limits on the right-handed couplings and the masses of the heavier gauge bosons. It should be noted that the experimental accuracy can be further improved by increasing the number of $\bar{\nu}_\mu e^-$ events.

(B) Neutrino Masses and Neutrino Oscillations

The question of the finiteness of the neutrino mass, for each of the three known generations, has been most crucial to a number of theories. It can answer the question whether the neutrinos could be Majorana particles, or whether there exist right-handed neutrinos. The experimental values of the neutrino masses at the present time are:

$$m(\nu_e) < 0.00007 \text{ MeV},$$
$$m(\nu_\mu) < 0.51 \text{ MeV},$$
$$m(\nu_\tau) < 250 \text{ MeV}.$$

On the assumption that the neutrinos of each generation are Majorana particles, Mohapatra and Senjanovic[25] have derived an expression for the neutrino mass in terms of the right-handed weak vector boson W_R:

$$m_{\nu_\ell} = \frac{m_\ell{}^2}{g m_{W_R}^2}$$

where g is the coupling constant in the standard gauge theory; m_ℓ, the charged lepton mass; m_{W_R}, mass of the right-handed weak vector boson.

If the neutrino masses are indeed unequal and non-zero, we could write[26] (consider two generations of neutrinos here only for the sake of brevity):

$$\begin{aligned} \nu_e &= \nu_1 \cos\theta_\nu + \nu_2 \sin\theta_\nu \\ \nu_\mu &= -\nu_1 \sin\theta_\nu + \nu_2 \cos\theta_\nu \end{aligned} \tag{13}$$

where θ_ν is an empirical mixing parameter; ν_1 and ν_2, the neutrino mass eigen-states. In the event that $\theta_\nu \neq 0$, we might have a neutrino oscillation process, $\nu_\mu \rightleftharpoons \nu_e$, very much similar to the $K_L^o - K_S^o$ system. The probability of finding the neutrino as an ν_e from an originally ν_μ beam is given by

$$P(\nu_e) = \sin^2(2\theta_\nu)\sin^2\left[\frac{(m_1{}^2 - m_2{}^2)\,\ell}{4p}\right] P(\nu_\mu) \tag{14}$$

where ℓ is the distance traversed by the neutrino; p, the momentum of the neutrino; m_1 and m_2, the mass of ν_1 and ν_2; $P(\nu_e)$, the probability of finding the neutrino in the state $|\nu_e\rangle$. Previously, physicists used to envisage doing a neutrino oscillation experiment by mounting a detector on a vehicle and vary the length ℓ away from the neutrino source. At lower energies, low fluxes and small cross sections lead to low event rates and make the experiments apparently impractical. With the advent of the Tevatron, the neutrino spectrum can extend to energies as high as 600 GeV and about 1000 neutrino interactions/hr. can be observed. The technique is to use a low effective density detector of ~100 meters in length,

and to compare the charged current interactions induced by electron neutrinos of different energies as a function of distance. If the mass difference is too large, the oscillation wavelength is too small to allow any observation and vice versa for too small a mass difference. Within a window of $\Delta m \simeq 1 \sim 10^3$ eV[27], there is a chance to observe the neutrino oscillations.

As a numerical example, we consider a hypothetical case:

$$m_1 = 0 \text{ eV},$$
$$m_2 = 100 \text{ eV},$$
$$\Delta\ell = 100 \text{ m(detector length)},$$
$$p = 600 \text{ GeV/c}.$$

The oscillation phase angle is given by

$$\Delta\phi = \frac{(m_2^2 - m_1^2)\Delta\ell}{4p} \simeq \frac{(10^{-7})^2 \times 10^4}{4 \times 600 \times (2\times10^{-14})} \simeq 2 \text{ rad.}$$

The oscillation wavelength is given by

$$\lambda \simeq \frac{2\pi}{2} \times 100 \text{ m} \simeq 300 \text{ m}.$$

The corresponding quantities for p = 100 GeV/c will be

$$\Delta\phi \simeq 12 \text{ rad.},$$
$$\lambda \simeq 30 \text{ m}.$$

Therefore, by comparing the charged current interaction rates as a

function of distance, ℓ, for neutrinos of different momenta, there could be a possibility of observing the neutrino oscillations and establish a much lower mass limits for the neutrinos.

(C) Decay of Long-Lived Neutral Particles:

In the neutrino production target, there could be new neutral particles produced which might live long enough to reach the detector. Their decay products could be detected and separated from ν interactions by spacing the detector modules with an air gap of ~0.5 meters. The appearance of event vertices in the air gap should indicate clearly the existence of such particles because there is no background[28].

There could also be neutral heavy leptons, coupled weakly to ν_μ and decaying into muon pairs. The presence of such particles signifies an underlying structure a little more complicated than that implicit in the standard model. Neutrino experiments to date placed a lower mass limit of ~3-4 GeV for such fermions. The Tevatron offers the prospect of searching for these leptons with heavier masses. From a theoretical point of view, a non-zero neutrino mass is in all likelihood accompanied by the presence of neutral heavy leptons; so that this study nicely complements the proposed experiment on neutrino oscillations.

Experimentally, the best means of determining the signal for neutral heavy lepton production is by studying the characteristic energy-independent invariant dimuon mass distribution[29], especially for those dimuon events with a small energy asymmetry. At the higher energies available at the Tevatron, one could expect a detectable signal for the production of heavy leptons with masses up to about 8-9 GeV[29].

III. Experimental Apparatus

In order to study the aforementioned subjects on $\overset{(-)}{\nu}_\mu e^-$ elastic scattering, neutrino oscillation and particle decays, the main detector should be a long, low effective density, fine-grained calorimeter of the type employed by us in E-253 for the measurement of $\nu_\mu e$ scattering cross section. This calorimeter measures the directions and energies of electrons, muons, and hadrons and identifies them by their interaction characteristics when they do not spatially overlap. Good angular resolution is of prime importance in indentifying the $\overset{(-)}{\nu}_\mu e^-$ events. In order to deal with ν_τ search and $\overset{(-)}{\nu}_e e^-$ scattering in beam dump experiments, two important related subjects to be discussed later, it is also most desirable to have the capability of measuring the direction and energy of each individual hadron produced in neutrino interactions if possible.

Following the non-magnetic calorimeter is a simple and standard magnetic spectrometer, made of toroidal magnets and drift-chambers, to measure directly the neutrino flux spectrum. By monitoring reactions such as

$$\nu_\mu(\bar{\nu}_\mu) + N \rightarrow \mu^-(\mu^+) + \text{Hadrons}, \tag{15}$$

or

$$\nu_\mu + n \rightarrow \mu^- + p, \tag{16}$$

and through Monte Carlo calculations, normalizations, acceptances, and biases can be determined.

(A) The Non-Magnetic Detector

The arrangement of a non-magnetic calorimeter is shown in Figure 3. There are 200 modules; 3m x 3m in cross section and 480 tons in total weight. Each module consists of one MWPC and one 1 r.ℓ. thick aluminum plate (~9 cm, including the aluminum walls of the MWPC).

The aluminum plates serve as both the target for interactions and the radiator for the detection. Aluminum is presently being chosen because it contains a larger number of atomic electrons per radiation length as compared to other dense materials such as iron, etc. If iron plates are required for the sake of economy, the counting rates for $\overset{(-)}{\nu}_{\mu} e^{-}$ scattering will then be reduced by a factor of two. Water radiator and target is another possibility but suffers from a reduction in inter-modular gap spacing which is important for new particle searches.

(1) The MWPC

The constructions of the MWPC[30] is shown in Figure 4a. The cathode planes are made of thick aluminum jig plates with copper-clad G-10 plates epoxied onto them. On the copper-clad G-10 plates, zigzag delay-lines are milled with a spacing of 2 mm. Delay-lines on the two cathode planes of one MWPC are arranged along orthogonal directions to measure both x- and y-positions of traversing particles in terms of time intervals.

This delay-line configuration offers a number of advantages other than being economic. For electromagnetic showers, there are too many particles involved in each chamber. It would be a difficult task in trying to digitize every one of

them. By capacitive action, this group of particles will induce a localized cluster of charges on the cathode planes. Afterwards, the induced pulse train will propagate along the long transmission line to the tap points, then be fed into the time-to-digital converters (TDC's). In order to minimize attenuations and dispersions along the delay-line, on each cathode plane we will break the delay-line into 20 pieces. Each piece of the delay-line will be digitized at one end (the other end can also be conncected to a TDC if economy allows). This arrangement will eliminate the left-right ambiguities, and also limit the maximum transit time to ~1 μsec.

The anode wires will be connected into a hodoscope configuration, 10 cm wide for each element. The signal from each element will be fed into an analogue-to-digital converter (ADC) to measure the energy deposition. Also, these anode signals will be used to form the experimental trigger. Since the beam pulse length should be of the order of 1 second, faster timing achievable with scintillators is unnessary because of the very low triggering rates expected.

(2) <u>The CCD Digitizer</u>

We have successfully developed a new type of TDC's using charge-coupled devices (CCD's). These CCD digitizers will be used on the cathode plane delay-lines. The principle of this device is illustrated in Figure 4b. The CCD is continuously clocked at 50 MH_z. The incoming pulse from a given cathode tap is thus quantized into 20 nsec intervals. Charges contained in

each interval will be loaded into successive CCD buckets. For each clock pulse, the charges in each bucket will shift one bucket position. When it reaches the end, a fast ADC will start to act, digitizing the charges stored in each bucket successively. By the mean time, a scanner will keep track of the CCD bucket number. In essence, the CCD digitizer works like a superscope because it retains the complete information of the profiles of the pulses on the delay-line. The charge information will provide measurements of energy depositions. The CCD bucket numbers will yield the track position information.

It should be noted that the track positions can be measured very accurately by the CCD digitizers. Since the pulse profile (or the charge distribution along the transverse direction) is known, we can weigh the position measurements by the corresponding charges to obtain the centroid positions properly. This will be particularly helpful for measuring electromagnetic showers. Also, we do not need tilted wire planes to resolve the combinatorial ambiguities. The absolute position of a particle (or the centroid of an electromagnetic shower) is given simply by the propagation time along the delay-line.

(3) <u>The Planned Test</u>

We are currently in the process of converting the existing E-253 electronics into CCD digitizers. The task involves re-

placing all the amplifiers and TDC's. There are 49 MWPC's, 1m x 1m in size. Altogether, there are 490 channels of CCD digitizers.

It is anticipated that the electronics can be finished sometime during the spring of 1980. We will then make a realistic test run in the Wonder Building to learn the performances of these devices. Additional testing in various test beams will also be performed to measure energy and angular resolutions for various particles and to develop pneumonics for identifying particles.

(4) The Resolutions

In E-253 at Fermilab, the TDC's only measured the "leading" and the "trailing" edges of an electron induced shower. Shower centroids were assumed to be the midpoint of the two edges. The angular resolution achieved in this manner for that experiment was ±5 mr. With this resolution, the $\nu_\mu e^-$ elastic scattering events were clearly separated from the copious π^0 background. Figure 5 shows the angular distribution of the E-253 results[16]. Figure 6 shows the corresponding transverse momentum distribution. The $\nu_\mu e^-$ signal to background was clearly capable of separation.

By converting the CCD digitizers mode, we anticipate improving the angular resolution to approximately ±1 mr. The energy resolution for electron detection should remain approximately the same, $\sigma(E_e)/E_e \simeq (20/\sqrt{E_e})\%$; and for hadrons,

$\sigma(E_h)/E_h \simeq (100/\sqrt{E_h})\%$.

If the tracks are not overlapping, we can follow each individual particle to obtain its energy by adding up the energy depositions measured by the CCD digitizers. The capability of measuring both the energy and angle of each particle in a multiple-track event is of utmost importance in some experiments, e.g., ν_τ search, and the (x,y) distributions of neutral current interactions. As far as we know, these difficult tasks have not been done yet mainly because of inadequate spatial and localized energy resolutions. The approach being adopted for the proposed detector cannont solve all these problems, but certainly shows promise for alleviating part of them.

(B) The Magnetic Muon Detector

A simple magnetic spectrometer, located behind the calorimeter, is required to detect the outgoing muons. Among many purposes, it is essential for determining the neutrino flux which we will explain in a later section. The magnetic muon detector is shown in Figure 7. It consists of two segments of toroidal magnets, each followed by a set of drift chambers. Each toroids has a modest size of 4 m in diameter and 1 m in depth. We could use those toroids already in existence. If the calorimeter of this proposal could be located in front of a magnetic spectrometer facility, we envisage then that there will be no necessity for us to build another muon detector.

(C) The Neutrino Beam

The neutrino spectra, using various focussing devices, as calculated by S. Mori[31], are shown in Figure 8.

For the $\overset{(-)}{\nu}_{\mu} e^{-}$ elastic scattering and the neutrino oscillation experiments, we propose using the sign-selected single-horn focussed beam because the wrong-signed neutrino backgrounds can be suppressed.

For the long-lived particle decay experiment, we can run in any one of the following three modes: single-horn focussing, quadrupole-triplet foccusing, and bare target. The experiment can be done in a parasitic mode.

(D) Equipment calibration

A hadron beam of rather weak intensity is needed for equipment calibration in the experimental hall. Specifically, the energy resolution and calibration for hadrons have to be measured carefully. This is particularly necessary if we want to know the energy of each individual hadron utilizing the CCD digitizing technique. Since the hadron beam always contain a few percent of electrons, we can utilize them to calibrate the calorimeter for electron detections. Questions on pion-electron separation, angular resolution, etc., can all be answered with the test beam.

(E) Beam Normalization

We have already mentioned that the main systematic error of experiments on neutrino interactions is from the uncertainty in our knowledge about the neutrino flux. With the combination of a fine-grained calori-

meter and a magnetic muon spectrometer, the energy distribution of the neutrino intensity can be measured directly. The method is to use a restricted central fiducial volume of the apparatus and measure the charged current interactions $\overset{(-)}{\nu}_\mu + N \rightarrow \mu^\pm$ + hadrons. In these reactions, the sign and the momentum of the outgoing muon are measured by the magnetic spectrometer, while the hadronic energy is determined by the calorimeter. The sum yields the incoming neutrino energy. Therefore, the intensities for both ν_μ and $\bar{\nu}_\mu$ can be separately determined.

The experimental determination of the ν_e and $\bar{\nu}_e$ components of the flux is not as easy. Unlike the $\overset{(-)}{\nu}_\mu$ case, we cannot simply rely upon the reactions

$$\nu_e + N \rightarrow e^- + \text{hadrons}, \tag{17}$$

and

$$\bar{\nu}_e + N \rightarrow e^+ + \text{hadrons}, \tag{18}$$

because (1) we cannot tell the sign of the electron charge, (2) there are single π^0 productions in the neutral current interactions of ν_μ and $\bar{\nu}_\mu$, and (3) there are $\overset{(-)}{\nu}_e e^-$ elastic scatterings. The problem, however, is not nearly as formidable as it appears. The beam composition is anticipated to be approximately 90% ν_μ, 10% $\bar{\nu}_\mu$, and $\lesssim$1-2% ν_e and $\bar{\nu}_e$. Once the spectra of ν_μ and $\bar{\nu}_\mu$ are known, we can compare the distribution for the reactions:

$$\nu_\mu + n \rightarrow \mu^- + p,$$
$$\bar{\nu}_\mu + P \rightarrow \mu^+ + n, \tag{19}$$

with those for the sum of the following two reactions:

$$\nu_e + n \rightarrow e^- + p,$$
$$\bar{\nu}_e + p \rightarrow e^+ + n. \qquad (20)$$

The shape of the distributions has be similar and the normalization constant has to be fixed by a Monte Carlo beam calculation. There are π^o contributions to reaction (20), mainly from the productions by $\overset{(-)}{\nu}_\mu$. Their rates can be calculated and subtracted from the measurements.

IV. Counting Rates and Backgrounds

Before proceeding to discuss the details about the counting rates, backgrounds, etc., for $\nu_\mu e^-$ and $\bar{\nu}_\mu e^-$ elastic scattering, we like to make a brief and general remark on this subject. In the past, we were deeply worried, and being repeatedly and correctly asked, about the problem of backgrounds for doing experiment on such rare processes. The questions were centered at π^0, quasi-elastic scattering and charged current interactions of $\overset{(-)}{\nu}_e$. In Experiment E-253 at Fermilab, $\nu_\mu e^-$ elastic scattering was measured with an instrumentation resolution of $\Delta\theta \simeq \pm 5$ mr. As illustrated in Figures 5 and 6, by applying the forward angular cut first and then examining the transverse momentum distribution, a signal-to-noise ratio of approximately 10:1 was achieved. Based on this empirical fact and the anticipated improved angular resolution of $\Delta\theta \simeq \pm 1$ mr, a signal-to-noise ratio of about or better than 20:1 is a reasonable expectation for the proposed $\overset{(-)}{\nu}_\mu e^-$ elastic scattering experiment at the Tevatron.

(A) Counting Rate for $\nu_\mu e^-$ and $\bar{\nu}_\mu e^-$ Elastic Scattering

For 3×10^{18} protons of 1 TeV incident upon the neutrino production target, single-horn focussing, and the proposed detector of 3 m x 3 m x (200 layers) x (9 cm Al/layer), we estimate that the total number of events for the reactions, $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ and $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$, are approximately 1,000 and 200, respectively. The assumed ν_μ and $\bar{\nu}_\mu$ fluxes are those given by Mori[31]. The fiducial volume is approximately 2.8 m x 2.8 m x (190 layers). The cross sections used are given by

$$\sigma(E) = \frac{G_V^2 \, m_e \, E}{2\pi} \left[(g_V \pm g_A)^2 + \frac{1}{3} (g_V \mp g_A)^2 \right] \tag{21}$$

where E is the energy of the incident ν_μ or $\bar{\nu}_\mu$; the upper signs inside the brackets are for ν_μ, and the lower signs for $\bar{\nu}_\mu$; the coupling constants are set to $g_V = 0$ and $g_A = -1/2$, corresponding to $\sin^2\theta_W = 1/4$ in the W-S model.

In the g_V - g_A plane, the ellipses corresponding to the statistics due to 1,000 $\nu_\mu e$ events and 200 $\bar{\nu}_\mu e$ events are shown in Figure 9. The prediction of W-S, $g_A = -1/2$, is also shown. It can be seen that the value of $\sin^2\theta_W$ can be measured to the accuracy of $\sim\pm 0.01$, quite comparable to the present precision of $\overset{(-)}{\nu}N$ interactions and eD scattering experiments. Since there are no theoretical complications due to uncertainty of strong interaction effects, this proposed experiment should be able to settle the question on the exact value of $\sin^2\theta_W$, if the W-S model is correct. Also, we emphasize once again, it also provide a model independent determination of g_V and g_A.

(B) <u>Background for $\nu_\mu e^-$ and $\bar{\nu}_\mu e^-$ Elastic Scattering</u>

The background for $\nu_\mu e^-$ and $\bar{\nu}_\mu e^-$ elastic scattering are from the following processes:

$$\begin{aligned} \nu_\mu + N &\rightarrow \nu_\mu + \pi^o + X, \\ \bar{\nu}_\mu + N &\rightarrow \bar{\nu}_\mu + \pi^o + X, \end{aligned} \tag{22}$$

and

$$\nu_e + n \rightarrow e^- + p,$$
$$\bar{\nu}_e + p \rightarrow e^+ + n. \tag{23}$$

The kinematics for the neutrino-electron elastic scattering is such that its characteristic angular width is given by $\theta_e \simeq \sqrt{m_e/E_\nu}$, which is much narrower that that for the π^o, $\theta_{\pi^o} \simeq \sqrt{M_N/E_\nu}$; where M_N is the nucleon mass. Therefore, the π^o background can be separated very easily from the $\overset{(-)}{\nu}_\mu e^-$ elastic scattering events by their angular distributions of the outgoing electromagnetic showers. This is illustrated by Figure 5, which is the result of Experiment E-253 measured at Fermilab.

The angular distribution of e^- (or e^+) from the quasi-elastic scattering of $\overset{(-)}{\nu}_e$ is sharper than that described by the characteristic angle, $\theta \simeq \sqrt{M_N/E_\nu}$, because of the elastic nucleon form factors[32]. Since the cross section is fairly large, $\sim 10^{-38}$ cm^2, a few percent of $\overset{(-)}{\nu}_e$ containation can, in principle, make an appreciable contribution to the forward peak corresponding to $\overset{(-)}{\nu}_\mu e^-$ elastic scattering. In reality, we do not have great difficulty in separating these quasi-elastic events from the $\overset{(-)}{\nu}_\mu e^-$ events. The technique is to examine the transverse momentum distribution of those events in the forward peak. The $\overset{(-)}{\nu}_\mu e^-$ events all have small p_T ($\leq$300 MeV/c) and their distribution is sharply peaked at $p_T \simeq 100$ MeV/c. On the other hand, quasi-elastic scattering of $\overset{(-)}{\nu}_e$ gives higher energy to the outgoing electron (positron) which leads to higher values of p_T and a broader p_T distribution, centered at $p_T \simeq 500$ MeV/c. As illustrated in Figure 6, which is the result measured with E_p = 350 GeV and $\Delta\theta \simeq \pm 5$ mr, the background events (including π^o's) can be easily subtracted. With the better angular resolution which we anticipate for this proposed

experiment, of $\Delta\theta \simeq \pm 1$ mr, both the angular and the p_T distributions are expected to be improved. Therefore, by the very straightforward double selection of small θ and p_T, the background problem can be satisfactorily resolved.

(C) Neutrino Oscillations

For 3×10^{18} protons at 1 TeV and with single horn focussing, approximately 7 million charged current interactions of ν_μ in the proposed detector will be detected. It is a reasonable assumption that the ν_e flux is $\lesssim 2\%$ of the ν_μ flux. Then we will anticipate ~140,000 events due to the charged current interactions of ν_e. If there are neutrino oscillations, $\nu_\mu \rightleftarrows \nu_e$, the number of ν_e induced charged current interactions may be appreciably enhanced. As the calorimeter is particularly suitable for the detection of electrons, we can perform a meaningful search of the neutrino oscillations with better reliability.

The distance from the neutrino source to the detector is approximately 800 m, the experimental sensitivity is approximately given by

$$\Delta m^2 \simeq \frac{4\,E_\nu}{\ell} = \frac{4\,E_\nu(2 \times 10^{-14})}{(8\times10^4)\,(10^{-18})} \simeq E_\nu \qquad (\mathrm{eV})^2$$

where E_ν is the neutrino energy in GeV. From the known production mechanism and the decay processes, we should be able to calculate approximately the ν_e flux for the case of no neutrino oscillations. If the detector, located at a distance of $\ell \simeq 800$ m downstream, sees a rate of ν_e charged current interactions several times larger than that anticipated, then the neutrino oscillation would be a suspect.

Since the proposed detector has a length of $\Delta\ell \simeq 100$ m, we will measure the reaction, $\nu_e + N \rightarrow e^- +$ hadrons, and analyze the results as a function of the longitudinal distance along the detector and the neutrino energy to see the finer details of the oscillation. We anticipate to narrow down the neutrino mass difference, $(\Delta m^2)^{1/2}$, to a few electron volts.

(D) Neutral Particle Decays

The possibility on the existence of new long-lived particles is totally speculative. There is no meaningful way available for us to estimate the counting rates. From the experimental point of view, it is going to be a very clean search. We will look for those events whose vertices fall between the detector modules. Since the background has to be production from air target by secondary beams, it will be totally negligible. The sources of these long-lived particles are not known. They could come from the proton dump, or the muon and neutrino interactions in the shielding berm. We should be able to observe the decay vertices if the lifetime is nearby $\sim 10^{-6}$ sec.

We propose to conduct this search on a parasitic mode.

V. Other Possibilities

Although we do not presently propose doing more than what has been already discussed and proposed, we would like to point out that this proposed calorimeter has the potential of being adaptable to other possible experiments because of its inherent excellent capability in electron detection and good spatial and energy resolutions. Specifically we believe that the apparatus can be easily adapted to the following possibilities:

(1) $\overset{(-)}{\nu}_e e^-$ Elastic Scattering

In the past, there had been designs for possible ν_e and $\bar{\nu}_e$ beam based the decay processes $K_L^o \to \pi^- e^+ \nu_e$ and $K_L^o \to \pi^+ e^- \bar{\nu}_e$. The beam intensities are relatively low[33]. It was pointed out by Albright and Shrock that the best way to produce copious ν_e and $\bar{\nu}_e$ beam is from the decay of the D meson in a high energy proton beam dump[34]. The anticipated fluxes are shown in Figure 10. Because the beam intensity decreases rapidly with angle, we use only a 2 mr cone to estimate the counting rates.

For the elastic scattering processes:

$$\nu_e + e^- \to \nu_e + e^-$$
$$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$$

the coupling constants are given by the W-S model as $g_A = 1/2$ and $g_V = 1$ for $\sin^2\theta_W = 1/4$. The ratios of the total cross sections are given by

$$\sigma(\nu_\mu e^-):\sigma(\bar{\nu}_\mu e^-):\sigma(\nu_e e^-):\sigma(\bar{\nu}_e e^-) = 1:1:7:3 \qquad (24)$$

With 3×10^{18} protons of 1 TeV on a beam dump, we anticipate that approximately 140 $\nu_e e^-$ events, 60 $\bar{\nu}_e e^-$ events, and 90 background events from the quasi-elastic scattering of ν_e and $\bar{\nu}_e$ will be observed.

The major difficulty of this experiment is the flux normalization. Since we do not yet have an exact knowledge of the D production mechanism (e.g. the A-dependence, etc.), there is no easy way to normalize the cross section. Also, we cannot separate the $\nu_e e^-$ events from the $\bar{\nu}_e e^-$ events. The $\overset{(-)}{\nu}_e N$ quasi-elastic scattering events can be subtracted out from the P_T-distribution.

(2) Search of ν_τ

It is generally believed that there are three generations of leptons and quarks. The members so far which have escaped detection are the t-quark and the ν_τ. It was pointed out by Albright and Shrock[34] that the best way to produce a ν_τ beam is from the F decays in a high energy beam dump. The reactions initiated by an incident $\overset{(-)}{\nu}_\tau$ are the following:

$$\overset{(-)}{\nu}_\tau + N \rightarrow \overset{(-)}{\nu}_\tau + \text{hadrons}$$

and

$$\overset{(-)}{\nu}_\tau + N \rightarrow \tau^\pm + \text{hadrons}$$

$$\tau^\pm \rightarrow \begin{cases} \overset{(-)}{\nu}_\tau + \text{hadrons} \\ \overset{(-)}{\nu}_\tau + e^\pm + \overset{(-)}{\nu}_e \\ \overset{(-)}{\nu}_\tau + \mu^\pm + \overset{(-)}{\nu}_\mu \end{cases} \qquad (25)$$

The only unambiguous way to identify the ν_τ induced reaction is to examine the decay mode of $\tau^\pm \rightarrow \overset{(-)}{\nu}_\tau + \mu^\pm + \overset{(-)}{\nu}_\mu$, and to construct the transverse-momentum vectors in a plane perpendicular to the incident $\overset{(-)}{\nu}_\tau$ as shown in Figure 11. The azimuthal-angle and the missing momentum distributions are also shown. In order to perform this task, it is clear that we have to be able to measure the momenta of the muon and the hadrons. Apparently, this proposed detector can do a fairly good, if not complete, job on this interesting subject.

One of the reasons for limiting our program is that the latter two possibilities are beam dump experiments and consequently require different beam lines and locations from those of our primary areas of interest.

VI. Program of Test

For a massive neutrino calorimeter as we are proposing, test and calibration of the apparatus are not small undertakings. We have to debug the hardware and the software. And we have to equalize the gain of each module, and to know the calibration constants and resolution functions. Since we apparently cannot move the detector around easily, we need to be able to test at the experimental location. This entails the following procedures:

(1) Hadron and Electron Beam

A hadron beam should be available to the apparatus. Its small electron component is equally useful. The calorimeter responds differently to the hadrons and the electrons. We have to calibrate the apparatus with both beams.

(2) Cosmic Ray Test

Once a fraction of the detector modules is equalized in gain (e.g. 20 to 30 modules), we can equalize the gains of the whole detector assembly using cosmic rays. By our experience with E-253, we can set the high voltages to ±2 volts for the MWPC's, and ±1 volt for the photo-multipliers. The total running period with cosmic rays was about two months.

(3) Muon Test

Timing of fast electronics and chamber alignment can be done with stray muons without any special requirements.

VII. Proposal and Request

We propose to build a non-magnetic calorimeter, as described above, to study some specific aspects of neutrino physics at Fermilab. Also, we will build the drift chambers for the magnetic muon detector if necessary.

We request the laboratory to provide us with the following items:

1. The laboratory space to house the detector together with the necessary utilities. An overhead crane may be required to handle the equipment.
2. Fast electronics from PREP. This will not include the CCD digitizers. (See Appendix 1)
3. A hadron beam for testing the detector.
4. Toroid magnets for muon measurements. This may not be necessary if the proposed detector can be located in front of a magnetic detector facility.
5. 200 aluminum plates, 3 m x 3 m x 7 cm, to be used as target/radiators or equivalent.

We anticipate finishing the construction of 200 MWPC's, together with amplifiers and CCD digitizers, within two years starting from the date on which funding commences. Most of the equipment can be installed and tested during this construction period.

We further request:

1. Three months testing time with the hadron and electron beam.
2. 3×10^{18} protons at 1 TeV on the neutrino production target and

with single-horn focussing to measure the cross section for $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$. We anticipate obtaining about ~200 events.

3. 3×10^{18} protons at 1 TeV on the neutrino production target and with single-horn focussing to measure the cross section for $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$. We anticipate obaining ~1,000 events.
4. Parasitic running time for neutrino oscillations and search for long-lived neutral particle decays.

Appendix 1

Cost Estimate

In this appendix, we only include the cost estimate for the non-magnetic detector proper. Laboratory space, hadron beam line, utilities, magnetic toroids, etc., are excluded at this time.

1.	Construction of 200 3 m x 3 m MWPC's, labor and material included @ $12,000/chamber.	$2,400,000
2.	Electronics for 200 MWPC's included all CCD digitizers, ADC's, and amplifiers.	$ 600,000
3.	200 aluminum plates 3 m x 3 m x 7 cm each, total weight ~380 tons.	$ 700,000
4.	Cables, H.V. and L.V. power supplies for chambers, gas manifold, tools, misc.	$ 500,000
5.	Contingency (10%)	$ 400,000
	Total	$4,600,000

Appendix 2

Manpower, Resources and Support

(1) Manpower

There are presently five senior physicists who will lead the proposed experiment and the construction of the facility. We will recruit about six post-doctorals and four graduate students to participate in this undertaking. Also, we are inviting physicists from other institutions to participate. Eventually we hope to increment the number of physicists to the level of about twenty.

The senior engineer of this collaboration is T. A. Nunamaker. He will supervise constructions of the equipment, as well as the necessary R & D.

(2) Resources and Support

In this collaboration, the Fermilab members are supported by DOE; V.P.I. members, by a research grant from the National Science Foundation; members from the Institute of High Energy Physics, by the PRC Government; and a member by N.S.F.

We are inviting other institutions to participate this collaboration. Negotiations by our collaborators from P.R.C. with their Government is also underway for equipment support. The projected cost of the detector can be shared by the participating institutions. Since it can be distributed over a period of 2 1/2 years, it should not appear as an unusual burden as far as funding of neutrino experiments is concerned.

The chamber construction will need a rather large working space and staging area. We plan to negotiate the use of the User's Support Center of Argonne National Laboratory.

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Figure Captions

Fig. 1 Determination of the νe coupling constants. The factorization constraint due to Sakurai is also shown.

Fig. 2 Loop corrections to the intermediate boson propagators.

Fig. 3 Schematic arrangement of the non-magnetic calorimeter. The dimension is 3 m x 3 m x 200 modules.

Fig. 4a Schematic of the MWPC.

Fig. 4b Schematic illustration of the CCD digitization. The ADC digitizes the charge in each CCD bucket, and the scanner records the CCD bucket number. The CCD is clocked at 50 MHz.

Fig. 5 The angular distribution of the reaction, $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$, measured in E-253 at Fermilab. There are 46 events in the angular range $0 \leq \theta \leq 10$ mr.

Fig. 6 The transverse momentum distribution of the events shown in Fig. 5 and within the angular range of $0 \leq \theta \leq 10$ mr. The "background" events have $E\theta^2 \geq 3$ MeV.

Fig. 7 Schematic of the magnetic muon spectrometer.

Fig. 8 Neutrino Spectra at the Tevatron.

Fig. 9 Determination of νe coupling constants with 1,000 $\nu_\mu e^-$ and 200 $\bar{\nu}_\mu e^-$ elastic scattering events, respectively.

Fig. 10 Neutrino fluxes from a 1 TeV proton beam dump, calculated by C. Albright and S. Mori. See footnote of Ref. 34.

Fig. 11 Distributions in (a) azimuthal angle of the transverse momentum vectors. H denotes the hadron vector; μ, the muon vector; and m, the transverse momentum vector of the two

missing neutrinos; ϕ, the angle between any two of the three vectors, and (b) missing momentum perpendicular to the beam direction and normal to the apparent production plane shown as solid curves for the chain reaction $\nu_\tau + N \rightarrow \tau^- + X$, $\tau^- \rightarrow \nu_\tau + \mu^- + \bar{\nu}_\mu$ with cuts $E_\mu > 4$ GeV, $E_H \geq 5$ GeV. The dashed curves refer to the corresponding $\bar{\nu}_\tau$ reaction.

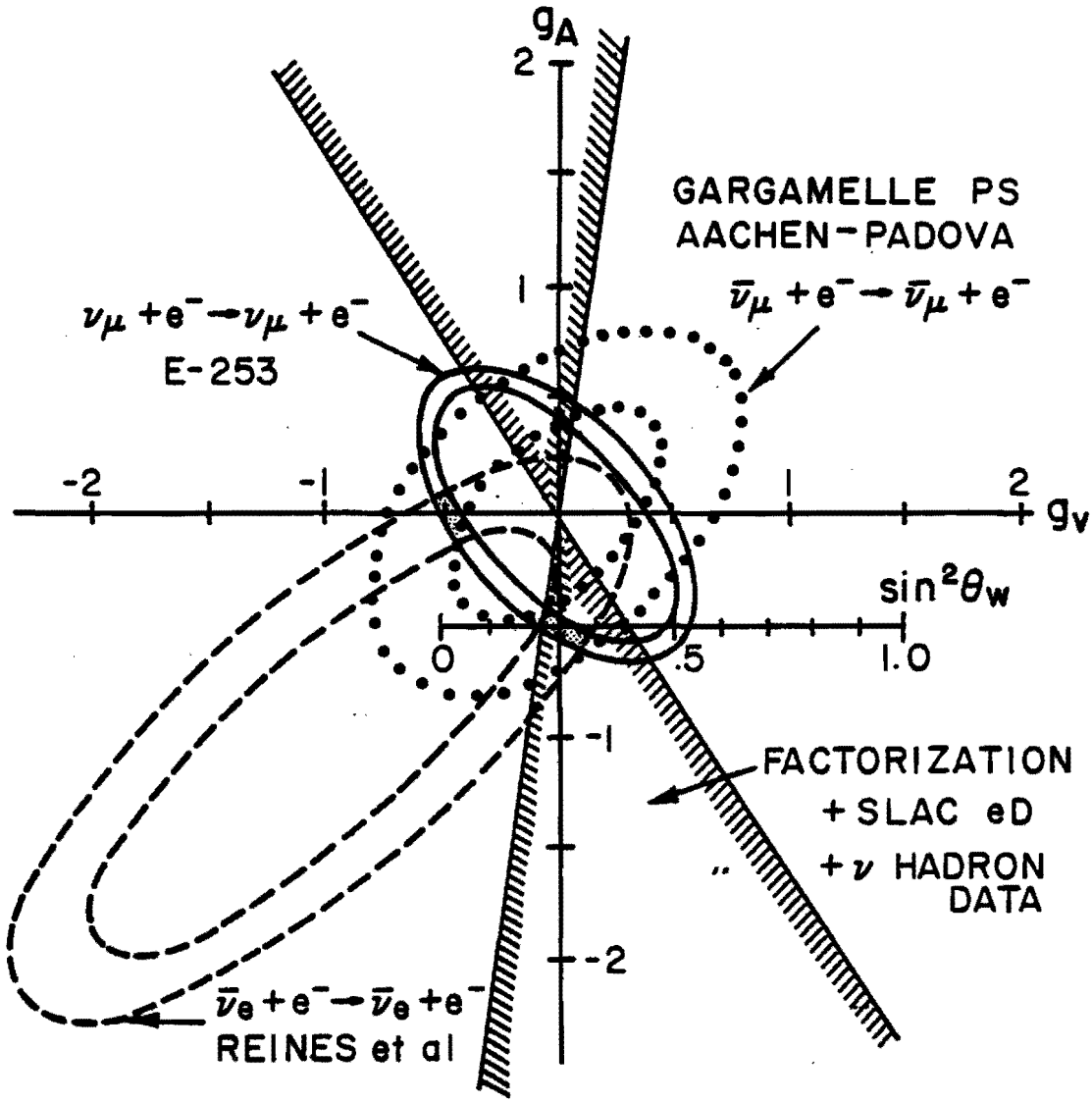

g_A
2
1
-1
-2
-2
-1
1
2
g_V
$\sin^2\theta_W$
0
.5
1.0
GARGAMELLE PS
AACHEN-PADOVA
$\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$
$\nu_\mu + e^- \to \nu_\mu + e^-$
E-253
FACTORIZATION
+ SLAC eD
+ ν HADRON
DATA
$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$
REINES et al

FIG. 1

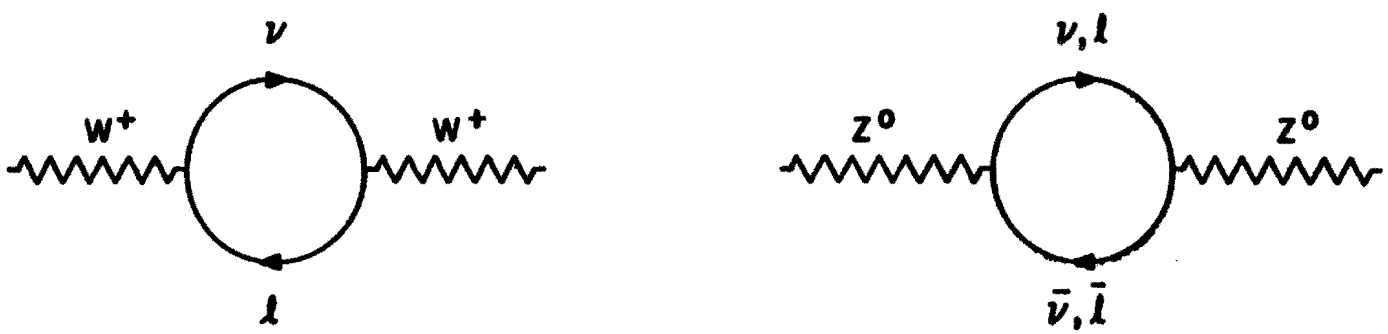


FIG. 2

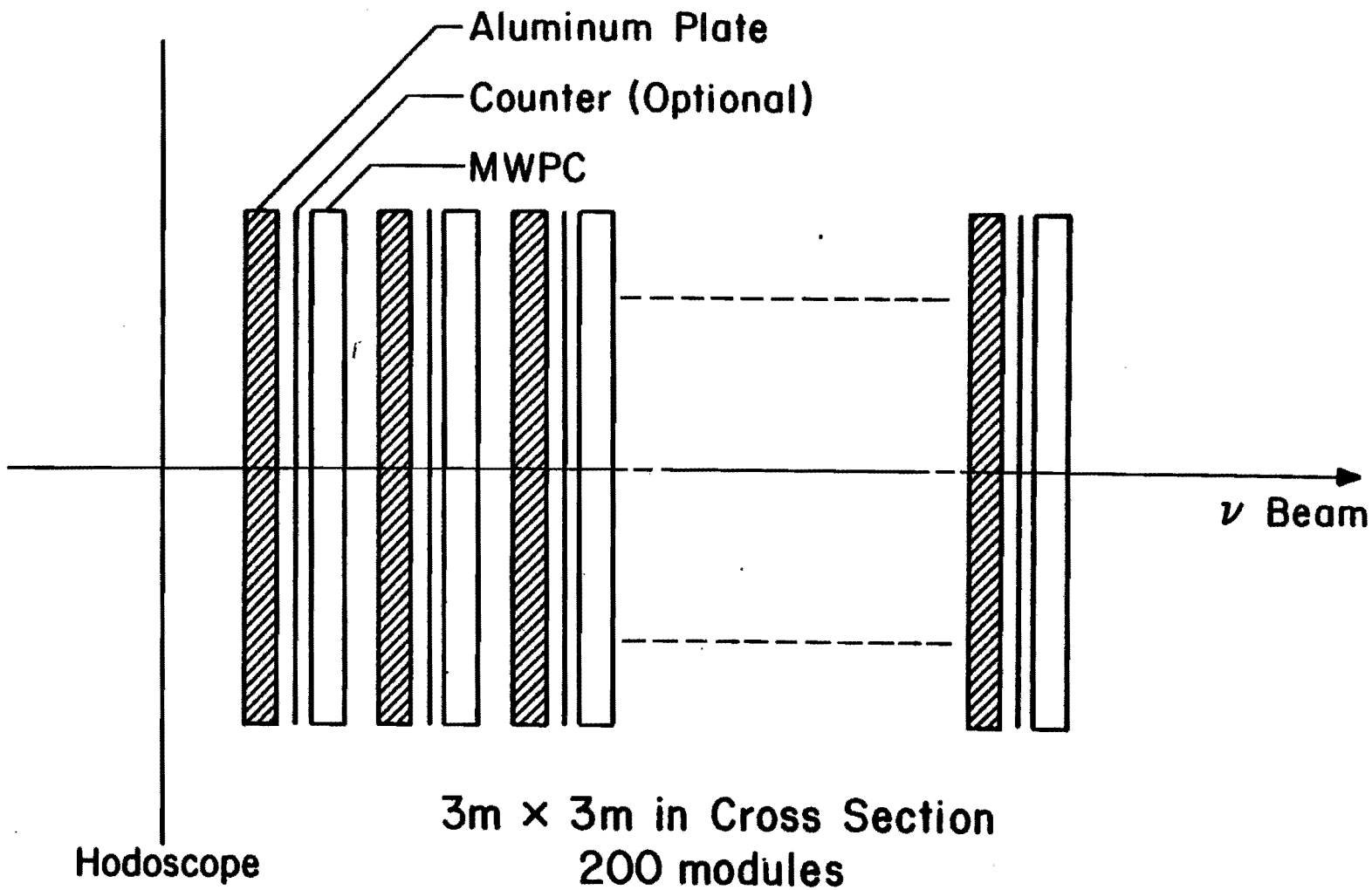

Aluminum Plate
Counter (Optional)
MWPC
ν Beam
Hodoscope
3m × 3m in Cross Section
200 modules

FIG. 3

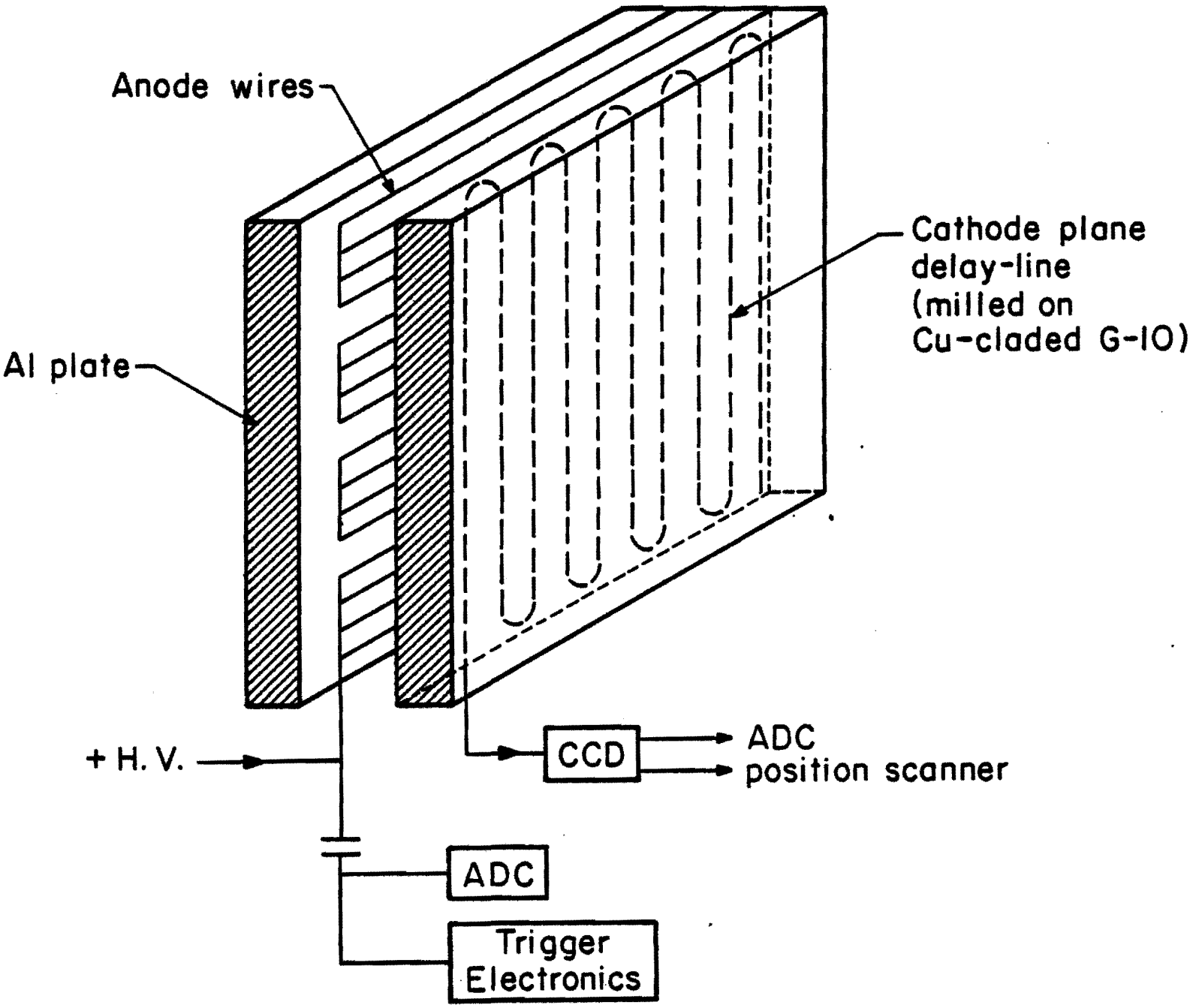

Anode wires
Cathode plane
delay-line
(milled on
Cu-claded G-10)
Al plate
+ H. V.
CCD
ADC
position scanner
ADC
Trigger
Electronics

FIG. 4a

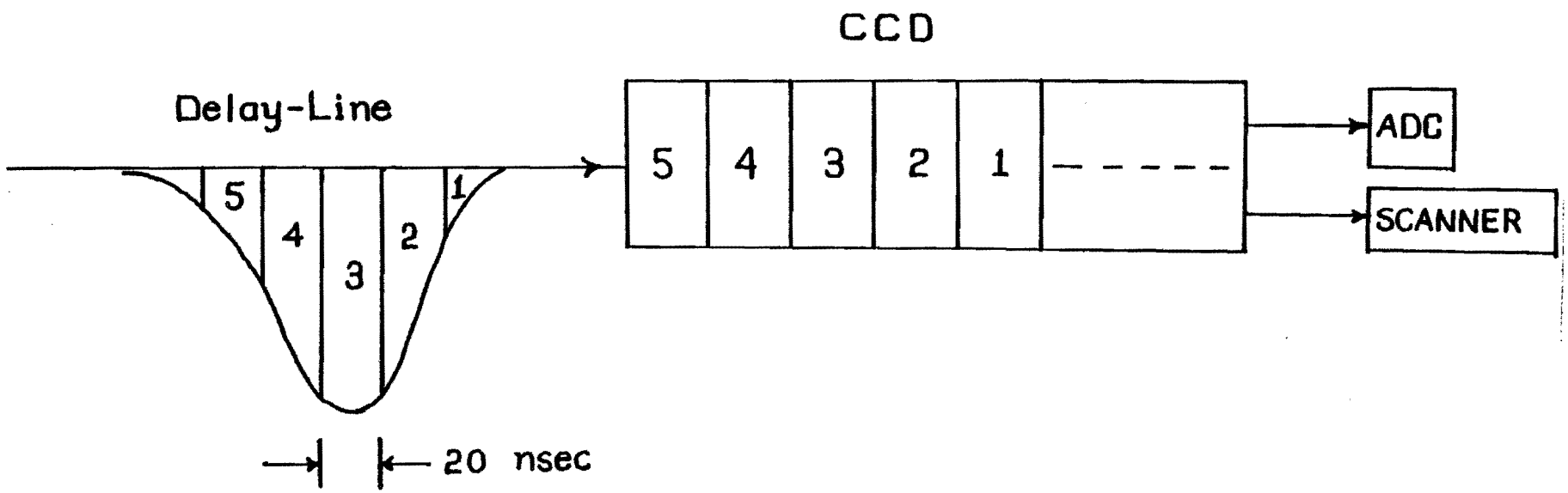


FIG. 4b

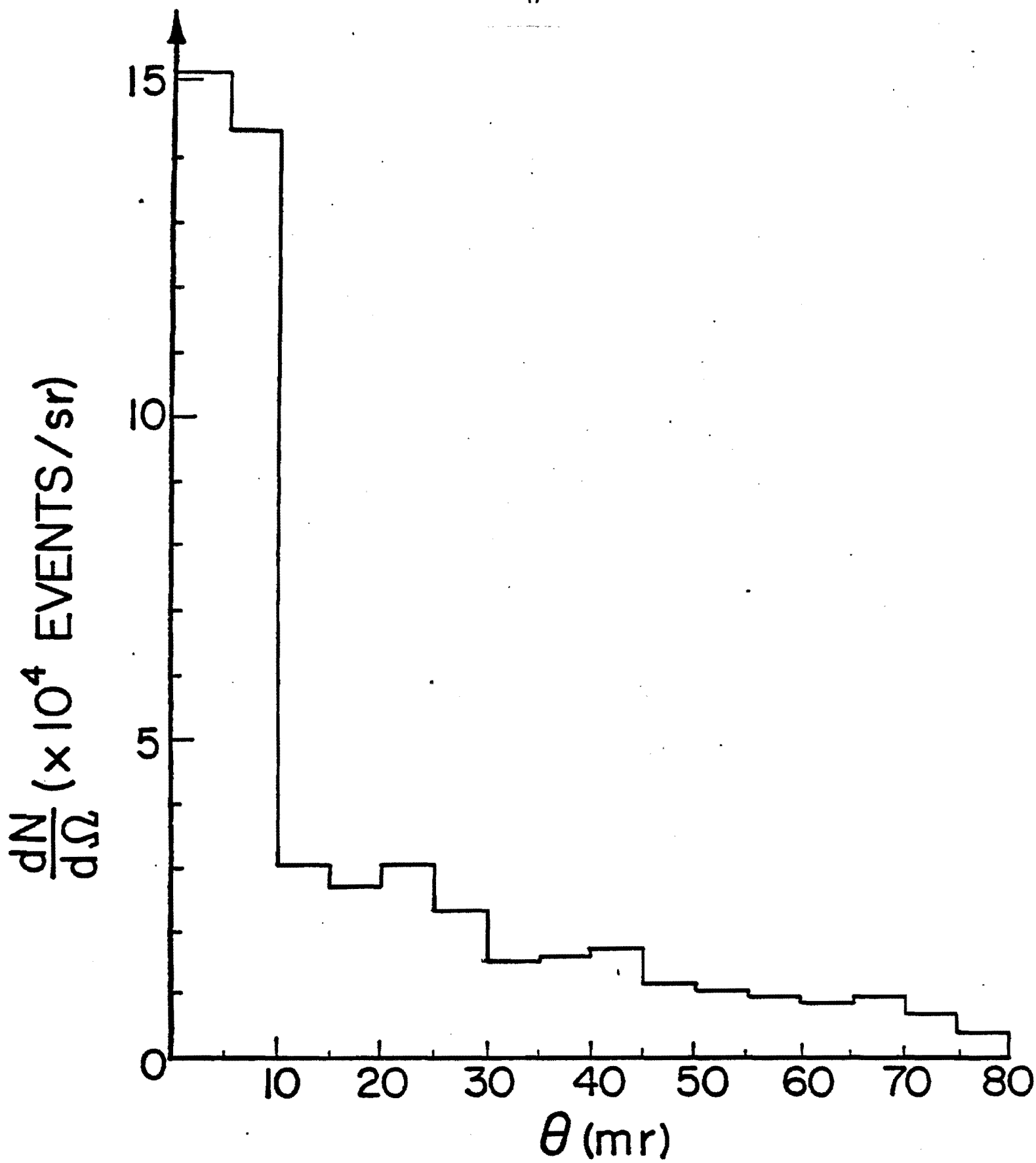

15
10
5
0
10
20
30
40
50
60
70
80
$\frac{dN}{d\Omega}$ ($\times 10^4$ EVENTS/sr)
θ (mr)

FIG. 5

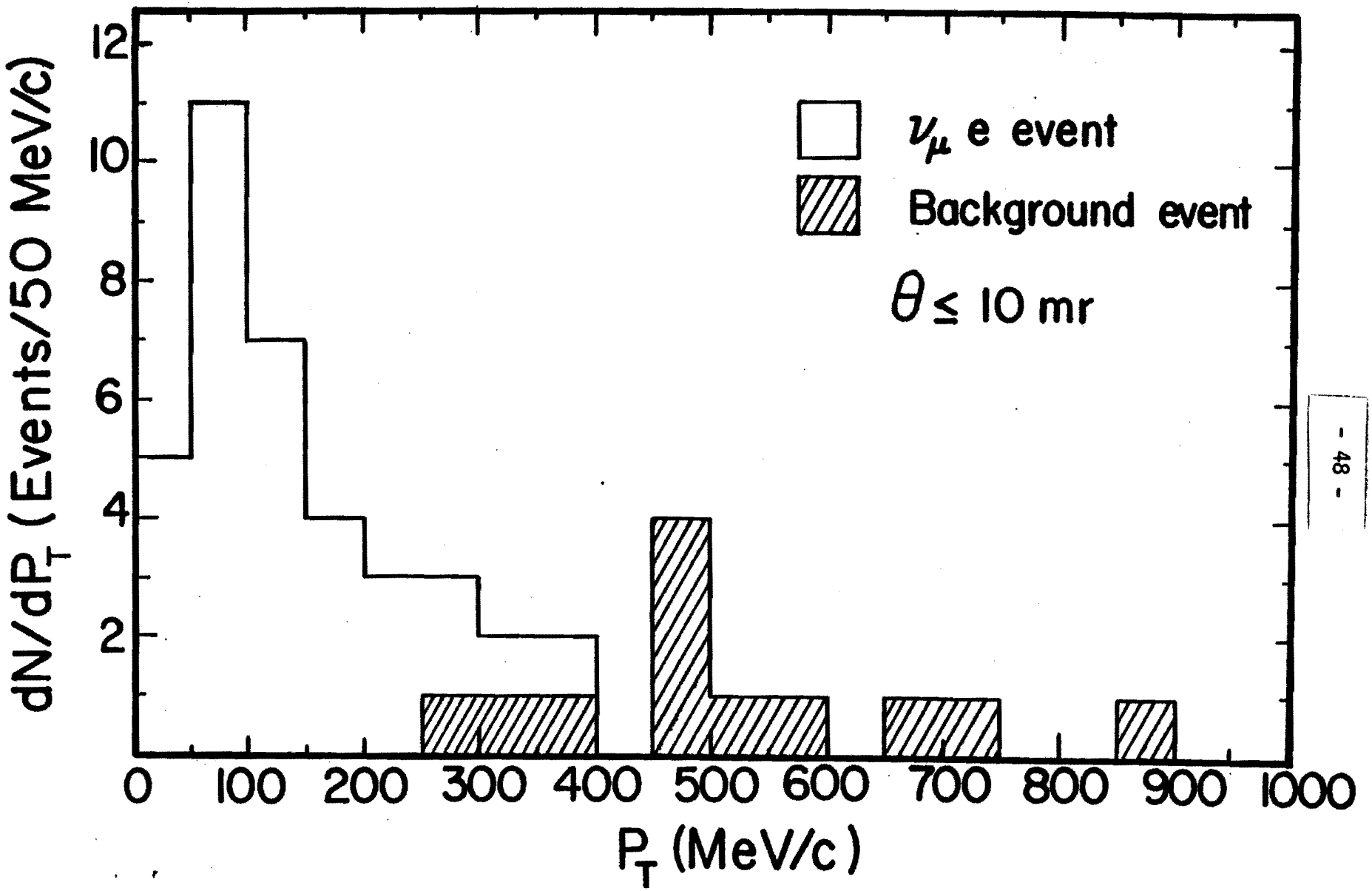

ν_μ e event
Background event
$\theta \leq 10$ mr
dN/dP$_T$ (Events/50 MeV/c)
P$_T$ (MeV/c)
0
100
200
300
400
500
600
700
800
900
1000
2
4
6
8
10
12

FIG. 6

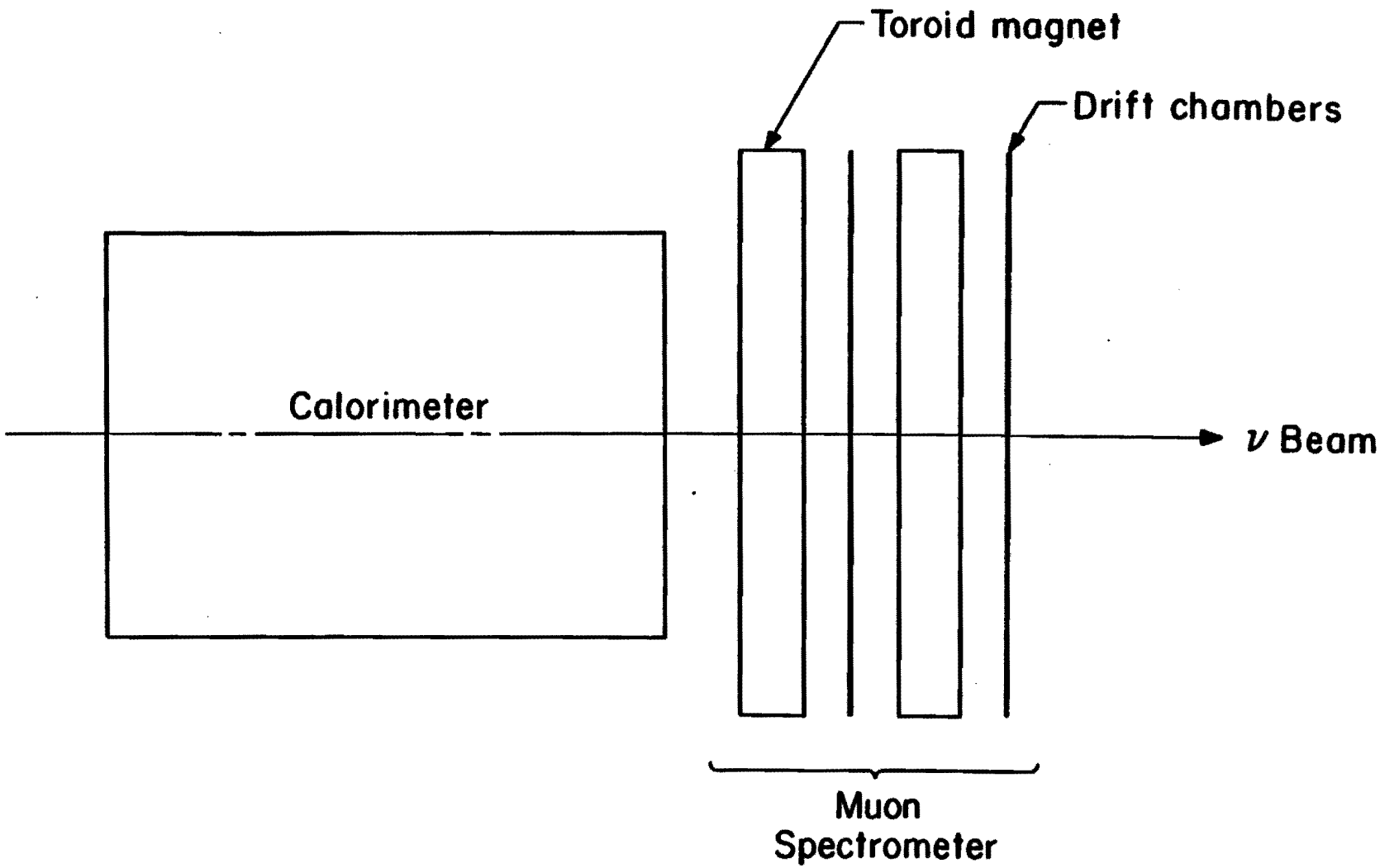
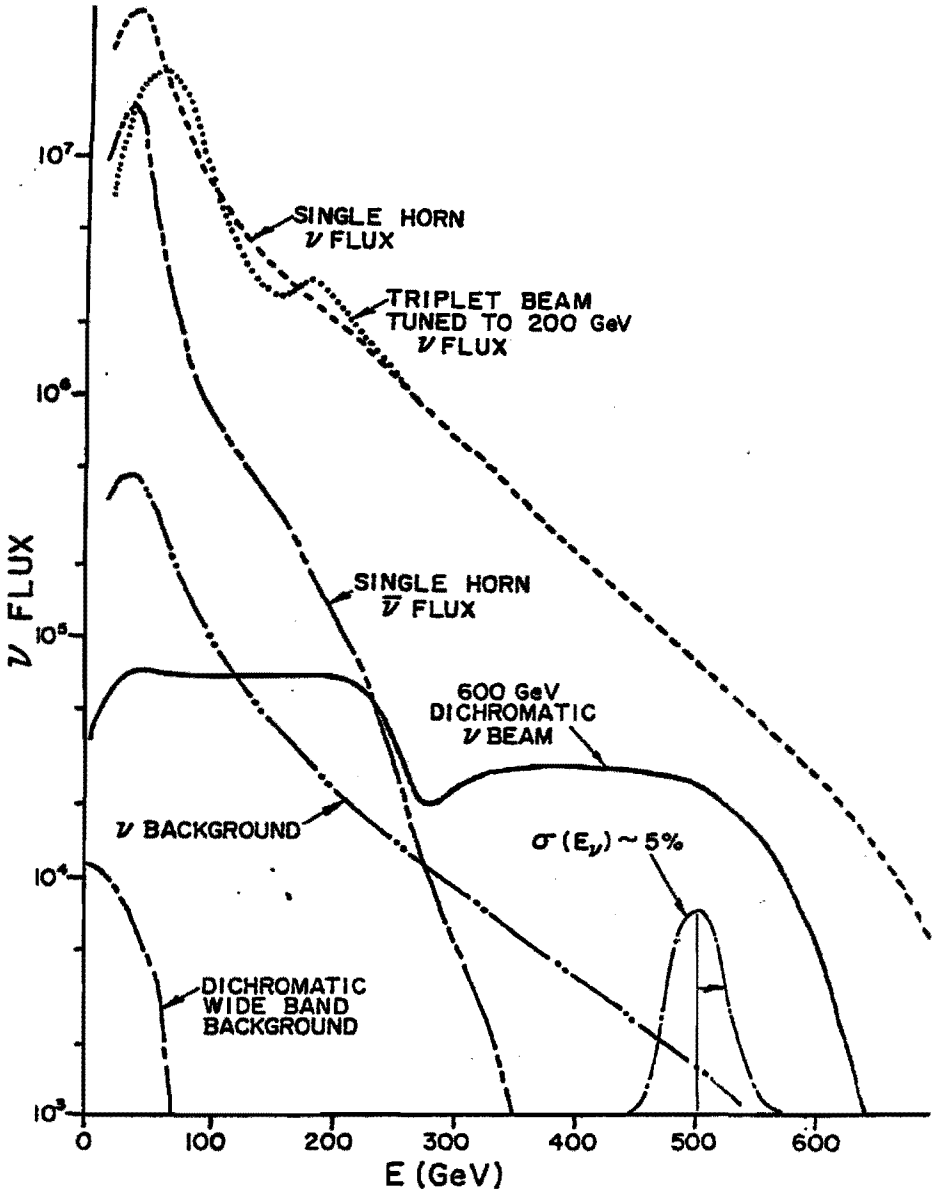

Toroid magnet
Drift chambers
Calorimeter
ν Beam
Muon
Spectrometer

FIG. 7



Tevatron Neutrino Fluxes
($\nu/m^2/GeV/10^{13}$ p's)
1-TeV Protons Incident on $1m^2$ Detector at 1400m Distance

FIG. 8

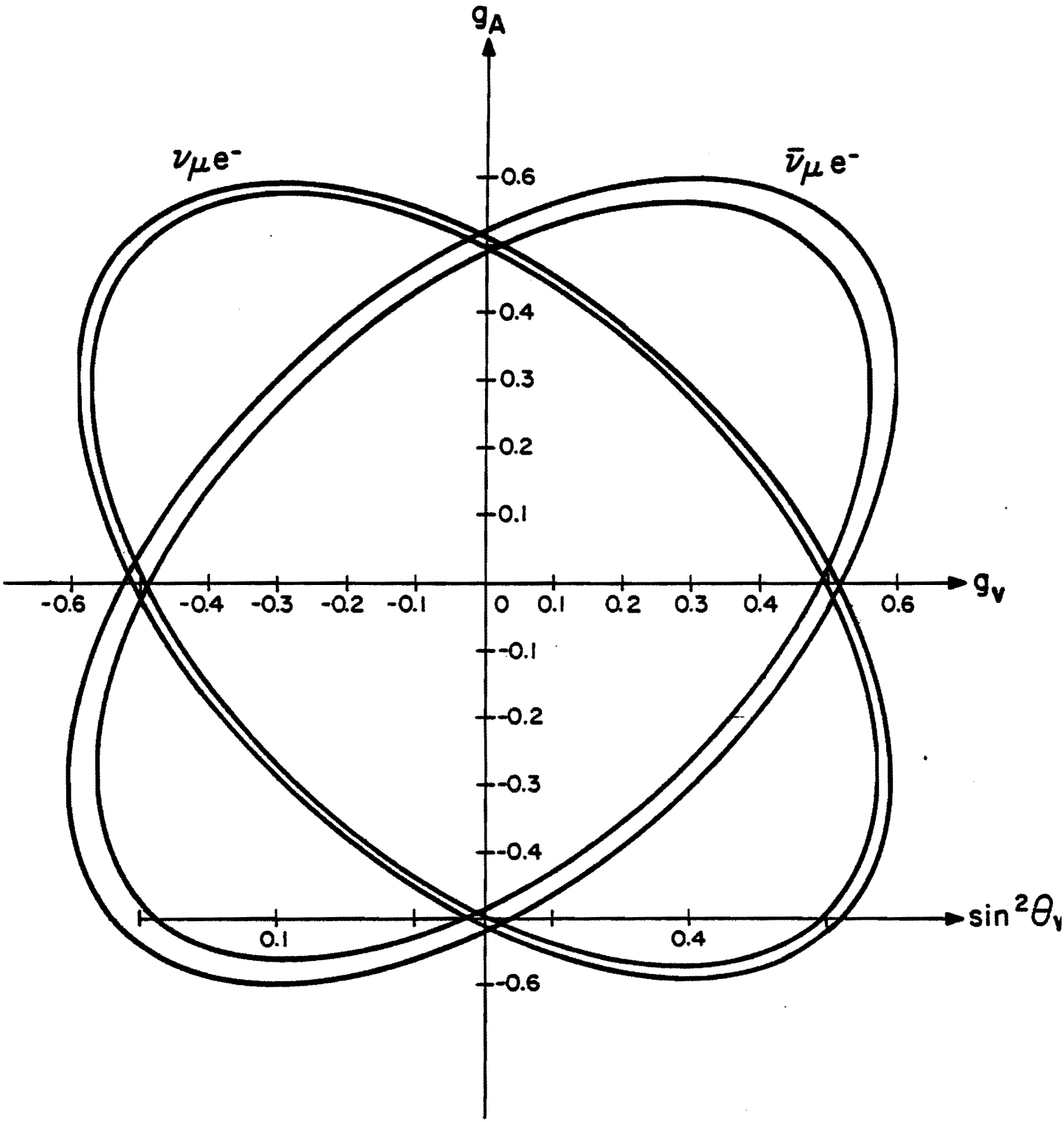

g_A
$\nu_\mu e^-$
$\bar{\nu}_\mu e^-$
0.6
0.4
0.3
0.2
0.1
-0.1
-0.2
-0.3
-0.4
-0.6
g_V
-0.6
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.6
$\sin^2\theta_V$
0.1
0.4

FIG. 9

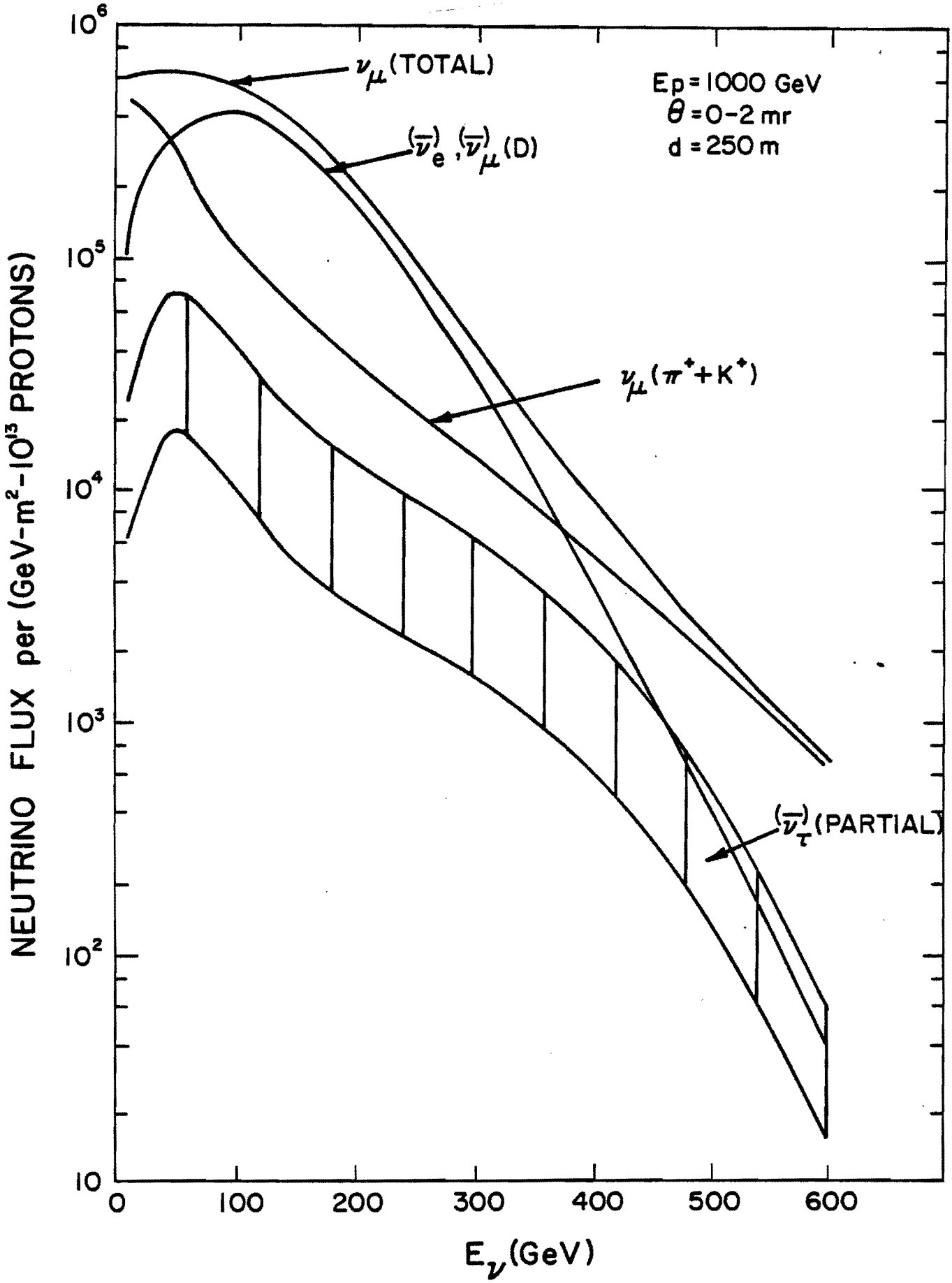

10^6
10^5
10^4
10^3
10^2
10
0
100
200
300
400
500
600
NEUTRINO FLUX per (GeV-m^2-10^{13} PROTONS)
E_ν(GeV)
ν_μ(TOTAL)
$(\bar{\nu})_e$, $(\bar{\nu})_\mu$(D)
$\nu_\mu(\pi^+ + K^+)$
$(\bar{\nu})_\tau$(PARTIAL)
Ep = 1000 GeV
θ = 0-2 mr
d = 250 m

FIG. 10

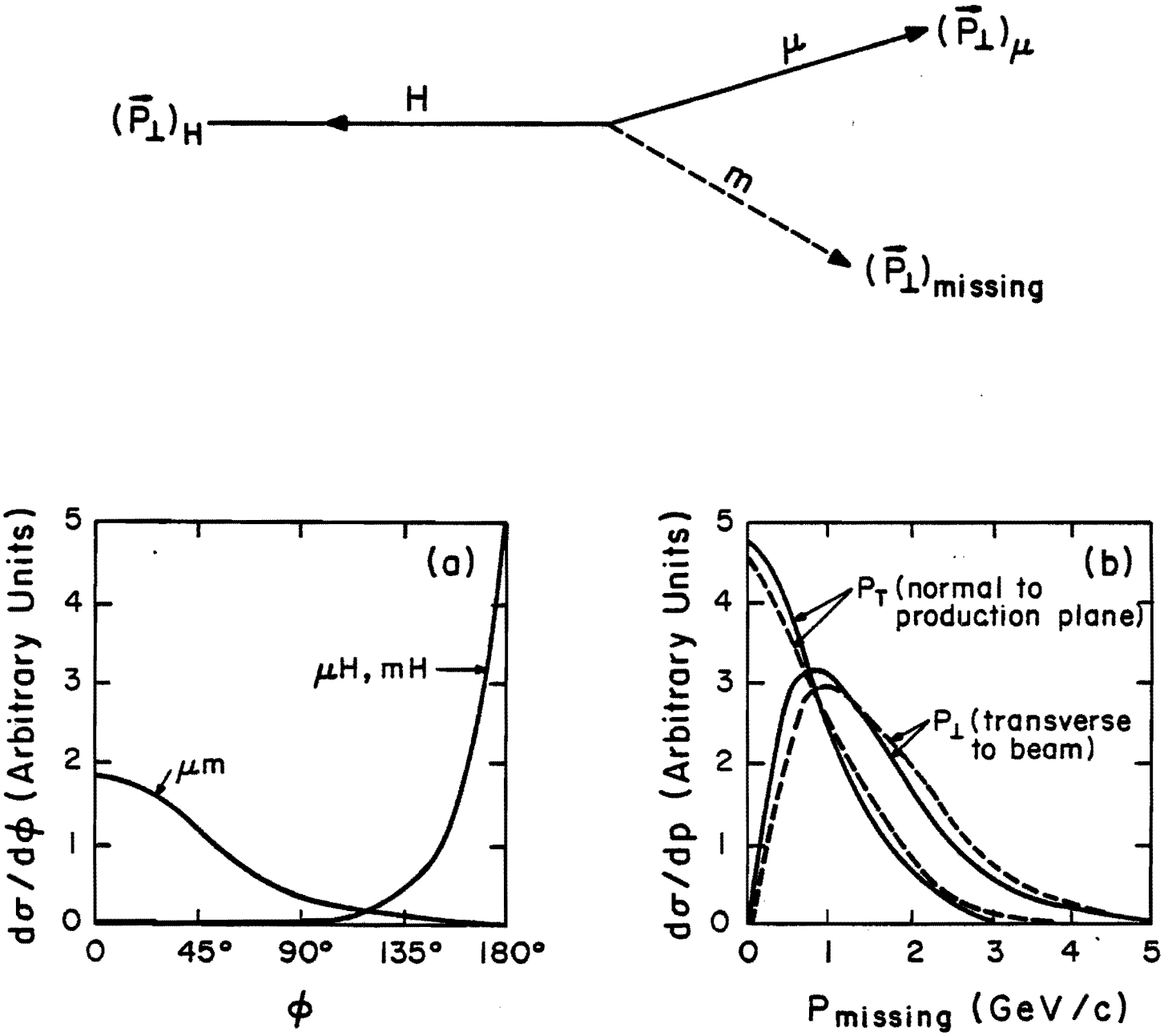

$(\vec{P}_\perp)_H$
H
μ
$(\vec{P}_\perp)_\mu$
m
$(\vec{P}_\perp)_{missing}$
(a)
$d\sigma/d\phi$ (Arbitrary Units)
μH, mH
μm
0
45°
90°
135°
180°
ϕ
(b)
$d\sigma/dp$ (Arbitrary Units)
P_T (normal to production plane)
$P_\perp$ (transverse to beam)
$P_{missing}$ (GeV/c)

FIG. 11

Proposal # 635
Letter
CD File
ML
PVL
PPO
RDO

Addendum A

Neutrino Oscillations and νe^- Scattering

Recently it has been pointed out[1] that neutrino oscillations can have a significant effect upon elastic νe scattering: they can amplify the $\nu_\mu e^-$ scattering cross section and diminish the $\nu_e e^-$ one. This can be illustrated by a beam of neutrinos which, at time t, is an admixture of ν_e and ν_μ:

$$|\nu(t)\rangle = \alpha(t)|\nu_e\rangle + \beta(t)|\nu_\mu\rangle, \tag{A1}$$

where

$$|\alpha(t)|^2 + |\beta(t)|^2 = 1. \tag{A2}$$

The νe elastic scattering cross section measured at time t is given by

$$\sigma(\nu(t)e^-) = |\alpha(t)|^2\, \sigma(\nu_e e^-) + |\beta(t)|^2\, \sigma(\nu_\mu e^-). \tag{A3}$$

Since $\sigma(\nu_e e^-) = 7\,\sigma(\nu_\mu e^-)$ for the value of $\sin^2\theta_W = 1/4$, obviously we will have the inequality:

$$\sigma(\nu_e e^-) > \sigma(\nu(t)e^-) > \sigma(\nu_\mu e^-), \tag{A4}$$

provided $\alpha(t)$ and $\beta(t)$ are non-vanishing. This observation definitely complicates the data analysis if neutrino oscillations indeed exist.

In order to study this effect, we use an interesting model, due to

(1) S.P. Rosen and B. Kayser, Preprint (June 1980).

Wolfenstein[2] and Zee[3], as a working example. In this model, the standard SU(2) x U(1) is extended by the addition of an extra Higgs doublet ϕ and a singlet charged Higgs h. Only one Higgs doublet is allowed to couple to the leptons and the singlet is used to change the lepton flavor. By a process shown in Figure A1, the neutrino oscillation can occur. The mass eigen-values are given by

$$\begin{aligned} m_1 &= m_o\ \sigma\ \sin 2\theta_\nu, \\ m_2 &= m_o(1 + \tfrac{1}{2}\ \sigma\ \sin 2\theta_\nu), \\ m_3 &= m_o(1 - \tfrac{1}{2}\ \sigma\ \sin 2\theta_\nu), \end{aligned} \tag{A4}$$

where m_o is a mass scale, σ is a small parameter (~0.01), and θ_ν is the neutrino mixing angle. The short wave-length oscillation, characterized by $\delta m_{12}^2 \simeq \delta m_{13}^2 \simeq m_o^2$, mainly induces $\nu_\mu \rightleftarrows \nu_e$. The long wave length oscillation, characterized by $\delta m_{23}^2 = 2m_o^2 \sigma \sin 2\theta_\nu$, main induces $\nu_\mu(\nu_e) \rightleftarrows \nu_\tau$. By taking the values of $\sin^2\theta_W = 1/4$, $m_o \simeq 20$ eV[4] (approximately the ν_e mass), $\sin 2\theta_\nu = 0.06$ (conforming to the limits set by GGM and the 15' B.C.) and $\ell \simeq 1{,}000$ m, we arrived at the following expression for the probability of finding ν_e in an initially ν_μ beam:

$$|\alpha(t)|^2 \simeq 0.0036\ \sin^2(500/E_\nu), \tag{A5}$$

where E_ν is the neutrino energy in GeV. By substituting the expression (A5) into (A3), the "apparent" value of $\sin^2\theta_W$ can then be solved as a function of neutrino energy and is shown in Figure A2.

---

(2) L. Wolfenstein, Preprint COO-3066-149 (May 1980).
(3) A. Zee, Phys. Lett., to be published (1980).
(4) R. Cowsik and J. McClelland, Phys. Rev. Lett. 29, 669 (1972).

This exercise illustrates the connections between the νe scattering and the conjectured neutrino oscillations. It makes this rapidly developing field even more interesting.

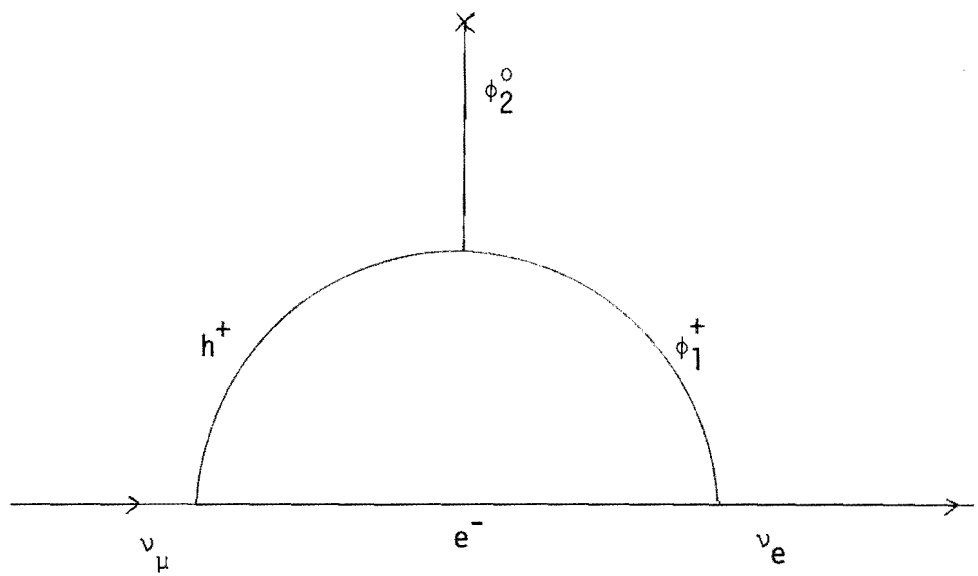


Figure A1: The Wolfenstein-Zee Model

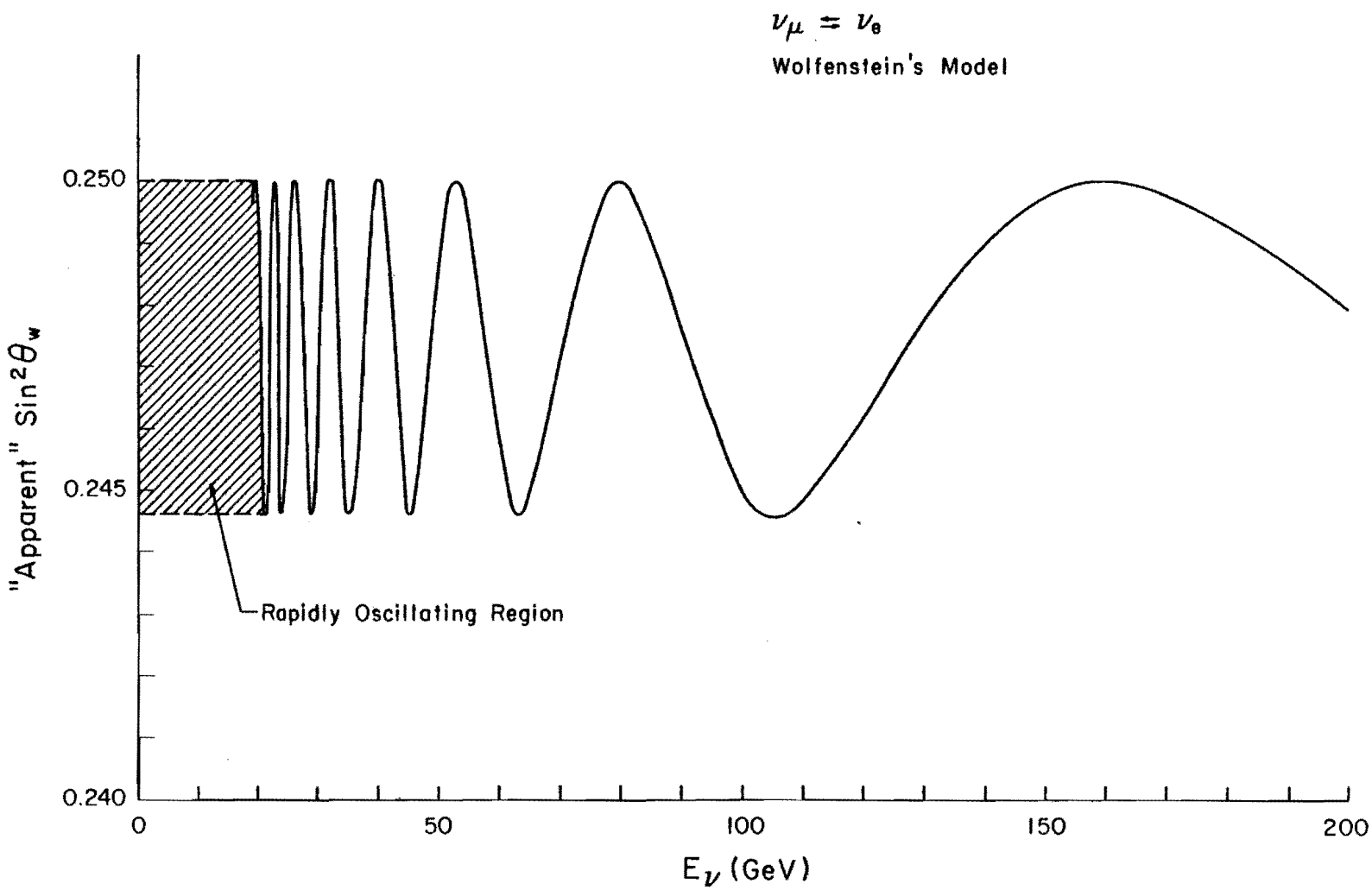


Figure A2: Effect of Neutrino Oscillations on $\nu_\mu e^-$ scattering. The input to the calculations are $\sin^2\theta_W = 1/4$ and $\ell = 1{,}000$ m.

Addendum and Revision of P635

I. Introduction

In 1980, the authors of proposal P-635 outlined a program of investigation in three important areas. They were the following:

1. Determination of the leptonic weak coupling constants, g_V and g_A, through measurements of $\nu_\mu e \rightarrow \nu_\mu e$ and $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$ scattering cross sections.
2. Search for neutrinos oscillations.
3. Search for decays of long-lived neutral particles, such as axions.

These areas of investigation remain as topical today as they were when originally proposed.

The Fermilab Program Advisory Committee in its 1980 Summer Meeting deferred action on the proposal, awaiting further developments on the part of the proponents. During the ensuing period, the authors have been actively developing the technical features as well as refining the physics goals of the proposed experiments. This addendum and revision updates the original proposal and will, hopefully, permit a reconsideration of the proposal by the Program Advisory Committee in its 1982 Summer Meeting.

II. Progress from 1980-1982

P-635 was a proposal in which the difficult but fundamental physics was proposed to be done by a powerful technique we had spent years in its development and improvement. Based upon excellent results obtained with delay line proportional chambers used in experiment E-253 in which the cross section for $\nu_\mu e \rightarrow \nu_\mu e$ was measured to the best accuracy to date, the authors proposed a detector which was 40 times larger than previously used. Furthermore, the proposed readout system for the chambers employed, as of that date, an untested new method for reading out these chambers. The new chambers were to be 3m x 3m in cross sectional area (compared to 1m x 1m used in E253) and were to employ a CCD (Charge Coupled Device) digitizing system. Understandably, some hesitation developed on the part of the PAC.

DIRECTOR'S OFFICE

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To proceed to demonstrate the feasibility and desirability of what was proposed, the authors initiated a step-by-step program of research and development which permitted an orderly, cost-effective, and measured approach as well as the investigation of interesting physics.

Since the summer of 1981, the group has been conducting a search for axion-like objects at SLAC. The apparatus used at SLAC has been the reconfigured 1m x 1m chambers of E253 outfitted with the new CCD readout system. In January, 1982, the experiment had a two-week long data-taking run in which one third of the requested beam was dumped onto the production target. Approximately 5600 triggers were recorded with 9.5 Coulombs of 20 GeV electrons. Almost all of that data has already been scanned and measured.

The run at SLAC fully demonstrated the success of the CCD readout system. Electromagnetic showers, hadron showers, and muon or hadron tracks were observed with high resolution and reliability as had been anticipated. Details of the readout system are included in Appendix I.

As a result of the success of the January run, the SLAC management has specified that a six week dedicated run be provided to the group to acquire the remaining data of the experiment. A decision was made to replace the 48 1m x 1m chambers with between 8 and 10 of the 3m x 3m chambers outfitted with the now demonstrated CCD readout system. The 3m x 3m chambers have been built and are now awaiting the fabrication of new amplifiers and CCD digitizers. The authors are confident that this system will become operative by the late summer of 1982.

The importance of these developments to P-635 is that by October, 1982, the group will have in hand the equipment to start the search for axion-like objects at Fermilab upon the completion of E-137 at SLAC. Possibly in as short a time as three months but certainly within six months, we would be capable of setting up an experiment at Fermilab with equipment of demonstrated capability. Questions of technical feasibility do not need to be conjectured or debated but can be answered by

data from conducted experiments.

III. The Modified Experimental Proposal

We have re-examined the physics goals of P635 and have come to the conclusion that a stage-by-stage approach, in which a "final" detector may evolve, would be the most logical and reasonable, consistent with the funding constraints. The modified experimental proposal is described as following:

(1) Search for Axion-like Objects

Initially, we like to set up a very modest apparatus to search for the axion-like objects. It is the natural extension to higher bombarding energies of the search experiment, E-137, at SLAC. The dominant decay mode we will look for at Fermilab is the process $X^\circ \rightarrow \mu^+\mu^-$, where X° represents the new neutral particles. At SLAC, we are searching for the decay mode $X^\circ \rightarrow \gamma\gamma$. This two-photon mode can also be automatically searched for on this proposed detector at Fermilab.

The detector is to be located approximately 600 meters downstream from the new Tevatron beam dump. It consists of sixteen 3m x 3m MWPC's interlaced with steel plates (1 r.l. thick each) and plastic scintillation counters, a 3m x 3m x 3m solid iron magnet. The 3m x 3m MWPC's have delay lines along the x- and the y-directions on the cathode planes. The signals are readout with CCD digitizers which can measure both the pulse heights and positions of particle tracks. The anode wires of each 3m x 3m chamber are connected into 8 groups and they can be used as "hodoscopes" for pulse-height measurements and triggering purposes. These 16 chambers are currently under construction. Eight of them are already finished and they will be used at SLAC in E-137 for the scheduled running in the Fall of 1982. We anticipate that the construction of the remaining chambers will be completed before the end of 1982. The details of the detector is shown in Figure 1.

Since most of the experimental apparatus, including an on-line computer system, is in existence, this axion search experiment should not seriously tax the Laboratory resources. The Laboratory would still be asked to provide us a building with utilities, the solid iron magnet, and the necessary fast electronics including NIM and CAMAC power crates.

The building housing the detector could be one of the size of the present Wonder Building. We ask that the building be approximately as long as the Wonder Building to allow for the inclusion of additional detector modules which would be required when attention turns later to neutrino experiments.

(2) The Neutrino Experiment

While the "axion" search experiment is being set up or operative, we will continue to construct more 3m x 3m chambers at a rate commensurate with our funding levels. With a total number of 50 chambers, we can conduct an outstanding $\nu_\mu e$ and $\bar{\nu}_\mu e$ scattering experiment in the future. These chambers can be added gradually to the front end of the apparatus provided that the housing has approximately the same size as the present Wonder Building. This detector, made of 50 3m x 3m modules, has about ten times the fiducial tonage of E-253. When coupled with the higher energy of the Tevatron operation, it is possible to acquire $\nu_\mu e$ and $\bar{\nu}_\mu e$ elastic scattering events in the 10^3 range. The 3m x 3m MWPC's with CCD readout possess the salient features of good angular resolution, fast speed, and multiple-track/shower capability. Also, it can identify electromagnetic showers, hadronic showers, and minimum ionizing particles. It is particularly suitable for the measurement of energy flow and for use in experiments such as the neutrino-electron scattering. The directions of electromagnetic showers or muons can be determined to approximately $\sim \pm 2$ mr by using chambers within the first five radiation lengths from the vertex.

We are persuaded that this option in the future is a sound one, both in terms of physics and economics. As it turned out, progress made in $\nu_\mu e$ and $\bar{\nu}_\mu e$ scattering during the past years has been much

slower than generally expected. It is quite clear that these processes are the best for the determination of $\sin^2\theta_W$ or alternatively g_V and g_A, the exact values of which are still an important physics issue. As pointed out by Veltman, if the experiment can be carried out with sufficient precision, then the radiative corrections can yield good physics on heavy quarks. For some time, it was anticipated that the measurement of forward-backward asymmetry in the pure leptonic process $e^+e^- \rightarrow \mu^+\mu^-$ should give a good determination of $\sin^2\theta_W$. Thus far, the storage ring results need much more improved precision; this leaves the neutrino-electron scattering as a very competitive alternative.

IV. Physics Goals of the "Axion-like" Particle Search at Fermilab

The physics space we can explore at Fermilab is estimated by Bjorken as the following:

Suppose the best object for a search is an X° coupled to quarks and leptons with mass greater than 200 MeV, then $X^\circ \rightarrow \mu^+\mu^-$ is the dominant decay mode. Assume that X° is produced like pions with

$$\frac{X}{\pi} \simeq 10^{-3} \left(\frac{1\ \text{GeV}}{F_X}\right)^2,$$

the decay width is

$$\Gamma(X^\circ \rightarrow \mu^+\mu^-) = \frac{M_X M_\mu^{\ 2}}{8\pi F_X^{\ 2}} \quad ,$$

where F_X is the decay coupling constant. Using these two expressions together with the experimental geography, we can estimate the counting rate as a function of M_X and F_X.

Since the Tevatron beam dump is approximately 300 m from Lab C of Neutrino Area, it is logical to locate the experiment ~300 m downstream from Lab C. Because the new Muon Lab is adjacent, the utilities can be conveniently brought over from there. For a small detector, the rate is

proportional to $\ell/(\ell + 300\ \mathrm{m})^2$ for this geography, where ℓ is the decay path available behind Lab C. For the 3m x 3m detector we are proposing, the angle it subtended is $\theta = \pm\ 1.5\ \mathrm{m}/600\ \mathrm{m} \simeq \pm\ 2.5\ \mathrm{mr}$; for $E_X \geq 100$ GeV this gives $P_\perp^{max} \gtrsim 250$ MeV. With an $X^\circ \to \mu^+\mu^-$ originating at 200 m from the detector, the separation of the two muons at the detector is approximately $(5\ \mathrm{m}) \cdot (M_X/1\ \mathrm{GeV}) \cdot (100\ \mathrm{GeV}/E_X)$. This is adequate for $M_X \simeq 200 \sim 300$ MeV, but deteriorates as the mass increases.

The rate is estimated by taking for the pion yield

$$\frac{\pi\ (E>100\ \mathrm{GeV};\ P_\perp < 200\ \mathrm{MeV})}{\text{Proton on Target (POT)}} \simeq 1,$$

which gives

$$\frac{X}{\mathrm{POT}} \simeq 10^{-3} \left(\frac{1\ \mathrm{GeV}}{F_X}\right)^2$$

Since

$$\frac{\gamma c\tau}{500\ \mathrm{m}} = 10^{-17}\ \frac{E_X M_p F_X^{\ 2}}{M_\mu^{\ 2} M_X^{\ 2}}\ ,$$

therefore

$$\frac{\text{Detected X}}{\mathrm{POT}} = 10^{10} \left(\frac{100\ \mathrm{GeV}}{E_X}\right) \left(\frac{M_X}{1\ \mathrm{GeV}}\right)^2 \left(\frac{1\ \mathrm{GeV}}{F_X}\right)^4.$$

If we ask for 10^{-17} or more detected X° per POT, then

$$F_X \leq (5000\ \mathrm{TeV}) \left(\frac{M_X}{1\ \mathrm{GeV}}\right)^{\frac{1}{2}} \left(\frac{100\ \mathrm{GeV}}{E_X}\right)^{\frac{1}{4}}\ .$$

The condition that X° reaches the decay region

$$\frac{\gamma c\tau}{500\ \mathrm{m}} \geq 1$$

translate into

$$F_X \geq (300 \text{ TeV}) \left(\frac{M_X}{1 \text{ GeV}}\right) \left(\frac{100 \text{ GeV}}{E_X}\right)^{\frac{1}{2}} .$$

The region in the M_X-F_X space which this experiment can explore is shown in Figure 2. Just for comparison, the region, which E-137 can explore at SLAC by detecting $X^\circ \rightarrow \gamma\gamma$, is shown in Figure 3. It should be emphasized that the decay constant, F_X, which E-137 can reach at SLAC is about 10^3 GeV; while at Fermilab, this proposed experiment can reach approximately 10^7 GeV.

There are three main sources of backgrounds; namely, (1) neutrino interactions between the Tevatron beam dump and Lab C, (2) neutrino interactions in the useful decay volume between Lab C and the proposed detector, and (3) the "sky-shine" produced by the deep-inelastic scattering of all the "spoiled" muons.

The neutrino interactions between the Tevatron beam dump and Lab C should not worry us because there will be over 100' of sweep magnets behind the beam dump to sweep out the charged particles from reaching the 15' bubble chamber. It is designed such that only less than ~ 10 μ's/10^{13} protons can enter the 15' bubble chamber. Additional sweeping power provided by the magnets of Lab E, the 15' bubble chamber, and Lab C, should have our proposed detector fully protected. The backgrounds due to the sky-shine of the "spoiled" muons have to have very large transverse momenta (≥ 5 GeV/c) in order to reach the proposed detector. Their effects are inconsequential because of the approximate $e^{-5P_\perp}$ dependence. Since there are approximately 2,700 kg of air in the useful decay volume, neutrino interactions can produce up to 10^4 background events per 10^{18} POT (~ 1 event/10 pulses). The majority of these backgrounds can be eliminated from triggering the apparatus by demanding that at least two charged particles are required, among other things, in the experimental trigger. This condition can be easily satisfied by the utilization of matrix logics

in conjunction with two 2-dimensional hodoscopes as shown in Figure 1. In the data analysis, the remaining backgrounds can be eliminated by utilizing cuts in the following facilities:

1. Dimuon identification,
2. Coplanarity,
3. Symmetry in momentum of the dimuon,
4. No accompanying particles,
5. Invariant mass and total energy.

V. The Request

We request the Laboratory to allow us to set up an experiment in the Neutrino Area to search for new, long-lived, and neutral particles, such as "axions", etc. We ask the Laboratory to provide us a detector housing $\sim$ 300 m downstream from Lab C, a 3m x 3m x 3m solid iron magnet, and fast electronics.

Initially, we request to run the experiment with $10^{18} \sim 10^{19}$ protons on target at the new Tevatron beam dump. In due course, we propose to enlarge the detector to 50 modules which will enable us to do a future neutrino-electron scattering experiment.

Appendix I

Delay-Line Chambers and CCD Digitizers

In this appendix, the essential features of the delay-line chambers and the CCD digitizers are briefly described.

1. The Delay-Line Chambers

On the cathode planes of the MWPC's used in E-253 at Fermilab and E-137 at SLAC there are delay-lines along both the x- and y-direction. They are continuous zig-zag conducting strips machine-milled on copper-clad G-10 plates. Typically, they behave like transmission lines of impedance ∿100 ohms. When a particle passes through the chamber, a positive signal will be induced on the delay-line due to capacitive coupling. The signal will then propagate along the delay-line at a speed of ∿5 nsec/m. By measuring the propagation time, one can obtain the track position.

The transverse spacing of the delay-line is 2 mm. For the 1m x 1m chamber we used in E-253, the delay-line was continuous over the entire cathode plane. Readout ports were tapped at 5 equi-distance points. This arrangement is required to take care of the attenuation and provides redundancy; but it introduces left-right ambiguities (although self-resolved) for the three ports in the middle. For the 3m x 3m MWPC's, the delay-line on each cathode plane is cut into 24 separate sections. One end of each section is properly terminated. The other end is connected to an amplifier, then fed to a CCD digitizer. This arrangement simplifies the data-reduction algorithm because the signals will all propagate along the same direction.

For the eight 3m x 3m chambers already built, the mechanical construction is very similar to that of the 1m x 1m chambers used in E-253 at Fermilab. The G-10 delay-line boards were glued onto 1/4" thick aluminum plates. Two of such plates are bolted together to form the

cathode planes of one chamber. In order to prevent the aluminum plates from buckling, aluminum "spiders" are welded to each plate to provide the necessary mechanical strength. This scheme is adequate but it makes the chambers rather heavy, weighing approximately 1,500 lbs. each. For the new 3m x 3m chambers under construction, the aluminum plates and the reinforcement spiders are replaced with "Hexcel" like boards. They are not only lighter, but also stronger. Each 3m x 3m chamber will only weigh approximately 350 lbs., and most of the weight comes from the G-10 delay-line boards.

2. The CCD Digitizer

The operation of the CCD digitizer is shown schematically as Figure 4.

The signals from a cathode-plane delay line are first amplified by an amplifier located on the chamber. The output is fed to a CCD digitizer (in a CAMAC crate) through a long coaxial cable. The CCD is continuously clocked by a 50 MHz oscillator. Upon occurence of each clock pulse, a 20 nsec slice of the input signal is loaded into a CCD bucket. The charges stored in the CCD buckets are shifted forward in sequence very much like a shift-register, except that it is operated in the anologue mode. Immediately after the occurence of the master experimental trigger, the signal is "frozen" in the CCD. Then an ADC (analogue-to-digital converter) will sequentially digitize the charges in each CCD bucket and store the results in the RAM (random access memory) of the module, waiting to be read into the on-line computer via the CAMAC data highway. This simple scheme offers an elegant method in measuring both the pulse heights and track positions simultaneously. The CCD bucket number represents the track position in quantum of 20 nsec, and the charges in CCD buckets provide direct information on pulse-height distributions. Since the master experimental trigger can happen within one clock pulse of 20 nsec, its timing is also separately digitized to the accuracy of 1/125-th of one CCD bucket width (20 nsec) to provide the vernier corrections. By mapping the particle position and dE/dx information into the CCD bucket space in this manner, the original pulse profiles are thus retained in the on-line computer for later detailed analysis. Physical effects, such as delay-line attentuations, dispersions, energy calibrations, propogation

velocities, etc., can all be taken into account precisely in the final data-reduction stage.

Figure 5 illustrates one example of the CCD information from one of the 1m x 1m cathode planes. Pulse trains from the 5 readout ports of a continuous delay-line are shown. Each bucket represents $\sim$ 8 mm in real space. Since we can determine the centroid of each pulse to the accuracy of a fraction of a bucket, by using 5 chambers at a spacing of 15" apart from each other, the direction of the track can be determined to the accuracy of $\sim \pm$ 2 mr.

As described previously, on each cathode plane of the 3m x 3m chamber, the delay-line is divided into 24 sections. Only one end of each section is connected to a CCD digitizer, the other end is terminated (in principle, a second CCD digitzer can also be used, instead of the termination, to provide redundancy if finance permits). Since all the detected signals are traveling along the same direction, there is no ambiguity in sorting out their spatial positions. The pattern recognition is helped enormously by the pulse height information, which is not available in the conventional wire chambers. Due to the use of the delay-lines, the multiple-track events can be handled naturally because they appear as pulse trains. Once the straight-line tracks are determined, one can see the longitudinal distribution of pulse heights along the track direction, as well as the distributions transverse to the track direction at each chamber. This information is particularly useful in particle identifications, e.g., the π/e separations, etc.. If the tracks of a multi-particle event do not overlap one can follow each individual track to determine its energy by adding up the pulse-heights along the track. In this manner, the CCD digitizer has opened up a revolutionary possibility which permits the simultaneous measurement of energy and direction of each individual track of a multi-particle event by a non-magnetic detector. This novel approach has gained attention lately. At SLAC, the design of a future SLC calorimeter has considered the use of CCD's along, more or less, the same line as described here.

Figure Captions

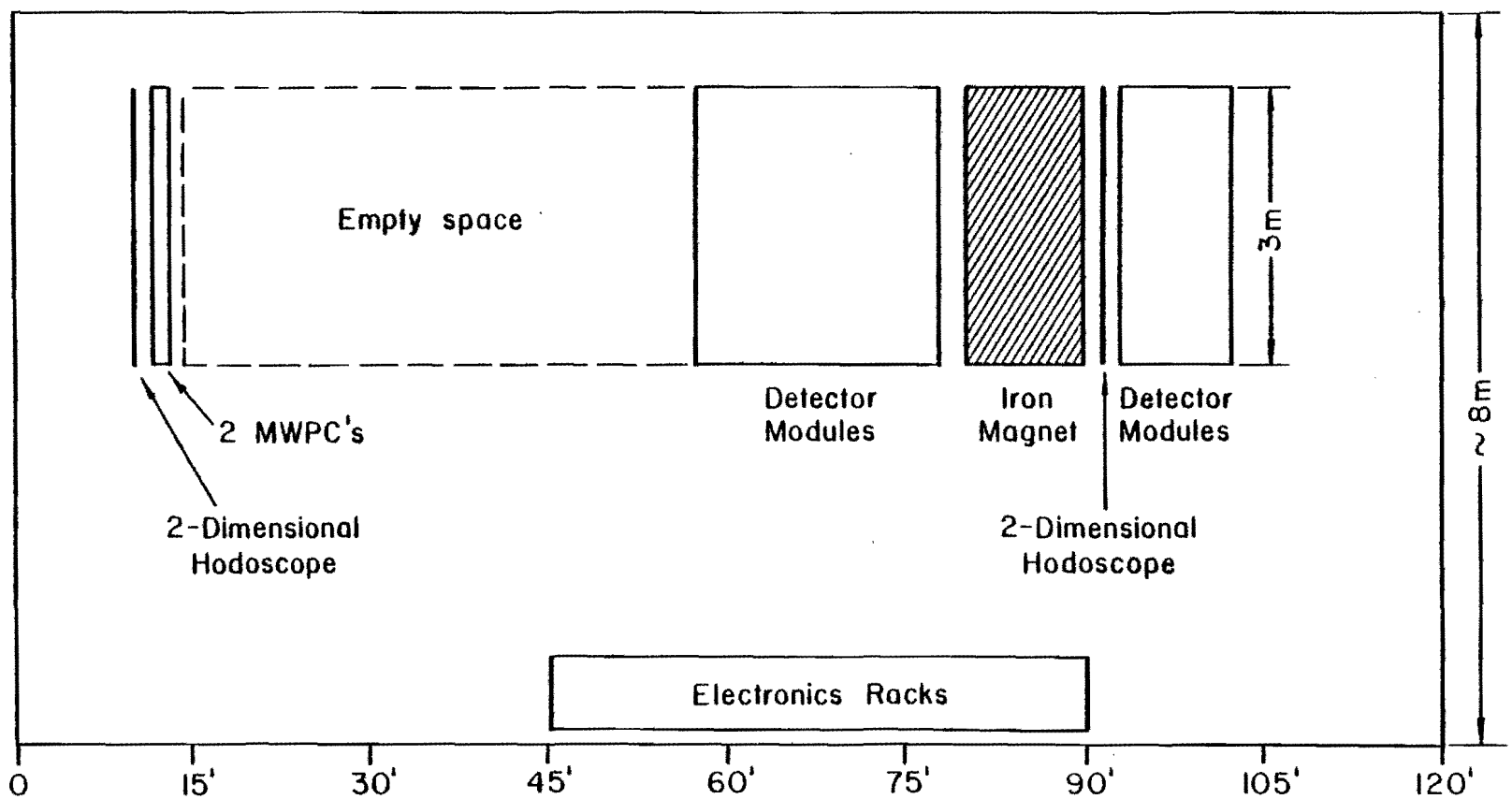
Figure 1 Schematic layout of the experimental apparatus.

Figure 2 The region in the F_X-M_X space which this proposed experiment can explore with the decay mode $X^\circ \rightarrow \mu^+\mu^-$.

Figure 3 The region in the F_X-M_X space which E-137 can explore at SLAC with the decay mode $X^\circ \rightarrow \gamma\gamma$.

Figure 4 Schematics of the CCD digitizer.

Figure 5 An example of the CCD data from one cathode plane of a 1m x 1m MWPC. They are readout from 5 equi-distance tap points of a continuous delay-line. The signals are the redundant measurements of a single shower.



Schematic Arrangement of the Experiment

Fig. 1

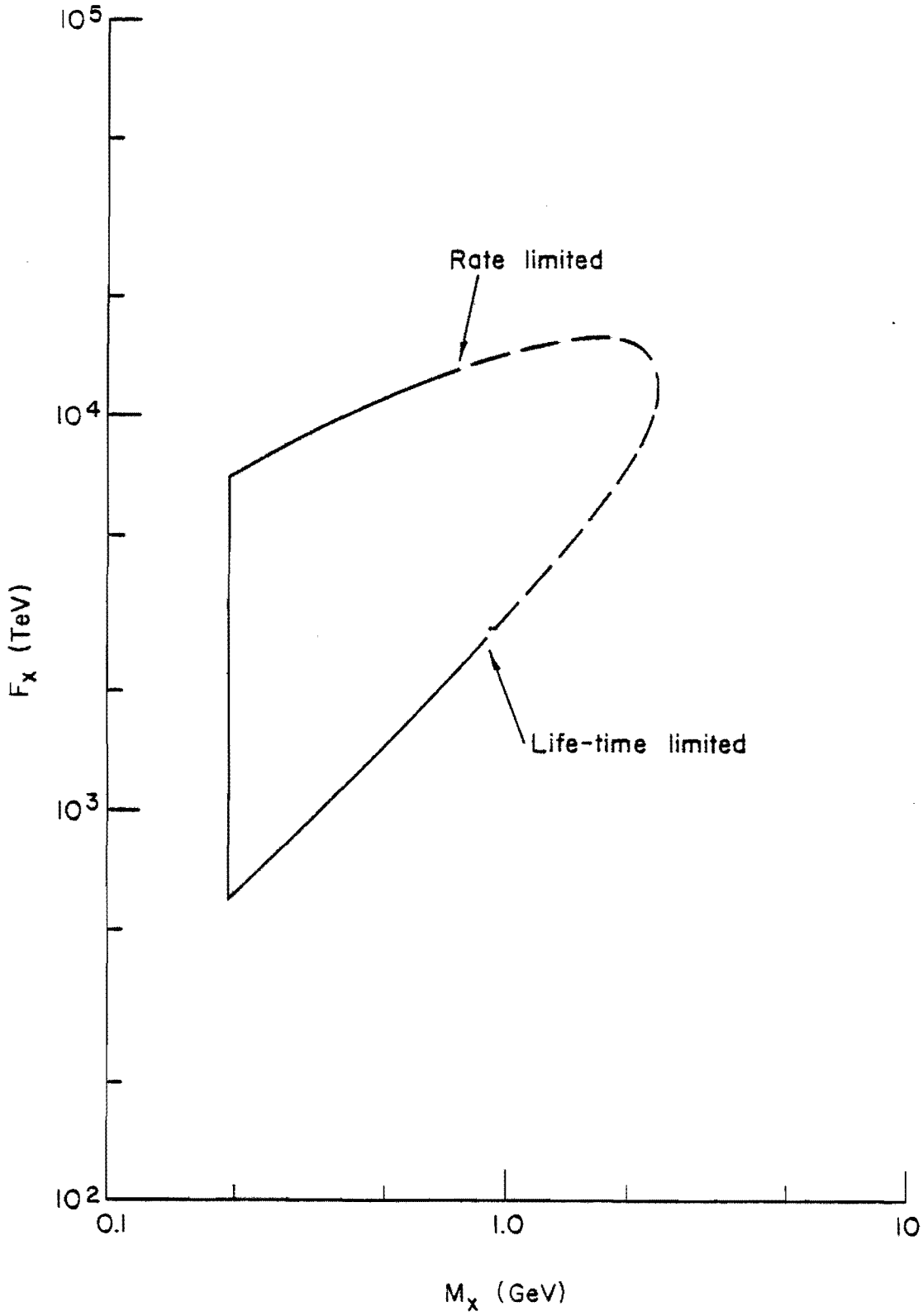

10^5
10^4
10^3
10^2
F_x (TeV)
Rate limited
Life-time limited
0.1
1.0
10
M_x (GeV)

Fig. 2

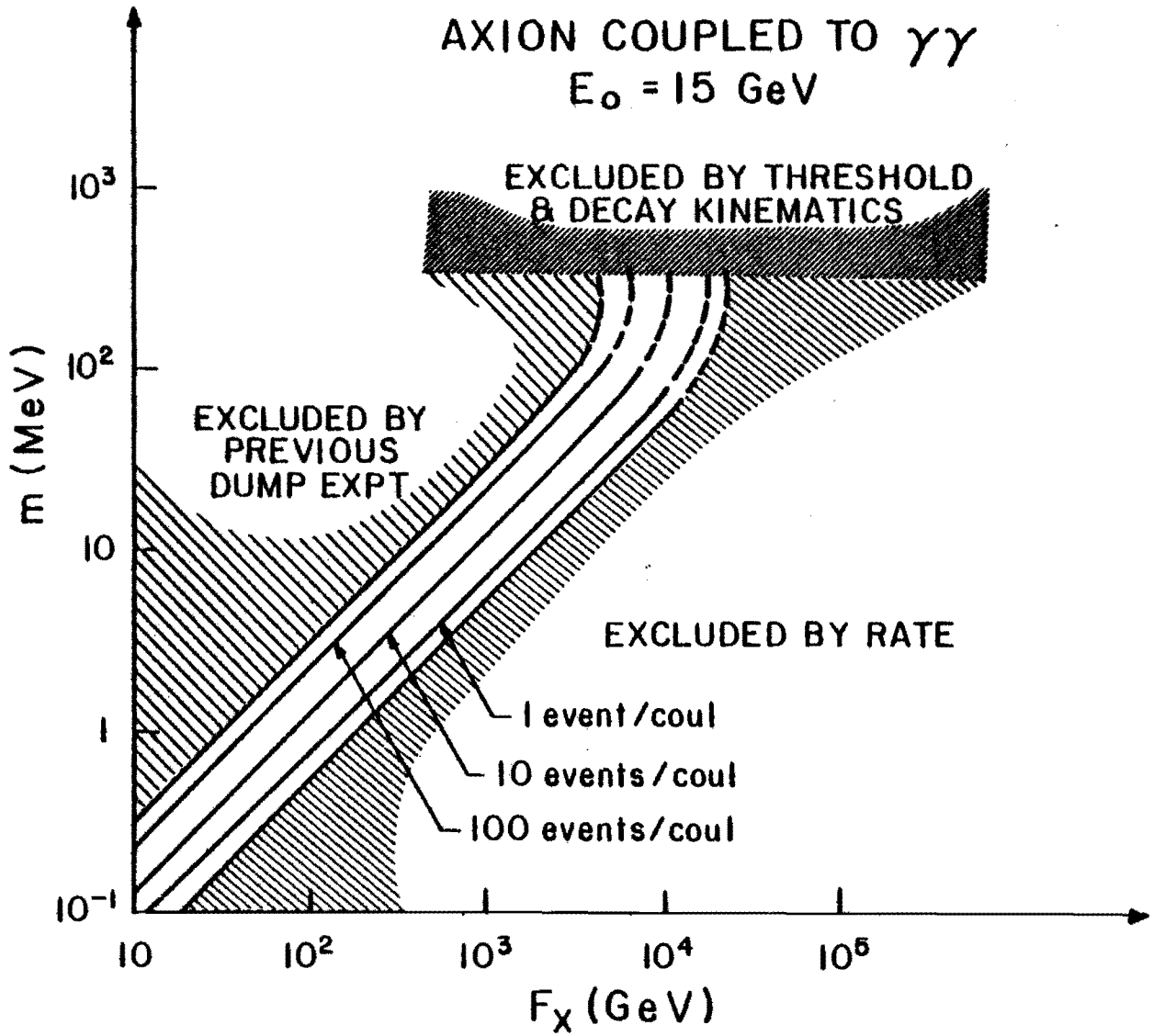
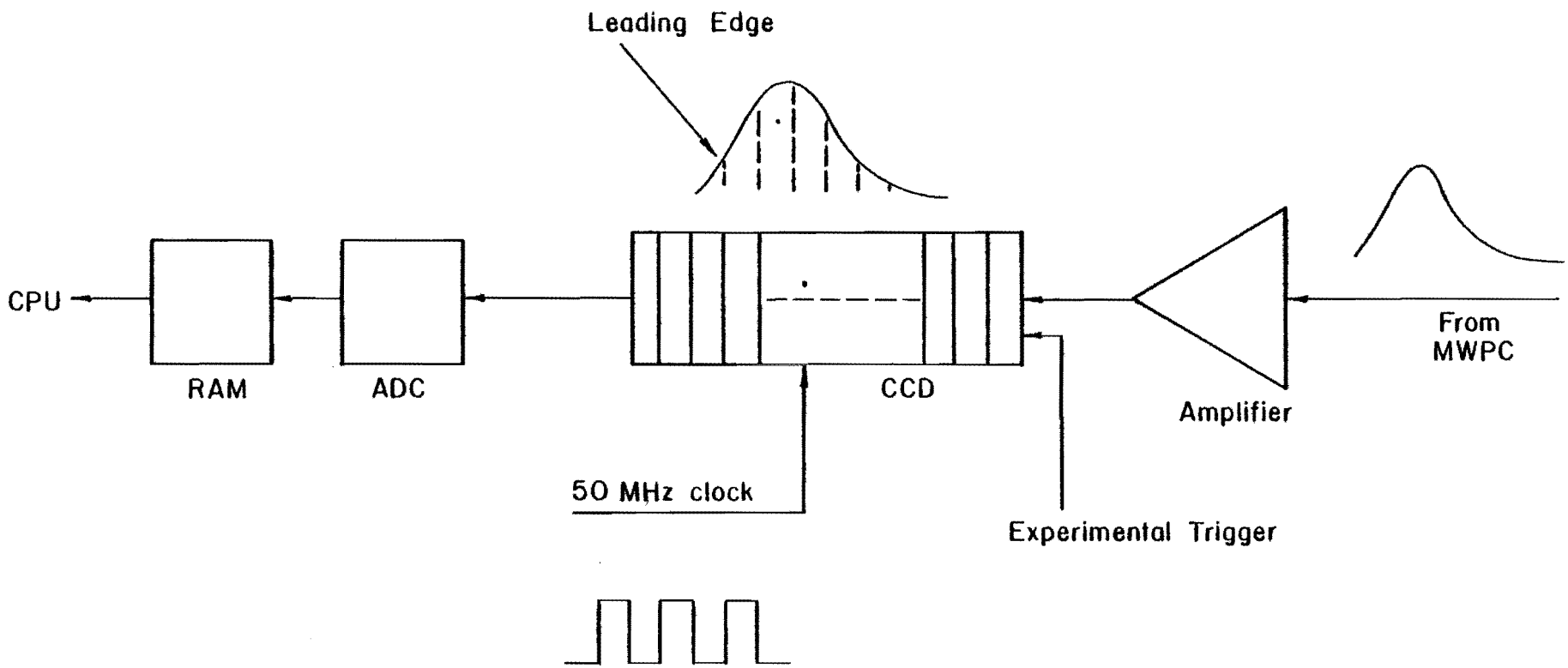
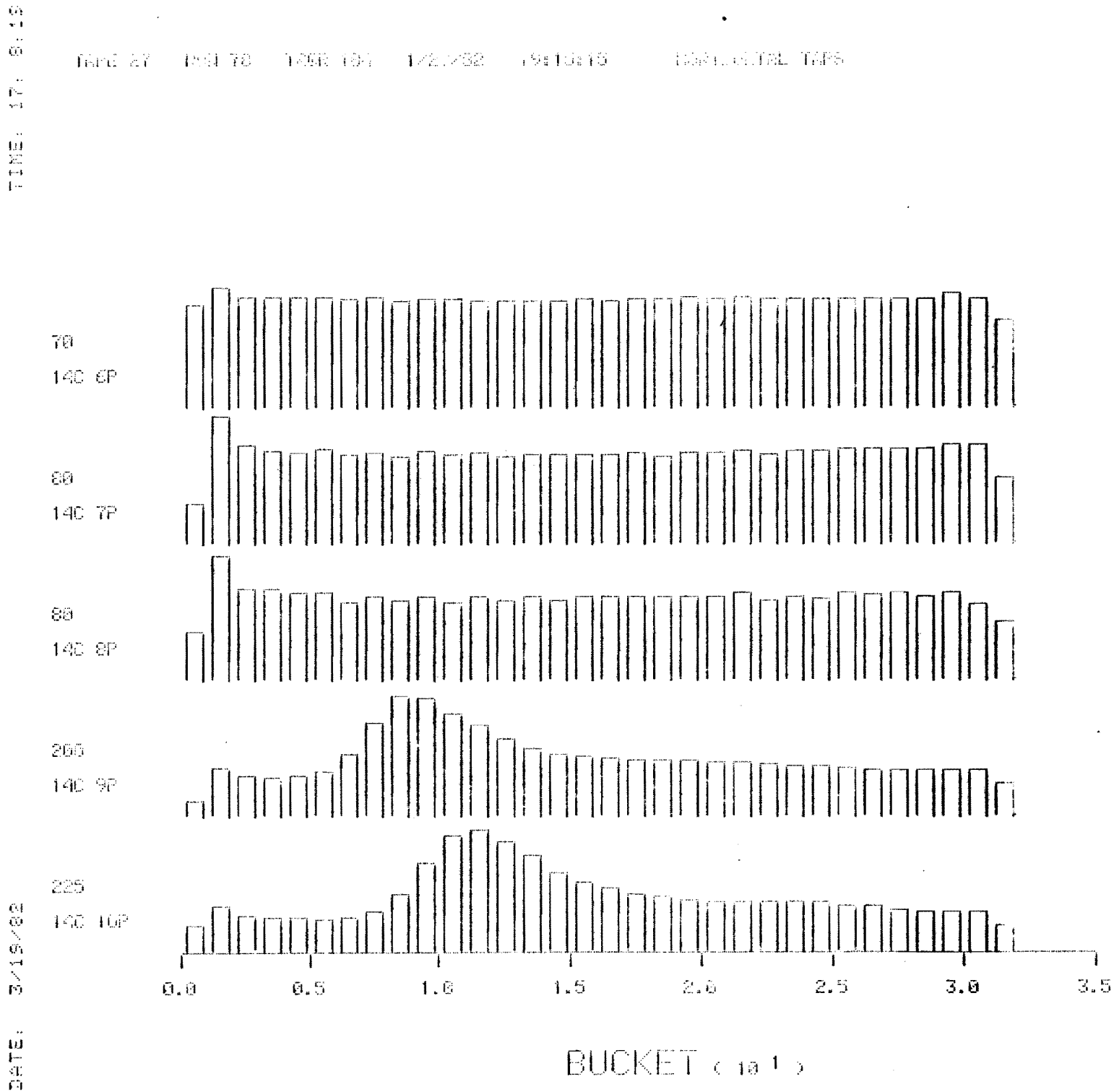

AXION COUPLED TO γγ
E₀ = 15 GeV
EXCLUDED BY THRESHOLD & DECAY KINEMATICS
EXCLUDED BY PREVIOUS DUMP EXPT
EXCLUDED BY RATE
1 event/coul
10 events/coul
100 events/coul
m (MeV)
10³
10²
10
1
10⁻¹
10
10²
10³
10⁴
10⁵
F_X (GeV)

Fig. 3



Schematics of CCD Digitizer

Fig. 4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DATE: 3/19/82
70
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80
140 7P
80
140 8P
200
140 9P
225
140 10P
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
BUCKET (10 1)

Fig. 5