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PRODUCTION OF W's AND STUDY OF DEEP INELASTIC

REACTIONS BY VERY HIGH ENERGY NEUTRINOS

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ABSTRACT: A spark chamber and scintillation counter experiment using very high energy neutrinos is proposed using a total of 2.10^{18} protons at 500 GeV in Area #1 at NAL. The purposes are simultaneously 1) to search for $\nu + Z \to Z + \mu^- + W^+$; $W^+ \to \mu^+ \nu$, $e^+ \nu$, and various hadron decay modes, 2) to analyze $\nu + A \to \mu^- + \Gamma$ (Γ = hadronic products) for large energy and momentum transfers and 3) to search with an unrestricted trigger and good analyzing power for low cross section or exotic reactions in this new energy region.

Names of Ph.D. Experimenters (by institutions; local leader underlined):

    Argonne National Laboratory: Y. Cho, L. Hyman, T. Romanowski (also Ohio State U.)

    Mass. Inst. of Technology: O. Fackler, D. Frisch

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    Northwestern U: J. Keren, S. Meyer, D. Miller

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Date: June 10, 1970

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II.   Physics Justification and Experimental Arrangement

We propose an experiment in Beam #1 at NAL with these simultaneous objectives:

1)   Search for production of the W-meson of weak interactions. A final state μ-meson would be observed in association with some of the decay products of the W, namely, $\mu\nu$, $e\nu$ and some hadronic decay modes.

2)   A comprehensive study of the deep inelastic scattering of the ν_μ and $\bar\nu_\mu$. This will be done with a primary emphasis on the large range of energy and momentum transfers that can be observed using a complex nucleus as a target. Coherent nuclear effects will be small.

3)   Search for low cross-section and new reactions.

These objectives will be taken up in order now with the detection of each reaction given in outline. Figure 1 shows a sketch of the apparatus, and Fig. 2 schematizes the functions of its parts.

Figure 3 shows the expected incident neutrino spectra based on the present design of Area 1 at NAL. Note that for convenience we will usually write equations only for ν_μ, treating $\bar\nu_\mu$, ν_e and $\bar\nu_e$ as contaminants except where a special effort is made to study their effects (II-2-b and II-3).

Final Spark Chamber
and Scintillator Plane

Magnetized
Iron Plates,
Scintillators,
and Spark Chambers

Thick
Magnetized
Iron

Lead
Plates and
Scintillators

Scintillator
Hodoscope Planes

Aluminum
Plate Spark
Chambers

INCIDENT
NEUTRINOS

etc.

etc.

5m

3m

0.3m

2m

Direct View
(field lens not
shown)
by 35mm Camera

Field Lens
for 90° Stereo

Mirror

Stereo
View
(above or
below)

Fig. 1

Aluminum Chamber · Shower Calorimeter · Magnetized Iron Chamber and Hadron Calorimeter · Magnetized Iron Momentum Analyzer
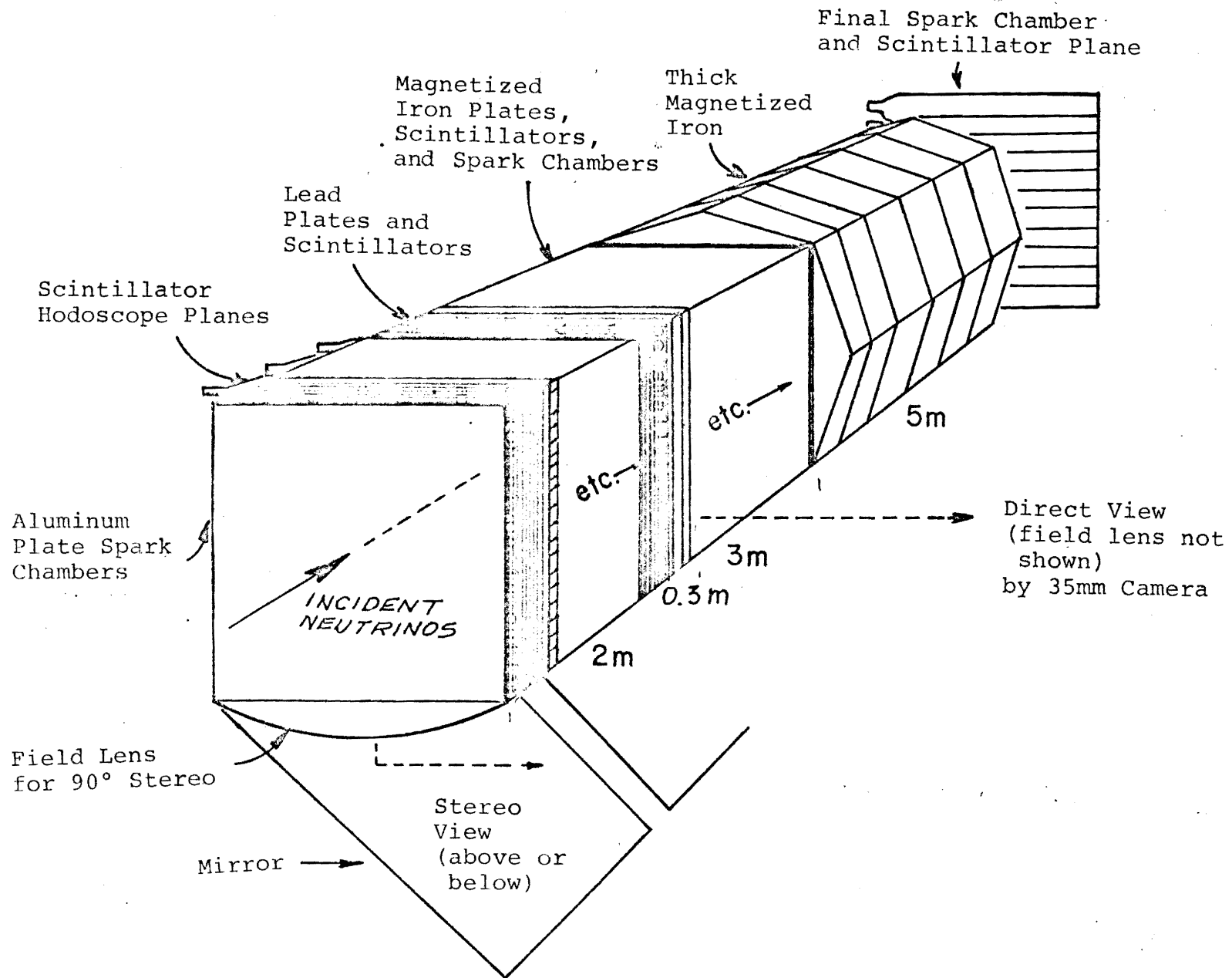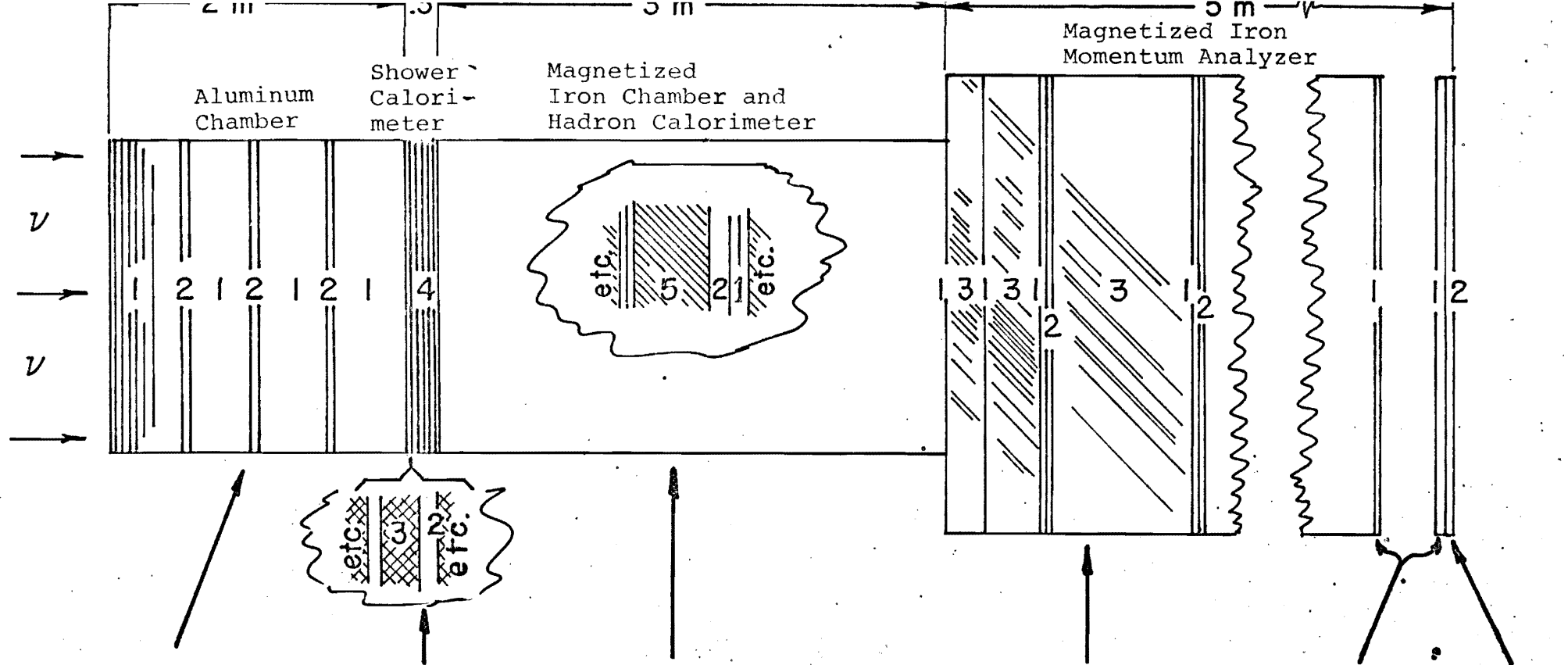
Components: 1/2" plate Al spark chamber (1), with plane of scin. counters (2) every half meter. Array totals 150 gaps; 11 radiation lengths; 10 tons.

½ Pb (3) Sandwich with scins (2); 12 layers; 30 radiation lengths; 7 tons.

2"Fe (5) toroidally magnetized iron sandwich with scins. (2) and spark chambers (1). Totals 30 layers; 1200 gm/cm^2;

Toroidally magnetized iron (3) with spark chambers (1) and scins. (2). Six sections of iron increasing from 1' to 4'. Totals 300 tons.

Spark chamber separated by 2'.

Last plane of scins

Purposes: Spark chambers give electron, gamma and hadron identification and angle measurements. Scintillators are part of hodoscope trigger throughout apparatus.

Electron energy measurement (±10%) by scintillators. Electronic showers removed. Part of hadron showers in Al measured.

Angle, Sign and range of muons measured by spark-chambers for ($.5 \lesssim E_\mu \lesssim 2$ GeV.) Hadron energy (±10%), measured by scintillators ("Hadrometer").

Bending magnet gives momentum of higher energy muons (> 10 GeV) to ±10%. Spark chambers between sections of magnet give range and sign for $2 \lesssim E_\mu \lesssim 10$ GeV.
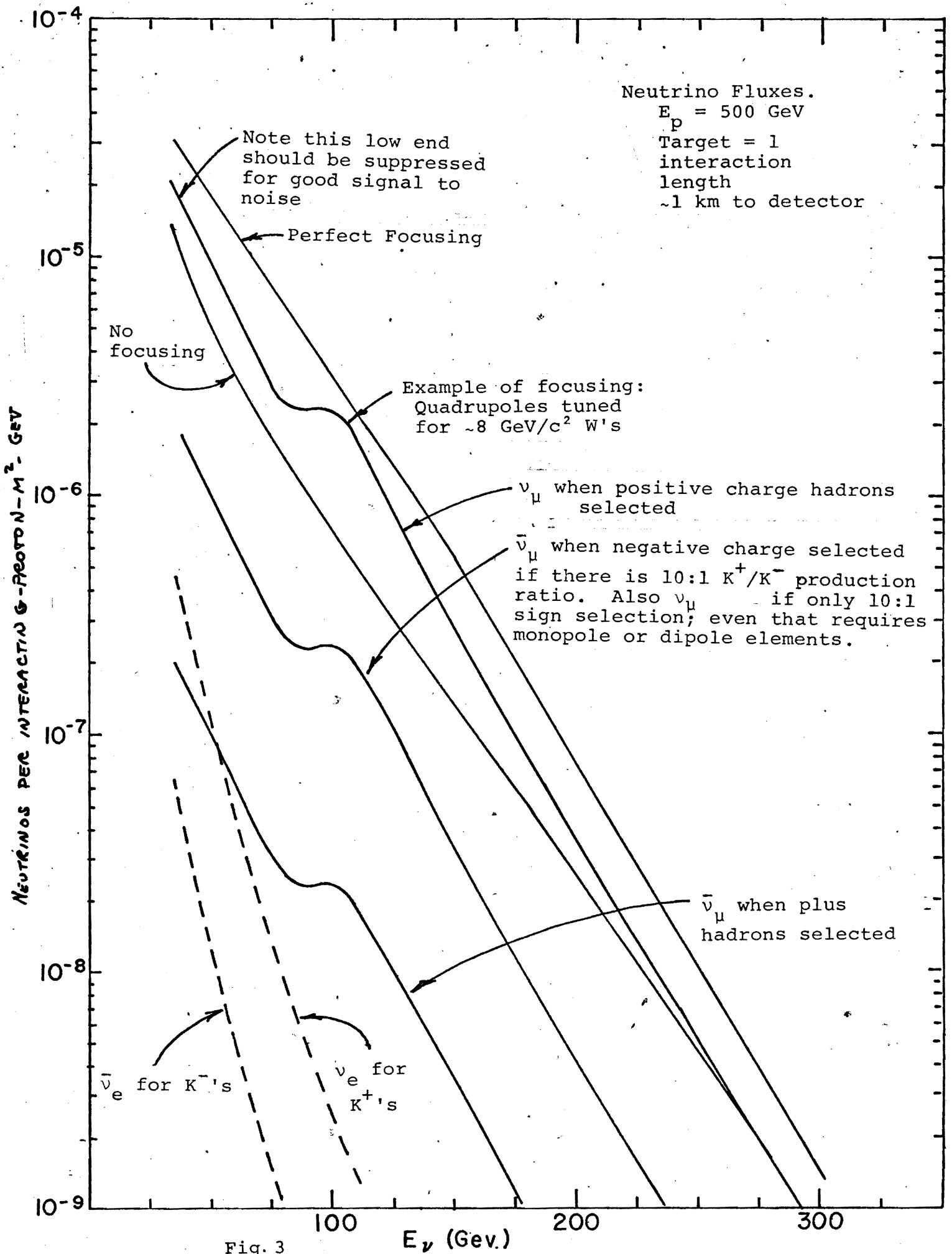
Angle of muons emerging.

Final hodoscope elements.

Figure 2

Fig. 3

II-1   W-Search

$$\nu + Z \to W^+ + \mu^- + Z \; \left(\begin{matrix}\text{coherent}\\ \text{incoherent}\end{matrix}\right) \quad (\text{Eq. 1})$$

followed by

$$W^+ \to \begin{matrix} \mu^+ + \nu \\ e^+ + \nu \\ \text{hadrons}(e.g., \; \pi^+\pi^0, \; K^+\bar{K}^0 \; p\bar{\Lambda}^0) \end{matrix}$$

II-1-a   Theoretical Background

The simplest expectation for the (so far pointlike)
weak interactions is that at high enough energies real charged
intermediate ("W") mesons can be produced as in Equation 1 and
Fig. 4, decaying into leptons ($\mu\nu$, eν) or hadrons ($\pi^+\pi^0$; p$\bar{\Lambda}^0$, etc.).
The branching ratios are not firmly predictable, except that
$\mu\nu$ and eν should be almost equal. Observation of large cross
sections which were equal for the two leptonic modes would give
strong evidence for either W-production or for some other
mechanism for an anomalously large 4-Fermion interaction.

The experimental setup we propose has good acceptance
for different types of events, so that we are not depending,
in this first search, on detailed predictions for W's of e.g.,
the lepton versus hadron decay branching ratio or the pro-
duction and decay angular distributions.

Total cross-sections per proton for production of W's
of various masses in an iron target are given as a function of
neutrino energy in Fig. 5. The differential cross-sections that
been calculated by Brown at BNL and Smith at SUNY and Hobbs
at MIT. The energy distributions of the μ's are shown in

Fig. 6, and their angular distributions in Fig. 7. The W's
are produced almost dead forward, and with almost the full
neutrino energy, so that those μ^+'s (about half the total)
with $E_\mu > E_\nu/2$ come off with an angle $\lesssim \frac{M_W}{E_\nu}$

II-1-b Detailed Purpose

The detection of W-events is schematized in Fig. 10
A search for charged W mesons over the mass range $M_W \lesssim 12$ GeV/c^2
will be made using ν_μ, $\bar{\nu}_\mu$ and, much less sensitively, ν_e and $\bar{\nu}_e$.
Targets of iron and aluminum will be used. Based on
$\frac{W \to \mu\nu}{W \to \text{everything}} = \frac{1}{3}$, the neutrino fluxes given by Fig. 3,
the detector parameters given in Fig. 2, and on acceptance of
only those events with $E_{\mu^-} > 1$ GeV, the expected numbers of W's
for different W masses are given in Fig. 8. Figure 9 indicates
a measure of the signal to noise.

Thus, about 20 μ-decay W's with a mass of 12 GeV/c^2
should be detected with this equipment in a 1000-hour run.
(12 GeV/c^2 W's are made mostly by neutrinos with E_ν's of
150 ± 50 GeV). In the high mass region, where few events are
expected, the event rate decreases by a factor of about three
for every 1 GeV/c^2 increase in W mass, so a multiplication by
three of beam intensity or detector mass is necessary to
extend the mass range by 1 GeV/c^2. The spectrum we use may
easily be low or high by a factor of 10 in the 150 GeV region,
so our mass limit should read 12 ± 2 GeV. Note that there is
appreciable coherent production only in the low M_W region, where
the high flux gives very high rates anyhow, so choosing iron and

aluminum vs. e.g., lead as the main targets gives little loss, but considerable technical simplification.

The triggers and signatures are given on Fig. 10. The main expected backgrounds against which the W-signatures must be recognized are also tabulated in Fig.10, and are estimated to be less than 10% of the signal. A brief discussion of the flux measurement problem will be given in Section II-2-b.

II-1-c Previous Results

The only fairly sure result of previous experiments is that $M_W \gtrsim 2$ GeV/c^2.

II-1-d Competing Experiments

All competing experiments are only in the planning stage. They are i) $e^+ + e^-$ colliding beam experiments at CEA, DESY, and possibly Novosibirsk; ii) bubble chamber experiments with neutrinos at Serpukhov and NAL; iii) other spark chamber experiments now being proposed with neutrinos at NAL and Serpukhov. In addition, proton or muon beams may be used at NAL to search for single μ's with high transverse momentum.

With respect to i), the mass range searched in colliding beams will extend up to only about 3 GeV/c^2.

With respect to ii), the main differences between a 15' hydrogen BC experiment and our proposal are 1) the tonnage of useful target; less than 1 ton of H_2 versus 50 tons of iron and 5 tons of thin aluminum. In addition, at small M_W, the coherent production from iron gives a further large factor in its favor, and 2) sensitivity to other decay modes: a 15' H_2 B.C. would give only marginal identification of high energy electrons.
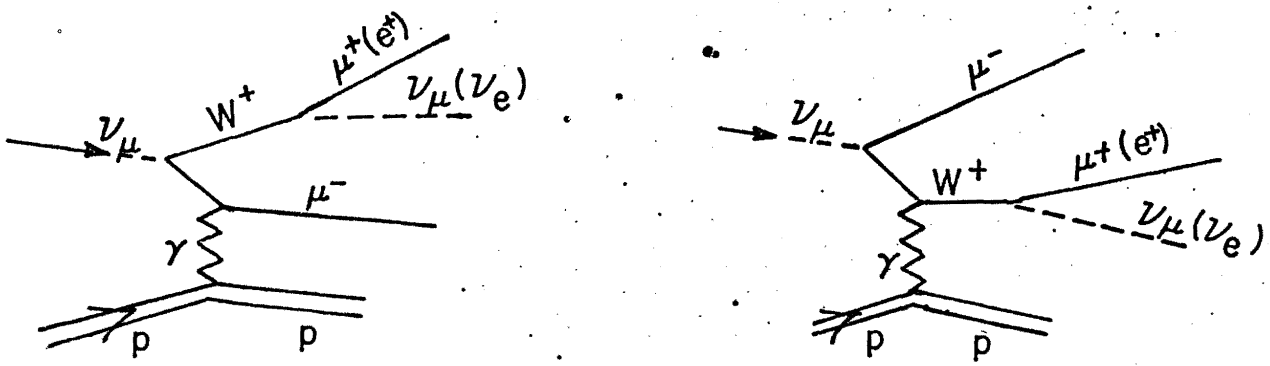
Spins: Initial   Final

$S_{z_\nu} = -1/2$ $S_{z_W} = -1$ $S_{z_\mu} = +1/2$

Decay distribution
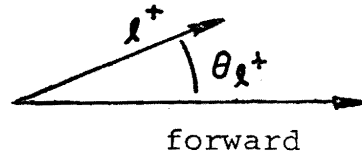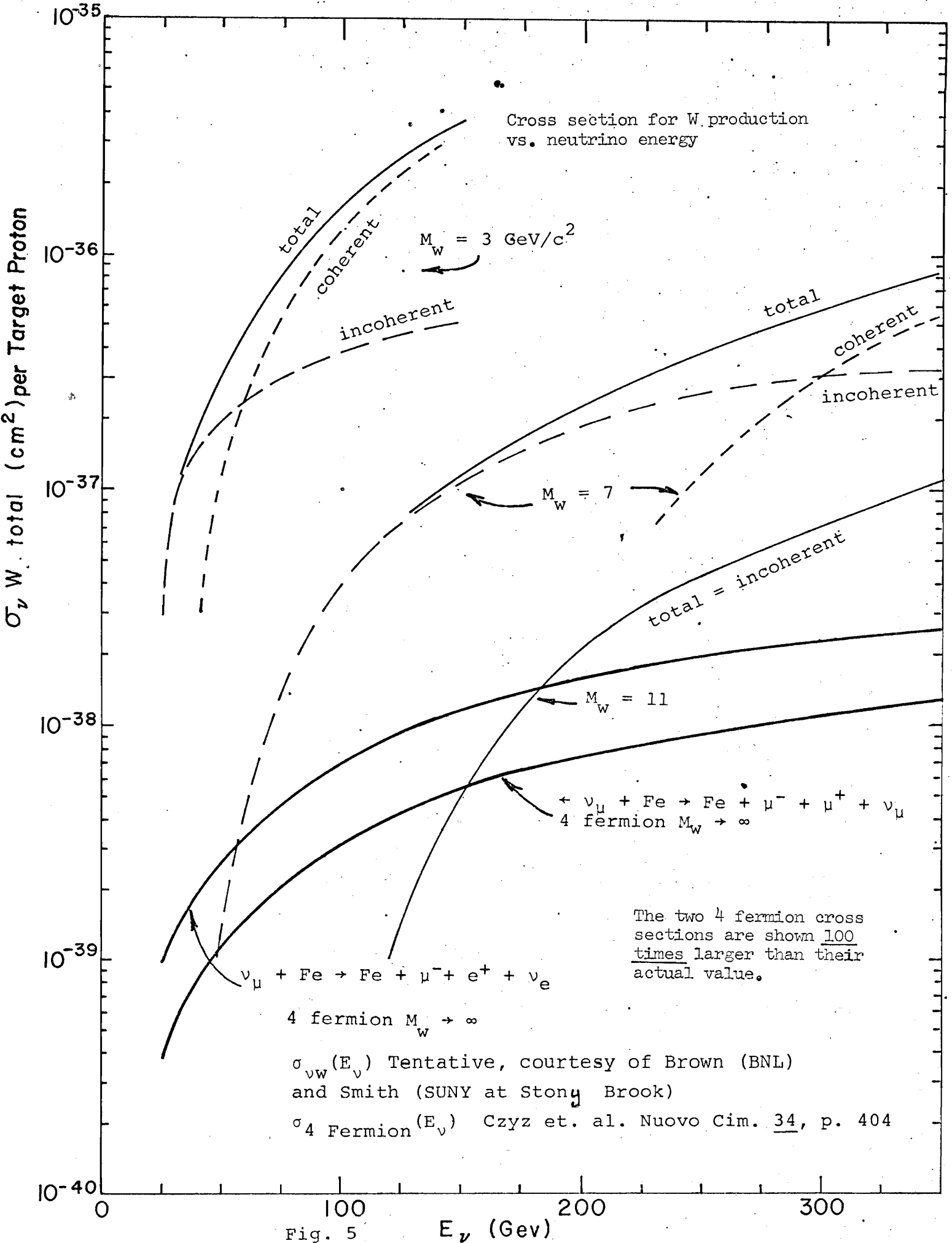of charged lepton: $\dfrac{dN_{\ell^+}}{d\Omega} \propto (1-\cos\theta_{\ell^+})^2$

Fig. 4

Cross section for W production vs. neutrino energy

$M_W = 3$ GeV/c^2

total

coherent

incoherent

total

coherent

incoherent

$M_W = 7$

total = incoherent

$M_W = 11$

$\leftarrow \nu_\mu + Fe \rightarrow Fe + \mu^- + \mu^+ + \nu_\mu$

4 fermion $M_W \rightarrow \infty$

The two 4 fermion cross sections are shown 100 times larger than their actual value.

$\nu_\mu + Fe \rightarrow Fe + \mu^- + e^+ + \nu_e$

4 fermion $M_W \rightarrow \infty$

$\sigma_{\nu W}(E_\nu)$ Tentative, courtesy of Brown (BNL) and Smith (SUNY at Stony Brook)

$\sigma_{4 \text{ Fermion}}(E_\nu)$ Czyz et. al. Nuovo Cim. 34, p. 404

Fig. 5 E_ν (Gev)

σ_ν W. total (cm^2) per Target Proton

Energy Distribution of μ^-'s
in $W^+ + \mu^-$
Production by Neutrinos with
Focused Spectrum from Fig. 3

$M_W = 7 \, GeV/c^2$

$M_W = 11 \, GeV/c^2$

$\frac{1}{N \, Total} \frac{dN/\mu^-}{dE/\mu^-}$ (GeV^{-1})

.2

.1

1   2   4   6   8   10   12

$E\mu^-$ (GeV)
FIG. 6

ANGLE OF μ^- IN W^+ PRODUCTION

$$\frac{d\sigma}{d(\cos.\theta_{\mu^-})} \text{ vs. } \cos.\theta_{\mu^-}$$

$E_\nu = 200$ GeV
$M_W = 7$ GeV/c^2

$E_\nu = 100$ GeV
$M_W = 7$ GeV/c^2

$E_\nu = 150$ GeV
$M_W = 11$ GeV/c^2

$E_{\bar{\nu}} = 200$ GeV
$M_W = 15$ GeV/C^2

$\overline{d(\cos.\theta_{\mu^-})}$

$\times 10^{-36}$

$\times 10^{-37}$

$\times 10^{-38}$

$\times 10^{-39}$

$< 10^{-40}$

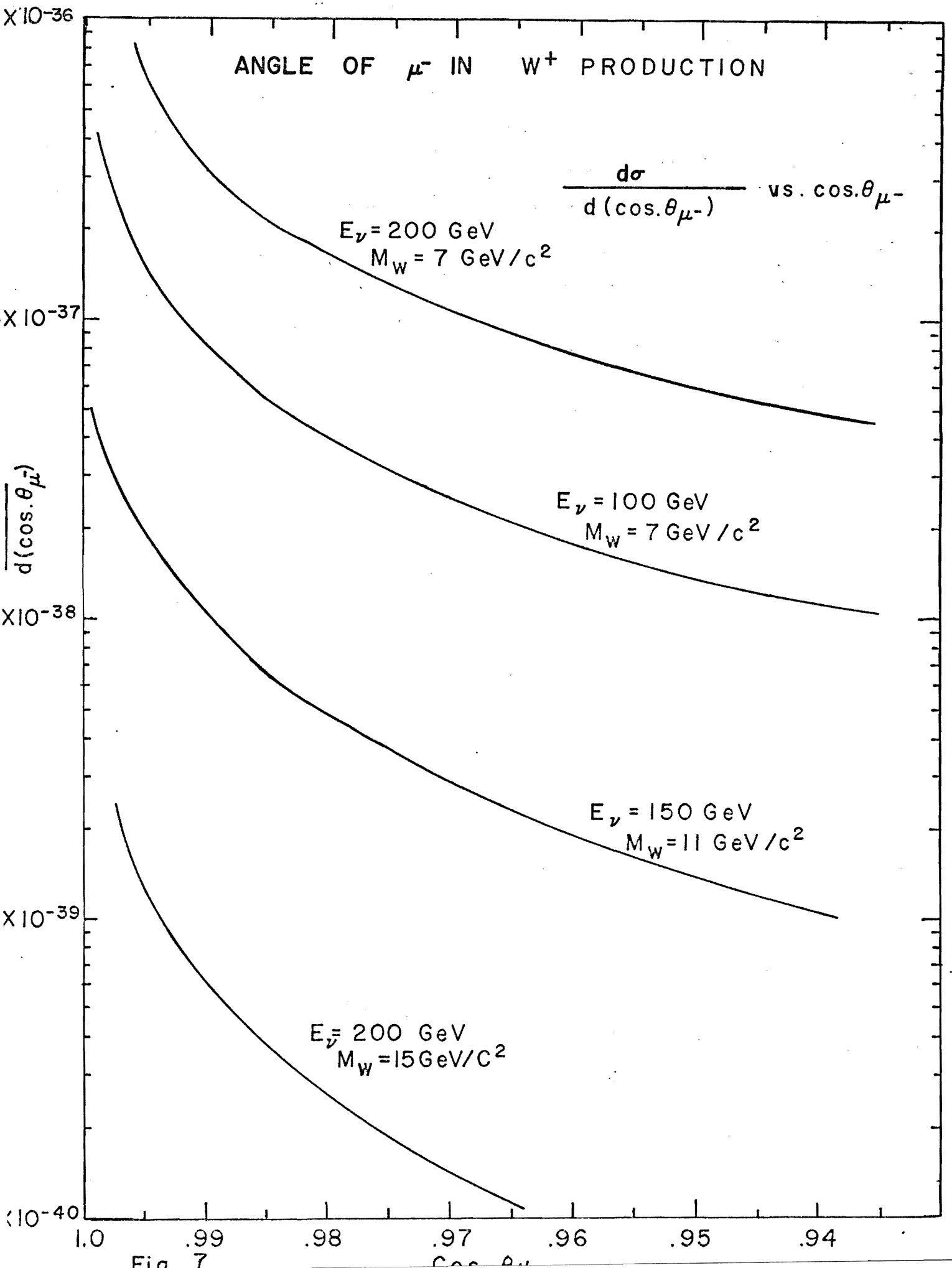1.0   .99   .98   .97   .96   .95   .94

Fig. 7 $\cos.\theta_\mu$

EVENTS FOR W-MESON PRODUCTION FOR $\mu^+\mu^-$ MODE

a) 2×10^{18} INTERACTED PROTONS AT 500 GeV

b) QUADRUPOLE FOCUSSED BEAM

c) 50 TON DETECTOR

d) $(W \longrightarrow \mu \nu)/(W \longrightarrow \text{all}) = 1/3$

e) 30% DETECTION EFFICIENCY OF $\mu^+\mu^-$

NUMBER OF EVENTS
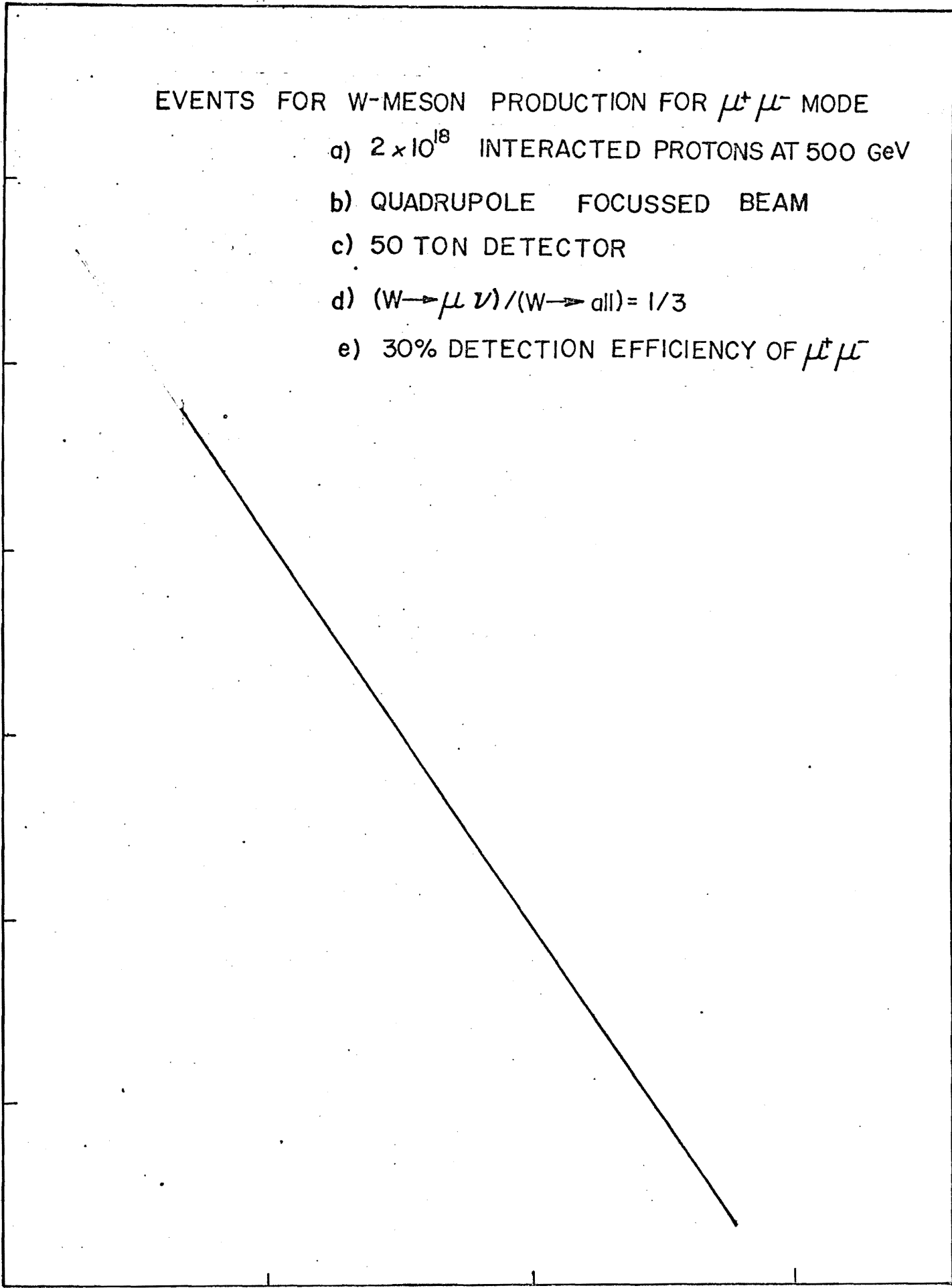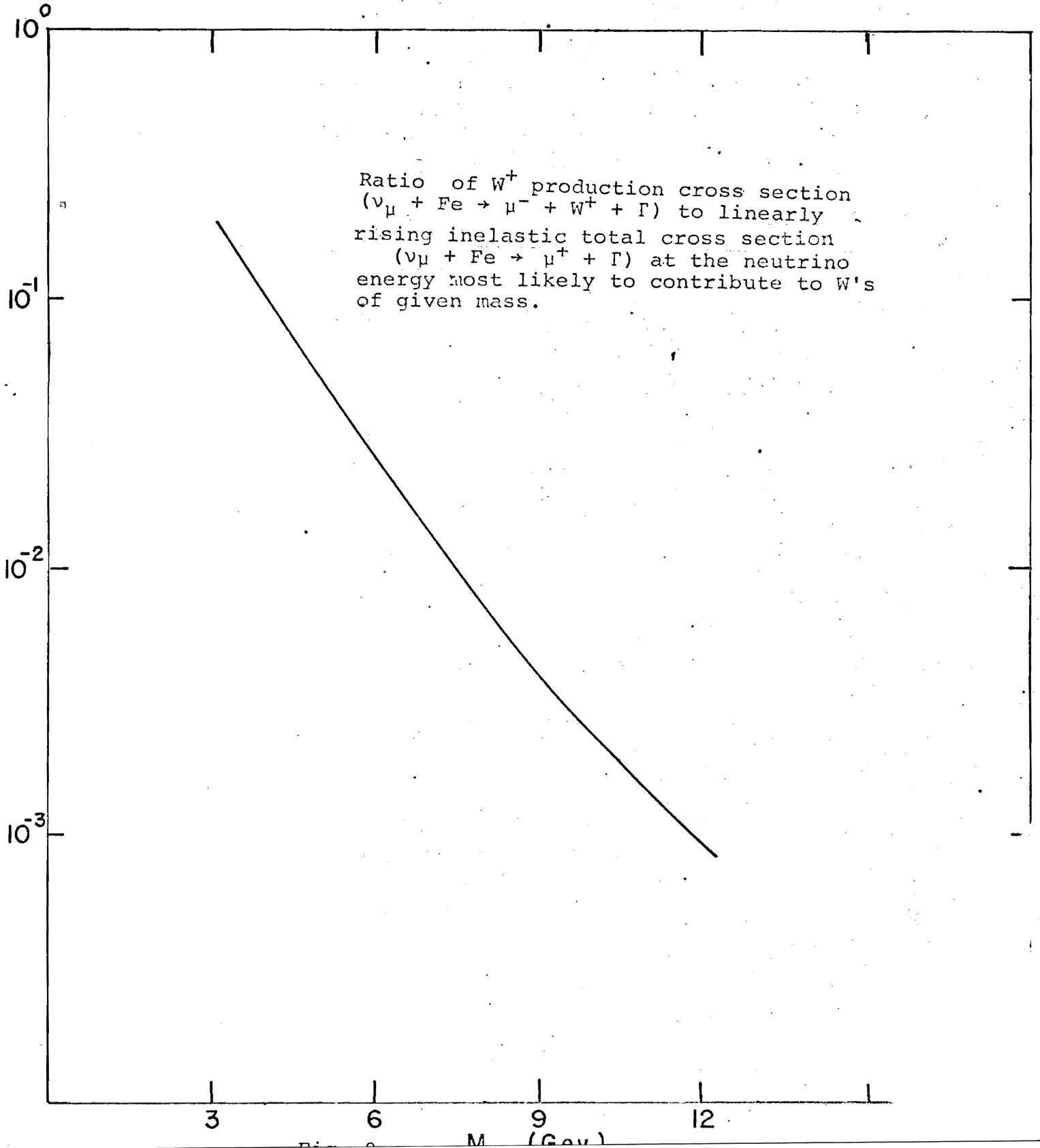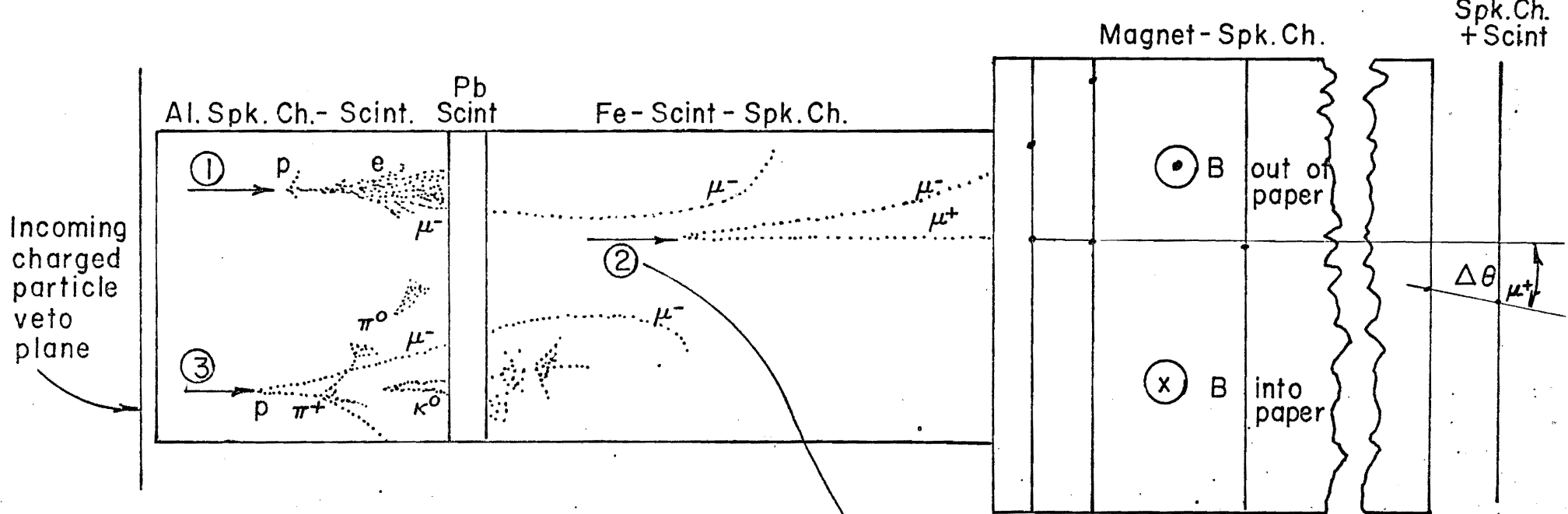
MASS OF W (GeV)

FIG. 8

Ratio of W^+ production cross section
(ν_μ + Fe $\to$ μ^- + W^+ + Γ) to linearly
rising inelastic total cross section
(ν_μ + Fe $\to$ μ^+ + Γ) at the neutrino
energy most likely to contribute to W's
of given mass.

SCHEMATIC OF W-EVENTS
FIG. 10

Event	Reaction	Trigger	Signature	Backgrounds
1	$\nu_\mu + Al \rightarrow$ $\Gamma + \mu^- + W^+$; $W^+ \rightarrow e^+ + \nu_e$	Big pulse in Pb scintillator and greater than or equal to .3 m track along beam in hodoscope in Al and Fe.	Not much Γ at vertex; greater than or equal to 20 GeV pulse in Pb scintillator sandwich; characteristic electron (vs. π^0) shower; E_μ- greater than or equal to 1 GeV	a) $\nu_\mu + Al \rightarrow Al + \mu^- + e^+ + \nu_e$. (4 Fermion coherent). Identifiable by: no Γ; μ^- usually very forward and high energy. (See Sec. II-3-i). b) $\nu_\mu + Al \rightarrow \Gamma + \mu^-$; $\Gamma \rightarrow \pi^0$ giving shower directly or $\pi^\pm$ charge exchanging to give shower. Negligible because: very unlikely shower has such high energy and μ^- such low energy; Γ would be large and/or shower structure would be different. c) $\bar{\nu}_e + Al \rightarrow \Gamma + e^+$; $\Gamma \rightarrow \pi^- \rightarrow \mu^-$. Negligible because less than or equal to 1% $\bar{\nu}_e$'s; only approximately 1% of π^-'s decay before interacting.

Event	Reaction	Trigger	Signature	Backgrounds
2	$\nu_\mu + Fe \rightarrow$ $\Gamma + \mu^- + W^+$; $W^+ \rightarrow \mu^+ + \nu_\mu$	Very long track along beam in hodoscopes.	Not much Γ at vertex; E_{μ^-} greater than or equal to 1 GeV; E_{μ^+} greater than or equal to 10 GeV; $p_{\perp\mu^+}$ greater than 1 GeV/c	a) $\nu_\mu + Fe \rightarrow Fe + \mu^- + \mu^+ + \nu_\mu$ *SAME AS IA*

b) $\nu_\mu + Fe \rightarrow \Gamma + \mu^-$; $\Gamma \rightarrow \pi^+ \rightarrow \mu^+$. Negligible because: very unlikely E_{μ^+} so high and E_{μ^-} so low; π^+ decays only 10^{-4} before interacting.

c) $\bar{\nu}_\mu + Fe \rightarrow \Gamma + \mu^+$ $\Gamma \rightarrow \pi^- \rightarrow \mu^-$. The ratio of this cross section for that for W production at the E_ν contributing most to W production is shown in Fig. 9, With 30:1 sign selection of the kaons which decay to make the neutrino beam, the $\bar{\nu}/\nu$ ratio should be approximately 10^{-2}, and only approximately 10^{-2} of the π^-'s decay before interaction. If the inelastic form factor stays large (Sec. II-2-a), this will give approximately 10% background for $M_W = 12$ GeV/c^2. Further pulse height and angle discrimination is possible but has not been studied.

Event	Reaction	Trigger	Signature	Backgrounds
3	$\nu_\mu + Al \rightarrow$ $\Gamma + \mu^- + W^+$; $W^+ \rightarrow \pi^+ + K_1^{\,o}$ $+ K_2^{\,o}$ (an arbitrary example)	Same as 1.	Not much Γ at vertex; greater than or equal to 20 GeV pulse in hadrometer; character- istic V's and interactions; E_{μ^-} greater than or equal to 1 GeV.	$\nu_\mu + Al \rightarrow \Gamma + \mu^-$; $\Gamma \rightarrow \pi^+ + K_1^{\,o} + K_2^{\,o}$ Same as 1b.

II-2   Deep Inelastic $\nu - \mu$ Exchange

$$\nu_\mu + A \rightarrow \mu^- + \Gamma \; . \qquad\qquad \text{(Eq. 2)}$$

The kinematics of this reaction are shown in Fig. 11.

II-2-a   Theoretical Background

The observation of unexpectedly strong inelastic elec-
tron scattering suggests that at least the vector part of the
weak interaction can fairly frequently give reactions with
very large momentum transfers as in Eq. 2 and Fig. 11.

Assuming the leptonic weak current is local, the
differential cross-section may be written as a function of
three form factors W_1, W_2, and W_3. These form factors depend
on the two quantities q^2 (the four momentum transfer to Γ)
and ν (the energy loss $E - E'$).

It has been found for the corresponding inelastic
electromagnetic scattering at SLAC that to a good approximation
$\nu W_2{}^{e.m.}$ is a function of the dimensionless variable $M\nu/|q^2|$
in the region $|q^2| > 1$ (GeV/c)^2 and $\nu > 1$ GeV. This property
has been called scale invariance. Assuming that the vector
current is conserved and $\Delta S = 0$, it is anticipated that W_2 in
the above expression will also exhibit scale invariance and be
given by the function $W_2{}^{(e.m.)}$ found at SLAC.

For purposes of illustration we plot $d^2\sigma/dE'd\cos\theta$ at
several angles using a particular model by Drell et.al. wherein
$W_3 = W_2 \dfrac{2M\nu}{|q^2|}$; $W_1 = \nu W_2 \dfrac{\nu}{|q^2|}$. Using the Stanford $R = 0$ solution

with νW_2 a function of $\frac{2M\nu}{q^2}$ only we obtain for $E_\nu = 100$ GeV the curves in Fig. 12. We also show for comparison the curve with $W_3 = W_1 = 0$ at $\theta = 2.0^\circ$ with νW_2 as before. This (dotted) curve can be regarded as a lower limit to the expected cross section, assuming scale invariance continues to hold and also C.V.C. For $E' = 50$ GeV, for example, the cross section is only very weakly dependent on muon angle. This corresponds to approximately constant $d\sigma/dq^2$ up to about $50 (\text{GeV/c})^2$. In general, the range in both q^2 and ν that willbe explored in this experiment is roughly one order of magnitude greater than in the corresponding electromagnetic scattering at SLAC.

The remarkable prediction of scale invariance is this very weak dependence of cross section on momentum transfer to the nucleus, with a large number of high energy muons produced at large angles. Observation of these should open up many possibilities for testing models of hadronic structure and dynamics:

1) The total cross-section for Eq. 2 should rise linearly with neutrino energy if W_2 is scale invariant, continuing the CERN observation: $\sigma_{\nu\mu-} = 0.6 \times 10^{-38} E_\nu$ cm^2/GeV-nucleon. The effect of a 10 GeV/c^2 W is shown in Fig. 13.

2) Measurement of the angular distributions for various q^2 and ν's should choose between various models through the ratios $W_1 : W_2 : W_3$. In addition, locality of the weak interaction will be tested.

3) Comparison of $d^2\sigma(\nu)/dq^2 d\nu$ and $d^2\sigma(\bar{\nu})/dq^2 d\nu$ (averaged

over protons and neutrons in the iron nucleus) over the entire

range of q^2 and ν will be sensitive to W_3, which is a highly

model-dependent quantity. It can be shown that there can be

up to a factor of three difference in the cross sections

$d^2(\nu Fe)/dq^2 d\nu$ and $d^2(\bar{\nu}Fe)/dq^2 d\nu$.

    4) Comparison of $\sigma(\nu n)$ with $\sigma(\nu p)$.

II-2-b Detailed Purpose

The detection of the inelastic scattering reaction is

schematized in Fig. 14. It will be studied with incident ν_μ

and $\bar{\nu}_\mu$ over the approximate ranges $40 < E_\nu < 300$ GeV,

$.5 < q < 10$ GeV/c, and $.05 < \dfrac{E_\nu - E_\mu}{E_\nu} < .9$, and $20 < E_\mu < 300$ GeV.

The main targets will be 20 effective tons of iron and 5 tons

of aluminum. The recoil momenta are so large that there would

be little value in using free protons rather than these complex

nuclei as targets. Based on scale invariance and on the para-

meters given in Fig. 14, the expected yield is given in Fig. 15.

A basic difference between this proposal and all prev-

ious neutrino experiments is that we propose measuring directly

the total hadron energy and the final muon energy. The sum of

these two energies will be identified as the incident neutrino

energy. Recent results on hadron energy measurements using

a scintillator iron sandwich are shown in Fig. 16. It is seen

that protons of energy 25 GeV can be measured to ±2.5 GeV. We

assume that other hadrons give similar results and for simpli-

city we take $\dfrac{\Delta E}{E} = \pm 10\%$. The magnet for which we have made a

preliminary design will be able to measure muons in the energy range $10 \leq E_\mu \leq 300$ GeV to about $\pm10\%$ $\Delta E/E$. Combining these errors the neutrino energy will be known to roughly $\pm10\%$ over the range $40 \leq E_\nu \leq 350$ GeV. Precise knowledge of the incident neutrino flux will require a careful survey of hadron yields, calculation from them of ν and μ fluxes, and ultimately verification of predicted μ fluxes. This is particularly difficult for high neutrino energies, where the more energetic μ's from π's mask the less energetic μ's from the K's that give the useful high energy ν's. It is likely that the neutrino flux can be determined with confidence to perhaps only $\pm20\%$. But since the flux will almost certainly fall off rapidly with neutrino energy, it will require an absolute accuracy of perhaps 5% or better in the systematics of determination of the average energy of neutrino events through measurement of the μ and Γ reaction products to match even this accuracy. If this is achieved, it will result in absolute neutrino cross sections with errors of the order of $\pm30\%$ at all energies.

The triggers, signatures and backgrounds are given on Fig. 14.

We are considering the choice between a CH_2- U comparison and a liquid H_2 - Fe comparison for measuring neutron-proton differences. In any case, the auxiliary target would be upstream of the aluminum chamber and would be only of the order of one interaction length thick.

II-2-c <u>Previous Results</u>: As given in II-2-a above, the CERN

results with E_ν < 10 GeV hint at scale invariance.

II-2-d <u>Competing Experiments</u>: Same as in II-1-d (page 6).
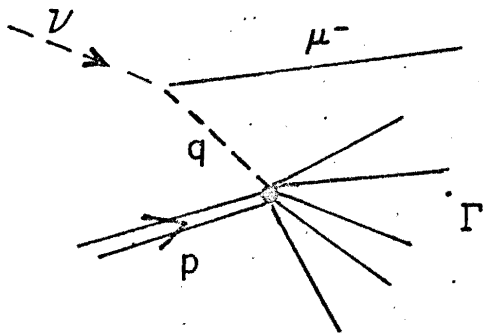
Kinematics:

   E is energy of incoming neutrino

   E' is energy of outgoing muon

   Γ represents outgoing hadrons

   q is the 4-momentum transfer from leptons to hadrons

   θ_Γ is lab angle of 3-vector part of q, and hence of the core of the hadron jet

   $\nu \equiv E - E'$

   $|q^2| \approx E E' \theta_\mu^2$

   $\theta_\Gamma = \theta_\mu \dfrac{E'}{\sqrt{q^2 + \nu^2}}$

   $M_\Gamma^2 = M^2 + 2M\nu - |q^2|$, M = NUCLEON MASS

Dynamics: $\partial^2\sigma/\partial E'\partial\cos\theta = G^2 E'/2\pi \left(\dfrac{E'}{\nu}\right) \cdot \left[W_2 \cos^2 \dfrac{\theta\mu}{2} + 2W_1 \sin^2 \dfrac{\theta\mu}{2}\right.$
(see p.7)
   $\left. \pm \dfrac{E + E'}{M} W_3 \sin^2 \dfrac{\theta\mu}{2} \right]$

G is weak interaction constant

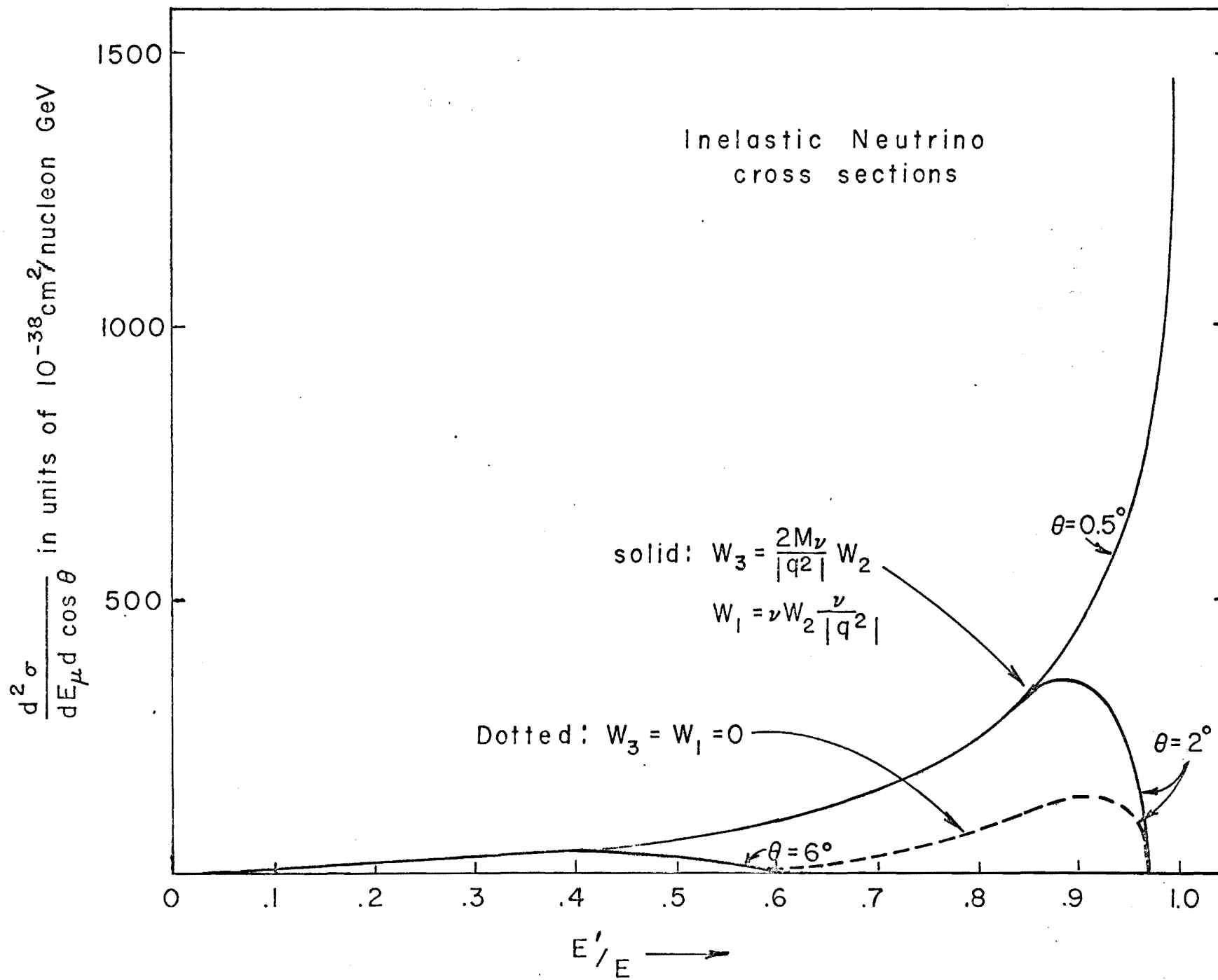W's are form-factors, functions of ν and q^2.

FIG. 11

Inelastic Neutrino cross sections
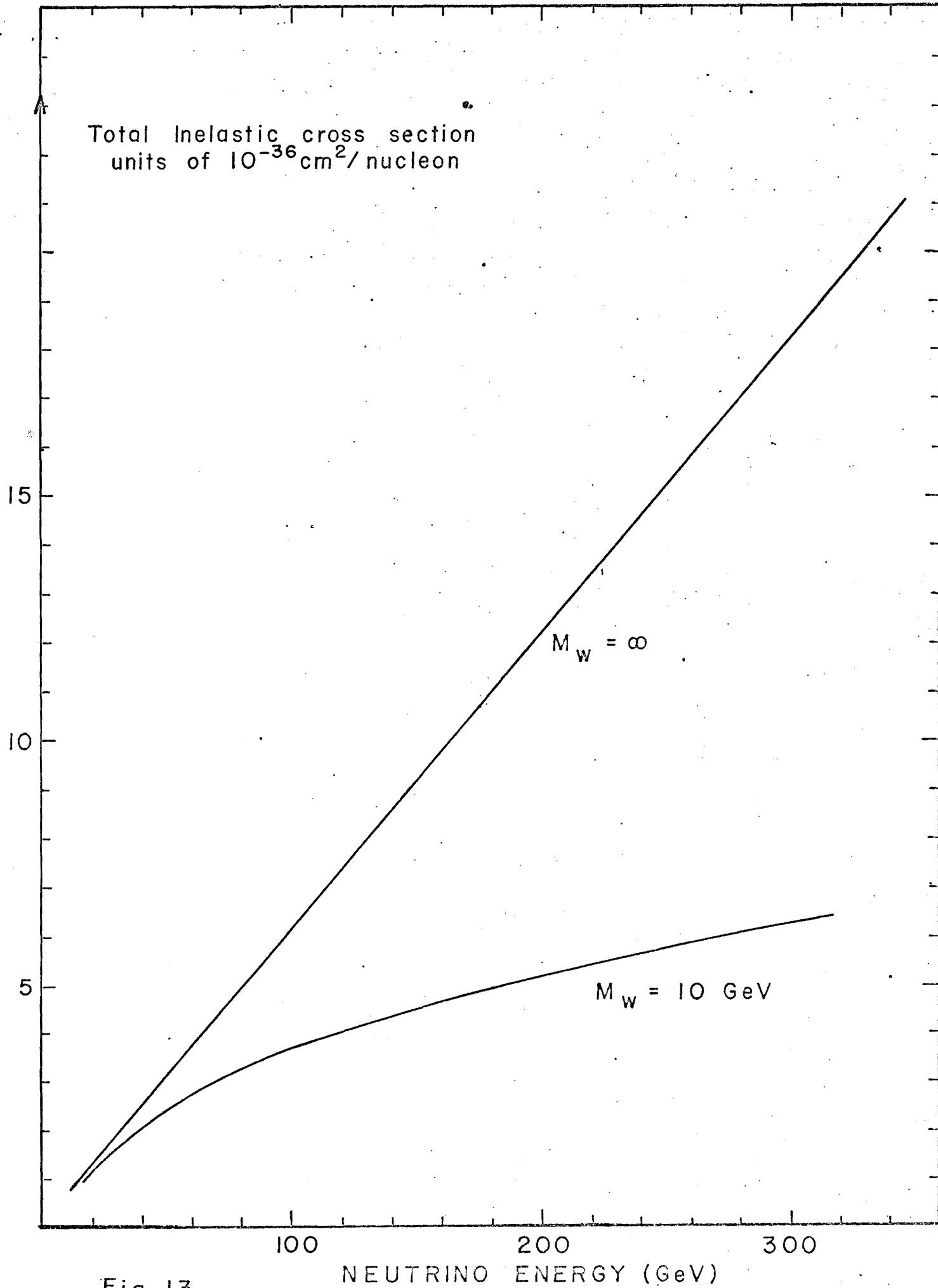
solid: $W_3 = \dfrac{2M\nu}{|q^2|} W_2$

$W_1 = \nu W_2 \dfrac{\nu}{|q^2|}$

Dotted: $W_3 = W_1 = 0$

$\theta = 0.5°$

$\theta = 2°$

$\theta = 6°$

$\dfrac{d^2\sigma}{dE_\mu \, d\cos\theta}$ in units of $10^{-38} \text{cm}^2/$nucleon GeV

$E'/E \longrightarrow$

FIG. 12

Total Inelastic cross section units of $10^{-36} cm^2$/ nucleon

$M_W = \infty$

$M_W = 10$ GeV

NEUTRINO ENERGY (GeV)

Fig. 13

5-Ton fiducial
volume of Al.

20-Ton fiducial
volume of hadrometer

B out

B in

Incident
neutino
direction

(2)

(1)   Γ

θ_{μ^-}

$\Delta\theta_{\mu^-}$

Event	Reaction	Trigger	Signature	Background
(1)	$\nu + Fe \rightarrow \mu^- + \Gamma$	Penetrating μ^- along beam direction	$E_\mu \rightarrow \sim 20$ GeV; Big Γ pulse and many prongs	$\bar{\nu}_\mu + Fe \rightarrow \Gamma + \mu^+ + W^-$; $W^- \rightarrow \mu^- + \bar{\nu}_\mu$ $E_+ < .5$ GeV in SOME cases, and so indistinguishable from π. Negligible if scaling holds but dominant if inelastics down by 10^3 and a LOW MASS IS PRODUCED (see Fig. 9)
(2)	Same, but in Al	Same as in (1)	Same as in (1). Some of hadron energy in Pb Scint.	SAME AS IN (1)

Fig. 14

Number of Events for
$\nu_\mu + Fe \rightarrow \mu^- + \Gamma$
in each interval $\pm 12\% \dfrac{\Delta E \nu}{E \nu}$
for 2×10^{18} interacting
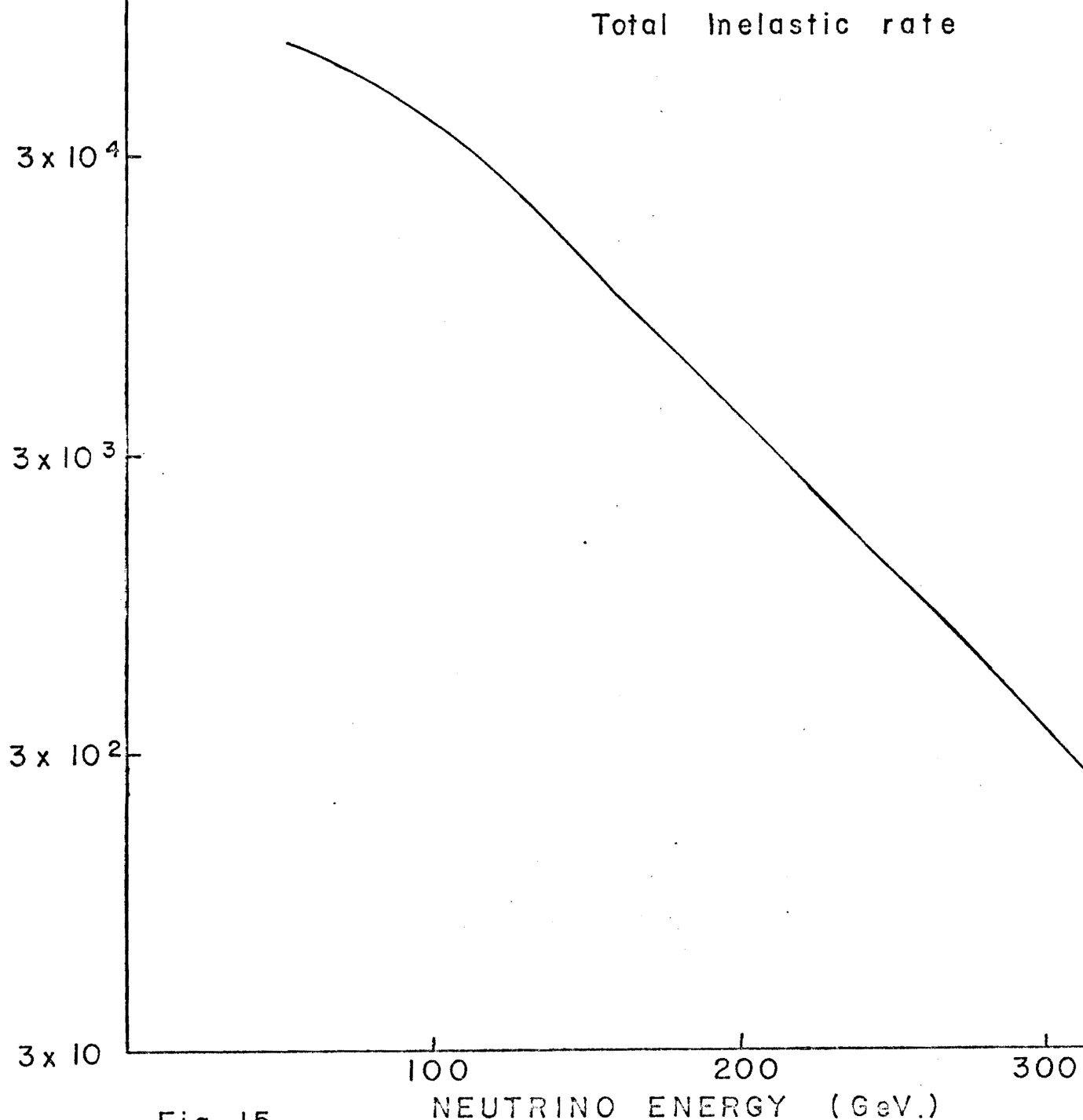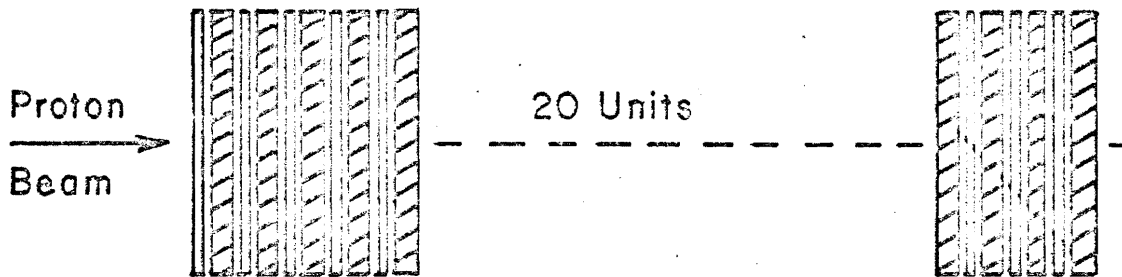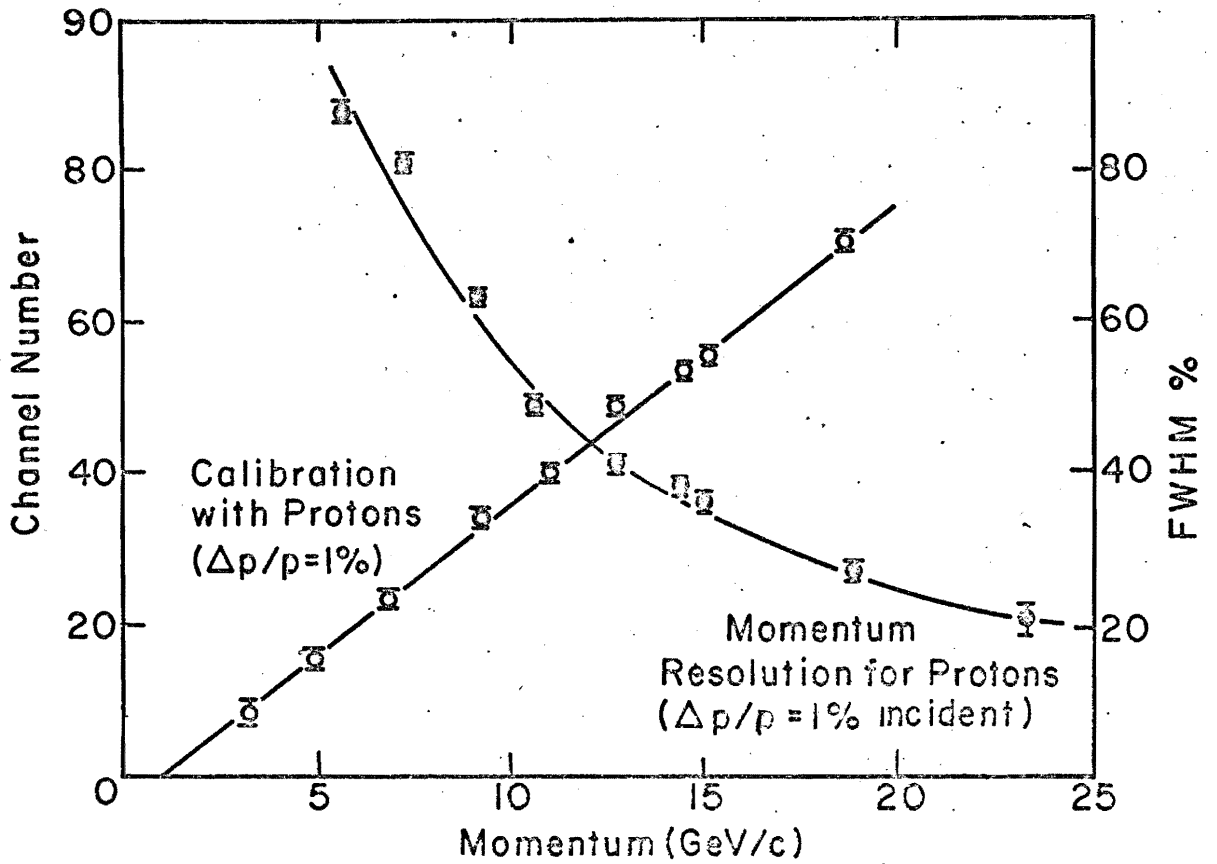Protons and a 20 ton fiducial
volume of detector

Total Inelastic rate

Fig. 15   NEUTRINO ENERGY (GeV.)

Hadron Cascade Total Absorption Counter

Fig. 16

II-3   Low Cross-Section and/or Exotic Reactions:

i.   4-Fermion Interactions: (These are predominantly coherent at these high E_ν.)

$\nu_\mu + Z \rightarrow Z + \mu^- + e^+ + \nu_e$ (See Note 1a, Fig. 10)

$\nu_\mu + Z \rightarrow \mu^- + \mu^+ + \nu_\mu$ (See Note 2a, Fig. 10)

The total cross-section for $\mu^- e^+$ and $\mu^- \mu^+$ are shown in Fig. 5. The angle and momentum distributions of the charged leptons have been calculated by K. Fujikawa (Ph.D. Thesis, Princeton, June 1970), but with neutrino energies only as high as 40 GeV. While we must await computations at higher E_ν, it seems likely that the angular distributions are much narrower for the 4-Fermion interaction than for real W production. We should observe approximately 30 examples of the 4-Fermion $\mu^- e^+$ from neutrinos with $50 \leq E_\nu \leq 100$ is from $100 \leq E_\nu \leq 150$ and 3 from $150 \leq E_\nu$. The $\mu^- \mu^+$ yield should be $\sim 40\%$ of this. The 4-Fermion reactions should be clearly separated by angle and momentum from real W's.

Observation of the expected cross-sections for the 4-Fermion interactions is complementary to observation of the W, so it is fortunate that the expected yields of these two 4-Fermion reactions are large enough to be measured, and yet small enough not to cause misinterpretation of W-events after kinematic separation.

ii. Lepton Non-Conservation: The ratio of $\bar{\nu}_\mu$ + Fe $\rightarrow \Gamma + \mu^+$ to ν_μ + Fe $\rightarrow \Gamma + \mu^-$ inelastic cross-sections will be measured. The $\bar{V}_\nu / V_\nu$ ratio in the beam will be obtained from

the hadron survey. Thus, the $(\Gamma + \mu^+)/(\Gamma + \mu^-)$ ratio for any given q^2 and ν from antineutrino contamination in the neutrino beam is predictable, and should be around 10^{-2}. A disagreement would be an indication of lepton/non-conservation of the $(\nu \rightarrow \mu^+, \bar{\nu} \rightarrow \mu^-)$ type.

iii. Neutral currents $\nu_e + e^- \rightarrow \nu_e + e^-$.

Electron neutrinos in the beam will make electron recoils in the aluminum spark chamber with energies ≥ 100 GeV, and with no other reaction product. Since few of the inelastic $\nu_e + Al \rightarrow \Gamma + e^-$ events should leave no visible recoil tracks, this exposure should be capable of setting an upper limit in the range on neutral currents at energies ≥ 100 GeV.

iv. Electron-Muon Universality.

The reaction $\nu_e + Al \rightarrow \Gamma + e^-$ will be compared with $\nu_\mu + Al \rightarrow \Gamma + \mu^-$ in the same regions of the $q^2 \nu$ plane. An approximate calculation of the ν_e spectrum is shown in Fig. 3.

A comparison to about $\pm 30\%$ will be possible up to about 50 GeV neutrino energy.

v. Quark and Magnetic Monopole Search: $\nu_\mu + Fe(Al)$ $\rightarrow \mu^- \Gamma^+ +$ quark.

While this is not the equipment of choice for these searches, the many layers of scintillation counters can give pulse height information on the ionization of a penetrating particle.

III. Apparatus and Cost

III-1. Neutrino Beam.

All of the neutrino reaction channels which have been
discussed require for their interpretation knowledge of the
number of neutrinos in any given energy interval. It is,
therefore, of great importance to determine the spectrum and
flux of neutrinos. We are willing to take responsibility for
hadron surveys appropriate to the needs of this proposal.
The primary responsibility for this activity will be taken
by the NAL members of our group.

We have discussed earlier the desirability of charge
separation of the parent hadrons. Analysis of our experimental
goals indicates that we should choose to enhance the high energy
end of the neutrino spectrum at the expense of the low energy
end. This enables us to keep the trigger open for the rarer
high energy events.

We are studying various devices which satisfy the above requirements and we are willing to assume the responsibility to see that sign selection and focusing devices appropriate to this proposal are constructed.

III.2.   Interaction and Detection Apparatus

The interaction and detection apparatus is shown schematically in Fig. 1. The scale of the apparatus is determined mainly by the following considerations:

(a)   The diameter of the neutrino beam pipe will be about 35", determining the approximate fiducial diameter of the detection apparatus for hadrometry.

(b)   The hadrometer (mean density $\sim$4) requires about 25 cm around the outer edges to contain the hadron cascade sufficiently well to maintain uniform efficiency and calibration over the inner fiducial region, and about 1 meter at the downstream end of the hadrometer to contain the longitudinal development of hadron cascades produced within the fiducial region. . The mass of the fiducial region should be comparable with that of the edges, so that the smallest economical hadronmeter meeting these specifications is about what we have designed, 2 m x 2 m x 3 m long. It is close to optimal for these reasons, it matches beam dimensions, and it is a practical size.

(c)   The diameter of the long bending magnet must be somewhat larger than that of the hadrometer to accommodate

these high energy muons that go off at angles of the order
of 1/10 radian; but the cost and inconvenience of subtending
very large angles limited our choice to an approximate cylinder
3 meters in diameter, toroidally wound. The length of the
iron is set at 5 meters by needing to analyze accurately the
bending of 300 GeV muons.

(d) The aluminum (the mean density ~1.3) spark chamber
is 2 meters long, i.e., 11 radiation lengths and 3.5 interaction
lengths thick. This enables electrons produced in the aluminum
to develop an identifiable shower, and some hadrons produced in
the chamber to interact in a characteristic way. Its diameter
is set by the rest of the system.

III-3   Data Format and Analysis

Conventional optical spark chamber techniques will be
employed. We have the following approximate available capacity
of high accuracy manually operated measuring machines.

M.I.T.	6	machine shifts/day
N.W.	8	machine shifts/day
ANL	3	machine shifts/day
NAL	6	machine shifts/day

This represents an average about 600 effective hours per week
of measuring. At a measuring rate of 5 per hour this gives
us 10,000 useful events accumulated per month. This is ade-
quate to extract interesting physics rapidly.

III-4   Listing of Equipment and Cost

The following is a listing of the equipment uniquely

required for this experiment and a rough estimate of the cost including design and labour. These costs are very approximate, since no engineering studies have been made.

Item	Cost
Hadrometer Iron (magnetized) and 5 meter Muon Momentum Analyzing Magnet with frame	$250 K
Scintillation counters, PM tubes and electronics	$125 K
Aluminum Spark chamber Modules with Associated Hardware	$100 K
Spark Chamber Photography (optics, film, etc.)	$ 50 K
Film Analysis and Computing	$200 K
Miscellaneous	$100 K
TOTAL	$825 K

We have the design experience and the local engineering support at NAL and ANL, to produce the necessary heavy hardware.

III-5   Time Scheduling for the Experiment

We propose that this experiment be performed in the following three phases:

1.   Hadron Beam Survey

The high hadron (in particular kaon) energies that are relevant for knowing the high energy (300 GeV) neutrino spectrum pose   technical difficulties in a conventional beam survey.

However, in pp collisions, due to the fore-aft symmetry of the reaction, low-energy backward kaons can easily be detected and related to fast forward kaons.

We are investigating this scheme for doing a survey of the high-energy yield of kaons and pions at energies up to 500 GeV. This approach was successfully used at the ZGS several years ago, and has been suggested by D. Jovanovich for use at NAL.

The experience at CERN has been that once the pp hadron yields are known, the yields from complex nuclei of low Z can be predicted to $\pm 20\%$. This procedure can be checked at kaon energies less than about 150 GeV where K, π separation will be technically possible in the early stages. For this check, we propose collaborating with the group using the high energy (150 GeV) survey spectrometer in Area 2, in mid 1972. The data on pion yields will also, as a by-product, be vital engineering information for muon shielding in Area 1. This work will be done primarily by the NAL part of the group.

2. Neutrino Beam

In 1972, the Area 1 schedule will begin to allow initial testing of charge separation and neutrino beam production and monitoring. We propose taking responsibility in this work.

3. Detection System

The tentative schedule for these chambers and associated systems therefore reads:

a. Design and construction, Fall 1970 - 12/71.

b. Preliminary testing, 1/72 - 6/72.

c. Modifications, if any, 3/72 - 9/72.

d. Start installation in Area 1, 9/72.

e. Testing and μ and hadron calibration, 1/73.

f. Ready for experiment, 4/73.

It is worth remarking that not all the running for the experiment needs to be done at 500 GeV; the experiment would be worthwhile at 200 GeV. In particular, much of the testing can be speeded up by running at the higher repetition rates possible at the lower energy.

III-6 Equipment and Facilities Required from NAL

1. A suitable building to cover the experimental detection equipment, with the usual utilities, including a 0.25 MW power supply for the muon magnet. A weight of about 500 tons must be supported.

2. Charge separation and focusing magnets for parents of neutrino beam.

3. Support for the hadron beam survey.

4. Proton, muon and neutrino beams monitoring equipment.

5. A small computer for beam flux, etc., monitoring and detection.

6. Electronics, etc., from the NAL Equipment Pool.

7. Use of the hadron and muon beam in Area 1 to calibrate the detection equipment.

8. Film development facilities.