A PROPOSAL TO STUDY NEUTRAL CURRENT NEUTRINO AND ANTINEUTRINO INTERACTIONS

Submitted to the 1977 Fermilab Neutrino Workshop
April 21-22, 1977

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ABSTRACT

We propose to build a liquid argon/iron hadron calorimeter to be used in conjunction with the HPWF muon spectrometer to study the neutral current interactions of neutrinos at Fermilab. The device will have an energy resolution of $\sigma_{E_H} = 0.5/\sqrt{E_H(\mathrm{Gev})}$, and the ability to measure the direction of the hadrons shower with an accuracy of $\sigma(\theta_H) = 0.004 + 0.6/E_H$ radians. We propose to carry out detailed studies of the cross sections as functions of $X = Q^2/2M_p\nu$, $y = \nu/E_\nu$ and W^2, the invariant mass of the hadronic final state. We will also be alert to any anomalous production of muons associated with neutral current events. We propose to situate the calorimeter such that only neutrinos from K meson decays enter the target. This ensures that the neutrino energy is known to better than 10% and that large kinematic ranges in x and y are covered.

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I. Introduction

After four years of experimentation in neutrino physics at Fermilab it is clear that we have only scratched the surface of the wealth of information to be gained from this exciting field. Several anomalies exist in charge current interactions that point to new and very interesting phenomena such as new quarks.[1,2] Experimentally, very little is known about neutral current interactions; it is reasonable to expect much excitement to be generated by careful and detailed studies.

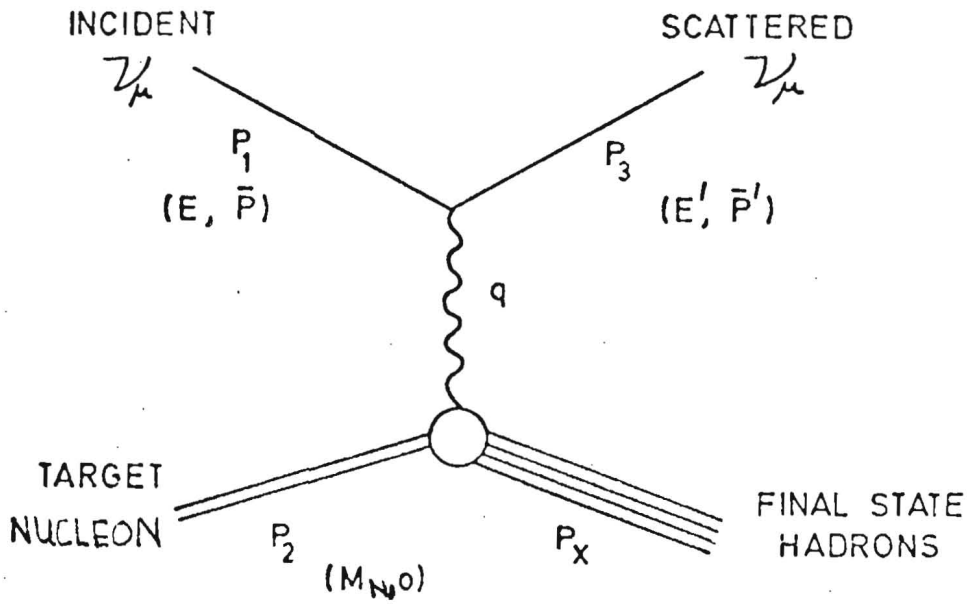
The present data from neutrino experiments often lack statistical power and, in the case of neutral currents, also lack adequate knowledge of ν and Q^2 (or x and y), to allow detailed studies to be made. These limitations induce theorists to use the data much the way drunkards use lampposts (for support rather than illumination).[3]

New technological developments allow the construction of an apparatus which we believe compares favorably with present efforts at CERN in both capability and time scale for the study of neutrino induced neutral current interactions with the dichromatic beam presently under construction at Fermilab.[4] We propose to build such a detector.

We first discuss the physics motivation behind such an endeavor. We then describe the proposed apparatus and compare it with existing experiments at the CERN SPS.

LOWEST ORDER FEYNMANN DIAGRAM FOR

$\nu_\mu + N \rightarrow \nu_\mu + X$



$q = P_1 - P_3$

$\nu = q \; P_2 / M_P = E - E'$

θ is the angle between $\bar{p}$ and $\bar{p}'$

$q^2 = \quad - 2EE' + 2\bar{p}\,\bar{p}' \cos\theta \leqslant 0$

$P_X^2 = (P_2 + q)^2 = M_N^2 + 2M_N\nu + q^2$

Since baryon number is conserved,

$P_X^2 \geqslant M_N^2$, which implies $-q^2 \leqslant 2M_N\nu$

A convenient and highly accurate expression is

$-q^2 = 4EE' \sin^2 \theta/2$

II. Physics Motivation

With the discovery of neutral current phenomena a few years ago we now face a situation similar to that encountered in the early days ($t \leq 1957$) of β-decay: we now must determine the nature of the effective Lagrangian governing neutral-current phenomena. The processes which have been observed include

$$\nu_\mu + N \to \nu_\mu + \text{hadrons}$$

$$\bar{\nu}_\mu + N \to \bar{\nu}_\mu + \text{hadrons}$$

$$\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$$

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

A fairly general candidate effective Lagrangian for these reactions is[33]

$$L_{eff} = \frac{G}{\sqrt{2}} \bar{\nu}_\mu \gamma\lambda (1 - \gamma_5) \nu_\mu \left[\begin{array}{l} \varepsilon_L(e) \bar{e} \gamma_\lambda (1 - \gamma_5) e \\ + \varepsilon_R(e) \bar{e} \gamma_\lambda (1 + \gamma_5) e \\ + (e \leftrightarrow \mu) \\ + \varepsilon_L (u) \sum_{i=1}^{3} \bar{u}_i \gamma_\lambda (1 - \gamma_5) u_i \\ + \varepsilon_R (u) \sum_{i=1}^{3} \bar{u}_i \gamma_\lambda (1 + \gamma_5) u_i \\ + (u \leftrightarrow d) \\ + (u \leftrightarrow S) \end{array} \right]$$

$$\left[+ (u \leftrightarrow c) \quad + \ldots \right]$$

$$+ \frac{G}{\sqrt{2}} \left[\begin{array}{l} \varepsilon_{LL} (e, u) \bar{e} \gamma^{\lambda} (1 - \gamma_5) e \sum_{i=1}^{3} \bar{u}_i \gamma_{\lambda} (1 - \gamma_5) u_i \\ + \varepsilon_{RL} (e, u) \bar{e} \gamma^{\lambda} (1 + \gamma_5) e \sum_{i=1}^{3} \bar{u}_i \gamma_{\lambda} (1 - \gamma_5) u_i \\ + \ldots \end{array} \right]$$

In constructing such a Lagrangian several vital assumptions are usually made.[33] These include:

(1) The neutrino emitted in ν-induced neutral current processes is the same type as the incident neutrino. This must include helicity: if neutral currents proceed through

$$\nu_{\mu L} + N \rightarrow \nu_{\mu R} + \text{hadrons}$$

this would imply the existence of a new degree of freedom, and concomitant scalar, pseudoscalar or tensor neutral current couplings.[7,34]

(2) The nonexistence of <u>off diagonal</u> neutral current reactions, e.g. charm changing processes such as $\nu_{\mu} + u_i \rightarrow \nu_{\mu} + c_i$. While the absence of $\Delta S = 1$ neutral currents and the motivation for charm (GIM mechanism) suggest their absence, this is not an inevitability and should be tested.

(3) The correctness of the 4-fermion nonderivative coupling structure of the Lagrangian.

(4) The use of the singlet fractionally charged quark structure. One might be able to build a Pati-Salam-like scheme,[35,36] with broken color degrees of freedom, which might look very different from the assumed Lagrangian.

These assumptions, and others can be tested in a high statistics high resolution neutral current experiment. These tests might include:

(1) Detailed studies of the x and y distributions of the neutral current cross section. Helicity flip with spin-zero exchange favors large-angle neutrino scattering; in the scaling limit this results in a y^2 distribution ($y = E_{hadron}/E_\nu$) for the inclusive cross section. The CITF group has studied this distribution and finds it relatively flat.[8] If the neutral current is diagonal, as is usually assumed, then for the (S, P) case (and the pure V or pure A cases)

$$d\sigma(\nu \to \nu) = d\sigma(\bar{\nu} \to \bar{\nu});$$

we know this is <u>not</u> true.[7] The behavior of these cross sections as a function of $x = Q^2/2m_p\nu$ and y will give information on the detailed structure of the neutral current and possibly allow a statement on combinations of S, P, T and V, A interactions to be made. Combinations of this sort are not ruled out by any data at present.

(2) Searches for evidence of narrow resonances in the invariant cross sections as a function of W^2, the invariant mass of the hadronic system. Any narrow structure would indicate the excitation of new degrees of freedom. As

in the production of charm by charged currents, the existence of single "wrong" signed muons would signal the produciton of new (or old, like charmed) particles and so off diagonal terms.

(3) Measurements of the E_ν and Q^2 dependence of neutral current processes would indicate whether any non-derivative terms manifest themselves at high energies.[32]

(4) It has recently been pointed[35] out that a clean test of the hypothesis that hadronic gauge color is physical (quarks are integerally charged) and that it is excited at relatively low energies ($E_{\nu,\bar{\nu}} \gtrsim 50$ GeV) is possible through accurate measurements of neutral current cross sections at high energies. It is noted that within this theory one expects to see significant rises in the neutral current parameters due to color excitation; σ^{ν}_{NC} should rise 40 to 45%, $\sigma^{\bar{\nu}}_{NC}$ 60 to 65%, $R_\nu \equiv \sigma^{\nu}_{NC}/\sigma^{\nu}_{CC}$ should rise about 20%, and R about 10%. The authors also remark that, unlike the situation with charged current scattering where either new flavor or color excitation may lead to a rise in these parameters, rises in neutral current parameters cannot easily be attributed to new flavor thresholds within the $SU(2)_W$ XU(1) gauge structure. They suggest that rises of this sort would point unambiguously to physical color excitation.

Charged Currents

Since the charged current neutrino cross section will be known quite well by 1979 we can use these events to directly measure the flux of neutrinos and antineutrinos incident on the detector. This will also allow careful comparisons of $d\sigma/dx$ and $d\sigma/dxy$ for charged and neutral currents to be made with little or no inherent systematic differences between the two data sets.

Comparisons of the production of multimuon final states for charged and neutral currents are also easily made.

We also note that because of our knowledge of the hadron direction we have 3 constraint fits for all charged current interactions; we only miss the mass of the hadronic system. Giving up E_ν we have a 2 constraint fit. This power will allow us to check any interesting details that may have been seen or hinted at in other experiments; we have a high resolution probe of the details of charged current processes.

In all of the above studies the important variables are $x = Q^2/2m_p\nu$, and $y = \nu/E_\nu$. It is essential to have the best possible resoltuion in x and y and the largest range, especially in y, if we are to make important statements about the structure of the weak interaction. It is here one decides to sacrifice statistics for accuracy and a large kinematic acceptance in these variables.

III. Apparatus

We propose to build a large iron/liquid argon calorimeter that would be used in conjunction with the Harvard-Penn-Wisconsin-Fermilab muon spectrometer with its spark chambers replaced by drift chambers. A drawing of the proposed experimental setup is given in Figure 1. An engineering drawing of the proposed calorimeter is given in Figure 2. Details are given in Table 1.

A. Calorimeter

The proposed calorimeter is contained in a dewar approximately 14 meters long and 4.7 meters in diameter. The calorimeter plates are steel, 1.5 mm thick and 3.6 m × 3.6 m square. Each "plate" is made up of 4 sections 3.6 m × 0.75 m × 1.5 mm; there are 1400 such plates. These plates are divided into 140 sections of 10 plates, every two plates of which are followed by a set of 2 planes of steel strips 2 cm wide and 1.5 mm thick, 3.6 meters long. The strips are oriented in the x and y directions. This permits a measurement of the direction of the shower, as well as its energy, as will be discussed later.

A study incorporating these ideas is given in Figure 2. Several engineering studies of different configurations have been made. The final size of the calorimeter is determined by the divergence of the neutrino beam which in turn is determined by the spot size of the primary proton beam at the target. To come up with a size of 3 m × 3 m for the fiducial area of the plates we assume a spot size of roughly 1 mm, which gives a pion and k-meson divergence of 0.22 mrad. This means that at 1 mrad the

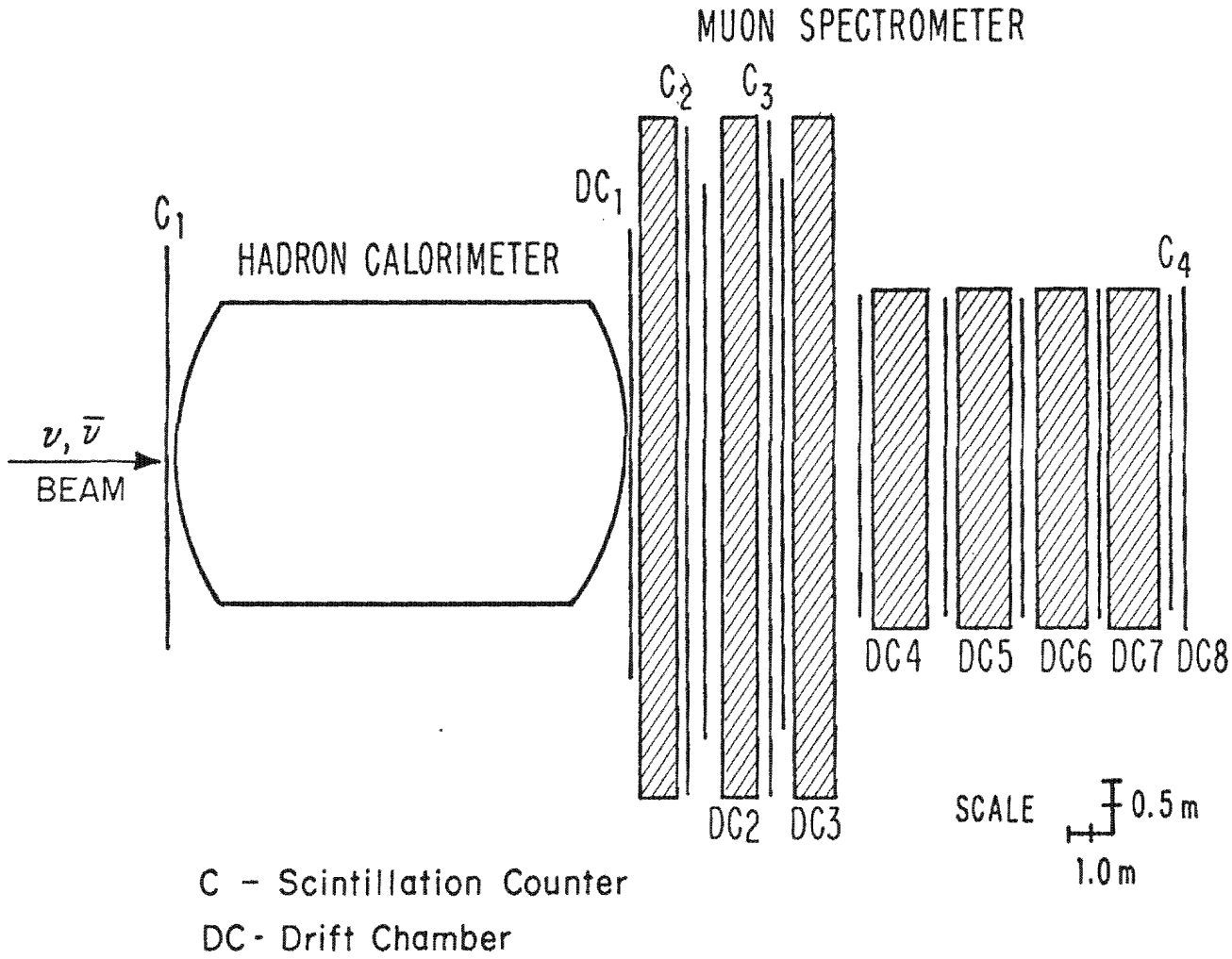
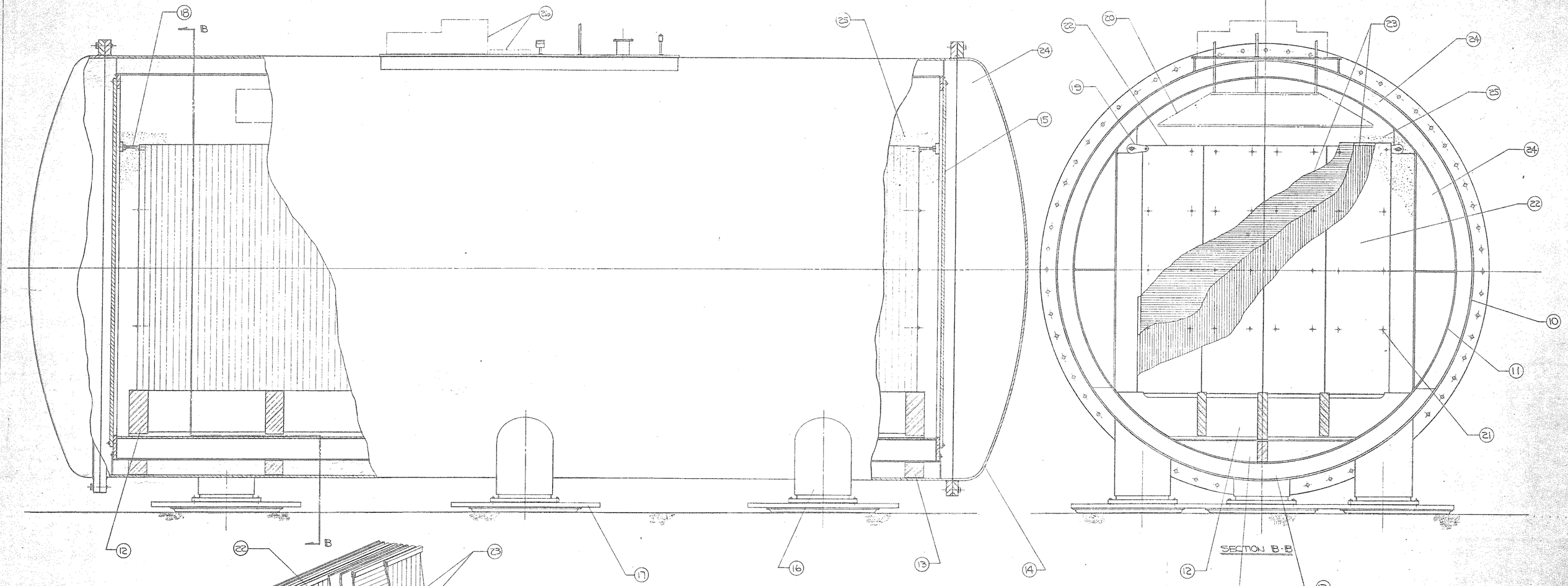
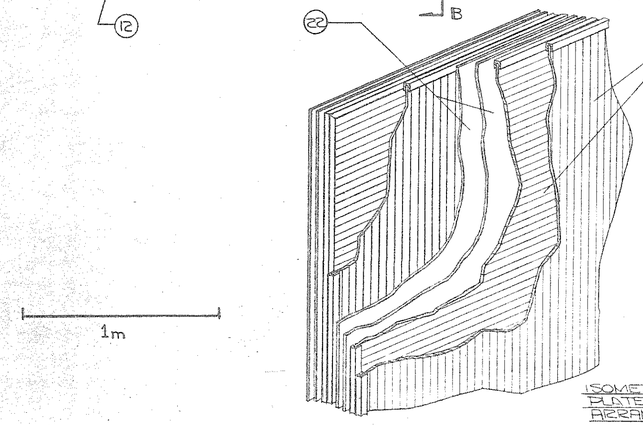


FIG. 1 EXPERIMENTAL ARRANGEMENT





ISOMETRIC OF STEEL PLATES AND X-Y PLANE MODULAR ARRANGEMENT

10 OUTER SHELL: CARBON STEEL
11 INNER SHELL: STAINLESS STEEL
12 G-10 SUPPORT FRAME
13 G-10 SUPPORT RING
14 VESSEL HEAD ASME TYPE, CARBON STL. BOTH ENDS
15 INNER CHAMBER CLOSURE PLATE, BOTH ENDS
16 LOW HEAT LEAK COLUMN SUPPORT (9)
17 AIR PAD TRANSPORT SYSTEM
18 PLATE MODUL SUPPORT ROD G-10
19 SUPPORT HINGE
20 CONVEYING COILS
21 PLATE SPACER RODS G-10
22 CARBON STEEL PLATES 15MM THICK, 2MM GAP X 3.6m SQUARE (1400 PLATES)
23 CARBON STEEL STRIPS 15MM THICK, 2cm WIDE; X 3.6m SQUARE, XY MODULAR (1400 REQD)
24 EVACUATED AREA WITH SUPER INSULATION
25 LIQUID ARGON LEVEL
26 MOUNTED ELECTRONICS

APPROX WEIGHT OF DETECTOR 550 TONS
VOLUME OF LIQUID ARGON NEEDED 180,000 LITERS
PHYSICAL DIM 5.7m DIA X 14m LONG

STUDY OF PROPOSED LIQUID ARGON CALORIMETER

SCALE 1/8"=1' DATE: 3/21/77
DRAWN BSS S-51206-A

Table 1

Target Calorimeter

Active Dimensions	$3.6 \times 3.6\ m^2$
Length	12.5 m
Sampling Step	1.5 mm iron (1.18 gm/cm^2)
Sampling Counter (Energy)	Liquid argon, 2 mm thick, iron plates $3.6 \times 3.6\ m^2$
Sampling Counter (Angle)	Liquid argon, 3 mm thick, iron plates 3.6 m × 0.02 m x and y, every 16 mm
Modularity	140 modules of 10, $3.6 \times 3.6\ m^2 \times 1.5$ mm plates and 5 sets of $3.6 \times 0.02\ m^2 \times 1.5$ mm x and y strips
Total Quantities	Target weight 327 tons Target thickness 4089 gms/cm^2 Total weight 788 tons 30,000 channels of electronics
Average Quantities	Density $\rho = 4.17\ gms/cm^3$ Radiation length: 8.75 cm Interaction length: 34.7 cm
Performance	Vertex Resolution $\sigma = 0.6$ cm Shower Direction $\sigma(\theta_H) = 0.004 + \frac{0.6(GeV)}{E_H}$ or ± 10 mrad at 100 GeV Hadron Energy Resolution $\frac{\sigma(E_H)}{E_H} = \frac{0.5}{\sqrt{E_{(H)}}}$

divergence of the neutrino beam is almost completely determined by the decay kinematics of pion and K-meson decay.

We can make use of this effect to almost completely eliminate the pion neutrinos from the detector and only accept kaon neutrinos, which will allow the energy to be known to roughly ± 9%. This accuracy depends on the angular divergence of the charged particle beam and its momentum resolution, assumed here to be ± 9%. This momentum spread completely dominates the knowledge of E_ν.

If the detector is large enough to detect neutrinos at ± 1 mrad, centered at about 2 mrad, a large fraction of the kaon neutrino spectrum is covered in a single exposure. This is discussed further in the section on the beam.

Dewar

The dewar design follows standard cryogenic practice. Its construction will be double walled steel with the space filled with superinsulation and evacuated. The supports will be low heat loss columns of the type used at Fermilab for superconducting magnets.[17] The heat loss per column should be roughly 100 milliwatts.

Both ends of the dewar will be removeable to facilitate construction of the calorimeter, which will proceed from the middle out in both directions. The support columns have air pads of the type used on large spectrometer magnets at Cornell[19] at the base. This will allow the calorimeter to be moved into place after being assembled in an open region.

The cooling will be carried out with liquid nitrogen through heat exchange coils inside the dewar. A reservoir will be used to store the liquid argon between fills and also to serve as a continuous supply during operation. The

purity of the liquid argon will be continuously monitored and purification initiated when necessary; the indications are[20] that purification will not be required very often. Figure 3 illustrates the liquid argon monitoring and purification system.

We expect the total heat loss from the calorimeter to be less than 4 watts.

The choice of the size and composition of the calorimeter were dictated by the desire for full shower containment and the best possible energy resolution coupled with a large acceptance, as discussed above, and good measurement of the direction of the shower. We discuss each in turn.

Shower Containment

Measurements of hadron shower development at 100 GeV in an iron-plastic scintillator calorimeter has recently been made by a CERN group.[31] The data show the somewhat surprising fact that the showers do not spread out radially as they develop horizontally; the shower is cigar shaped. This indicates that, in iron, only 30 cm need be allowed radially to totally contain the shower.[31]

A group at Oak Ridge[21] has calculated shower development in iron-liquid argon, iron-plastic scintillator, and uranium-liquid argon for a variety of hadron energies. Indications are that in order to contain at least 99% of a hadron shower greater than 6 collision lengths (3 absorption lengths) horizontally with respect to the axis of the shower development must be allowed. Measurements by two CERN groups[20,31] and by CITF[22] and HPWF[22] verify these numbers. This is illustrated in Figure 4 taken from reference 20.

We have allowed 6 collision lengths horizontally in order to insure that we have essentially complete containment. We have also allowed 5 collision

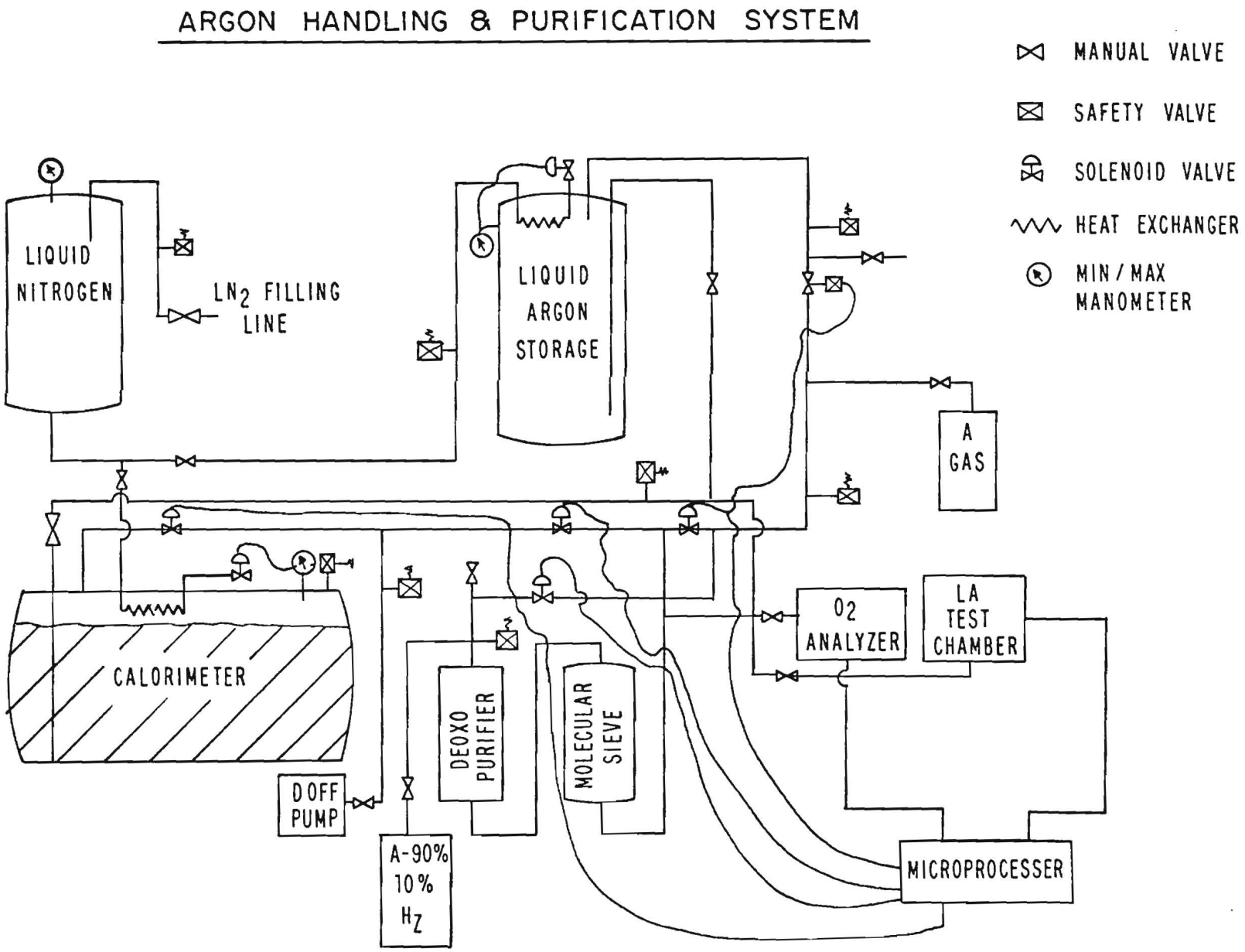

ARGON HANDLING & PURIFICATION SYSTEM
MANUAL VALVE
SAFETY VALVE
SOLENOID VALVE
HEAT EXCHANGER
MIN / MAX MANOMETER
LIQUID NITROGEN
LN2 FILLING LINE
LIQUID ARGON STORAGE
A GAS
CALORIMETER
DOFF PUMP
DEOXO PURIFIER
MOLECULAR SIEVE
A-90% 10% H2
O2 ANALYZER
LA TEST CHAMBER
MICROPROCESSER

FIGURE 3

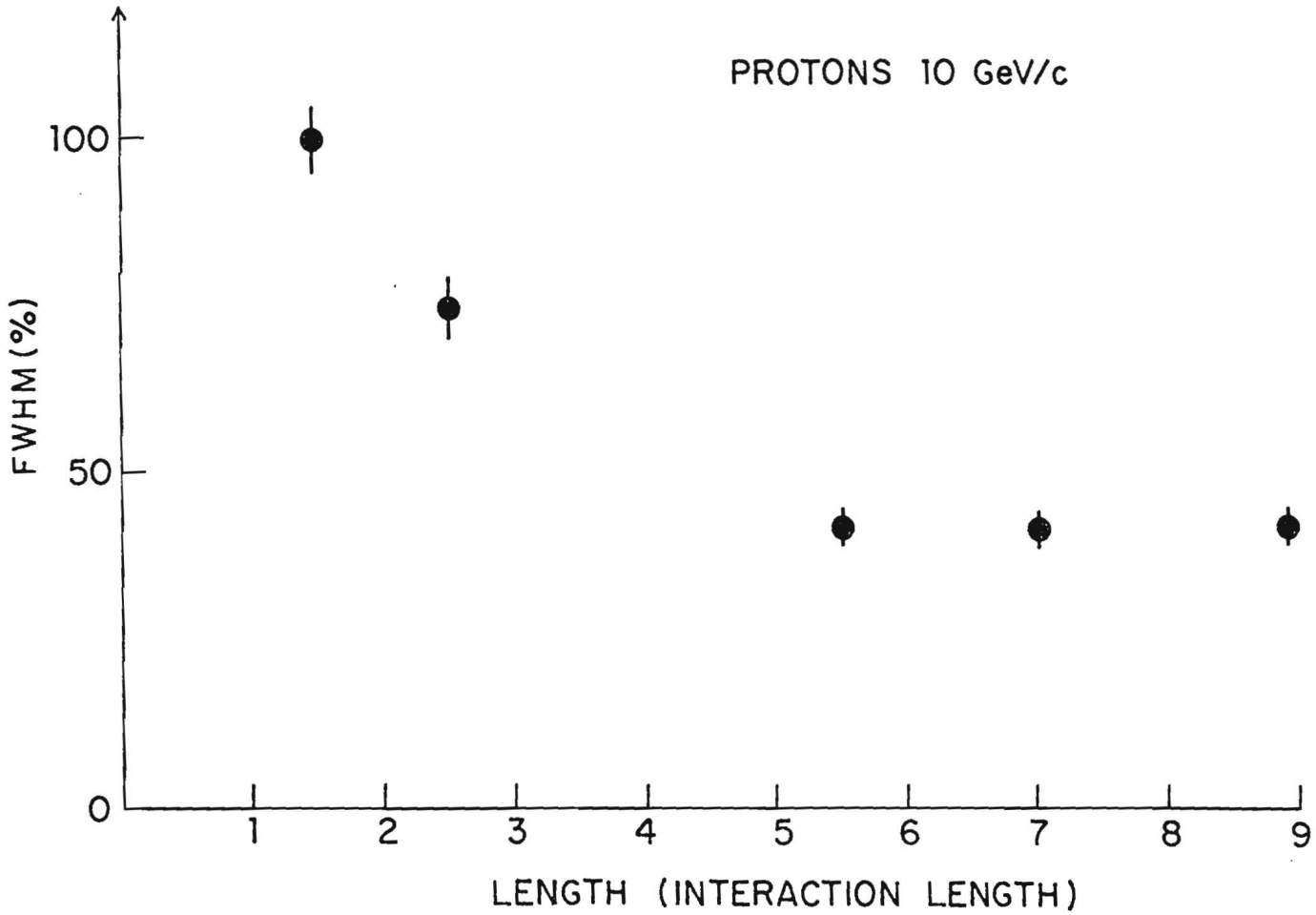

PROTONS 10 GeV/c
FWHM (%)
100
50
0
1
2
3
4
5
6
7
8
9
LENGTH (INTERACTION LENGTH)

FIGURE 4

lengths in front of our fiducial volume to filter out hadrons in the beam.

Energy Resolution

Here we follow almost verbatim the discussion in reference 20.

Factors Which Limit the Resolution in Hadron Calorimeters

It may be useful to summarize briefly the processes which occur in a hadronic cascade. The hadron interacts with a nucleus after approximately one interaction length, generating typically several charged pions and several neutral pions, depending upon the incident energy, as well as a number of relativistic protons and a number of nuclear fragments. These last will be neutrons of energies of a few MeV and charged particles of very short range, including slow protons, deuterons, α-particles, and heavier fragments. The photons from neutral pions rapidly lead to electromagnetic showers which deposit all their energy by ionization of relativistic electrons. The charged pions and relativistic protons go about another nuclear interaction length and make further nuclear interactions which lead to the same kinds of particles in the final state. The nuclear fragments rarely interact again, but deposit their energy near the first interaction in the form of high ionization density tracks. The neutrons deposit their kinetic energy by elastic and inelastic collisions, and upon being captured by nuclei yield their binding energy of a few MeV in the form of photons, although this may happen at distances of many interaction lengths from the original source. Certain forms of energy are not visible in the absorber as ionization. These are: energy lost by neutrinos, mostly from pions at rest; high energy muons from decays which

have very long range; and that energy which is required to break up the nuclei, or nuclear binding energy. Most ionization detectors are also less than completely sensitive to particles of high ionization density, so that some of this ionization is effectively lost. In some absorbers it may be very difficult to retain all the energy of the neutrons. For example, in iron the interaction cross-section for neutrons of a few MeV energy is very small.

It is interesting to look at the results of the Oak Ridge Group[21] on the form in which ionization is eventually deposited, as shown in Table 2. It can be seen that the most important forms in which energy is deposited are due to the electromagnetic cascades from π°'s, as well as that due to slow particles. The fast pions deposit relatively little of the whole. It is also surprising what a large fraction of energy goes into nuclear binding energy.

A useful simple picture of the cascades is to consider them as being made up of two componenets: an electromagnetic shower component due to the neutral pions, and another component associated with the nuclear fragments. The division of energy between these shown in Table 2 is only true on the average, while individual events show a large fluctuation in the ratio of these two components because their contributions are determined largely by the nature of the very first interaction, where only a few particles are involved, particularly at low incident energies. The different response of a calorimeter to each of these two components proves to be the most important phenomenon affecting the performance of hadron calorimeters.

In the light of the above discussion, we may list those fluctuations which limit the resolution of hadron energy measurement.

i) *Fluctuations in the leakage of ionizing particles.* This can be reduced by making the absorber sufficiently large, but the range

Table 2

Average fractional energy deposition by particle type for 10 GeV proton interactions in an iron-argon calorimeter[a)]

Type of energy deposition	Percent of total
Primary proton ionization	2.3
Secondary proton ionization	31.6
Secondary $\pi^{\pm}$ ionization	8.2
$\mu^{\pm}$ ionization	0.05
Electromagnetic cascade	21.0
$Z > 1$ ionization	2.4
Residual nuclear exitation energy	3.7
Neutrons with energy > 10 MeV transported to a radius $\gtrsim$ 2 interaction lengths	4.9
Neutrons with energy < 10 MeV	3.9
Nuclear binding energy plus neutrino energy	20.6

a) T.A. Gabriel and W. Schmidt, Calculated performance of iron-argon and iron-plastic calorimeters for incident hadrons with energies of 5 to 75 GeV, ORNL/TM-5105 (1975).

of high energy muons is such that they cannot possibly be contained. There is also a loss of particles out of the face of the absorber through which the incident particle enters, albedo. This can be eliminated if we reject those events where the interaction is in the first interaction length of the absorber. However, if we are not willing to accept substantial inefficiencies, this effect remains to limit the energy resolution.

ii) *Fluctuations in the leakage of non-ionizing particles.* Neutrinos will escape from any absorber. Hadrons are in principle retained, except for albedo, but in practice an absorber which is large enough to contain most hadrons still leaks neutrons of a few MeV, particularly when a material such as iron is used.

iii) *Fluctuations in nuclear binding energy* necessary to disrupt the nuclei in the cascade. This energy is not directly detectable.

iv) *Fluctuations in the saturation of the detector response* to particles of high ionization density. This saturation of response is present in almost every detector of ionizing radiation, but to different degrees. It can cause the effective loss of most of the energy corresponding to slow protons and heavier nuclear fragments.

v) *Sampling fluctuations.* These are the fluctuations associated with the fact that in most calorimeters not all of the ionization is measured, but only periodically sampled. Even in those few detectors which use a homogeneously sensitive detector, some dead regions in the absorber are unavoidable and therefore may contribute a fluctuation of this type.

vi) *Noise.* This includes effects of photon statistics in scintillation detectors, amplifier noise, and signal distortions due to slow neutrons from previous events or pile-up of events occurring within the time resolution of the detector.

vii) *Fluctuations due to non-uniform response.* This effect would be absent in an ideal detector, but many calorimeters which have actually been built clearly suffered to some degree from this effect. We include here such effects as the non-uniform response across a given section of the detector, and different responses due to errors in calibration between different sections of a detector.

The CERN group[20] has concluded that, in a detector of sufficient size so that leakage of fast particles is not important, the resolution is dominated by nuclear fluctuations.

It is clear that the best way to compensate for these fluctuations is with U^{238} plates where one gains by fission amplification. However, measurements made at CERN[32] indicate that, in order to get adequate angular resolution, it is necessary to sample radially along the shower at intervals of 1 radiation length: for uranium this is 3 mm! The resolution in the angle of the shower dominates the hadron energy resolution when applied to the uncertainty in $x = Q^2/m_p\nu$; this is illustrated in Figures 5 and 6.

We have found that iron (steel) allows a significantly better measurement of the angle, by almost a factor of 5, using a strip sampling width of 2 cm ($\sim$ 1 rad length). We lose only a factor of 2 or so in the energy resolution with iron over uranium. This is shown in Figure 7 where we plot energy resolution

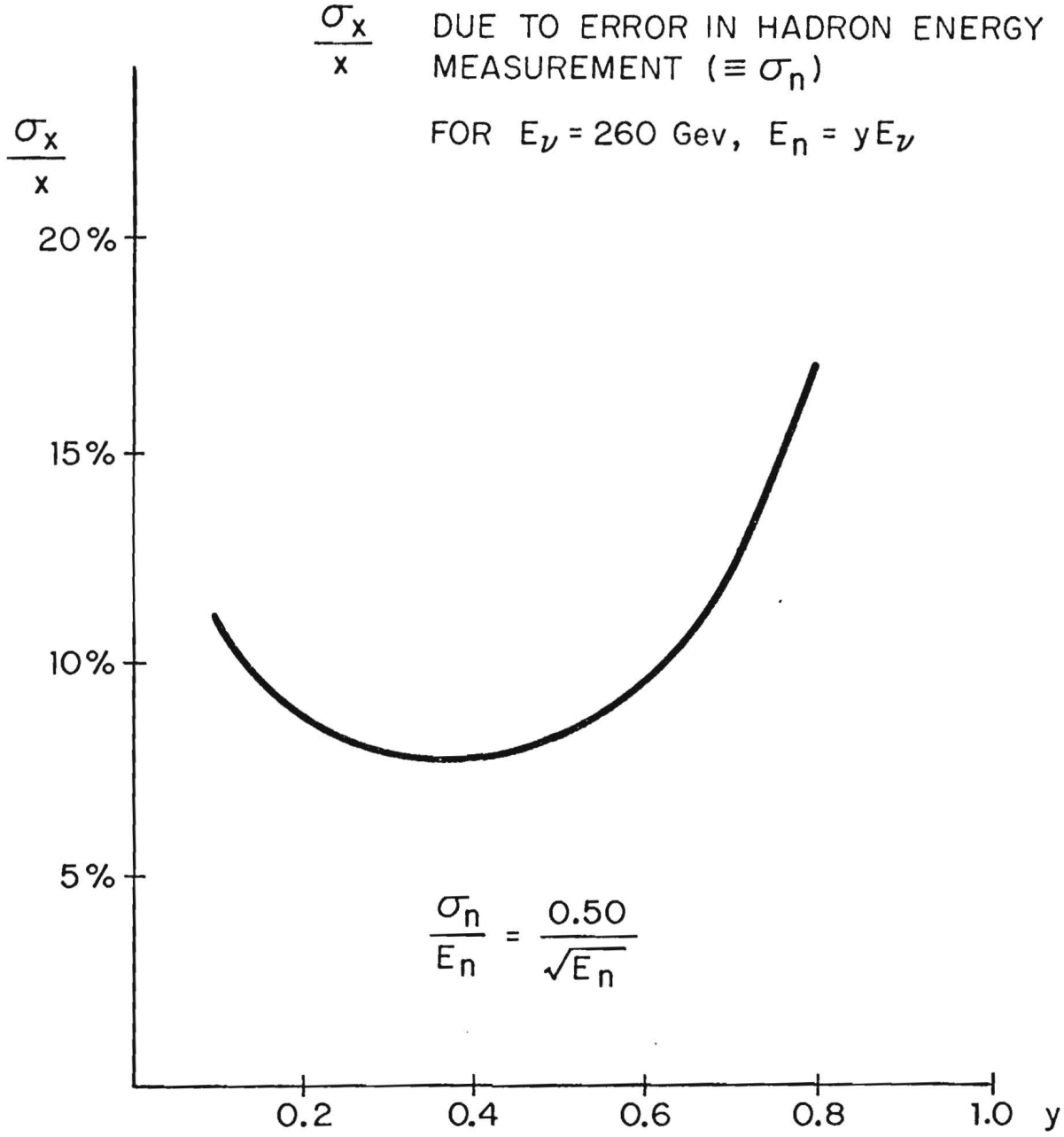

$\frac{\sigma_x}{x}$ DUE TO ERROR IN HADRON ENERGY MEASUREMENT ($\equiv \sigma_n$)
FOR $E_\nu = 260$ Gev, $E_n = yE_\nu$
$\frac{\sigma_x}{x}$
20%
15%
10%
5%
$\frac{\sigma_n}{E_n} = \frac{0.50}{\sqrt{E_n}}$
0.2
0.4
0.6
0.8
1.0
y

FIGURE 5

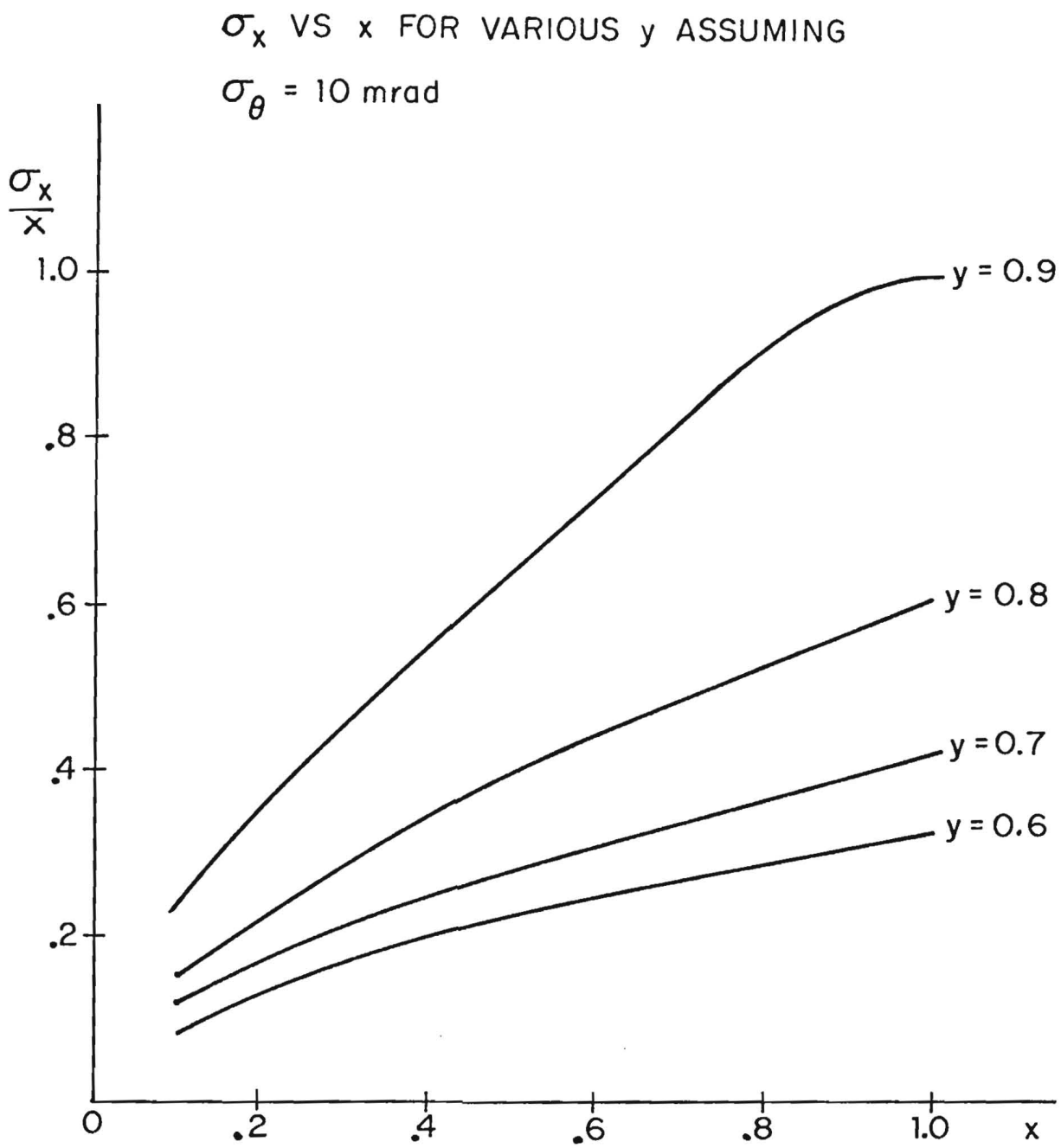

σ_x VS x FOR VARIOUS y ASSUMING
σ_θ = 10 mrad
$\frac{\sigma_x}{x}$
1.0
.8
.6
.4
.2
0
.2
.4
.6
.8
1.0
x
y = 0.9
y = 0.8
y = 0.7
y = 0.6

FIGURE 6

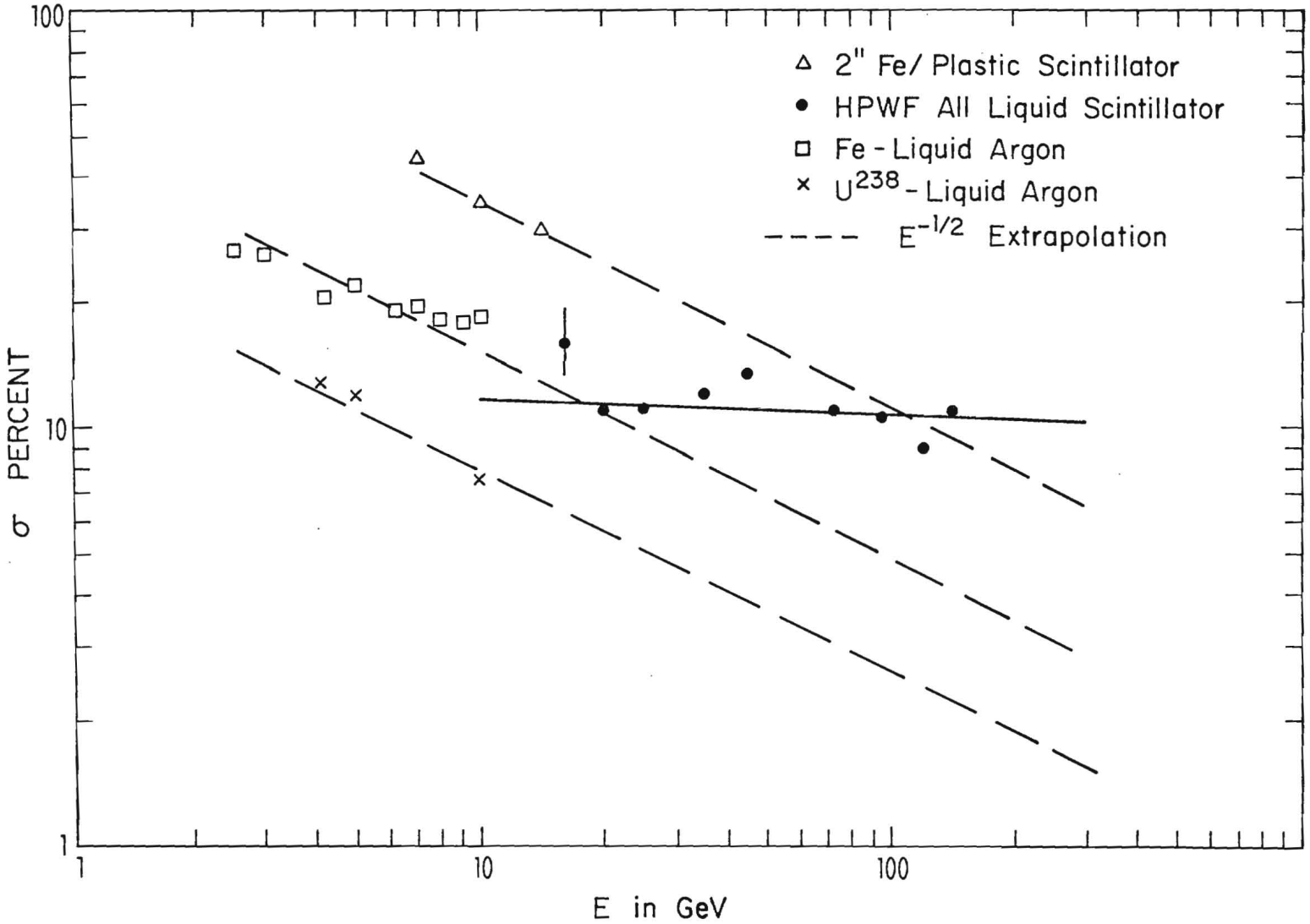


FIG. 7 RESOLUTION VS. ENERGY

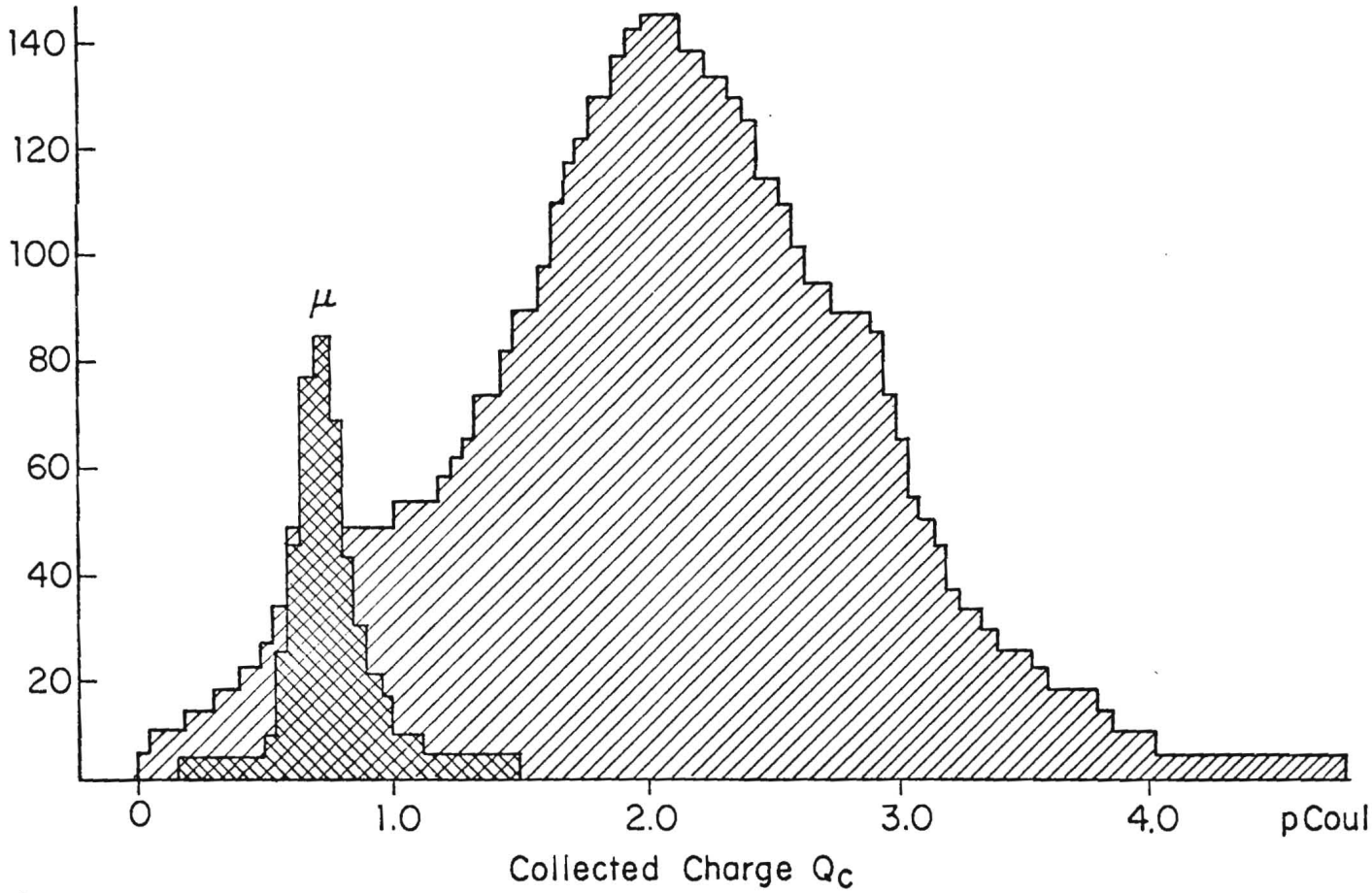
vs energy for Fe/plastic, Fe/liquid argon, and U^{238}/liquid argon. Iron/liquid argon is still superior in energy resolution to Fe/plastic, again by a factor of two or so.

Resolution in x and y

A SLAC/LBL group[26] has measured the position of a shower produced by 4 GeV/c electrons incident on a lead/liquid argon calorimeter to 2 mm using 2 cm samplings across the face of the shower and five samplings along its length. Measurements with a 10 GeV/c pion beam incident on an iron/liquid argon calorimeter have been made at CERN.[20,27] These measurements, although much more crude than the SLAC/LBL studies, indicate that at least 2 cm resolution on the centroid of the change distribution for hadron showers can be achieved, if the sampling is fine grained enough.

This group also indicates that single muons can be distinguished easily from hadrons as is shown in Figures 8 and 9 taken from reference 22. Figure 8 shows the collected charge for 10 GeV/c π^- and μ^- gotten by demanding that the region around a "track" contain less than 4 times the amount of charge deposited by a minimum ionizing particle. In Figure 9 this criteria has been strengthened by demanding that this associated charge be less than 1 times minimum ionizing: it is claimed that no muons are lost by making this cut. These measuremtns indicate that it is possible to track a single minimizing particle through the calorimeter; we will then have essentially 100% acceptance for muons from charged current interactions. This should reduce the contamination of these events in our neutral current sample to a negligible amount.

Recent measurements at CERN[32] indicate that, at 22 GeV, a resolution of $\sigma(\theta_H) = 30$ mrad can be achieved. Measurements at lower energies indicate that the formula


140
120
100
80
60
40
20
μ
0
1.0
2.0
3.0
4.0
pCoul
Collected Charge Q_c

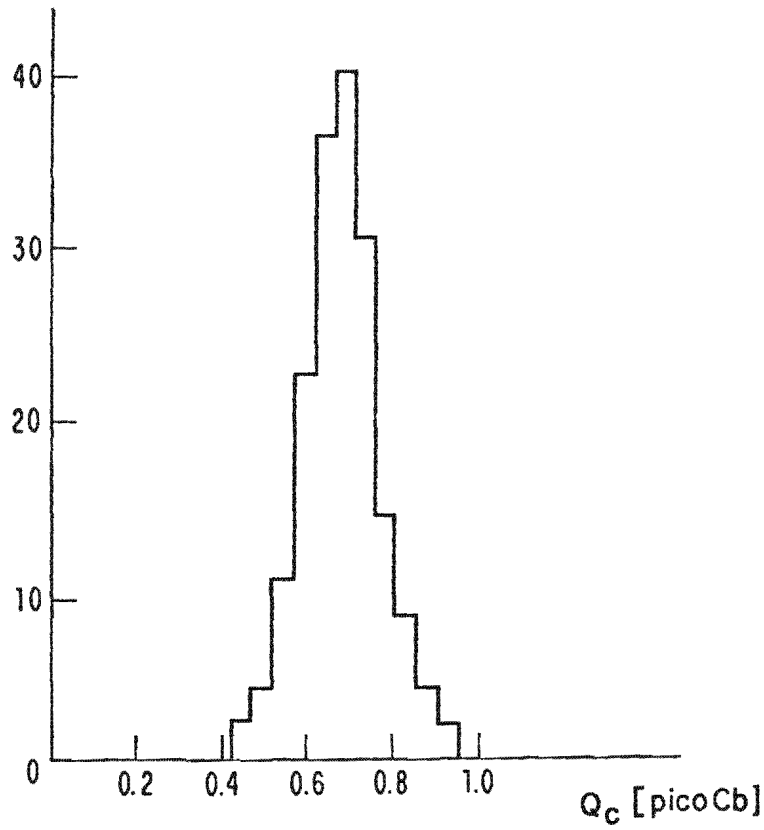


FIGURE 9

MUON SIGNAL OBTAINED BY MORE RESTRICTIVE CONDITIONS; EFFICIENCY IS UNCHANGED.

$$\sigma\left(\theta_H\right) = 0.004 + \frac{0.60 \text{ GeV}}{E_H}$$

is a good representation of the data. This implies $\sigma\left(\theta_H\right) = 10$ mrad at 100 GeV. With the geometry we propose, which is similar in sampling frequency to the test calorimeter used at CERN, we expect similar angular resolution.

Using the proposed geometry we have calculated, using Monte Carlo methods, the resolution in $x = Q^2/2m_p\nu$ in the following way. Monte Carlo data were generated according to the distribution $\sigma\alpha(1 - x)^3$. The data were then passed through the apparatus with appropriate resolutions and a fit was made to the result. This is shown in Figure 10 for a sample of only 2000 events; we take $E_\nu = 260$ GeV $\pm$ 9%, $E_{Hadron} > 150$ GeV, $\sigma_{E\ Hadron} = 0.75/\sqrt{E_h}$ and $\sigma\left(\theta_H\right) = 10$ mrad. The $\sigma\left(\theta_H\right)$ is a pessimistic estimate at these energies. Fitting to the analyzed distribution a function of the form $A(1 - x)^N + C$ we get $N = 2.77 \pm 0.17$, to be compared with the input distribution of $N = 3$. The agreement is good.

We have calculated, via Monte Carlo, the ability of the detector to measure the difference between a flat distribution in y and $f(y) = (1 - y)^2$. We have taken a worse case

$$\sigma_{E\ Hadron} = 0.75/\sqrt{E_H}$$

$$\sigma\left(\theta_H\right) = 10 \text{ mrad},$$

and neutrino energies gaussian distributed around $E_\nu = 260$ Gev with a $\sigma = 9\%$ which is what we expect for a given neutrino energy. We have fit to the function $f(y) = C + A(1 - y)^2$ for an experiment of 500 events. The results are given in the following table.

$$f(y) = C + A(1 - y)^2: \quad 0.2 \leq y \leq 0.9$$

A	C	$\frac{A}{A + C}$	Analyzed $\frac{A}{A + C}$ for 500 Events
0	1	0	0.09 ± 0.23
1/2	1	0.5	0.40 ± 0.18
1	1	0.5	0.52 ± 0.16
1	0.5	0.67	0.66 ± 0.15
1	0	1	1.03 ± 0.06

This indicates that in a 2,000 event experiment, in most regions of x, y and E_ν, good measurements of A can be made.

B. HPWF Muon Spectrometer

We envisage using the HPWF muon spectrometer with the present spark chambers replaced by drift chambers. We feel that the noise generated by the present optical chambers will be intolerable considering the sensitive electronics demanded by the calorimeter. Drift chambers of the appropriate size have been built at Harvard and may be made available for use with this facility. If they are not we plan to build the needed chambers.

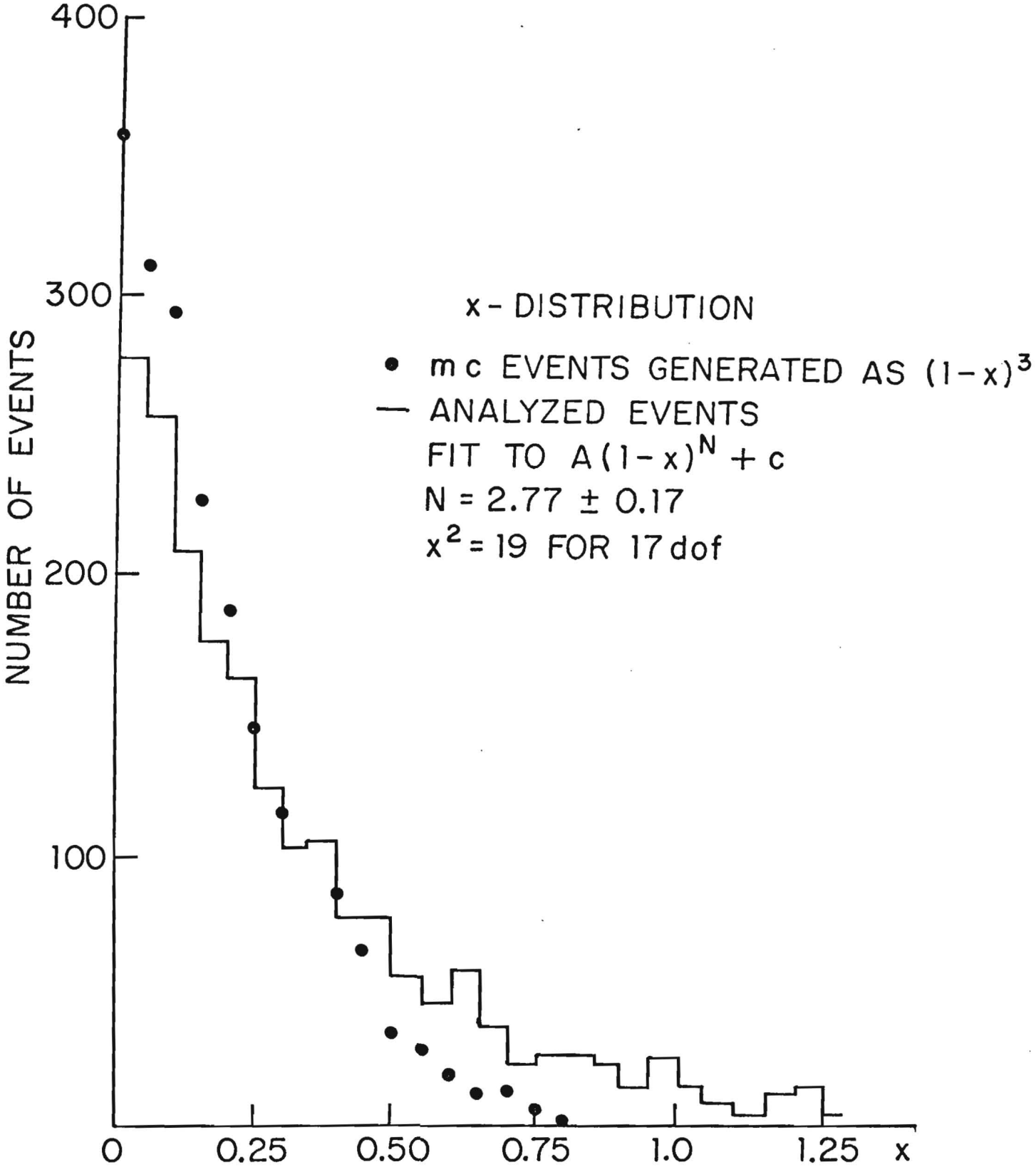

400
300
200
100
NUMBER OF EVENTS
x - DISTRIBUTION
• mc EVENTS GENERATED AS $(1-x)^3$
— ANALYZED EVENTS
FIT TO $A(1-x)^N + c$
$N = 2.77 \pm 0.17$
$x^2 = 19$ FOR 17 dof
0
0.25
0.50
0.75
1.0
1.25
x

FIGURE 10

IV. The Beam and Event Rates

The final size of the fiducial volume was determined by our desire to make high statistics measurements of neutral current phenomena over a large kinematic region, using the dichromatic beam that is presently being built at Fermilab.[4] The calculated spectra of neutrinos and antineutrinos expected from this beam are shown in Figures 11 and 12 respectively.

In order to have a large y coverage, which demands a good knowledge of the incoming neutrino momentum, it is necessary to situate the detector away from zero degrees with respect to the beam line. This fact is illustrated in Figure 13. Here we have plotted neutrino energy against lab angle. The first thing to note is that the neutrinos from pion decay are all concentrated at less than 1 mrad from zero degrees while the neutrinos from k-decay extend beyond 5 mrad. The second fact is that the region from 1 to 3 mrad contains neutrinos in the range 70 GeV < E_ν < 210 GeV. The neutrino energy is known, from the angle of the neutrino, which means the position of the interaction across the face of the detector, to an accuracy defined by the momentum resolution of primary K-meson beam, ± 9%. There is essentially no background from π-neutrinos! A detector that subtends ± 1 mrad centered at 2 mrad with respect to the nominal beam line would cover the entire y range; energy deposition cuts which severely limit the y range accessible to study unnecessary.

We have calculated the event rate expected in the proposed detector situated at 2 mrad with a fiducial volume of 3 m × 3 m × 12 m which is 4090 gms/cm^2 × 9 m^2 of target. The results are given in Tables 3 and 4 for neutrinos and antineutrinos, where we have taken into account the loss in solid angle. We note that the number of events per day, roughly 100, is less by a factor of about 60 than

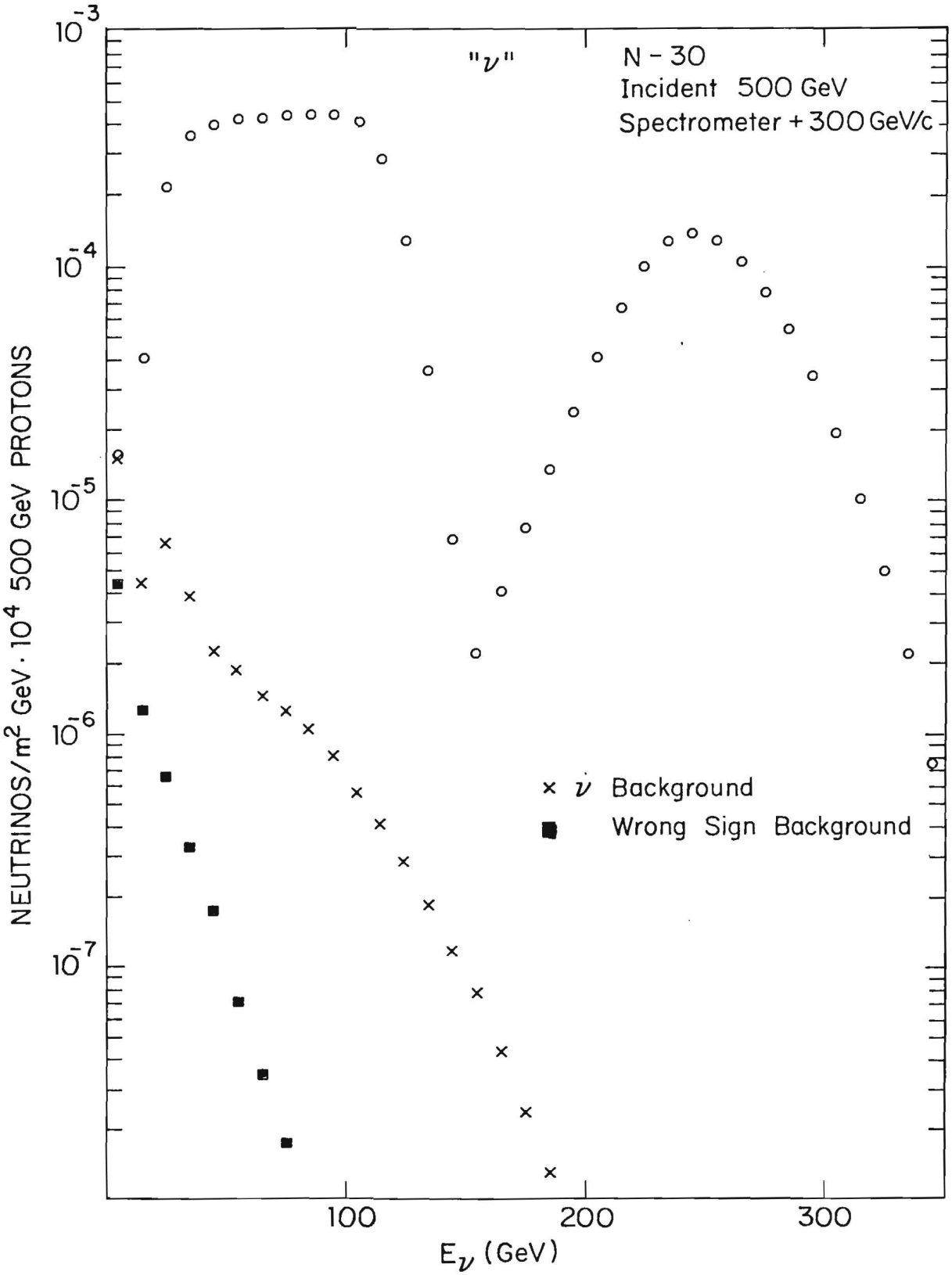

"ν"
N - 30
Incident 500 GeV
Spectrometer + 300 GeV/c
× ν̄ Background
■ Wrong Sign Background
NEUTRINOS/m² GeV · 10⁴ 500 GeV PROTONS
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
100
200
300
E_ν (GeV)

FIGURE 11

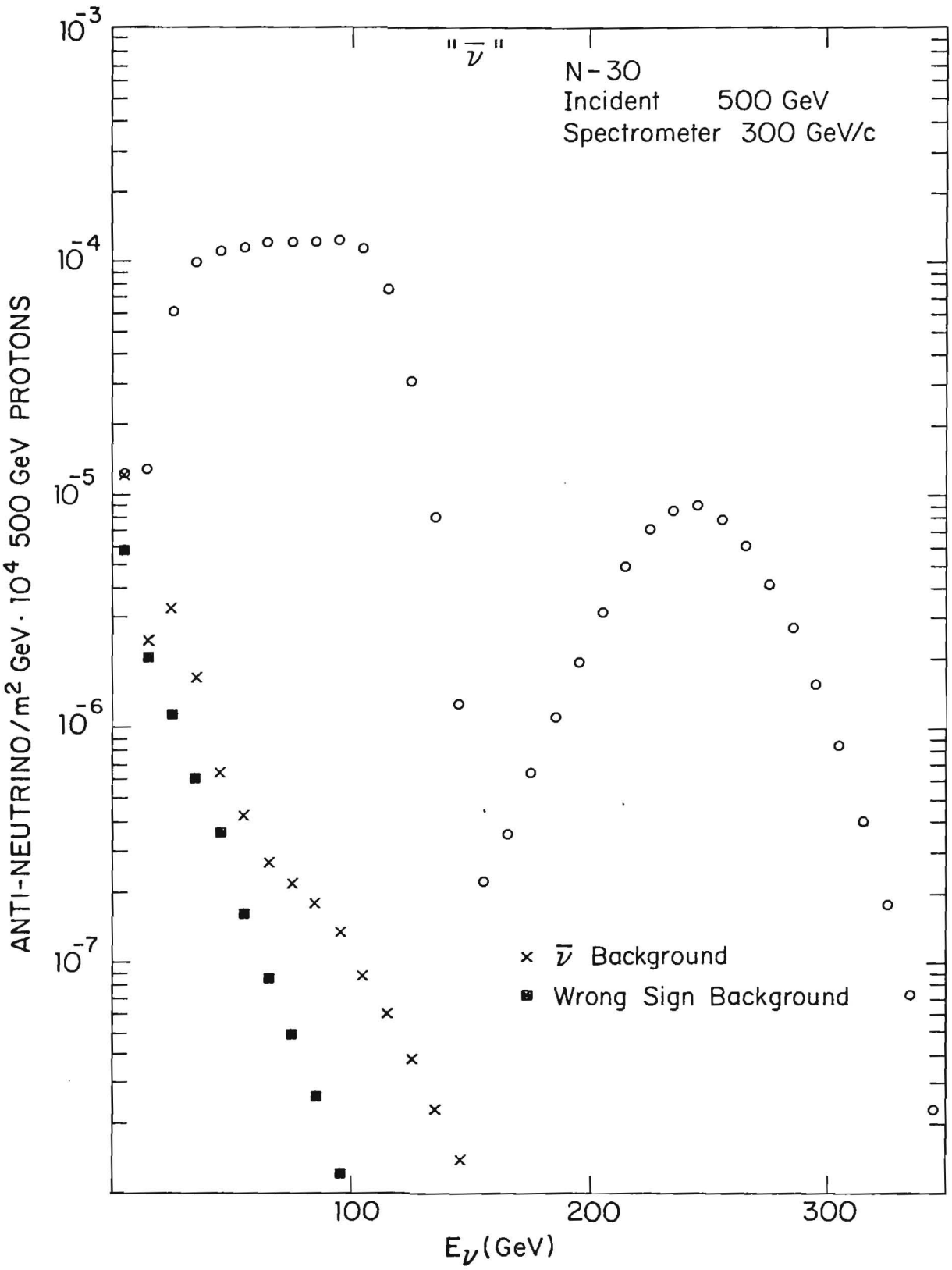

"$\bar{\nu}$"
N-30
Incident 500 GeV
Spectrometer 300 GeV/c
$\bar{\nu}$ Background
Wrong Sign Background
ANTI-NEUTRINO/m^2 GeV · 10^4 500 GeV PROTONS
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
100
200
300
E_ν (GeV)

FIGURE 12

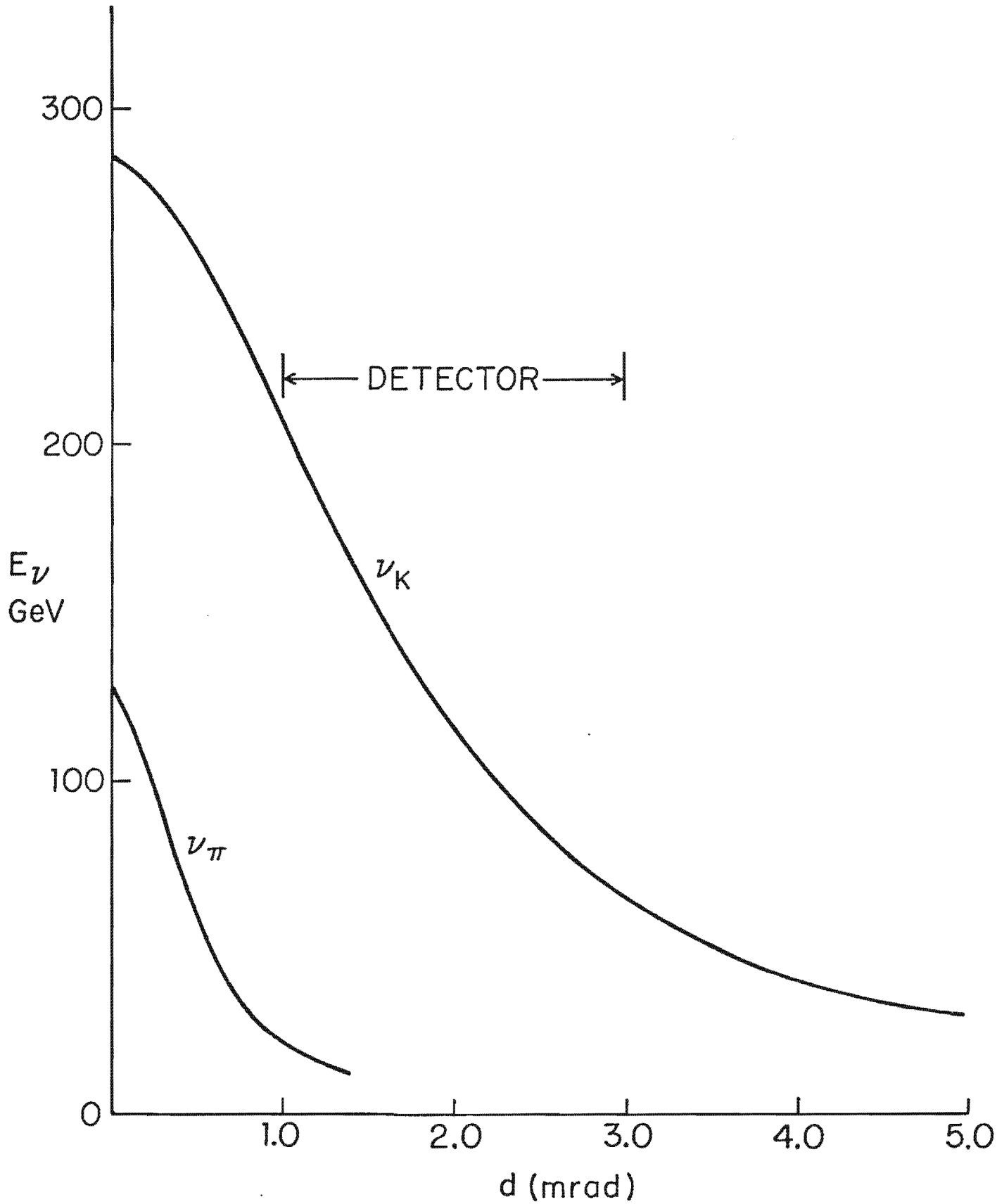


FIG. 13 E_ν VS DECAY ANGLE IN THE LAB FOR E PRIMARY = 300 GeV

Table 3

Event Rate - Neutrinos

$$\left(\sigma^{\nu} = 0.83\ E_{\nu} \times 10^{-38}\ \mathrm{cm}^2\right)^1$$

E_{ν} (GeV)	# Events per 10^{13} Protons on Target
70	9.53×10^{-7}
80	1.96×10^{-6}
90	3.99×10^{-6}
100	7.84×10^{-6}
110	1.65×10^{-5}
120	2.86×10^{-5}
130	5.30×10^{-5}
140	9.54×10^{-5}
150	1.84×10^{-4}
160	3.71×10^{-4}
170	6.95×10^{-4}
180	1.23×10^{-3}
190	2.33×10^{-3}
200	4.03×10^{-3}
210	7.44×10^{-3}
Total:	$0.0165/10^{13}$ protons

100 Events/Day

Day $\equiv$ 5 pulses/min $\times$ 20 hrs.

Table 4

Event Rate - Antineutrinos

$$\left(\sigma^{\bar{\nu}} = 0.28\ E_{\nu} \times 10^{-38}\ cm^{2}\right)^{1}$$

$E_{\bar{\nu}}$ (GeV)	# Events per 10^{13} Protons on Target
70	----------
80	----------
90	----------
100	2.99×10^{-7}
110	5.06×10^{-7}
120	9.65×10^{-7}
130	1.79×10^{-6}
140	3.22×10^{-6}
150	5.86×10^{-6}
160	1.10×10^{-5}
170	1.95×10^{-5}
180	3.72×10^{-5}
190	6.55×10^{-5}
200	1.06×10^{-4}
210	1.93×10^{-3}
	$2.18 \times 10^{-3}/10^{13}$ protons

13 events/day

what one would get at zero degrees. However, if we are to study the details of neutral currents we must know the incoming neutrino energy; moving away from zero degrees seems the best way of accomplishing this goal. This fact indicates that bubble chambers are not suitable for this kind of study because the event rates would be prohibitively low.

Since we plan to build the calorimeter in a way that facilitates moving it, we can optimize its position for the largest flux with an acceptably low contamination from pion neutrinos.

V. Comparison with CERN SPS

	This Proposal	WA 1*	WA 18+
Useful Target	4089 gms/cm^2	8558	2200
E_h-Resolution (σ)	50% $E^{-1/2}$	90% $E^{-1/2}$	55% $E^{-1/2}$
X-Resolution	20 - 30%	None	20 - 30%
Beam	Dichromatic N-30 Beam	Dichromatic and wide band	Dichromatic
Cost	$\$1.4 \times 10^6$	------	------
Completion	∿2 years after approval	Data taking	Fall 1978
Goals	ν, $\bar{\nu}$ neutral currents; W^2 strucutre in cross sections; comparisons with charged currents with very good resolution in x and y; anomalous events in neutral currents	------	------

* Steinberger

\+ Winter

VI. Preliminary Cost Estimate

1. Dewar	$100K[a]	
2. Plumbing	30K[b]	
3. Air pads	40K[c]	
4. Electronics	600K[d]	
5. Steel plates and steel strips	350K[e]	
6. Drift chambers	(100K)[f]	
7. Computer	(40K)[g]	
8. Liquid argon storage and supply	(60K)[h]	
9. Trigger counters	50K[i]	
10. Contingency (20%)	229K	
Total:	$1399K	($1599K)

Assembly: 5 men × 1 year

a. Engineering estimate for a double walled carbon and stainless steel dewar. Includes internal G-10 support structure.

b. Includes oxygen monitoring devices. Does not include microprocessor.

c. Engineering estimate for 900 ton support system.

d. Cost of 30,000 channels of electronics, microprocessor and cables. Assumes the use of hybrid integrated circuits and the multiplexing of 1000 channels of sample and hold electronics per ADC. Design work in progress.

e. Approximately 471 tons of ready to use (smooth and punched) steel plate, 1.5 mm thick, at a cost of $744/ton. This may go down to $500-$600/ton.

f. Drift chambers of the size required already exist. It is hoped that they can be acquired for the muon spectrometer. If not the cost will be approximately $10K per chamber.

g. A computer of appropriate size and speed (PDP 11/45 or PDP 15) can be acquired without new expenditures.

h. This includes liquid nitrogen and liquid argon storage and transfer pipes. We assume that this will be supplied by Fermilab. This does not include the cost of argon or nitrogen which we also hope Fermilab will provide.

i. Trigger counters will be placed inside the calorimeter in 5 places along its length. The counters are 2 feet × 6 feet in a 2 × 6 array. We assume $300/square meter for scintillator, $200 per phototube and $50 for shield and base. This comes to $7800/plane.

VII. Summary

We propose to carry out a high statistics study of the interaction of neutrinos with matter. To do this we propose to build a liquid argon-iron hadron calorimeter to be used in conjunction with the HPWF muon spectrometer with the spark chambers replaced by drift chambers. The device we propose is uniquely suited to study neutral current reactions; it is also an excellent tool for the study of charged currents.

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