AEC RESEARCH AND
DEVELOPMENT REPORT

PROJECTED LAB-E DICHROMATIC ELECTRONIC DETECTOR FACILITY*

B. C. Barish, J. F. Bartlett, A. Bodek, K. W. Brown, D. Buchholz,
F. S. Merritt, F. J. Sciulli, L. Stutte, H. Suter†

California Institute of Technology
Pasadena, California 91125

and

E. Fisk and G. Krafczyk

Fermilab, Batavia, Illinois

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Spokesmen: B. Barish and F. Sciulli

Abstract

We describe here the detection system as envisioned to pursue dichromatic ν-physics in the new Lab E facility at Fermilab. Physics proposals to use this facility are described in separate documents.

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(I) Introduction

Two years ago the first neutrino interaction had yet to be observed at Fermilab. It was not known at that time whether the cross section would continue to rise above 10 GeV (in fact there were indications from cosmic ray experiments to the contrary), or even whether a W-boson might exist with a mass of say 2.5 GeV/c^2.

Put in this perspective the progress in neutrino physics has been truly outstanding. Let us just review briefly the primary results so far reported by the Caltech-Fermilab group. The physics can be divided into two parts: (A) the study of the structure of hadrons (deep inelastic scattering) and (B) the study of the weak interaction at high energies.

(A) HADRONIC STRUCTURE

(1) Tests of Scaling and Point-Like Structure: Qualitatively it is clear that ν-N collisions at least approximately behave like point-like interactionseven for $E_\nu \sim 100$ GeV. This is implied both from the magnitude and the at least approximate linear rise of the cross sections. More quantitatively we have performed a test of scaling by including a propagator in the fit to Q^2 distributions. The result is no "scaling" breakdown with 90% confidence for $\Lambda \gtrsim 10.4$ GeV/c^2. The sensitivity of this scaling test is comparable to the best tests that have been reported: deep inelastic e-p from SLAC; and μ-p inelastic results from NAL (however, the latter indicatesa possible violation).

(2) Antiquark and/or Non-Spin 1/2 Scattering: In the simple quark picture of the nucleon the neutrino mainly scatters from spin 1/2, quark-like constituents. This picture is confirmed by our

measured ratio $\frac{\sigma^{\bar{\nu}}}{\sigma^{\nu}} = 0.33 \pm .08$. This ratio being so near 1/3 places severe limitations on the amount of non-spin 1/2 and antiquark scattering allowed (~ 25% and 10% respectively).

(3) Charge of the Constituents: The magnitude of $\alpha_{\nu} + \alpha_{\bar{\nu}}$ when compared with electron scattering determines the mean square charge of the constituents. The magnitude of the cross sections measured by the Caltech-Fermilab group implies a mean-square fractional charge, and is inconsistent with integral charge constituents.

(B) WEAK INTERACTIONS

(1) W-boson: A direct search for production of W-bosons by looking for the $W \rightarrow \mu\nu$ decay mode has yielded a limit $M_W \geq 8$ GeV. Also, the test for a propagator in the Q^2 distribution can be interpreted as yielding $M_W > 10.4$ GeV with 90% confidence.

(2) Gauge-Theory Heavy Lepton: Gauge Theories predict the existence of heavy leptons, neutral currents, or both. We have conducted the most sensitive search by far for these heavy leptons. In a search for the leptonic decay of this particle, it is determined that its mass would be in excess of 8 GeV unless the branching ratio were extremely small. More recently, a search for the hadronic mode combined with the previous result requires $M > 7.5$ GeV independent of decay branching ratio. This result, though negative, is highly significant, since it rules out a class of Gauge Theories (i.e. Georgi-Glashow) and puts severe constraints on any future theory of the weak interaction requiring new leptons.

(3) Our search for neutral currents in the reactions $\nu + N \rightarrow \nu +$ hadrons and $\bar{\nu} + N \rightarrow \bar{\nu} +$ hadrons was carried out in March. As reported in London and Érice we believe the experiment provides conclusive evidence for neutral currents near the reported levels.

These are the primary results to date. We have gained a great deal of experience in obtaining them. We are extremely excited at the prospect of pursuing these interesting physics questions further, and feel that we understand much better how to answer those questions.

A major upgrading of the experiment over the next couple of years will enable us to continue to carry out a very productive physics program. Most of our plans represent significant improvements where the experiment has its major limitations. These plans, as outlined below, are in the context of relocating the experiment in a new location at the end of the neutrino berm.

(II) Beam

We are presently engaged in a systematic beam design for a more acceptable dichromatic beam. This new beam, in order to incorporate features that will overcome the most serious present limitations, must have

(1) Good solid angle acceptance.

(2) Reduced wide-band neutrino background from decays prior to the decay-pipe entrance.

(3) Clean dumping of the EPB at all secondary energies.

(4) Good momentum definition without compromise of solid angle accepta ce.

Table II.1 gives the parameters of a preliminary version from this study compared with the present beam. The major new features include (a) somewhat larger targeting angle; (b) intermediate focus; and (c) use of quadrapole triplets. Figure II.1 shows the distribution in neutrino energy to be expected, compared with a typical distribution from the present beam. The beam in its final form will allow secondary momentum resolution to ± 5%.

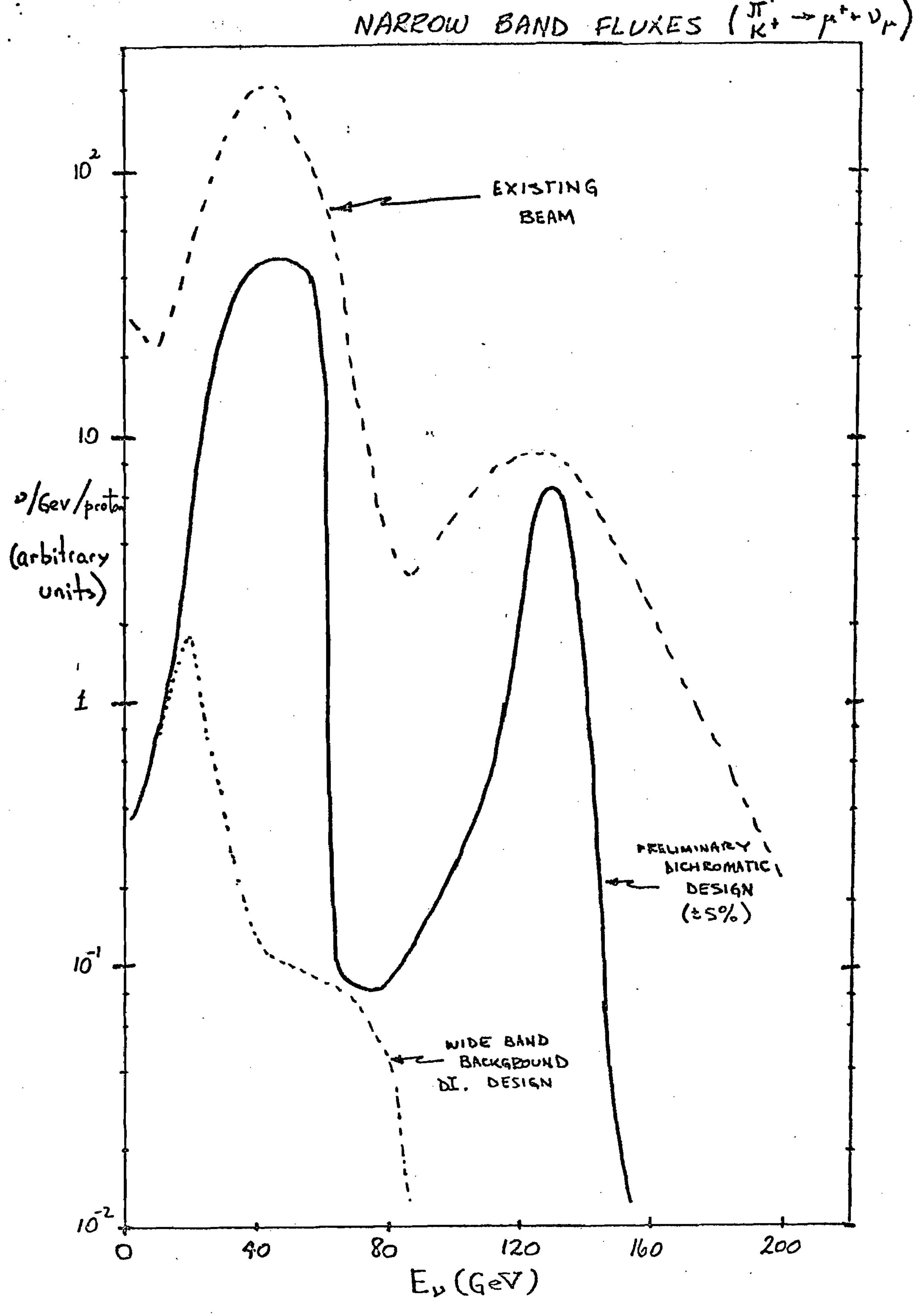
Initially, serious attempts were made to construct a satisfactory beam inside the constraints of the 200 foot long target tube. It is clearly apparent at this point that such a beam cannot be built in less than 300 feet. (The Cern dichromatic beam requires > 330 ft. longitudinally.) This means that the correct dichromatic beam will require some physical modification to the targeting (ν-hall) region.

Table II.1

Comparison of Present and Tentative Dicromatic Beams

Property	Current Beam	New Beam
Length	~ 200 ft.	~ 350 ft.
Maximum Momentum	~ 200 GeV/c	300 GeV/c
Targeting Angle	6 mrad	11.5 mrad
Production Angle	0	0
Angular Acceptance:		
Horizontal	± 3.04 mr	± 3.55 mr
Vertical	± 1.22 mr	± 2.27 mr
Solid Angle Acceptance	11.63 μsr	25.32 μsr
Momentum bite (defined by collimators)	best ± 18% to maintain reasonable solid angle	Intermediate Focus ± 5% or larger
Beam properties at end of decay pipe for $\frac{\Delta p}{p} = \pm 5\%$		
Beam Width	± 8.4"	± 2.34"
Horizontal Divergence	± 0.55 mr	±0.254 mr
Beam Height	± 3.3"	± 4.33"
Vertical Divergence	± 0.16 mr	±0.34 mr
Spot Size at Target		
Horizontal	.070"	.079"
Vertical	.118"	.079"

FIGURE II.1



NARROW BAND FLUXES ($\pi^+, K^+ \to \mu^+ + \nu_\mu$)
EXISTING BEAM
PRELIMINARY DICHROMATIC DESIGN (±5%)
WIDE BAND BACKGROUND DI. DESIGN
ν/Gev/proton (arbitrary units)
10²
10
1
10⁻¹
10⁻²
0
40
80
120
160
200
Eν (GeV)

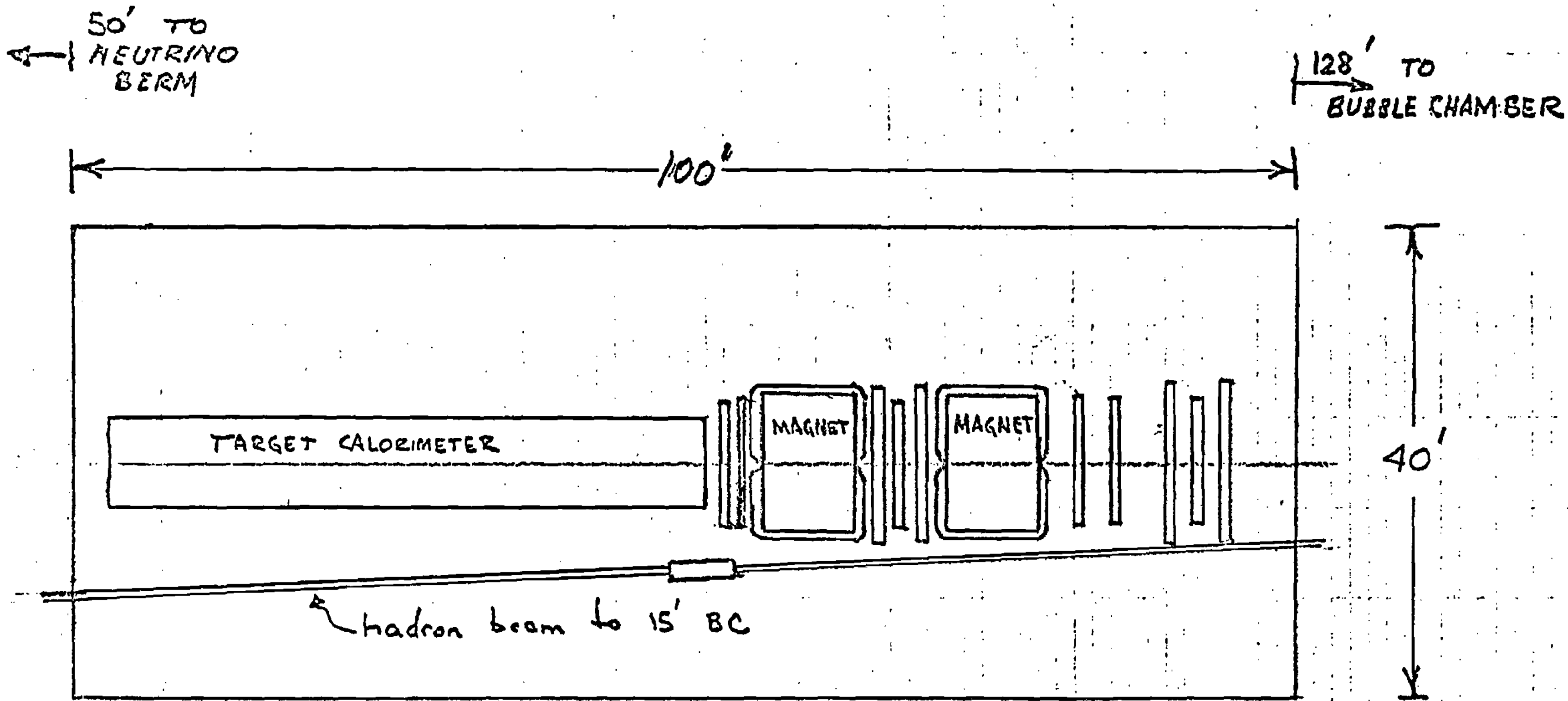
(III) New Building (Lab-E)

The Lab-E facility that is planned for dichromatic neutrino physics is located immediately downstream of the neutrino dirt shielding, about 100 feet upstream of the 15' bubble chamber (see figure III.1). This location compromises somewhat the solid angle subtended by the detector, but removes one major problem that has beset the experiment--lack of adequate shielding. The present wonder building location is to be used by the neutrino laboratory for tests of magnetic shielding.

Figure III.1 shows the geometry of the new building. With a concrete floor, overhead crane, and larger transverse dimensions, the flexibility and maneuverability which were so lacking in the wonder building should become reality. The hadron beam to the 15' bubble chamber passes through the east side, allowing testing of calorimetry modules there. We are presently investigating the potential for bringing muons into the apparatus, either from the hadron beam, or by deflecting the muon beam further upstream. This is an essential feature which will provide important alignment information. Also, muons interacting via "$\mu^- + N \rightarrow \mu^- +$ hadrons" can provide much more direct calibration of calorimetry with hadronic final states similar to that coming from neutrino-induced reactions. This is especially important if the hadronic final states begin to provide additional information to that presently used (see section V.).

The ability to move both target and magnet transversely to the beam direction provides the additional ability to utilize the high energy kaon neutrinos, while reducing the lower energy pion neutrinos (see proposal No. 320) By moving the apparatus instead of mis-steering the beam, the hadron beam will remain centered in the decay pipe so that loss of decay path and background from interaction in the decay pipe walls will present no problem.

FIGURE III.1



50' TO NEUTRINO BERM
128' TO BUBBLE CHAMBER
100'
40'
TARGET CALORIMETER
MAGNET
MAGNET
hadron beam to 15' BC

(IV) Spectrometer Assembly

The spectrometer assembly that is planned for the new building consists of two toroidal iron core magnets and a multiwire spark chamber array. Each magnet is 8' long and has a diameter of 11.5'. The magnet windings go through a 10" diameter hole in the center of the magnet. The magnet steel is cut in half along an entire horizontal diameter. A 3/8" air gap maintained by aluminum shims separates the two halves of each magnet. The air gap allows a direct measurement of the magnetic field B as a function of radius. One of the magnets has been constructed and is ready to be assembled in the new building. Bids for the construction of an identical second magnet have been sent out.

The magnet windings consist of 48 water cooled copper tubes. The magnet will be driven at 1200 amperes for a total of 60,000 amp-turns. The two magnets can be satisfactorily driven by a single NAL Trans-Rex 500 KW power supply.

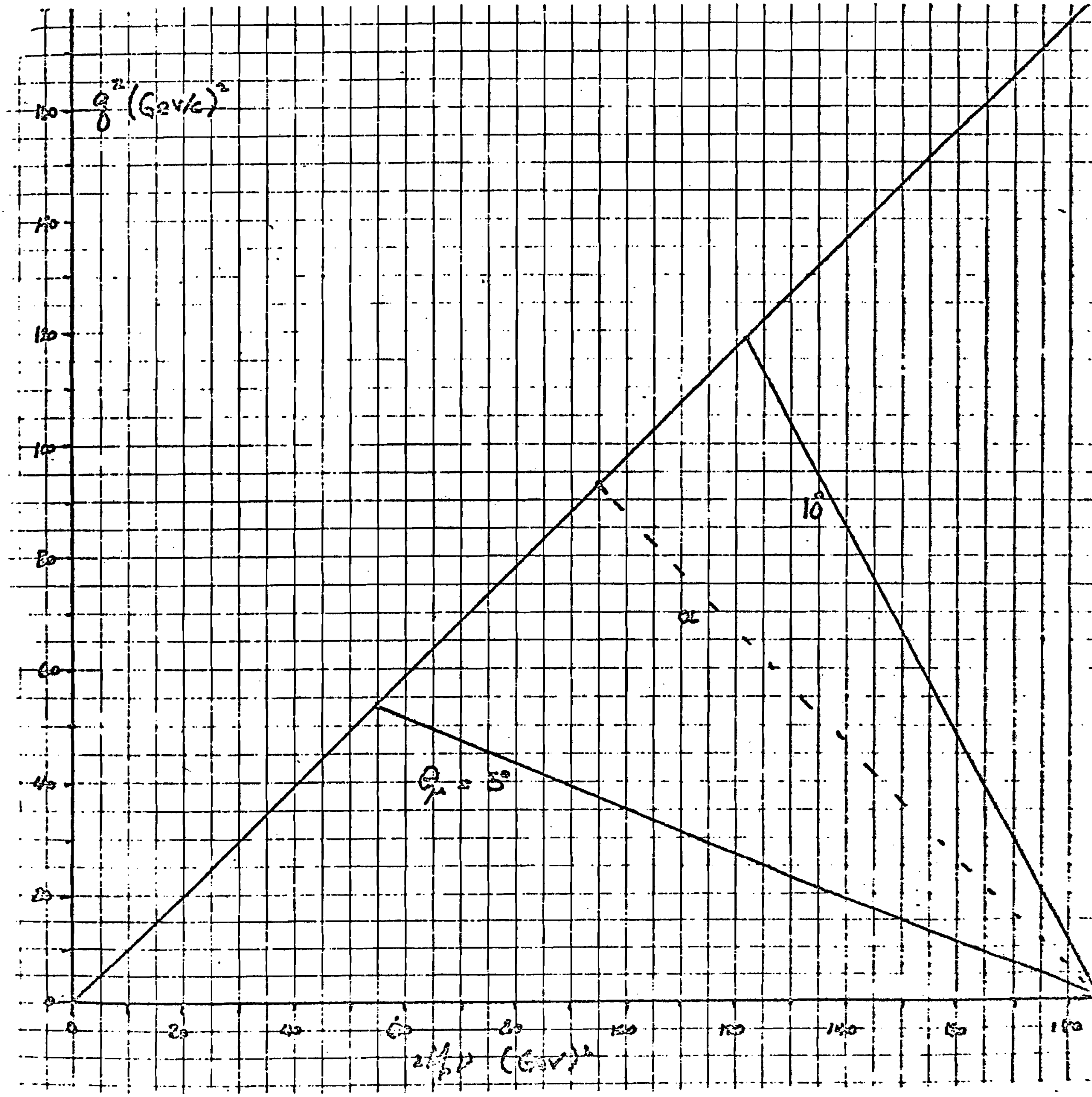
The calculated field in each magnet is approximately constant to ±10% (the field varies from 17.1 kilogauss at the magnet edge to 21.3 kilogauss near the center). The variation in the field is not important because the value of the field will be directly measured by the probes which can be inserted in the gap. Using the median field of 19 kilogauss we obtain $\int B\,dl = 46.4$ kilogauss-meters for each magnet. The bend angle for a muon of momentum p traversing both magnets is given by $\beta = \frac{2.78 \text{ (radians)}}{p \text{ (GeV)}}$. The error in the determination of the muon momentum is dominated by multiple scattering in the magnet steel. The fractional error due to multiple scattering is independent of momentum and is about ± 9%.

The above spectrometer assembly should be compared with the present setup which consists of a single 5' diameter, 8' long magnet with an average field of 15.5 kilogauss (12,000 amp-turns). The error due to the multiple scattering in this magnet is about ± 18%. There is an additional ± 8% error due to the uncertainty in the value of the magnetic field.

In addition to reducing the error in the determination of the momentum of the final state muon, the new spectrometer assembly will substantially increase the acceptance for detection of large angle muons. Both improvements are necessary for adequate measurements of cross-sections and inelastic structure functions at higher energies. This is illustrated in figures IV.1 and IV.2. Figure IV.1 shows the available Q^2 and ν region for an incident neutrino energy of $E_\nu = 100$ GeV. Lines of the secondary muon angle θ_μ are shown for 5° and 10°. The interesting large Q^2 events are also the large angle events. More important is the fact that an improved acceptance at large angles is essential in the determination of whether the interaction was caused by a neutrino originating from kaon or pion decay. This ambiquity can be resolved if the total final state energy is determined to an accuracy of 30%. When the muon misses the magnet, the ambiguity can be resolved by the determination of the hadronic state energy alone only if the large angle muon carries less than half the energy. For a given incident neutrino energy E_ν, there is an angle α above which the energy of any final state muon is less than $(1/2)\ E_\nu$. This angle is calculated as follows. At the angle α, the highest energy of the secondary muon occurs at the elastic peak or at $E'_\mu = E_\nu / \left[1 + (2E_\nu/M)\sin^2\alpha/2\right]$. Setting $E'_\mu = (1/2)E_\nu$ we obtain $\alpha = 2 \arcsin\ (M/2E_\nu)$. This angle α as a function of E_ν is shown in figure

Figure IV. 1

Kinematics of $\nu + N \rightarrow \mu^- +$ hadrons



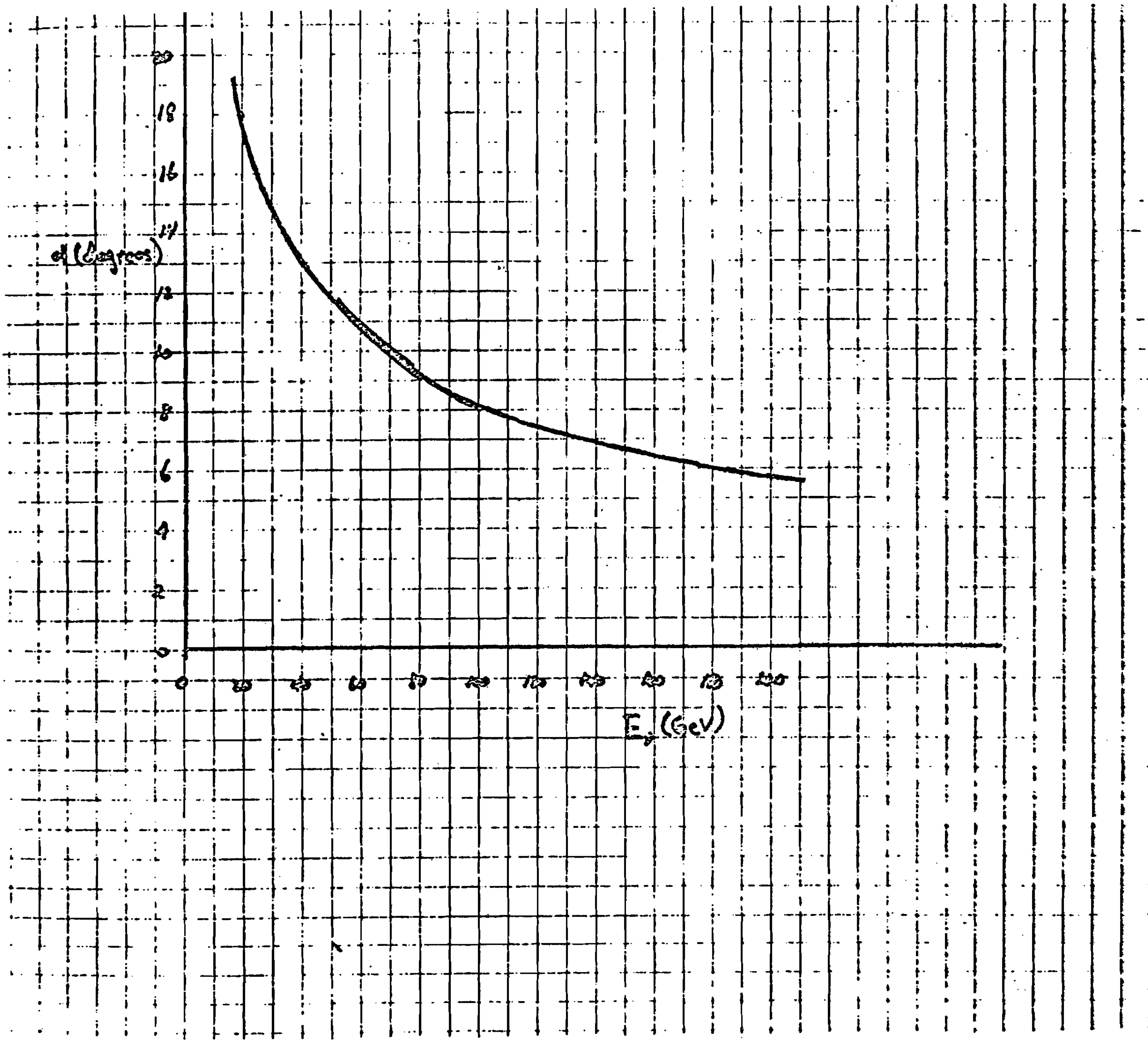
IV.2. For our experiment to adequately measure the total neutrino cross-section down to E = 80 GeV we need a spectrometer that has a reasonable acceptance up to angles of about 10°.

Figure IV.3 shows one proposed configuration of the new spectrometer assembly with respect to the present target calorimeter. Figure IV.4 shows the geometrical efficiency for the detection of final state muons as a function of angle. Also shown for comparison is the efficiency had the old 5' magnet been used in the same configuration. It is clear that the small magnet is not adequate. The target fiducial volume that was used in the calculation was z = 41', x = 50" and y = 50". The new larger magnet assembly will allow us the option of increasing the x and y fiducial volume to 86" x 86" (by the replacement of the present 5' x 5' target modules with larger 8' x 8' modules) without appreciable loss of efficiency.

The new spectrometer assembly provides two independent momentum determinations; one from each magnet. This way we will be able to identify events for which the muon experienced a large scattering or energy loss in one of the magnets. Although small in number, these events, if not identified, could distort the measured distributions in x at the high x region where counting rates are low.

For experiments such as the investigation of neutral currents, W-boson and heavy lepton searches, the acceptance for detection of large angle muons can be increased at the price of reduced momentum resolution. This is accomplished by placing additional target modules in the 5' gap in front of the first magnet. The error in the determination of the momentum is dominated by multiple scattering (±9%) if the lever arm between spark chamber planes is sufficiently long to permit a good determination of the entering and exiting angles. The configuration shown in figure IV.3 yields an error due to track reconstruction which is negligible at small momenta and is

Figure IV.2: Muon angle, α, beyond which more than half the neutrino energy goes into hadrons.



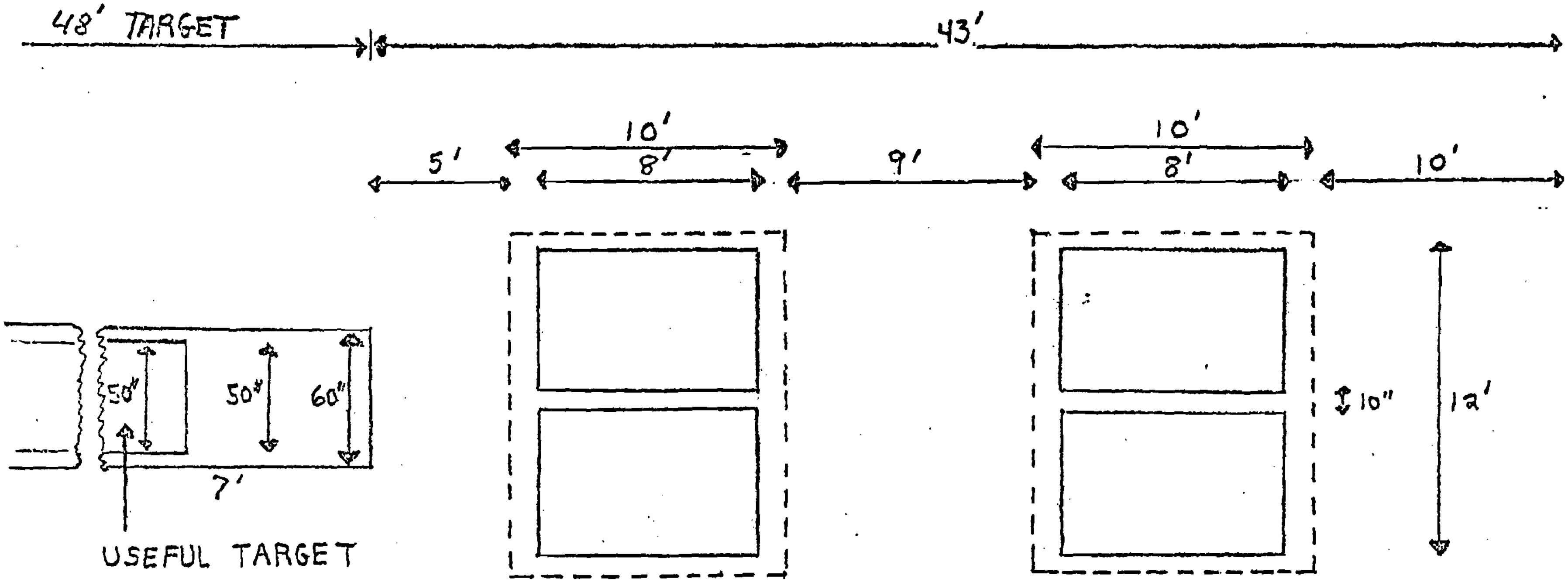
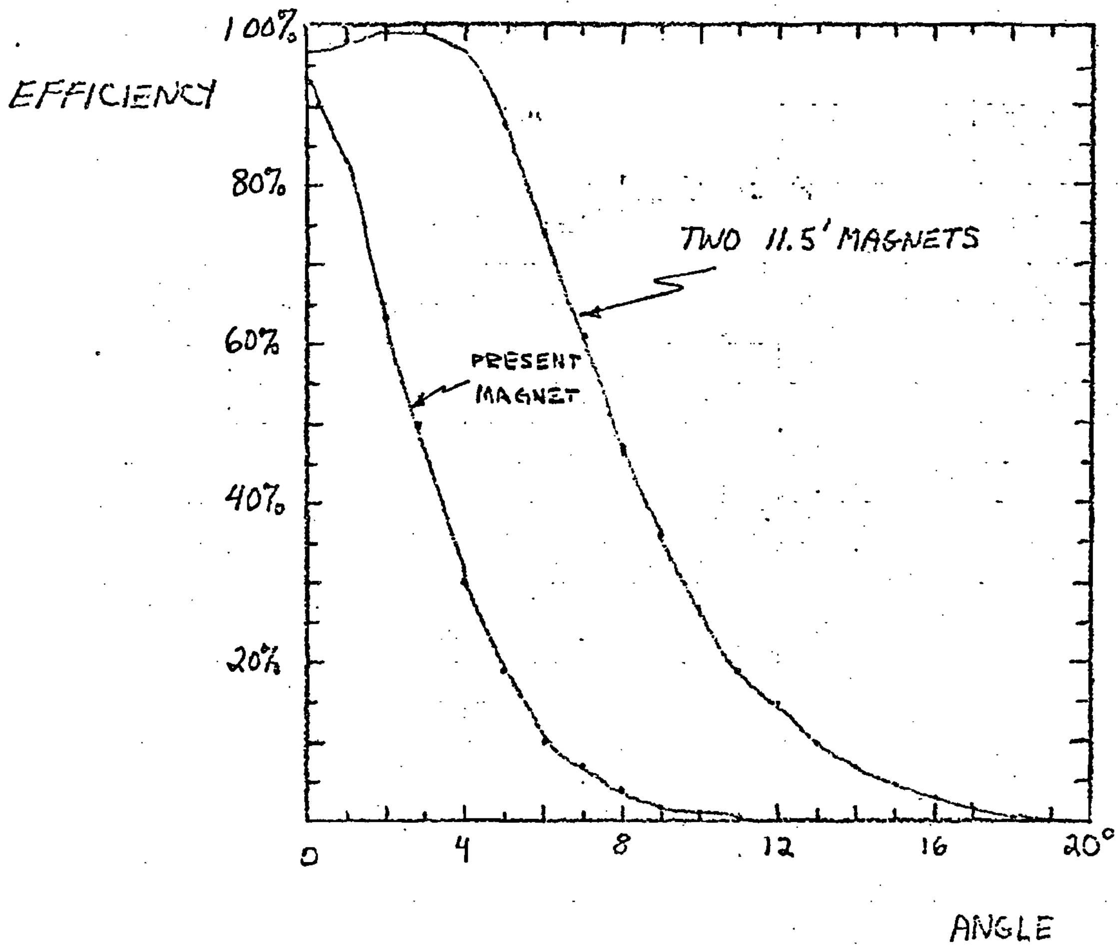


FIG. IV.3



EFFICIENCY
100%
80%
60%
40%
20%
TWO 11.5' MAGNETS
PRESENT MAGNET
0
4
8
12
16
20°
ANGLE

FIG. IV.4

equal to the multiple scattering error at a momentum of 340 GeV. Were the air gap in front of the first magnet replaced with target modules, then the determination of the momentum of high energy small angle events will be primarily accomplished with the second magnet. A momentum measurement based only on the second magnet will have a 12.7% error due to multiple scattering and error due to track reconstruction which is equal to the multiple scattering error at a momentum of 230 GeV. A momentum measurement based only on the first magnet will also have an error of 12.2% due to multiple scattering, but an error due to track reconstruction which is about twice as large at a momentum of 230 GeV.

Both magnets will be placed on rollers such that they could be moved out of the neutrino beam line. This will allow us to exploit wide-angle kaon neutrinos (see section III) and to calibrate the spark chamber positions using straight-through muons. Similarly, a check on the calibration of the magnets can be accomplished by moving the magnets into the hadron beam which passes within the new building boundaries, and using the muon component of that beam.

(V) Target-Calorimeter

The present calorimeter detector has worked substantially as expected. Figure V.1 shows the energy resolution on incident protons for 30 GeV and 200 GeV protons. After two years experience with this device, where it has proved invaluable for understanding the qualitative aspects of charged and neutral current neutrino reactions, we see quite specific areas for improvement.

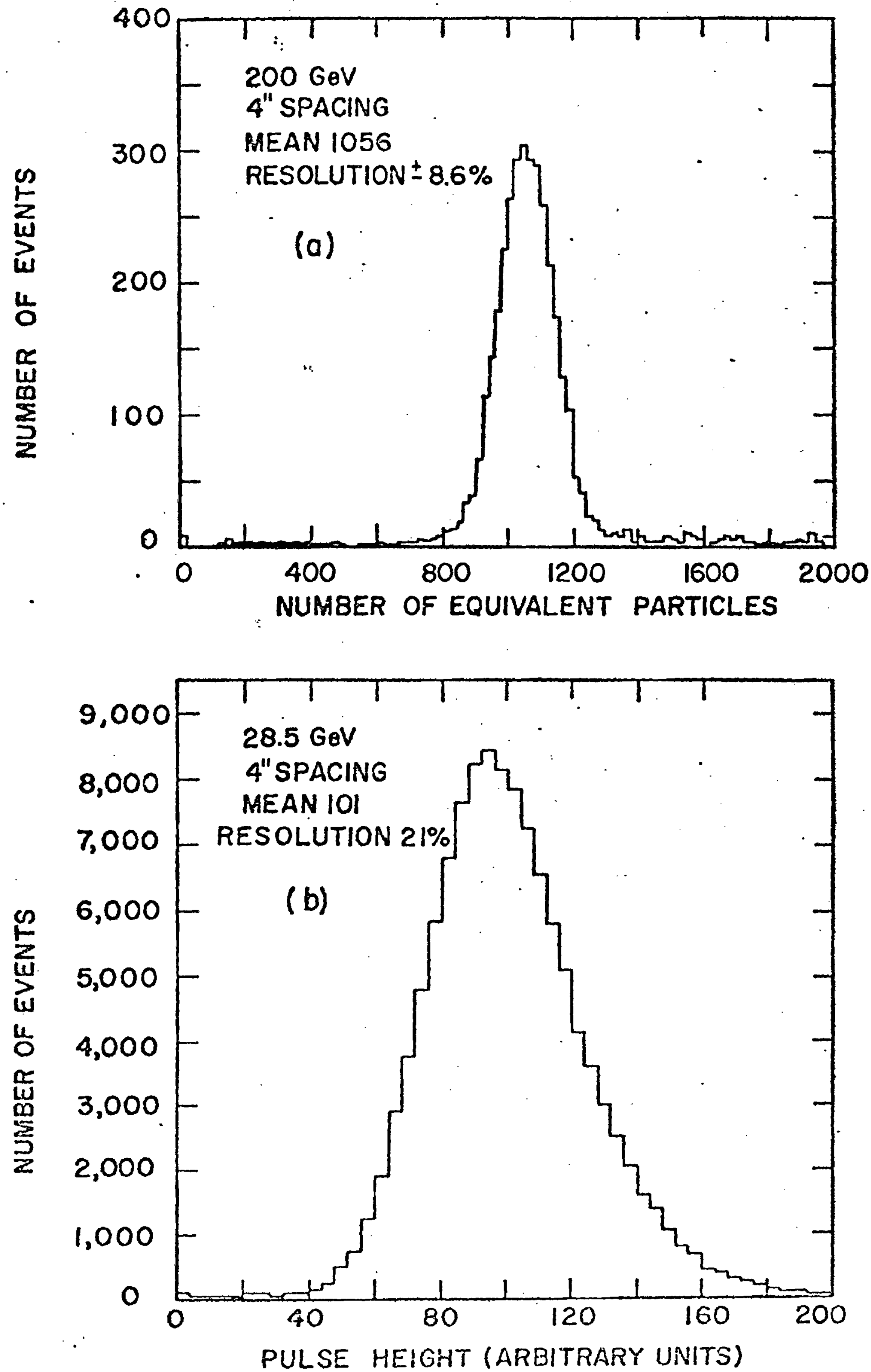
(1) Improved overall resolution, especially at lower energies. A substantial improvement can be made by a moderate reduction in spacing between samples (from 4" to 2" spacing).

(2) Larger transverse dimensions to better contain hadronic showers, to allow better fiducial volume cuts for neutral currents, and to increase the solid angle at the new experimental location.

(3) Use of spatial information on the hadron shower to overconstrain the kinematic variables, and substantially improve the resolution in some kinematic regions.

(4) A most important consequence of larger transverse dimensions would mean that we would identify all except very low energy muons from charge current reactions, regardless of angle, by penetration. Presently, we can only identify a muon by longitudinal penetration. This will substantially reduce the charged current background in a neutral current experiment.

The first two are straight forward extensions of the present arrangement. Items (3) and (4) will require substantial detector development and a more detailed understanding of the development of the hadronic shower. The general idea was discussed in a communication to the PAC last summer.



200 GeV
4" SPACING
MEAN 1056
RESOLUTION ± 8.6%
(a)
NUMBER OF EVENTS
0
100
200
300
400
0
400
800
1200
1600
2000
NUMBER OF EQUIVALENT PARTICLES
28.5 GeV
4" SPACING
MEAN 101
RESOLUTION 21%
(b)
NUMBER OF EVENTS
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
0
40
80
120
160
200
PULSE HEIGHT (ARBITRARY UNITS)

That note discussing the various kinematic variables is included again, here. How well one can actually do in practice and what instrumentation is required is now being studied.

The problem is an obvious one for the neutral current reactions, where no information is available for the outgoing lepton. Therefore, the kinematic description relies entirely on the narrow band beam (for the neutrino energy) and on the hadronic final state. But there also exists certain difficulties for charged currents. This is illustrated in figure IV.1 showing the region Q^2-ν plot accepted by even the new spectrometer magnet. Lines of constant muon angle, θ', are shown. The events at the largest Q^2 are invariably at the largest angles; the prospect of measuring their energies with conventional magnets requires huge expenditures for steel. For example, an 18 foot diameter magnet in our apparatus would still capture only those muons with $\theta' < 0.3$ rad. Even when the events have their muon energy measured, resolution on $Q^2 = 2\,EE'\,(1-\cos\theta')$ and $x = Q^2/2M\nu$ represents a serious difficulty. From the uncertainty in the muon energy, we have

$$\frac{\Delta x}{x} = \frac{\Delta Q^2}{Q^2} = \frac{\Delta E'}{E'} .$$

This means that at the largest x-values, some non-trivial fraction (dependent on resolution) of the events will appear to lie outside the kinematic range.

We feel that for this kinematic region of large θ, spatial information on the hadron system might ultimately be a superior approach. Of course for studying the details of neutral currents it is the only approach.

Much work needs to be done before we will be able to precisely define the features of this new calorimeter-detector. Prototype work for instrumentation, test calorimeter studies, and various monte carlo calculations are underway. This note only describes the kinematical ideas.

RESOLUTIONS, OVERCONSTRAINTS, AND THE MEASUREABLE PARAMETERS IN NEUTRINO DEEP INELASTIC SCATTERING

For neutrino scattering from heavy targets, in deep inelastic reactions of the type

$$\nu_\mu + N \rightarrow \mu^- + \text{hadrons}$$

the variables which have generally been considered "measureable" are

E_μ = energy of outgoing muon;

E_h = energy of hadron shower;

θ_μ = angle of outgoing muon;

E_ν = energy of incident neutrino.

The last can come independently of the others from specific (narrow band) beam setups. In principle, the measurement of the above constrains, even over-constrains, the problem. The variables of interest usually are

$$Q^2 \approx 2\, E_\nu\, E_\mu\, (1-\cos\theta_\mu) \quad \text{and} \quad \nu = E_h$$

or

$$x = \frac{Q^2}{2M\nu} \qquad y = \frac{\nu}{E_\nu}$$

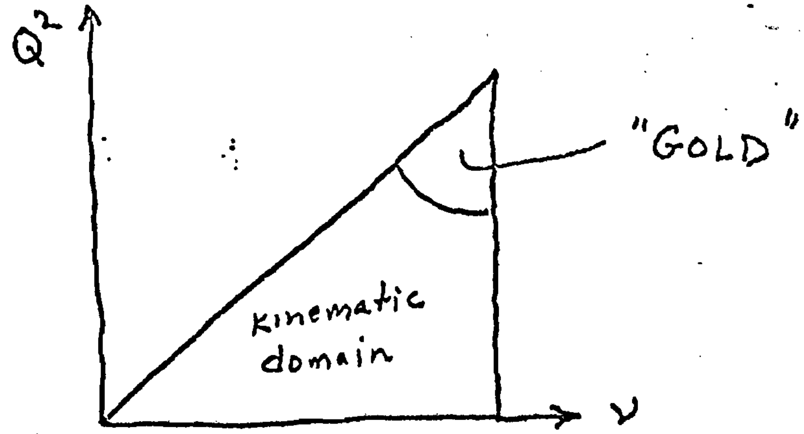
However, with finite resolution on the measureables, very poor resolution may result on, for example, x or y. In addition, practical solid angle acceptance of a real apparatus will result in events (often the most interesting events) with one or more measureables unobtained.

In terms of x, y, and E_ν, the measureables are approximately

$$E_\mu = E_\nu\,(1-y) = E_\nu - \nu$$

$$E_h = E_\nu\, y \qquad = \nu$$

$$\theta_\mu^2 = \frac{2M}{E_\nu}\,\frac{xy}{1-y} = \frac{Q^2}{E_\nu(E_\nu - \nu)}$$



For example, the very exciting prospect of using the largest Q^2 events means one must go to very large ν as well.

Note: for $Q^2 \rightarrow Q^2$ max

$\nu \rightarrow E_\nu$

then $E_\mu \rightarrow o$

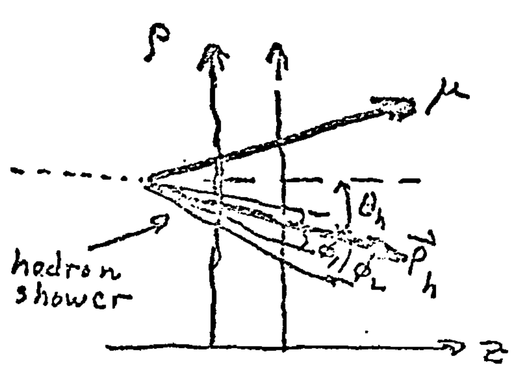
$\theta_\mu \rightarrow 90°$

and events miss a finite-size magnet.

For these very events for which we have no measure of E_μ, we must measure ν and Q^2 relative to zero (with E_h and $\theta_\mu^{\,2}$). This can result in very poor accuracy.

We suggest that there are other variables which can be measured in the hadron shower. This follows up on a technique devised by R. Walker and A. V. Tollestrup for detection of π°'s.

Consider the production of a hadronic final state in a neutrino collision, of invariant mass, W, and mean vector momentum, $\vec{P}_h$, at an angle, θ_h, relative to the direction of the incident neutrino.



The invariant mass can range over the value $M < W < \sqrt{2M_\nu}$, i.e. up to 20 GeV for a 200 GeV neutrino interaction.

By sampling the subsequent shower development as a function of the transverse coordinate, ρ, at different z position, the appropriate first and second moments can be obtained:

$\langle \theta_h \rangle$ = mean direction of the hadronic state relative to the neutrino direction

and $\langle \phi^2_h \rangle$ = mean square angular deviation of hadronic energy relative to $\vec{P}_h$.

It is estimated at this time that it is practical to achieve with standard calorimeter techniques for say ν = 200 GeV, roughly

$$\langle \theta_h \rangle \text{ to } \pm .005$$

$$\langle \phi_h^2 \rangle \text{ to } \sim 2 \times 10^{-4}$$

These new measureables provide independent measures of the kinematic variables

$$\langle \phi_h^2 \rangle \approx \frac{W^2}{\nu^2} \approx \frac{2M}{\nu} \quad (1-x)$$

$$\theta_h^2 = \frac{2M}{E_\nu} \quad \frac{x(1-y)}{y}$$

For example

$$W^2 \approx 2 M\nu - 2 M\nu x$$
$$= Q^2_{max} - Q^2$$

measured directly the difference of Q^2 from its <u>maximum</u> value.

Similarly, for $x \rightarrow 1$ $(Q^2 \rightarrow Q^2_{max})$

$$1 - y = \frac{E_\nu \theta_h^2}{2M x} \qquad y \approx \frac{E_\nu \theta_h^2}{2M}$$

$$E_\nu - E_h \approx \frac{E_\nu^2}{2M} \theta_h^2$$

gives E_h <u>relative to its maximum value</u>.

Quite definitely, measurement of these additional parameters will provide greatly improved resolution of the kinematic variables.

Calculations of the intrinsic calorimetry limitations in the moments are proceeding. At the same time, the various technical possibilities for the position dependence (proportional chambers, spark chambers, ion chambers) are being investigated.

VI. Summary

When the narrow band beam was proposed four years ago, it was primarily envisaged as the most promising avenue for measuring accurate total cross-sections in the high energy regime. In the first short test with this measurement, done less than a year ago, the expectations were more than fulfilled. With the crude, phase-0 version of this beam, measurements were made at one energy to typical accuracies of 20%. This was better by 50% than we expected for this first look. Later this year, with some improvements in monitoring and with more statistical precision, we expect to do ± 15% measurements with the same beam.

During this period, it has become generally recognized that a narrow band beam can be of much more general use than simple measurements of total cross-sections. The sensitive heavy lepton search, and definitive corroboration of the neutral current phenomena attest to this fact. That this is recognized can be seen in the enormous effort that Cern is putting into the construction of a good dichromatic beam.

A true dichromatic beam with detector improvements such as we have described here should definitely be capable of the objectives described in the attached proposals. But, with judicious design for the target-calorimeter, a large range of new possibilities may also occur:

(1) $\nu_e + N \rightarrow e^- + \text{hadrons}$

(2) $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$

(3) $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$

(4) Neutral and charged current four-fermion reactions

e.g. $\nu_\mu + Z \rightarrow \mu^- + \mu^+ + \nu_\mu + Z$

Each of these processes is important for understanding the nature of the weak interactions. The main thrust of these remarks is to indicate that we believe that the future possibilities in this new facility (Lab E) are very rich. There is great flexibility and the apparatus can evolve to respond to the physics needs. Rather than take the "shotgun" approach, however, we have attempted to focus on the primary objectives on which we have focussed in the past:

(1) Measurements of the differential distribution from deep inelastic scattering;

(2) Measurements of the total neutrino cross-sections;

(3) Measurements of inclusive neutral current processes.

A qualitative improvement in the first two goals will be obtained with the spectrometer and beam changes described in this report. For goal No. 3, we feel that a substantial modification to the target-calorimeter is required. With a favorable construction schedule for the beam and new building, we could meet the following timetable:

September 1974--August 1975

(1) Complete objectives in present Wonder Building location with present narrow band beam.

(a) E 320

(b) E 21

(c) E 306

(2) Construct Lab E Building and dichromatic beam.

(3) Design new target-calorimeter.

May 1975--September 1975

(1) Move to new Lab E and install new dichromatic beam.

September 1975--September 1976

(1) Phase 1 experiments in new building. (Attached)

- $d\sigma/dx\,dy$

- σ_{tot}

(2) Build and install new target calorimeter.

September 1976

(1) Neutral current experiments with new target-calorimeter. (attached)

(2) ?

This schedule would permit true exploitation of the narrow band concept at Fermilab in a wide variety of possible experiments. Our own emphasis has been on the charged and neutral current processes, but there remain rich fields to be explored. We consider this to be an open facility, and welcome involvement by others in the development of the new calorimeter-detector.

Lab-E can evolve into a highly flexible, mobile, and precision detector. Together with a good dichromatic beam, Lab-E will insure the Fermilab of accurate and exciting neutrino physics for many years to come.