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HIGH STATISTICS STUDIES OF CHARGED CURRENT INTERACTIONS USING THE TEVATRON QUAD TRIPLET BEAM

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SECTION I : MOTIVATIONS FOR A QUAD TRIPLET RUN.

The efforts of the CCFR group over the last several years have been directed toward measuring the properties of neutrino interactions in the region of 100 GeV and beyond. We begin by reviewing what has already been accomplished in order to see what areas are limited by statistical error and may be significantly improved by a high statistics run using the quad triplet beam.

Since the commissioning of Lab E, there have been two major runs: E616 (1980) and E701 (1982). Analysis of the E616 results are now almost complete and will be briefly summarized below. The oscillation results from E701 are also complete; results have been presented in several conferences and a Physical Review Letter will be published in the next few months. The E701 data are now being incorporated into the E616 sample and will complement these results by roughly a factor of two in numbers of events.

The results from the E616 run are briefly summarized:

(1) Measurement of the total neutrino and antineutrino cross sections as a function of energy, $40 < E_\nu < 250$ GeV. These data have been published in Physical Review Letters.[1] They are consistent with a linear rise in the cross section over the energy range. The slope of this rise is roughly 10% higher than several previous measurements.

(2) Neutral current analysis: The determination of $\sin^2\theta_W$ from the neutral current events is almost complete (final radiative corrections are being studied). The preliminary new result has been presented at Erice[2] and will be published in the near future. Preliminary indications are that $\sin^2\theta_W \simeq .24 \pm .012$, a value that is somewhat larger, and also more precise, than previous measurements. A similar value has recently been reported from the CDHS group at the last Lepton-Photon conference.[3]

(3) Measurements of the charged current structrue functions: F2(x,Q2) and xF3(x,Q2). Preliminary results have been presented[4] and are being finalized. We are preparing a paper on second order QCD fits to the data which provide measurements of Λ_{QCD} (see Appendix A).

(4) Measurements of opposite sign dimuons: These provide values for the fraction of the $q\bar{q}$ sea which carries strangeness, and also provide one of the best measures of the fragmentation of charm into D-mesons. A paper on these results is being prepared.

(5) Continued investigation of same sign dimuons: This is a phenomenon that is still not well understood. Corroborations[5] of our previous results[6] demonstrating the existence of same sign dimuons have been presented, but theoretical calculations[7] of possible sources of the events are too low by an order of magnitude.

A quad triplet run can contribute little to the first two items. The dominant errors in total cross-section measurements are due to flux uncertainties, so a quad triplet run can do little to improve this measurement. In determining $\sin^2\theta_W$ from neutral current events, statistical errors are important, particularly in using the Paschos-Wolfenstein ratios. However the narrow band beam is needed for these measurements since it allows incident neutrino energy to be determined from the interaction point. We believe this information is essential for precision measurements of a process in which a large fraction of the final state energy is unobserved. In addition to allowing an event-by-event determination of the scaling parameter $y = E_h/E_\nu$, this information is used in applying cuts to the events to reject charged-current background. Since the energy-position correlation is missing in a quad triplet beam, systematic errors will become much larger than with the narrow band beam (this is true even if a sign-selected quad triplet beam is used). Such errors would be larger than the present statistical errors; therefore we do not see any improvement in neutral current studies from the quad triplet run, and in fact do not plan to record neutral current events.

For the analysis of structure functions from neutrino data, statistical errors in measuring the shape of the x-distributions (and the changes in shape) are important, and statistical error is the dominant source of uncertainty in determining Λ_{QCD} both from F2(x) and from xF3(x). We expect

an increase of more than a factor of 10 in the event sample of E616 from a quad triplet run, particularly at high Q^2, and this is a primary motivation for such a run. A precise measurement of Λ_{QCD} is, and will continue to be, important in verifying the validity of QCD and in testing grand unified theories. The quantitative benefits to be gained from the quad triplet run, as well as the limitations due to cross-section and flux uncertainties, will be discussed in more detail in section IV.

Opposite sign dimuon events have now been measured in many different neutrino experiments, and are consistent with production expected from charm decay. This makes such events a very good probe of the strange sea, and they have been used to measure the strange sea component in the E616 analysis and by CDHS.[8] The data from a quad triplet run have strong advantages over both of the previous measurements as discussed in section V. Even with considerably tighter cuts on events, the new data would increase the E616 sample by more than a factor of 10.

One of the most interesting questions to be faced in neutrino physics is determining the source of same-sign dimuon events. These events, reported by CFNRR and later by many other experiments, were cited[9] in the summary talk of the recent Cornell Lepton-Photon Conference as being the single greatest "threat" to the Standard Model. The quad triplet run will produce an estimated 680 such events above background, compared to a present world sample of 136 and the present E616

sample of 14.

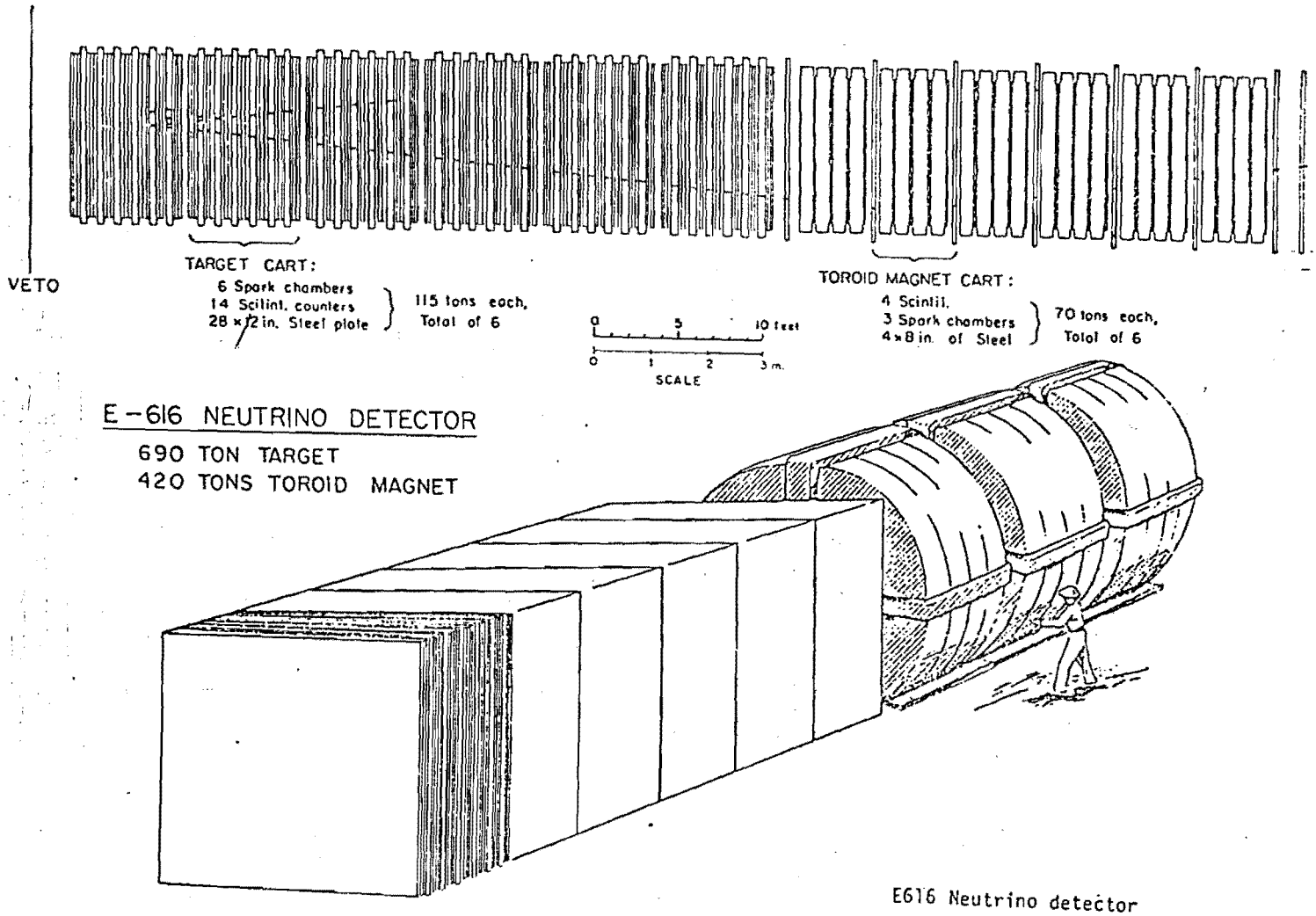
These three areas -- opposite sign dimuon events, same sign dimuon events, and improved structure function determination -- are important areas of neutrino physics that can be explored considerably better than presently with the data from a high intensity quad triplet run, because of both the higher statistics and the higher energy. The Lab E apparatus is now undergoing extensive changes which will make it possible for the first time to take advantage of such a high-rate and high-energy run.

In section II we describe the detector, with emphasis on the recent modifications. In section III we delineate exactly what we expect from the quad triplet run in terms of data; and in sections IV - VI we return to the three physics topics mentioned above to examine more precisely what we expect to gain from the new data.

SECTION II : DESCRIPTION OF THE APPARATUS.

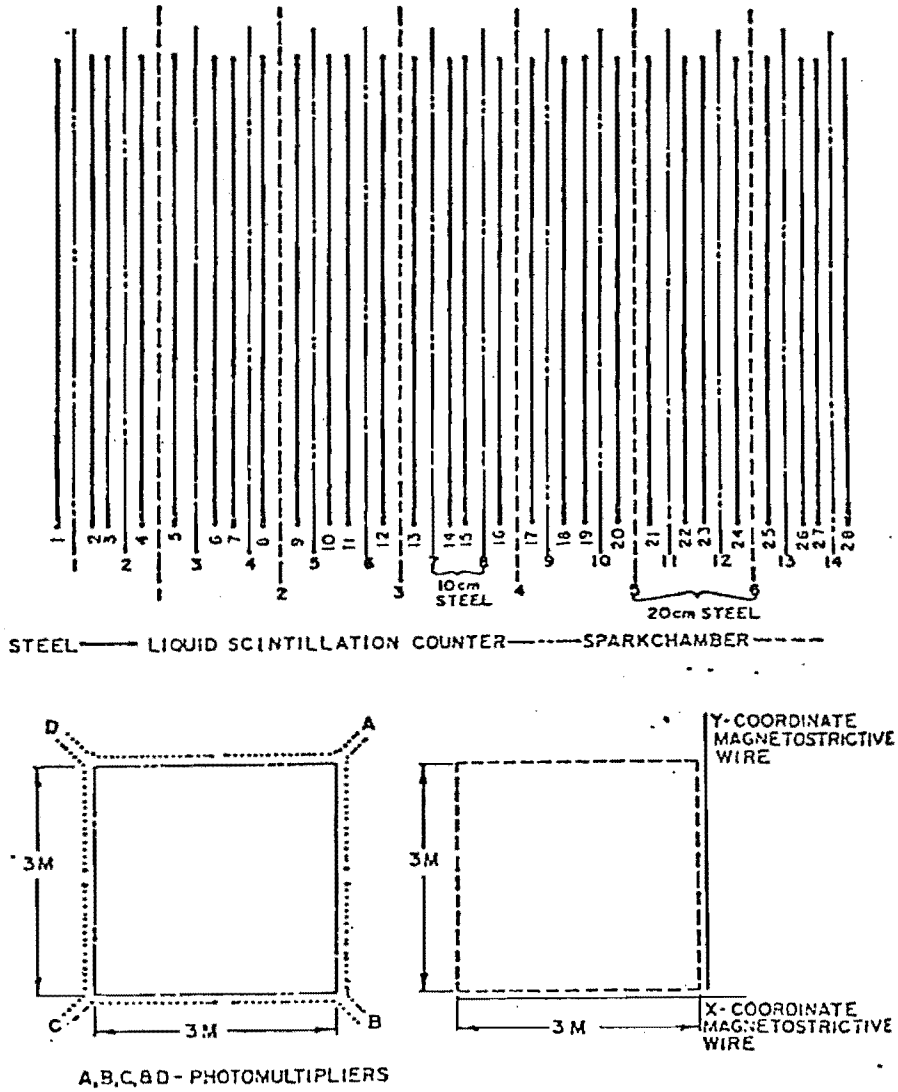
The E616 neutrino detector is currently being upgraded for Tevatron neutrino beams. This modification consists of: 1) replacing all the spark chambers with drift chambers which permit high event rates and precise tracking; 2) modification of the data collection electronics to allow buffered data acquisition and consequently higher rates; and 3) an increase in the lever arm of the muon spectrometer. The new drift chambers are described at the end of this section. Figure 1 shows the E616 apparatus and Figure 2 the upgraded detector. The detector consists of a 680 ton target calorimeter and a 450 ton muon spectrometer. Six modularized "carts" comprise the target calorimeter, with each cart containing 28 5cmX3mX3m steel plates, 14 scintillation counters, and 6 tracking chambers (7 in the upgraded version).

Hadron showers are sampled after every 10cm of steel, and there is charged particle tracking after every 20cm of steel. The target calorimeter counters are mineral oil scintillators measuring 2.5cmX3mX3m and viewed by four photomultiplier tubes via wavelength shifter bars. Calibration is accomplished using hadrons and muons from a hadron test beam, and with muons from charged-current events during the run. Position dependence of the counter response has been measured with the hadron test beam and also with hadron showers from charged



E616 Neutrino detector

FIG 1a



Arrangement of target cart scintillation counters and spark chambers.

FIG1b

UPGRADED LAB E DETECTOR

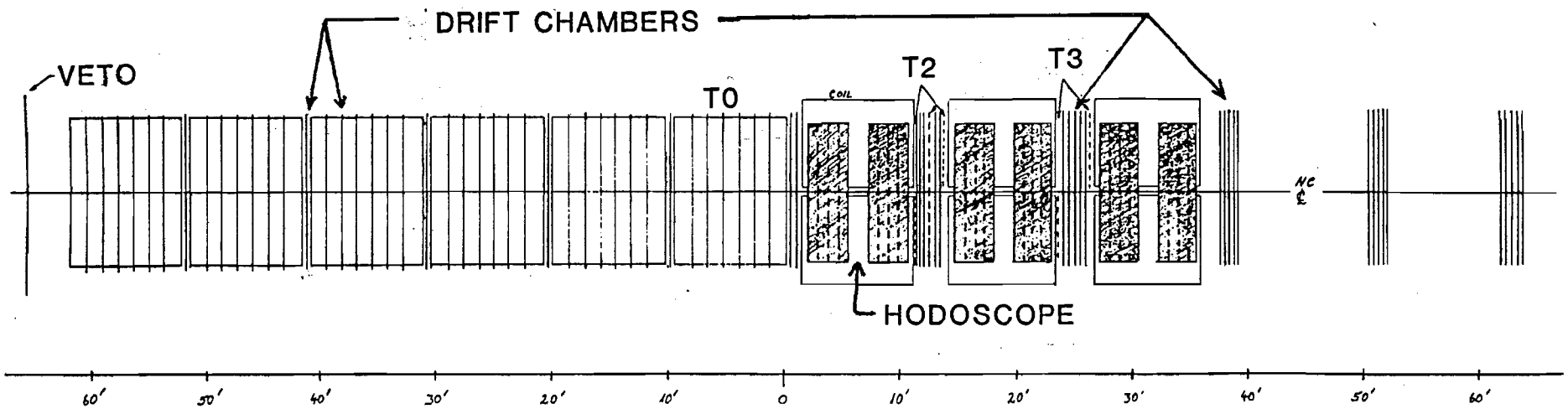


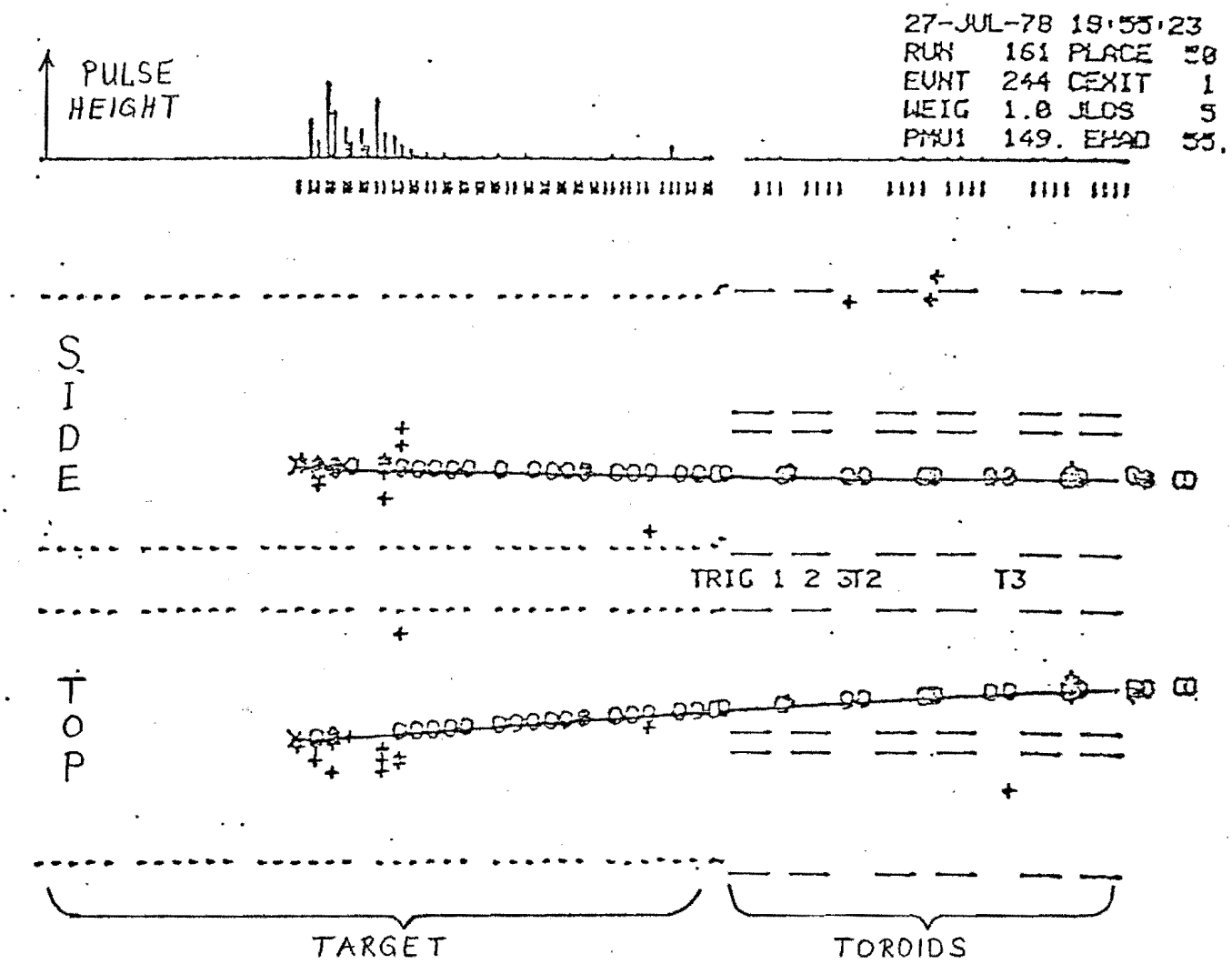
FIG 2

current neutrino interactions. A hadron energy resolution $\sigma(E_{had})=0.89\sqrt{E_{had}}$ has been achieved with this calorimeter[10].

Charged particle tracking chambers are employed in the target to track muons as part of their momentum reconstruction, and also to determine the transverse position of vertices for both charged current and neutral current events. Figure 3 shows a typical charged current event from E616.

Vertex determination has been impaired in the past by the spark chamber performance in hadron showers. The drift chambers are expected to improve this problem. The new chambers give a measured 250 μm resolution and employ a multi-hit readout free of deadtime. Each cell has two sense wires to eliminate left-right ambiguity even if many particles are present. An additional small inefficiency in finding the vertex of neutral current events has been caused by the lack of chambers in the gaps between carts. This problem is being remedied by adding a new drift chamber in each gap, so that the chamber spacing will be uniform throughout the calorimeter.

The muon spectrometer consists of six toroidal steel magnets having a total transverse momentum kick of 2.4 GeV/c. Each toroid measures 81cm long by 3.5m in diameter, with a 25cm diameter central hole for passage of the coil. Each toroid is split into four steel discs which are each followed by acrylic scintillator counters. A fast hodoscope will be placed in the gap halfway through the first toroid to aid in



Charged current event

FIG 3

providing a reference time for the drift chambers.

Tracking chambers are located between the toroid coils and downstream of the toroids; the upgraded design calls for sets of five chambers at positions 4m and 8m downstream of the last toroid. From E616 data it was determined that muon momenta are reconstructed with an accuracy in $\sigma(p)/p$ of of 11% from multiple scattering and $0.008\% \cdot p$ (where p is in GeV) from position resolution and lever arm. For all E616 momenta the 11% multiple scattering term dominates the resolution. With the better drift chamber position and alignment resolution and the 8m lever arm, E652 should obtain the same 11% resolution even for the highest energy Tevatron muons. In addition, the drift chamber electronics will digitize the leading and trailing edges of each pulse. The pulse width found from this information will be used in separating the hits accompanied by delta-rays generated in the toroid steel.

Data for physics analyses are taken with three types of trigger topology. The scintillators used to form the trigger are shown in Figure 2; "T0" consists of majority logic applied to the eight target calorimeter counters just in front of the toroid, while T2 and T3 are scintillators behind the first and second toroids respectively. A veto scintillator precedes the calorimeter. Two of the trigger topologies are based on muon signatures. "Trigger-1", or the muon trigger, requires a minimum ionizing signal in the target calorimeter and a signal in T2 or T3; this ensures that a muon has entered the spectrometer. The other trigger for muons, "trigger-3" or the

penetration trigger, requires more than 5 GeV measured in the calorimeter and minimum ionizing signals in 12 or more target counters, which is associated with a muon penetrating more than 1m of steel. "Trigger-2", the hadron energy trigger, demands that at least 10 GeV total energy be measured in the calorimeter. This trigger is primarily useful for neutral current events, and it overlaps considerably with triggers 1 and 3.

Event rates of 30 - 40 per 1 millisecond spill are expected with the quad triplet beam at Tevatron energies. By far the greatest impact of the Lab E upgrade will be the ability to take event rates of up to 60 per millisecond spill. The previous experimental deadtime of 18 milliseconds, due to the spark chambers, will be reduced to less than 12 microseconds through use of drift chambers and fast encoding buffered TDC's and ADC's. The drift chamber drift time across a cell is 1.6 microseconds. The TDC electronics continuously records chamber hits in a 2 microsecond deep front end memory. After each trigger, the TDC is dead for only the 8 microseconds required to encode the contents of the front end memory into the event buffer. The E616 calorimeter deadtime of 2.2 milliseconds per event will be reduced to 11.7 microseconds through use of new ADC's (LRS 4300) with buffer memories (LRS 4302). Between spills, the contents of each TDC buffer memory are transferred to the computer through the Nevis transport system developed by W. Sippach and the ADC buffers are read through CAMAC.

E616 spark chambers are being replaced with drift chambers having the same dimensions and constructed on the same HEXCEL honeycomb panels as were the spark chambers. These new chambers are presently under construction at Fermilab. Each panel carries cells containing horizontal wires on one face and vertical wires on the other. The total chamber thickness remains 6cm so that the new chambers can be inserted into the existing slots in the Lab E target. Figure 4 shows the layout of one of the 24 cells on a chamber plane. A cell contains two 30μm diameter sense wires separated by 4mm; they are electrically isolated from one another by a 127μm diameter field wire between them. Cross talk between wires of a cell is at the 5% level. The 6 cm drift field is shaped by ten copper strips on G-10 panels. A field of 670 volts/cm is applied to the strips by means of a resistor chain. Figure 5 illustrates the drift path. Accurate spacing of the wire triplet is achieved by embedding the wires into four thin nylon spacers along the 3m wire run. There is no intermediate support for the wires, which therefore sag 194μm at the center of the chamber. Tests with a cosmic ray telescope obtain a resolution of 250μm for this chamber design. A gas mixture of 50% argon/50% ethane will be used with a flow rate of about 0.10 lpm per chamber.

The electrical properties of the chamber and the preamplifier cards have been carefully engineered so that the chambers may be used as gas calorimeters at a later date. This would be useful for measuring the direction of the hadron

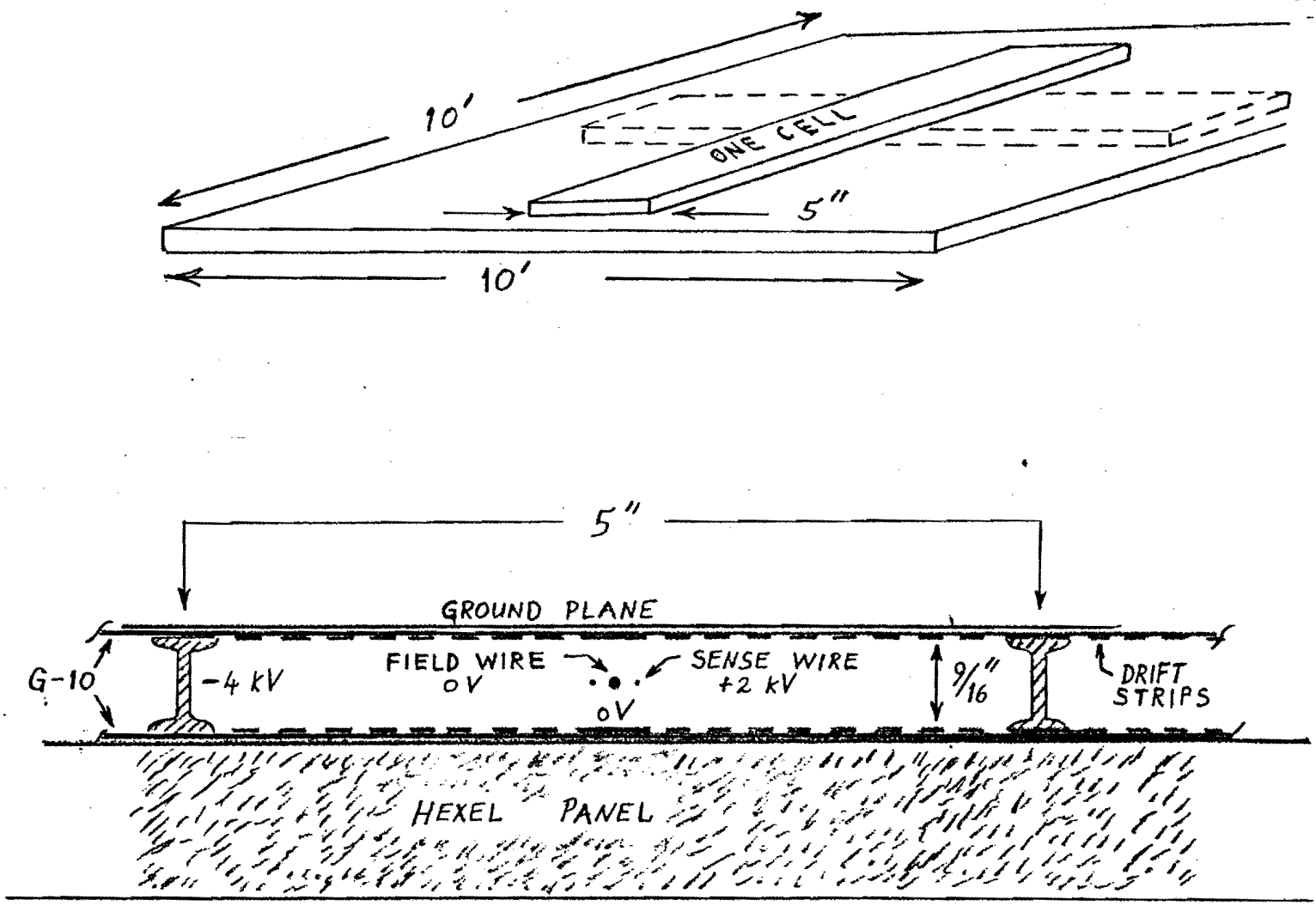

10'
ONE CELL
5"
10'
5"
GROUND PLANE
G-10
-4 kV
FIELD WIRE
0V
SENSE WIRE
+2 kV
0V
9/16"
DRIFT STRIPS
HEXEL PANEL

FIG 4

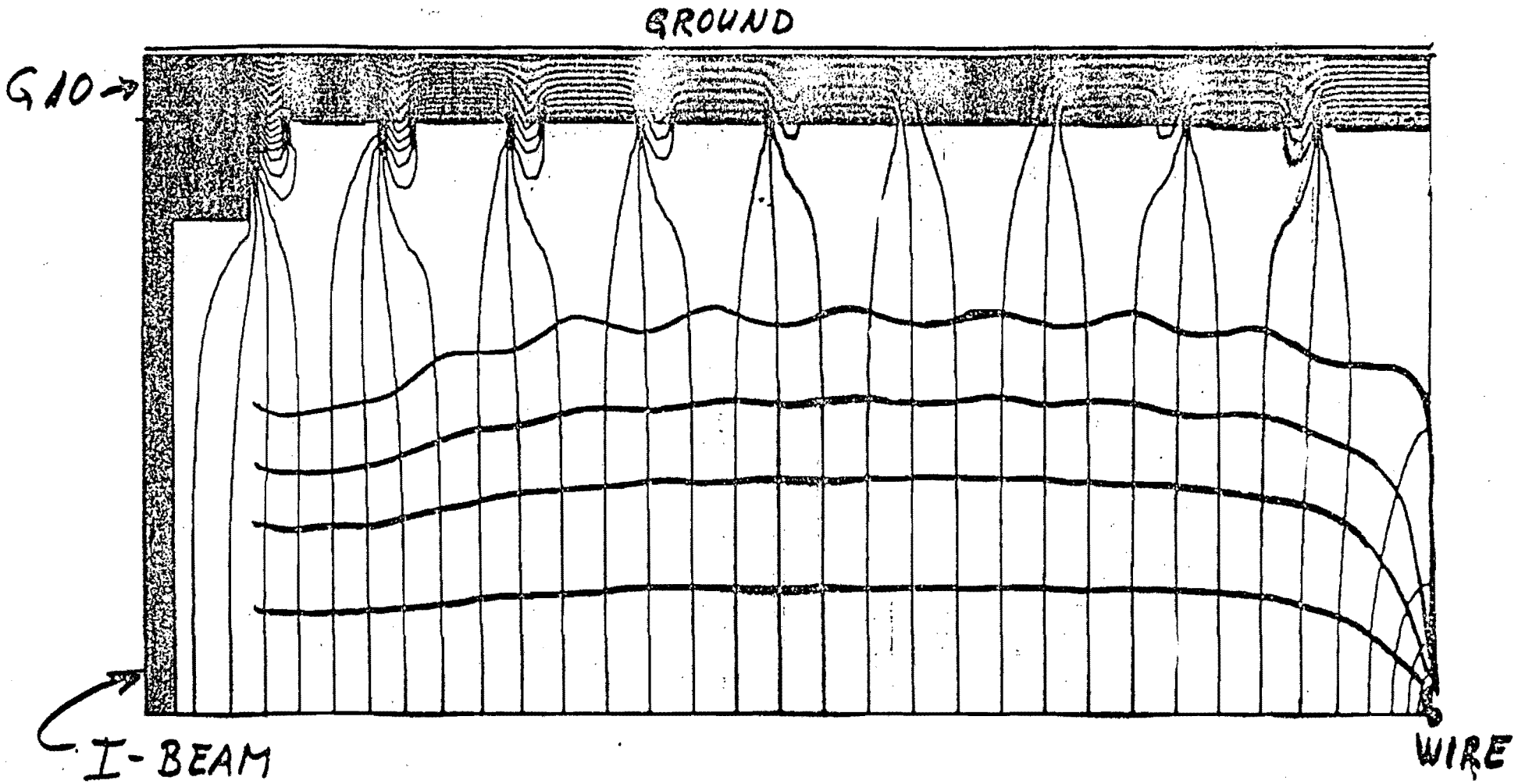


FIG 5

energy flow. Such an upgrade would call for the addition of flash ADCs to the receiving electronics. To allow for this possibility, the preamplifier cards produce an amplified limited signal for input to the TDCs and a linear signal which can be used as input to an ADC. Currently each cell is being gain-mapped with a ^{109}Cd source and an external ADC attached to this linear preamp signal.

SECTION III : DESCRIPTION OF THE PROPOSED RUN.

The proposed run will use the Tevatron Quad Triplet beam, tuned for 300 GeV, as described in Fermilab TM-1190.[11] We anticipate 10^{13} protons on target per spill over a 1 msec spill. Assuming a 16 week run with 100 hours of beam per week and one spill every 60 seconds, this gives a total of 100,000 spills and 10^{18} protons on target.

In TM-1190, Malensek and Stutte calculate neutrino interaction spectra (for charged currents events only) normalized to a 100 ton, 1.5 m radius detector in Lab C. Correcting for the higher flux/area in Lab E and the higher mass (500 tons in the active trigger region), we calculate from their spectra a rate of 45.5 ν and 7.6 $\bar{\nu}$ interactions in Lab E per spill (10^{13} protons on target per spill).

Using the standard Monte Carlo program used for the E616 analysis, we calculate trigger rates per pulse (not including deadtimes) of

	ν	$\bar{\nu}$	Total
Trigger 1 (muon thru toroid)	30.8	5.6	36.4
Triggers 1 and 3 (any muon)	41.3	7.1	48.4
Trigger 1,3, and 2 (E_{had})	56.5	9.0	65.5

(Note that trigger 2 events include neutral currents). These trigger rates, with a 1 msec spill, would obviously have been unthinkable in the past since the deadtime per event was about

20 msec. With the new drift chambers and buffered readout, the deadtime per event will be 11.7 μsec. This gives a total livetime of 57% if all three triggers are used and 64% if only triggers 1 and 3 are used (charged current events only).

The important physics that we see in this run requires CC events, and in particular events with a measured muon momentum (trigger 1). Trigger 3 events (CC triggers in which the muon misses the toroid trigger counters) will be useful for measuring trigger efficiency and acceptance. Neutral current triggers are not useful, since the backgrounds from CC events at large y are greater with the quad triplet than with the narrow band beam (the same cuts on events cannot be applied). Therefore we plan to run with the muon triggers only (triggers 1 and 3). If the trigger rate is higher than expected, we may also prescale the trigger 3 events.

This gives a total live trigger rate of 26.4 ν and 4.5 $\bar{\nu}$ per pulse with a 1 msec spill, and a total of about 3 million recorded charged current events.

In order to measure and eliminate any bias in acceptance, we will run 50% of the time with the Lab E toroids focusing μ^- and 50% of the time focusing μ^+. The trigger rates in the two cases are virtually identical.

To ensure shower containment, fiducial cuts will reject events within 10" of the edge of the apparatus and within 20 counters (2 meters of steel) of the toroids[11]. This reduces the data sample by about 25%, giving 19.6 ν events and 3.4 $\bar{\nu}$ events per spill, or 1,960,000 ν events and 335,000 $\bar{\nu}$ events

over the run. The comparable event sample in E616 was 150,000 ν events and 23,000 $\bar{\nu}$ events.

In the E616 analysis, several fairly stringent cuts were made to minimize resolution effects and to make acceptance calculations simple and clean. These include:

1) requiring the triggering muon to be focusing
2) requiring the triggering muon to extrapolate in a straight line from the vertex to inside the trigger counter T2, at least 5" away from the edge.
3) requiring $E_{had} > 10$ GeV and $E_{\mu} > 4$ GeV
4) requiring $\theta_{\mu} < 200$ mrad

We expect to be able to relax the first of these at least, but for the purpose of comparing to E616 we make all of the same cuts. This gives a total good event sample from the quad triplet run of 670,000 ν and 130,000 $\bar{\nu}$ events. The comparable event sample in E616 was 65,000 ν and 7,000 $\bar{\nu}$ events. That is, we expect an increase of more than a factor of 10 over E616 even requiring the triggering muon to be focusing. If we relax this requirement, as we believe we can do without increasing the systematic uncertainty, we can further increase both the ν and $\bar{\nu}$ samples by at least 60%.

The total reconstructed energy of the E616 data, with all the five energy settings combined, is compared to the expected quad triplet data in Figures 6 and 7. Identical cuts were placed on both sets of events. Similar plots for Q^2 are given in Figures 8 and 9.

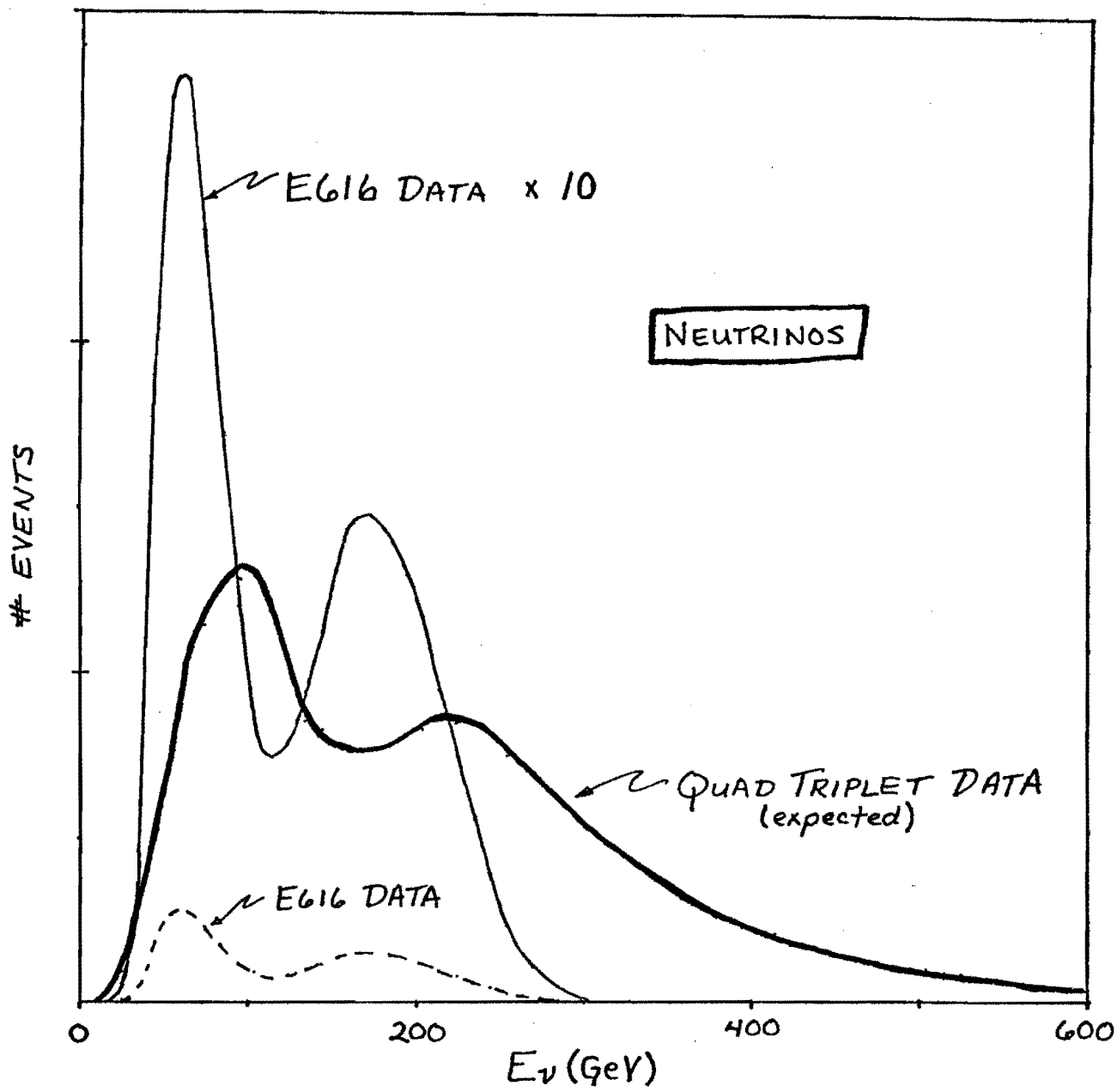

E616 DATA x 10
NEUTRINOS
EVENTS
QUAD TRIPLET DATA
(expected)
E616 DATA
0
200
400
600
E_ν (GeV)

FIG 6

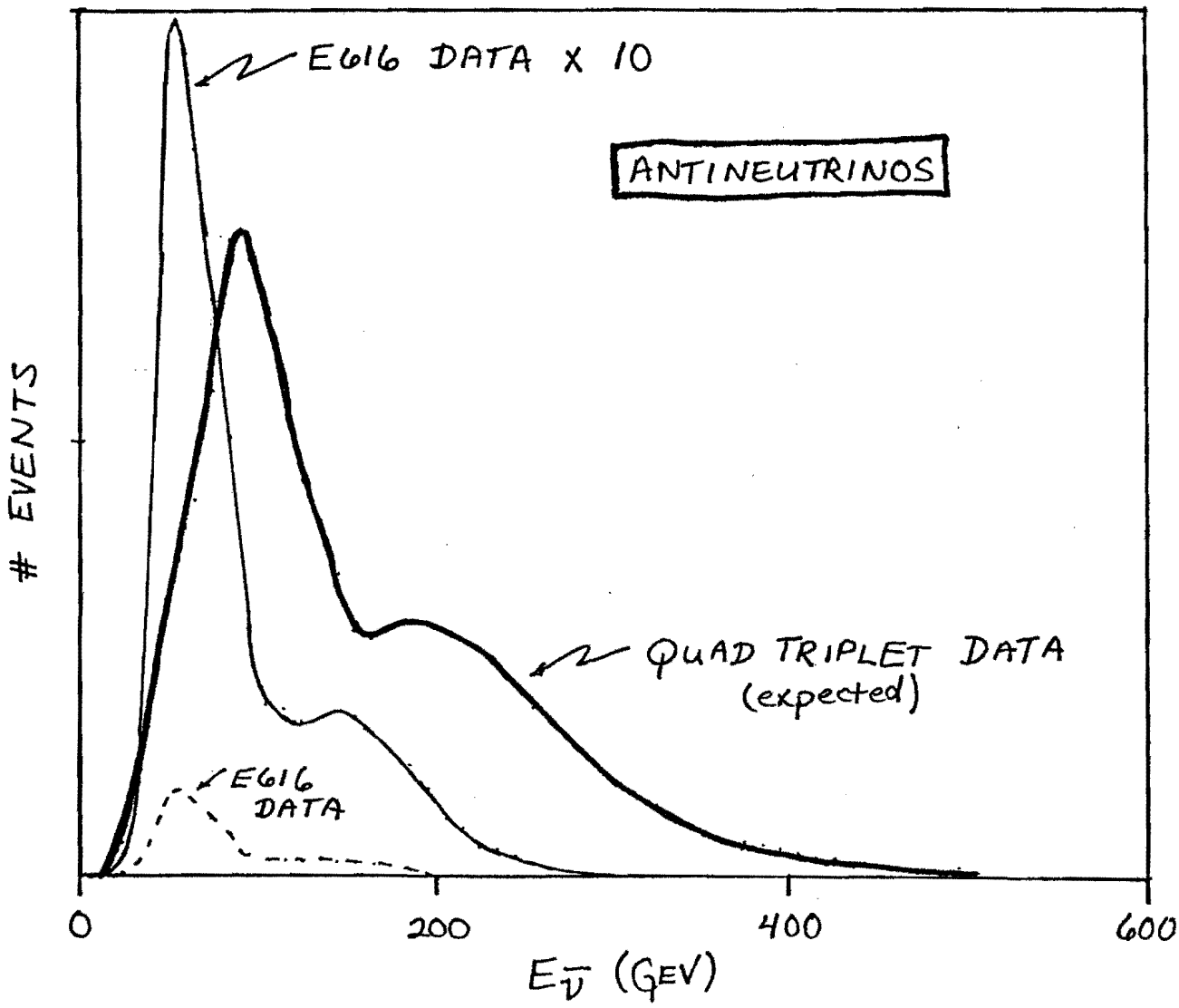

E616 DATA X 10
ANTINEUTRINOS
EVENTS
QUAD TRIPLET DATA
(expected)
E616
DATA
0
200
400
600
$E_{\bar{\nu}}$ (GEV)

FIG 7

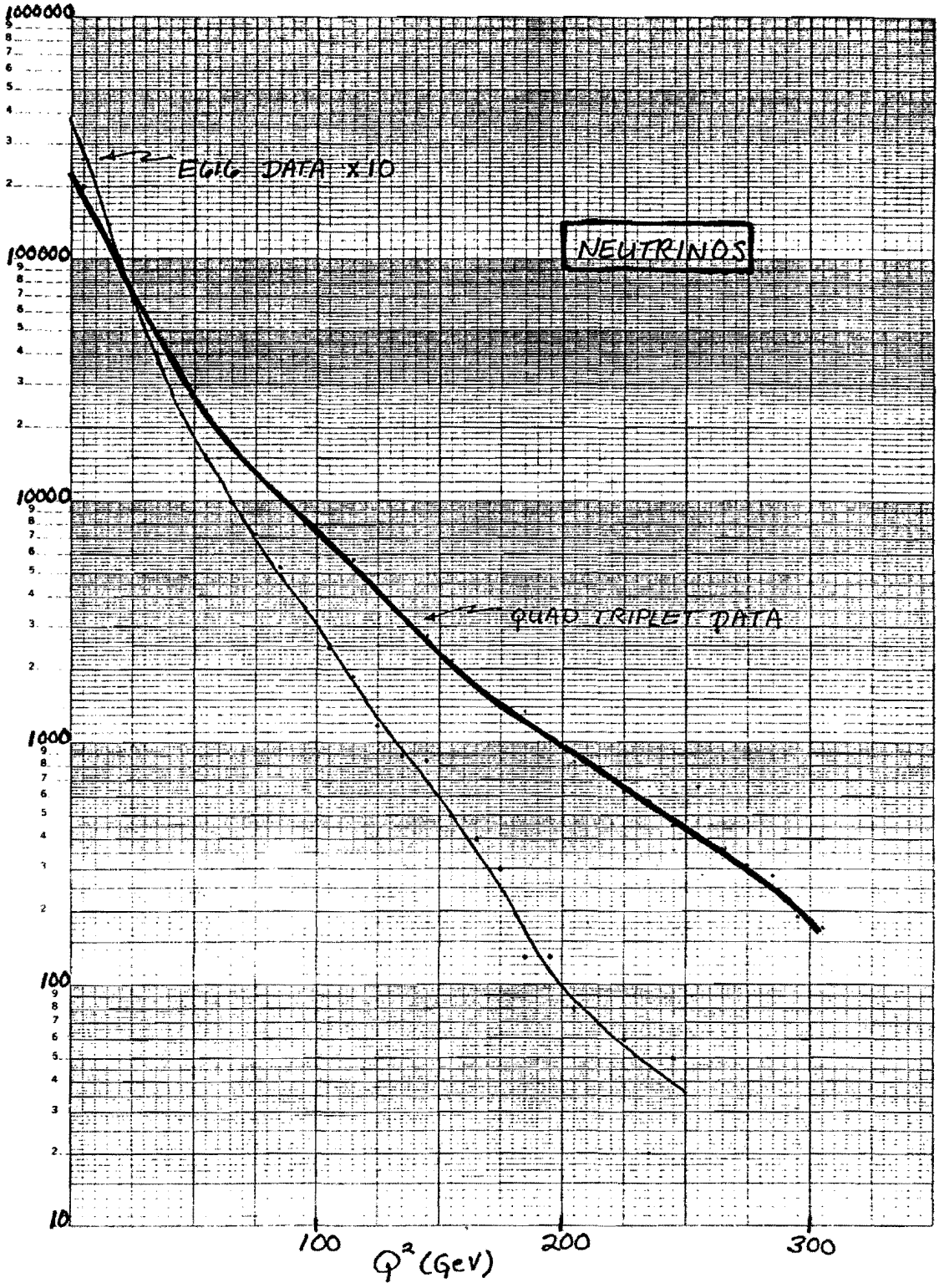

1000000
100000
10000
1000
100
10
EGIG DATA X10
NEUTRINOS
QUAD TRIPLET DATA
100
200
300
Q² (GeV)

FIG 8

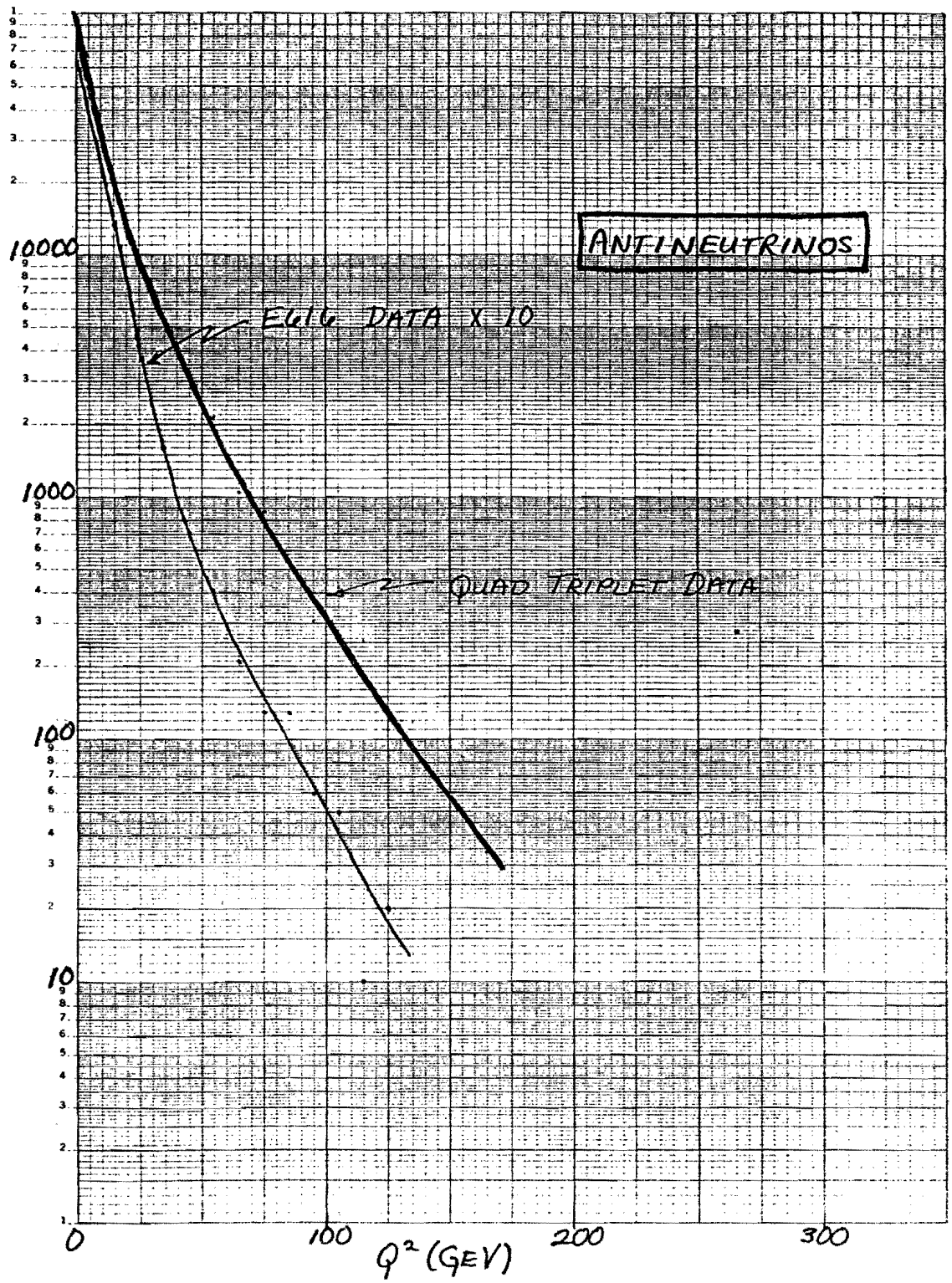

ANTINEUTRINOS
EGIG DATA X 10
QUAD TRIPLET DATA
10000
1000
100
10
0
100
200
300
Q² (GEV)

FIG 9

Three points should be noted about these spectra:

1) The quad triplet event sample is greater than the E616 sample by a factor of 10 for neutrinos and a factor of 18 for antineutrinos.

2) The quad triplet spectra extend to much higher energy and Q^2 than the narrow band spectra.

3) The quad triplet spectrum is smooth and relatively flat. This reduces possible problems of resolution smearing.

SECTION IV: STRUCTURE FUNCTION ANALYSIS.

A. Comparison of Event Analysis with the Quad Triplet and Narrow Band Beams.

The advantages of the quad triplet beam in terms of event rate are obvious. But what are the disadvantages? Two of these have already been mentioned: 1) flux normalization using the monitors in the decay pipe is impossible; and 2) the separation of events into ν_μ^π and ν_μ^K interactions, and the very useful relation between interaction point and incident neutrino energy, are lost. These effects make total cross section and neutral current measurements less satisfactory. However, they do not have much effect on the rest of the analysis.

Determination of Incident Neutrino Energy

In the quad triplet beam, the interaction point cannot be used to determine the energy of the interacting neutrino. But even in the E616 structure function analysis this position-energy correlation of the narrow band beam was not used to determine neutrino energy -- rather, the reconstructed neutrino energy was used. Since the resolutions of the detector are 11% for P_μ and $0.89/\sqrt{E_h}$ for hadron energy, a 200

GeV neutrino interaction with y=.5 would give δP_μ = 11 GeV and δE_h = 8.9 GeV, and hence have $\delta E_{tot}/E_{tot}$ = 7.1%. On the other hand, the momentum spread of the hadron beam in E616 was 10%, and the resolution on E_ν was also worsened by beam dispersion and vertex position measurement. The reconstructed neutrino energy was therefore a better measurement even with the narrow band beam. Moreover, the energy spectrum of the quad triplet beam is fairly smooth (not steeply falling) as shown in figures 6 and 7. Therefore feed-down due to energy resolution is not a very large effect. Figure 10 compares the actual energy spectrum to the reconstructed spectrum for Monte Carlo events passing all cuts. The difference in rate in any 10 GeV energy bin, over the region $20 < E_\nu < 540$ GeV, is at most 5%; this small difference can be corrected for with good precision.

Determination of Acceptance

A very straightforward and model independent method of measuring acceptances for neutrino events has been used in the past. First, cuts are applied to the events so that the acceptance depends on geometry alone. The muon from each event is extrapolated in a straight line from the event vertex through the first toroid to the trigger counter T2. If the extrapolated track lies outside a 55" square (5" from the edge of the trigger counter), the event is rejected. The cut

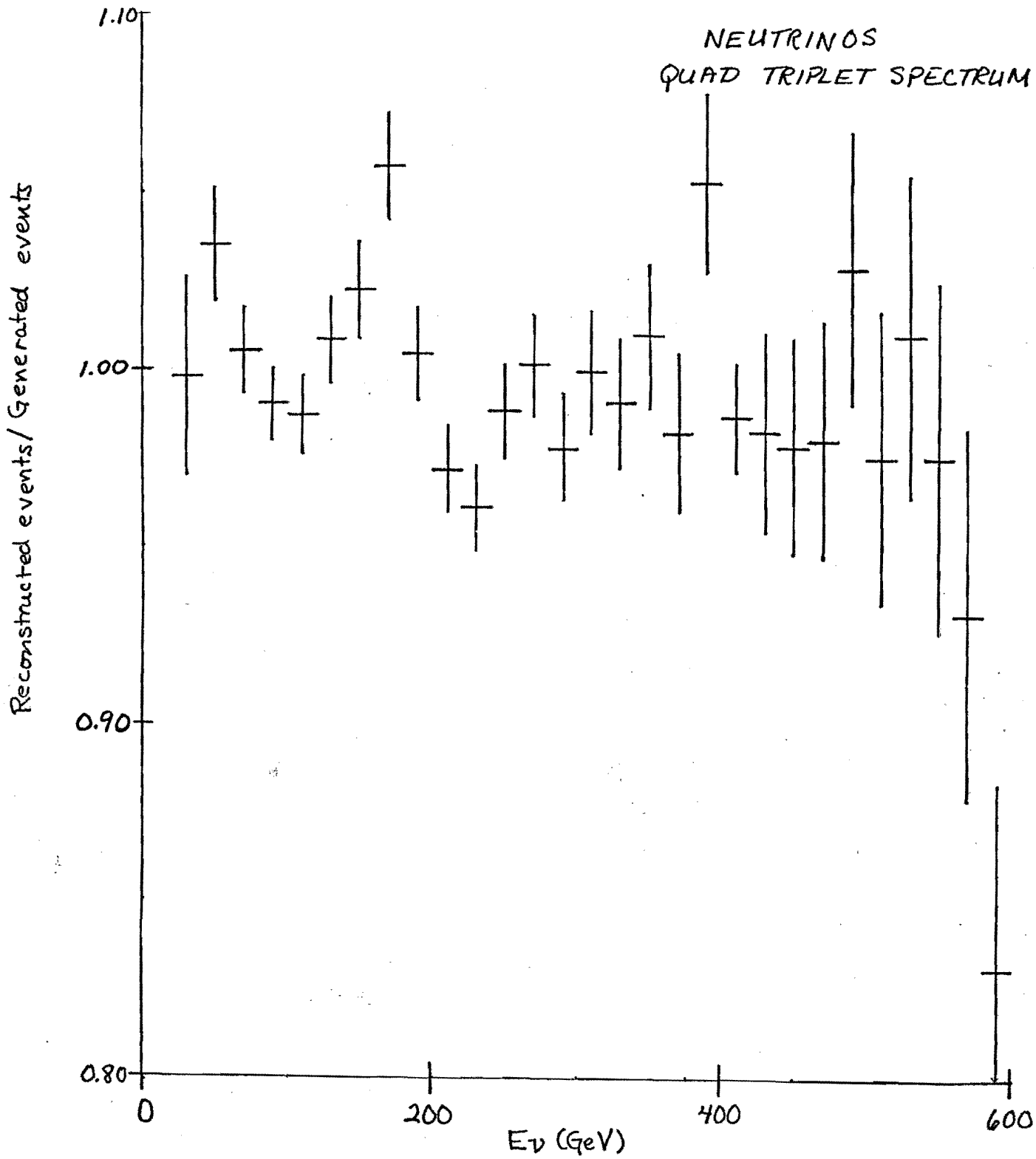

NEUTRINOS
QUAD TRIPLET SPECTRUM
Reconstructed events/ Generated events
1.10
1.00
0.90
0.80
0
200
400
600
Eν (GeV)

FIG 10

therefore depends only on vertex position and muon production angle, and not on the muon momentum or the magnetic field. Any interaction passing this cut will necessarily have a muon passing through the trigger counter (provided the muon is focusing and has a momentum of at least 4 GeV), since the magnet is focusing inward. This is the reason for requiring the muon to be focusing, as mentioned in section III.

Acceptance can then be calculated analytically from the events passing this cut. The production plane of each event is azimuthally rotated through 360 degrees and the fraction of the time the muon would pass the cut is calculated. The event vertex is also translated along the beam direction over the entire fiducial region, and a similar efficiency for passing the cut is calculated. An efficiency f, equal to the fraction of the time that such an event would pass the T2 cut, is calculated for each event, and the event is assigned a weight 1/f. The weighted distributions of these events are therefore fully corrected for acceptance, except for the class of events which have such large muon production angles that they never pass through T2 no matter where the interaction occurs. This remaining small inefficiency is corrected using Monte Carlo extrapolations.

This weighting procedure works equally well for quad triplet, narrow band, or any other kind of beam. Since the quad triplet events are higher in energy than the narrow band, the technique will in fact work even better here. Therefore correcting for acceptance of the detector is not a more severe

problem with the quad triplet beam.

Flux Normalization

In analyzing data from the quad triplet run, it will be necessary to combine data from different energy regions into an $F_2(x,Q^2)$ vs Q^2 plot for different regions of x. In order to do this one needs to know the relative flux normalization of the different energy regions. This can be done using the same two techniques that have been used with the narrow band beam.

The first technique uses the fact that $F_2(x,Q^2)$ and $xF_3(x,Q^2)$ must be independent of E_ν if x and Q^2 are fixed. By comparing rates for different E_ν but with the same x and Q^2, one can determine the relative normalization of the different energies. This fitting procedure is described in detail in the theses of two of the E616 students,[13] and was the primary method of normalizing different energies in that experiment. The normalization obtained in this way was more precise than that using the measured fluxes, since the latter were subject to fluctuations due to systematic errors in the flux measurements.

The second way of normalizing different energies is to assume that the cross sections rise linearly with energy, as indicated by E616 and CDHS data. QCD effects change the shape of the distributions, but have very small effects on overall

normalization. The relative flux for a given energy bin can therefore be determined from the number of events in that bin, provided the acceptance of the detector is well understood. This method was used as a check in the E616 analysis and agreed very well with the first method.

Both of these two methods gave a more precise relative normalization than did the flux measurements of the narrow band beam. Each method should work as well or better in the quad triplet analysis (the first method is limited by statistics in E616). The absolute levels of ν and $\bar{\nu}$ flux, which are also required, are set by the cross-section slopes measured with the narrow band beam.

In short, the use of the quad triplet beam does not compromise the structure function analysis in any respect.

There are only three aspects of the narrow band beam which would be at all advantageous to the physics discussed in this proposal:

1) Absolute flux determination is possible in the narrow band beam, while in the quad triplet beam it is not. This normalization is necessary in the analysis of structure functions in order to determine xF_3, F_2, and the gluon distribution. However, the cross-section normalization will be available from narrow band runs both before (E616, E701) and after (E652) the quad triplet run.

2) The narrow band beam allows a check on the calibration of muon and hadron energy, since they should sum to the beam energy. Since parameters are overdetermined in a narrow band beam experiment, this and other checks on systematics can be made. Such checks were made in the E701 run last year, and will be repeated in the Tevatron narrow band run which immediately follows the quad triplet run; not having them in the quad triplet run is therefore a trivial disadvantage.

3) The narrow band beam makes it possible to measure the missing energy carried away by neutrinos in the final state in multi-muon events; no such measurement is possible in the quad triplet beam. However, the missing energy measured in E616 and predicted by Monte Carlo methods is small (12% of the neutrino beam energy on average), and the error in its measurement is large (typically ± 100%). Not having this rather imprecise measurement is not a serious defect. Almost all of the CDHS dimuon data has in fact come from a horn beam, and the quad triplet beam has important advantages over that beam as discussed in section V.

In short, we believe that the good control of normalization and of systematics of a narrow band run, combined with the high statistics of a quad triplet run, will give a balanced experimental program. Both kinds of beam are needed for the best and most complete measurements of neutrino interactions.

B. Improvements in Structure Function Measurement

The most important parameter to be determined by measurements of structure functions is the quark-gluon coupling constant α_s, or equivalently Λ_{MS}. These parameters are fundamental to our knowledge of the strong interaction, and are important in testing new theoretical ideas (e.g., grand unified theories) and comparing to other experimental measurements. For example, SU(5) predicts the relation

$$\sin^2\theta_w = 0.2087 + 0.006 \ln(0.4 \text{ GeV}/\Lambda_{\overline{MS}})$$

The value of Λ_{MS} can be measured separately using either $F_2(x,Q^2)$ or $xF_3(x,Q^2)$. A measurement of Λ using xF_3 alone has many advantages over fits to F_2. The evolution of xF_3 does not depend on the unknown gluon distribution, and the extraction of xF_3 is independent of both $R = \sigma_L/\sigma_T$ and the amount of strange sea in the nucleon. However, although the measurement using xF_3 is less subject to systematic uncertainties, it is more subject to statistical error since it involves a subtraction of ν and $\bar{\nu}$ data.

The present measurements of the QCD parameters from the E616 data, using xF_3 alone, give

$$\Lambda_{MS} = 90 \begin{smallmatrix} +160 \\ -80 \end{smallmatrix} \begin{smallmatrix} +90 \\ -45 \end{smallmatrix} \text{ MeV}$$

$$\alpha_s = .204 \pm .079 \pm .045$$

where the first error is statistical and the second is systematic.

Due to the factor of 18 increase in $\bar{\nu}$ statistics, data from the quad triplet run will reduce the statistical error by nearly a factor of 4, making it smaller than the present systematic error. However, some of the systematic errors can also be reduced by higher statistics. For example, errors in relative normalization occur in comparing the rates for different energies in the same regions of x and Q^2, and account for about a third of the total systematic error. But these errors are statistical in nature, and will clearly be greatly reduced in a quad triplet run. Additional systematic errors due to uncertainty in the relative ν and $\bar{\nu}$ cross sections may be reduced by using low y data to improve the <u>relative</u> normalization between ν and $\bar{\nu}$. We believe the total errors on α_s and Λ can be reduced by a factor of 2 to 3.

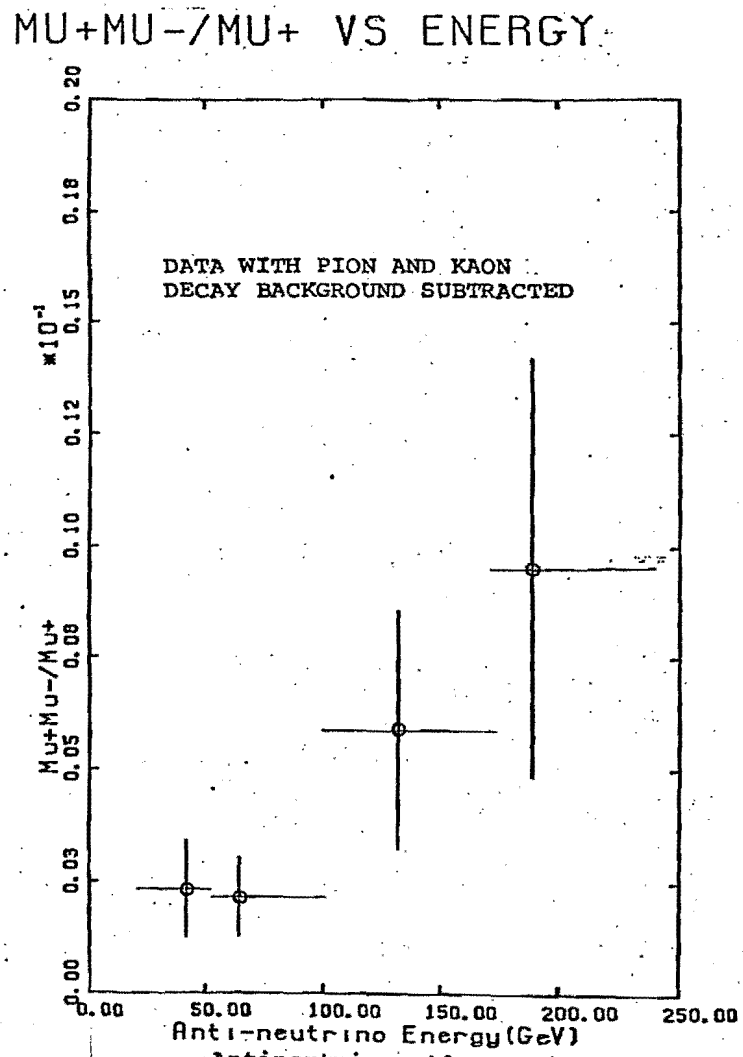
The measurement of Λ using F_2 is also dominated by statistics, although correlations with the gluon parameters are very important. It is not possible at present to measure the gluon distributions using E616 data alone. The statistical precision is simply not adequate to allow minimization techniques to converge sensibly. Combining our data with other information (e.g., $\bar{q}(x)$ at large x from CDHS or theoretically motivated assumptions on parameters) permits a determination. Data from a quad triplet run will permit extraction of a gluon distribution directly from our data. The precision of this determination will be better than those presently made even with assumptions.

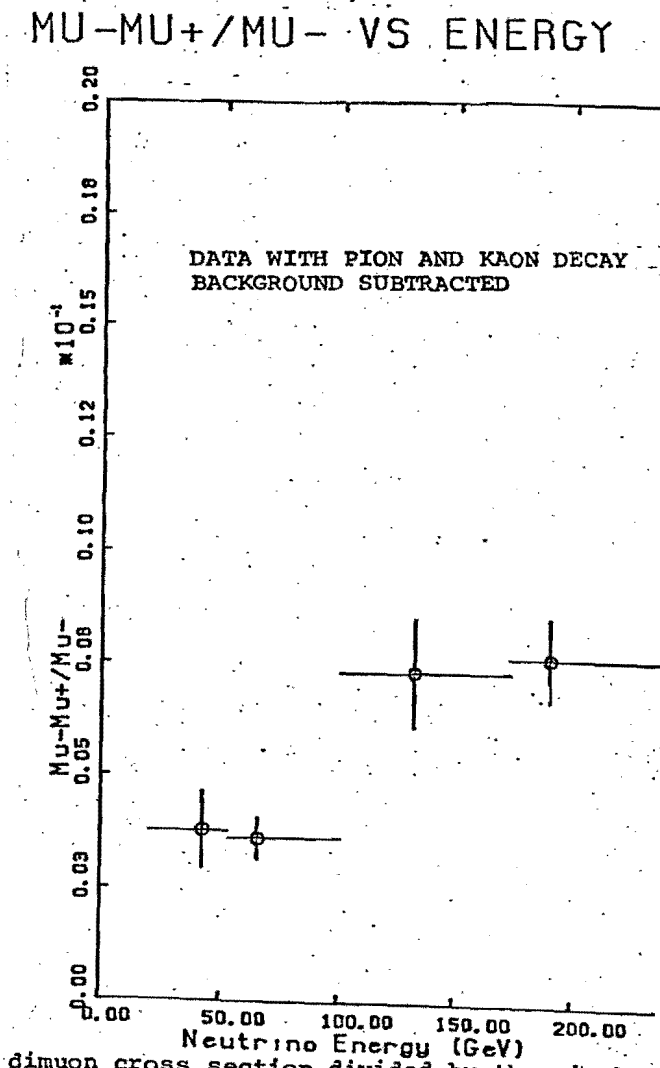
SECTION V: OPPOSITE-SIGN DIMUONS.

The opposite-sign dimuon events from E616 consist of 484 dimuons from incident neutrinos and 42 from incident antineutrinos, with a minimum muon momentum cut of 4 GeV/c. The ratio of opposite-sign dimuon events to single muon events as a function of incident neutrino energy is shown in Figure 11. The CDHS collaboration, in a horn-focused wideband beam, has collected 10,300 neutrino induced events and 3,500 antineutrino induced events. Their data, with a minimum muon momentum of 5.5 GeV/c, are shown in Figure 12. The statistical power of a wideband run is evident in the comparison of Figures 11 and 12.

The data from an exposure of 1.0×10^{18} protons on target in a quad triplet run would include 6000 ν induced and 1000 $\bar{\nu}$ induced dimuons, with a higher minimum muon momentum cut of 10 GeV/c. The number of neutrino events expected as a function of visible energy is compared to the E616 and CDHS spectra in Figure 13. The average visible energy of the quad triplet events is 239 GeV for neutrinos and 189 GeV for antineutrinos. Less than 1% of the present world sample of dimuon events have greater visible energy than this. Because of the high energy and high rate, the quad triplet data will have a considerable impact on dimuon physics.

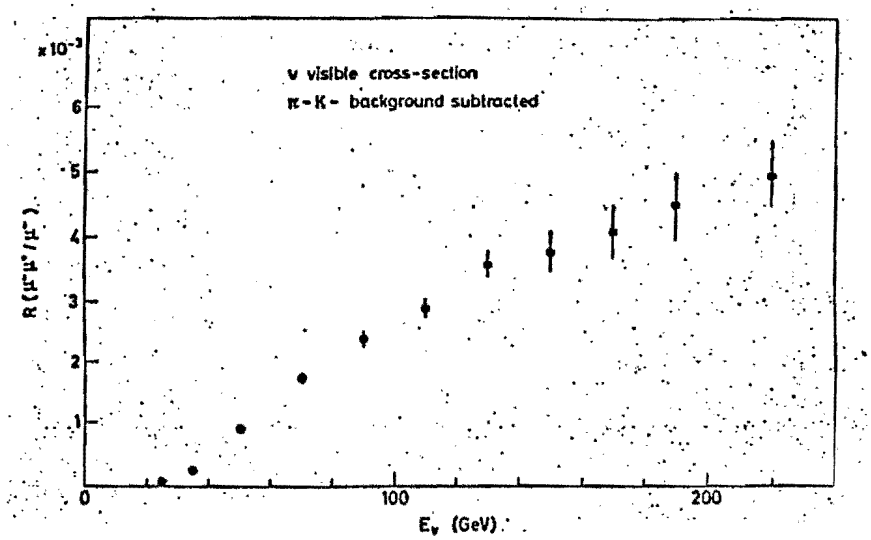
The data of both E616 and CDHS are consistent with the

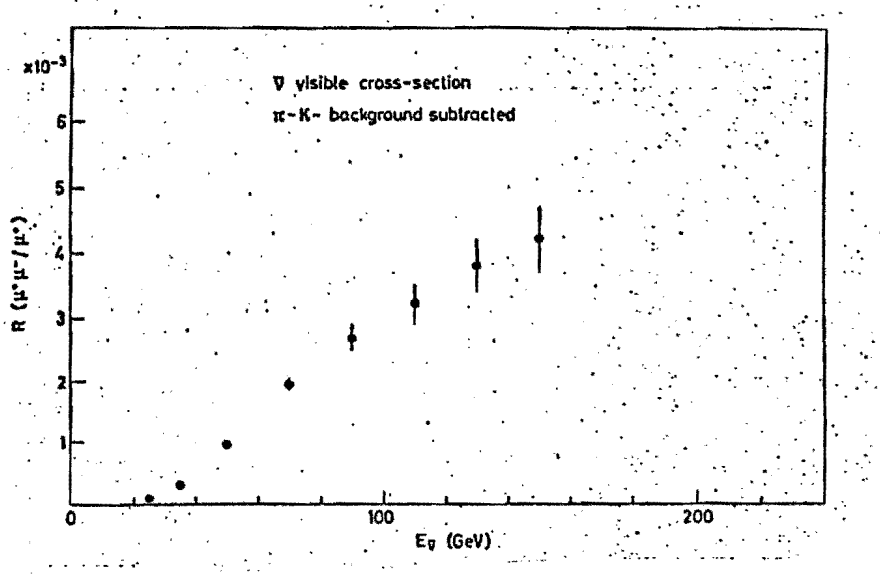




Antineutrino and neutrino opposite-sign dimuon cross section divided by the single cross section for the CFRR narrow band data with minimum muon momentum of 4 Gev/c.

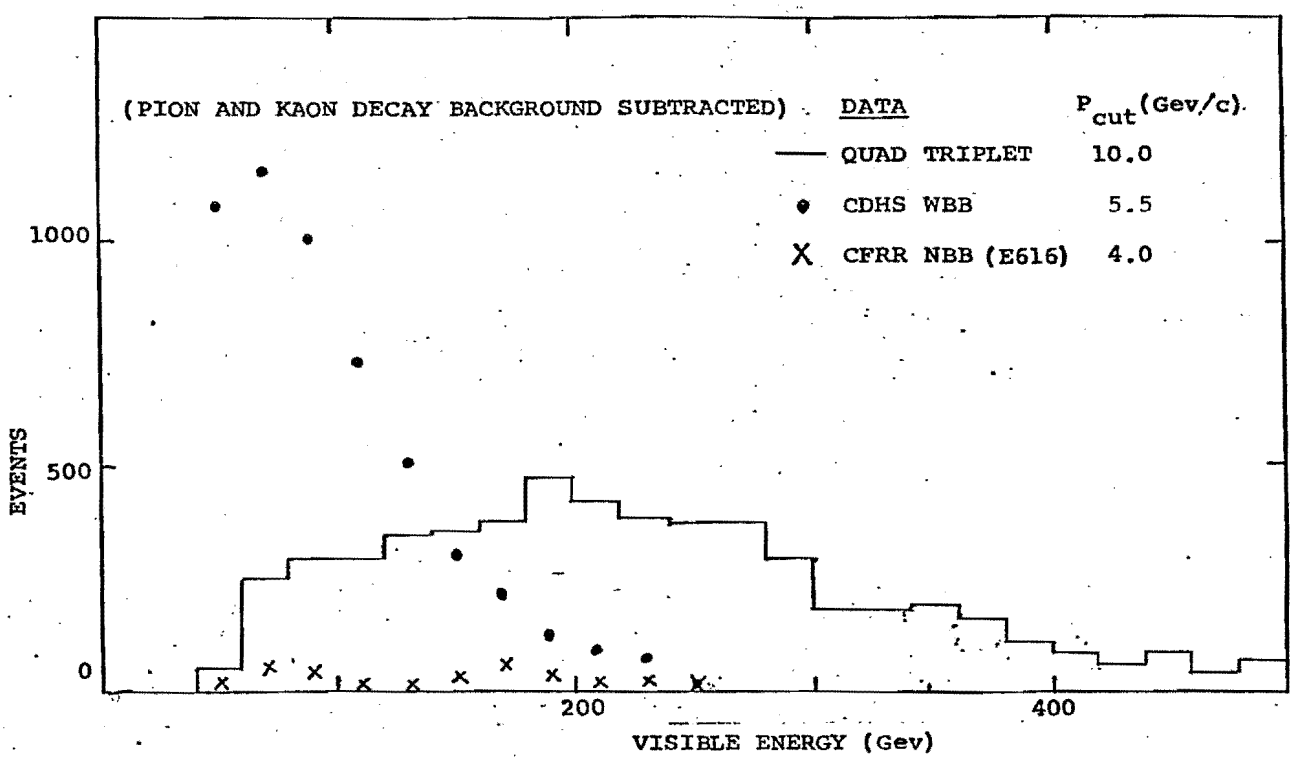
FIG 11





Antineutrino and neutrino opposite-sign dimuon cross section divided by the single muon cross section for the CDHS wide band data with minimum muon momentum of 5.5 Gev/c.

FIG 12



Visible energy spectra for neutrino opposite-sign dimuon data from CFRR, CDHS, and a Monte Carlo simulation of the Quad Triplet run.

FIG 13

mechanism of charm production followed by muonic decay. The principal background is the decay of pions and kaons in hadronic showers. The GIM mechanism gives the following predictions for dimuon production from an isoscalar target:

$$\frac{d\sigma^{\nu}(\mu^+\mu^-)}{dxdy} \propto [(d+u)\sin^2\theta_c + 2s\cos^2\theta_c]$$

$$\frac{d\sigma^{\bar{\nu}}(\mu^+\mu^-)}{dxdy} \propto [2\bar{s}\cos^2\theta_c] ,$$

Because of the strange quark's contribution to these cross sections, the study of dimuon production in neutrino scattering is an excellent way to study the strange sea. The CFRR collaboration has done this and determined that $2s/(\bar{u}+\bar{d}) = 0.50 \pm 0.20$. The CDHS group has also done this with their wideband sample and finds $2s/(\bar{u}+\bar{d}) = 0.50 \pm 0.09$. Since these data are not far enough above charm threshold, there is an additional uncertainty depending on the effective charm quark mass chosen. This can cause as much as a factor of two error in the determination of the strange sea.[14,10]

The bulk of the quad triplet dimuon data is of high enough energy to be beyond charm mass threshold effects. The average Q^2 is 49 GeV^2/c^2 for neutrinos and 29 GeV^2/c^2 for antineutrinos. The data therefore provide a large sample of opposite sign dimuons covering heretofore kinematically inaccessible regions. The data will cover a sufficient Q^2 range to investigate the Q^2 dependence of dimuon production in a region where charm production has saturated.

The quad triplet data will have one other important advantage over the CDHS data. The analysis of any broad band dimuon data will require Monte Carlo correction for the missing energy of the events. Since the CDHS horn spectrum is falling very rapidly with energy (as can be clearly inferred from Figure 13), this can introduce a large uncertainty in the measurement of charm production.[14] The quad triplet spectrum, on the other hand, falls gradually with increasing energy. The difference in the two spectra is obvious in Figure 13. Therefore the corrections to the quad triplet data will have a much smaller effect on the interpretation of the data.

SECTION VI: SAME-SIGN DIMUONS.

A. Present Experimental Situation

Same-sign dimuon events produced in neutrino-nucleon interactions have been observed by a number of experiments.[5] The CFNRR and HPWFOR experiments were the first to show a conclusive signal above background.[5,6] Within statistical errors, the results from the various measurements are consistent (Figure 14) and show a clear signal above π and K decay background that rises with energy to a level of $\simeq 10^{-3}$. The results shown in Figure 14 are for neutrino induced same-sign events.

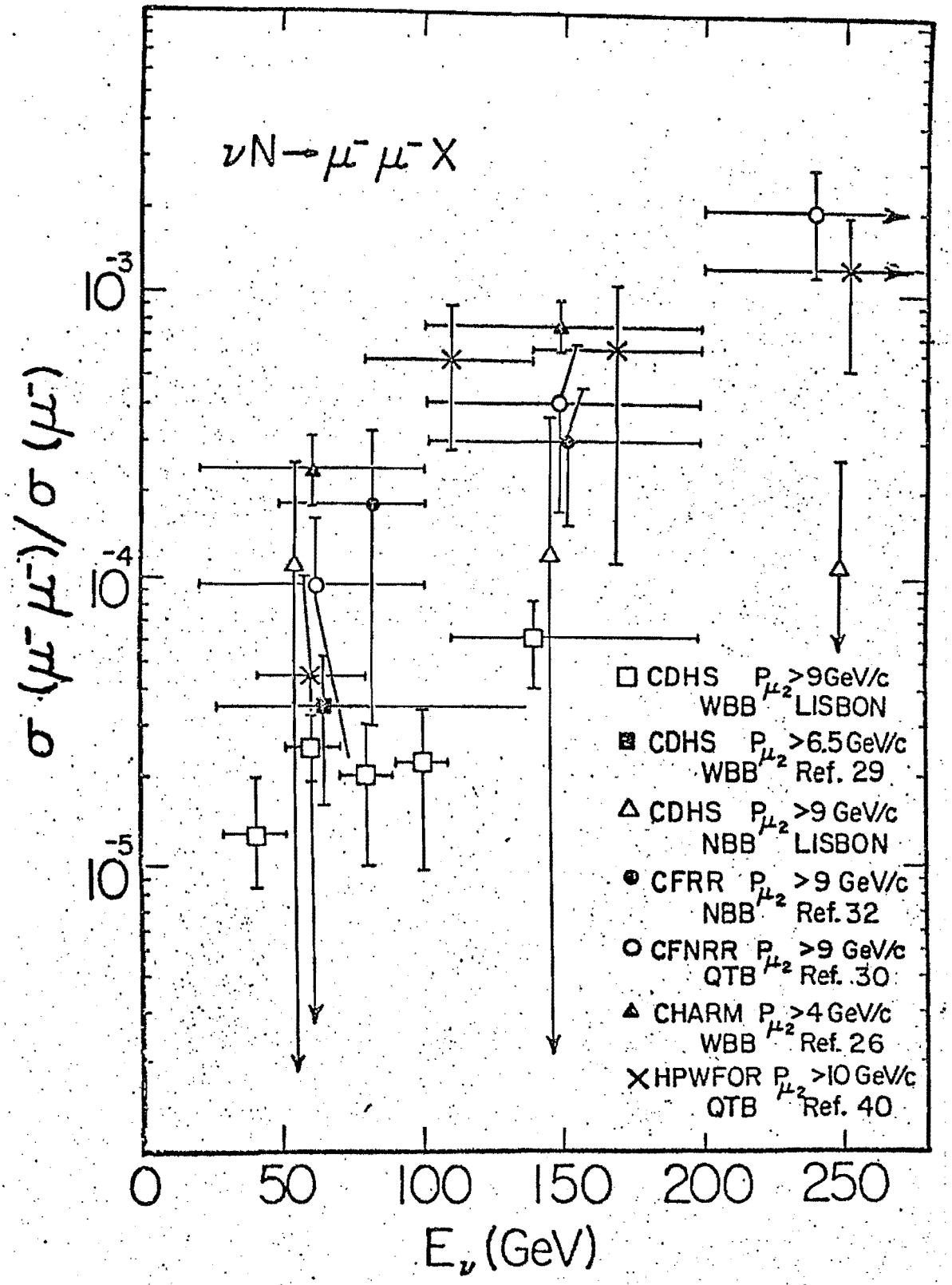
The experimental evidence for production by antineutrinos is very meager. Such events have been reported by the CDHS and CHARM collaborations. The CDHS group attributes most of their observed events to background and gives a prompt rate of:

$$\frac{\sigma(\bar{\nu}_\mu N \to \mu^+\mu^+ X)}{\sigma(\bar{\nu}_\mu N \to \mu^+ X)} = (4.3 \pm 2.3) \times 10^{-5}$$

The CHARM collaboration reports:

$$\frac{\sigma(\bar{\nu}_\mu N \to \mu^+\mu^+ X)}{\sigma(\nu_\mu N \to \mu^-\mu^- X)} = 0.5 \pm 0.2$$

Both experiments use the CERN wideband beam, with $\langle E_\nu \rangle \simeq 50$ GeV.



Neutrino like-sign dimuon rates vs. E_ν.

FIG 14

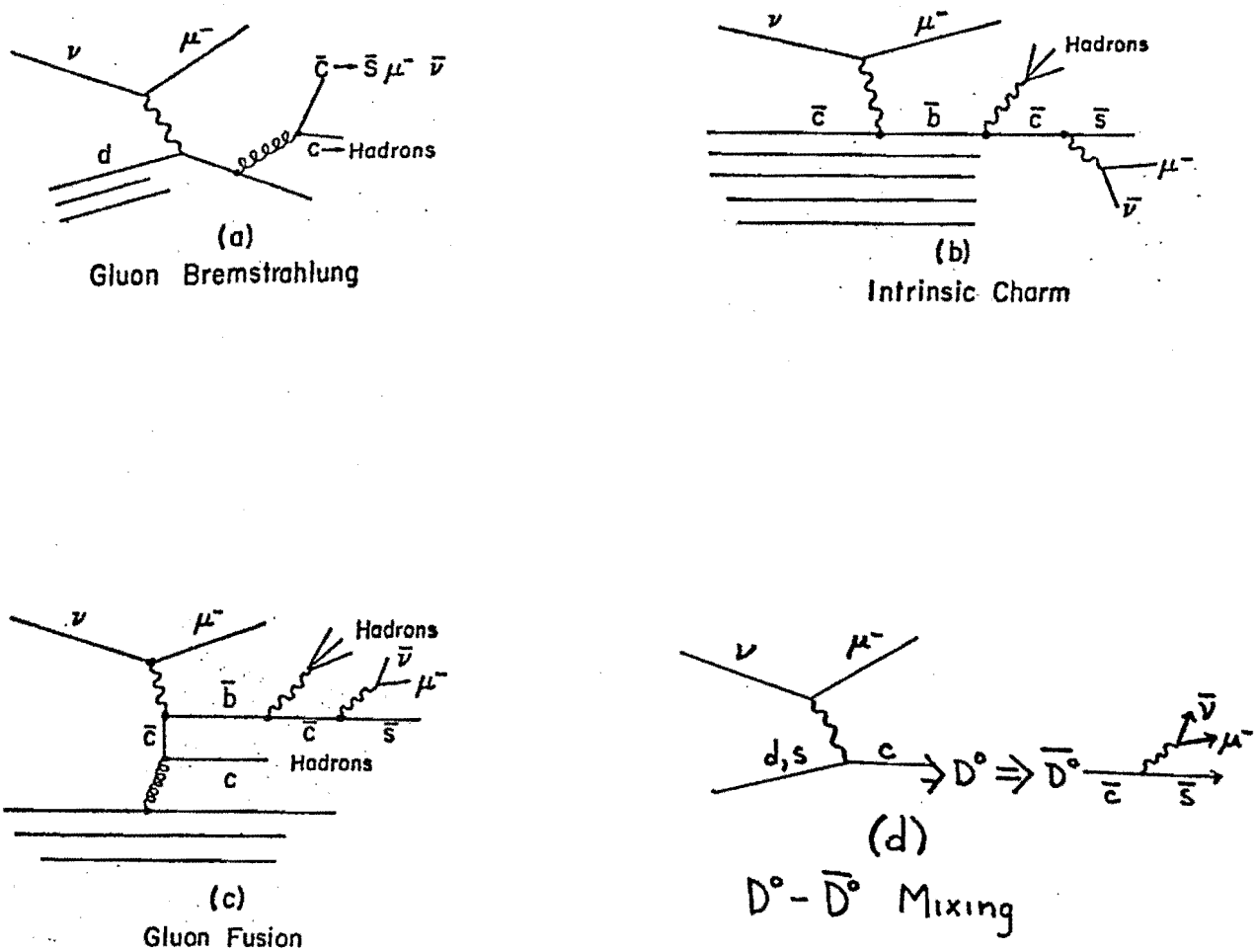
B. Models for Same-Sign Dimuon Production

At present, the origin of same-sign dimuons produced in neutrino interactions is not understood. Various theoretical models[7] have been proposed to explain the observations, but the calculated rates from these models are below the observed production rates by about an order of magnitude. Figure 15 shows diagrams for four such models; the calculated rates are:

	Model	$\sigma_{\mu^-\mu^-}/\sigma_{\mu^-}$
(a)	Gluon Bremsstrahlung	5×10^{-6}
(b)	Intrinsic Charm	$< 4 \times 10^{-7}$
(c)	Gluon Fusion	1×10^{-5}
(d)	D^0-$\bar{D}^0$ Mixing	$< 4 \times 10^{-4}$

A purely phenomenological calculation has also been done by Godbole and Roy[14], who simply assumed enough diffractive $c\bar{c}$ production (1%) to explain the like-sign production rate. This assumption has no strong theoretical basis and the usefulness of the calculation is in showing the kinematical effects of $\bar{c}$ production at the hadron vertex.

Additional experimental information is available from bubble chamber and emulsion studies of neutrino interactions. The Columbia-BNL 15 ft bubble chamber experiment does not observe the expected enhancement in V^0 rate associated with same-sign dilepton events if the source is associated charm production. A similar result has also been recently reported by the Gargamelle group at the CERN SPS. The E531 hybrid



Diagrams of different models which could contribute to same-sign dimuon production. Each appears to be too low in magnitude to account for the observed signal.

FIG 15

emulsion experiment at Fermilab has also put stringent limits on the rate of associated charm production. For a mean neutrino energy of 40 GeV, they find:

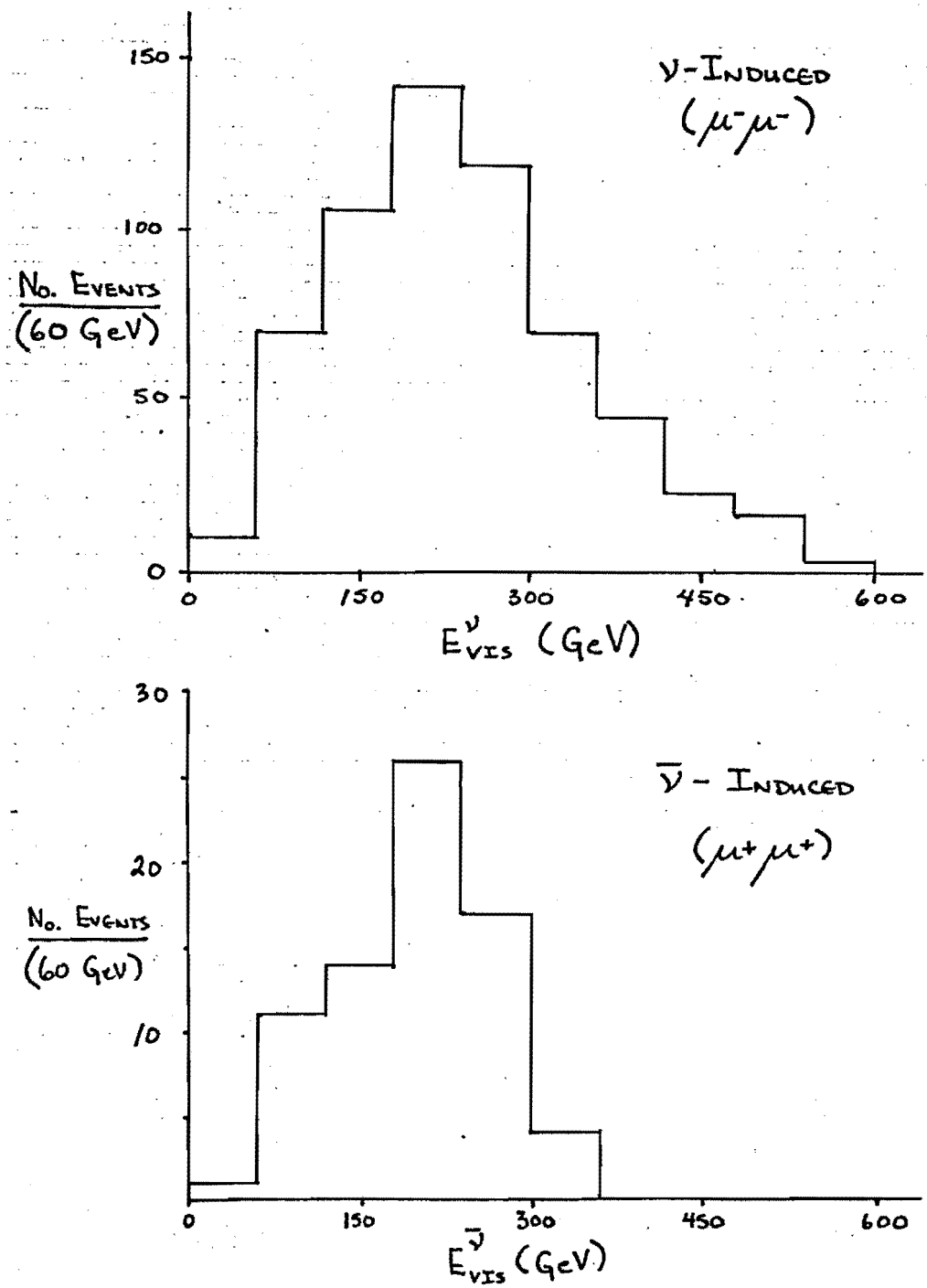
$$\frac{\sigma(\nu_\mu N \rightarrow c\bar{c}X\mu^-)}{\sigma(\nu_\mu N \rightarrow cX\mu^-)} < 5.9\% \ (90\% \ \text{C.L.})$$

This translates into a limit on same-sign dimuons of

$$\frac{\sigma(\nu_\mu N \rightarrow c\bar{c}X\mu^- \hookrightarrow \mu^-\nu_\mu X)}{\sigma(\nu_\mu N \rightarrow \mu^- X)} < 5.3 \times 10^{-4} \ (90\% \ \text{C.L.})$$

C. Same-Sign Dimuons from the Quad Triplet Beam

A three to four month run using the Tevatron quad triplet beam and the upgraded Lab E detector will provide a unique opportunity to study same-sign dimuons at much higher energy and with one to two orders of magnitude more events than previous studies. The data of such a run would include approximately 6000 neutrino induced opposite-sign and 600 same-sign dimuons. Also, the experiment should observe antineutrino-induced same-sign dimuons and collect approximately 80 of them if their production rate is similar to neutrino induced events. Figure 16 shows the expected energy distribution for the same-sign events. The present world sample of prompt same-sign events includes 111 events from neutrinos and 25 from antineutrinos.



Energy Distribution for Same-Sign Events

FIG 16

With this large sample of same-sign events, new types of studies should be possible which could help to unravel the source of same-sign events. For example, measurements of the x and y distribution will give information on the source of the initial struck quark. The transverse momentum of the second muon with respect to the hadron shower direction is related to the mass of the decaying object. In all these studies, better statistics and lower backgrounds than previous measurements are essential.

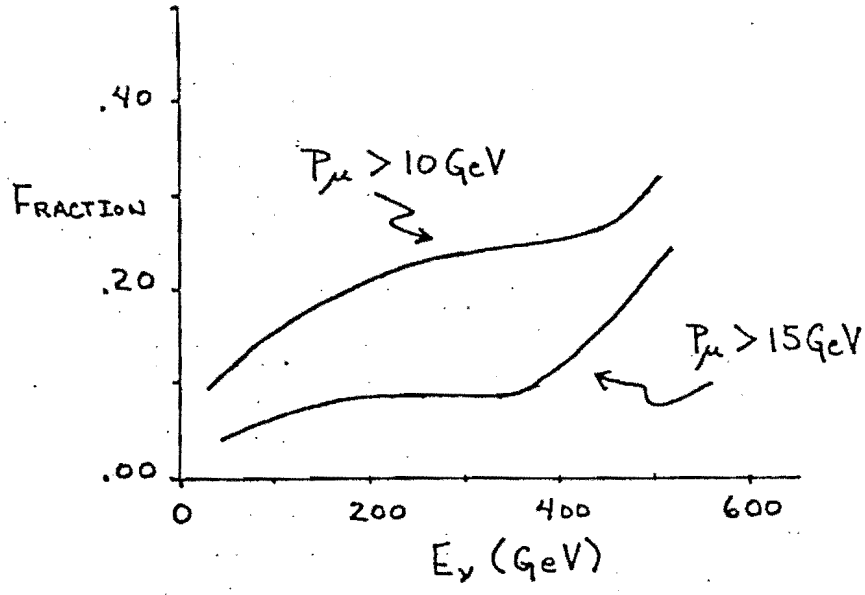
A comparison of the same-sign events with the tri-muon events taken during the same run is also another tool for understanding production mechanisms. As can be seen from Figure 15, most proposed sources have at least two weak decays (the exception being D^0-$\bar{D}^0$ mixing). Thus, if any of these mechanisms are responsible for the same-sign events, then there should be trimuon events with the same kinematics at 8-10% of the same-sign rate. With the improved statistics of a quad triplet run, this would give about 70 ν and 7 $\bar{\nu}$ induced trimuon events for the comparison. (A recent paper by Smith and Valenzuela[15] has used the comparison of same-sign and tri-muon events to strengthen the argument for $c\bar{c}$ pairs as the source. They find that 30% of ν induced trimuons could come from associated charm production.)

D. Expected Rates and Backgrounds

The primary advantage of the Tevatron quad triplet beam is the high intensity at high energy. The higher energies allow one to probe multi-muon production in a new unexplored region. On the negative side, though, these high energy events have increased background contamination.

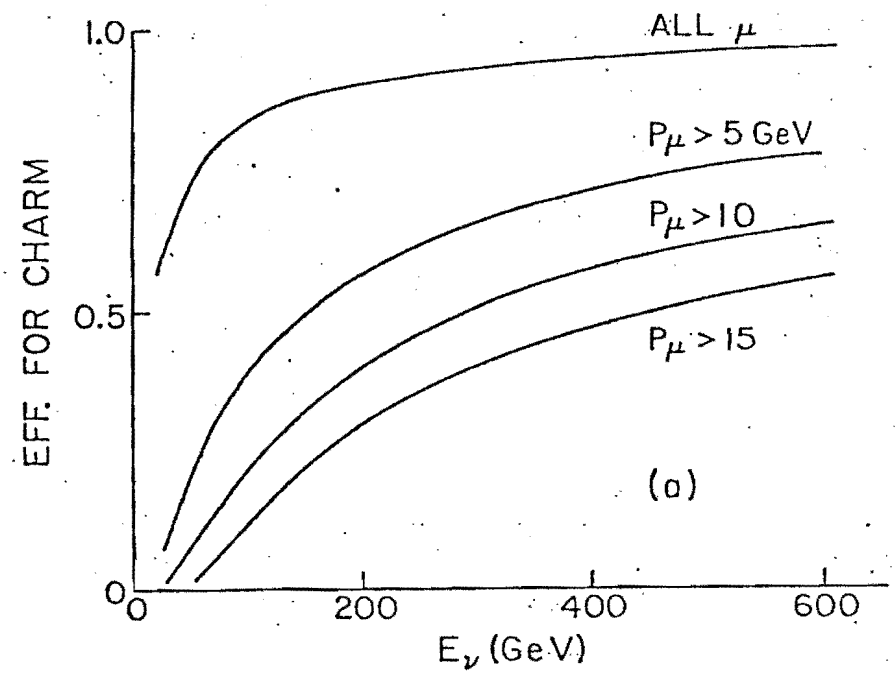
The main background to a measurement of prompt same-sign dimuons is the non-prompt π and K decay in the hadronic shower. Our group has done extensive studies of this background and has developed a method to reliably calculate the level and kinematic distribution. In this method, neutrino and anti-neutrino particle production rates from BEBC are combined with measured muon production rates by hadrons from Fermilab experiment E595. Figure 17(a) shows the percentage of background to signal for different minimum momentum cuts on the second muon. To reduce the overall background to 10% requires a second muon momentum cut of 15 GeV. To a lesser extent, this cut also reduces the prompt signal. Figure 17(b) shows the efficiency for detecting an opposite-sign dimuon for various muon momentum cuts; the models of same-sign events shown in Figure 15 give similar efficiencies.

A four month run of the 300 GeV quad-triplet beam with 10^{18} protons on target yields the following numbers of opposite-sign and same-sign events:



The estimated fraction of same-sign dimuon events which are due to pion and kaon decay, plotted versus the incident neutrino energy. The curves represent different cuts on the second muon.

FIG 17(a)



Efficiency for observing charm induced opposite sign dimuon events versus the incident neutrino energy. The various curves correspond to different momentum requirements for the second muon.

FIG 17(b)

Neutrino Induced	2.18×10^6	$\nu_\mu N \rightarrow \mu^- X$
	$P_\mu > 10$ GeV	$P_\mu > 15$ GeV
Opposite-sign ($\mu^-\mu^+$)	5760	4080
($\mu^-\mu^+$) π/K Background	443 (7.6%)	155 (3.8%)
Same-sign ($\mu^-\mu^-$)	849	606
($\mu^-\mu^-$) π/K Background	213 (25%)	56 (9.1%)

Anti-Neutrino Induced	4.13×10^5	$\bar{\nu}_\mu N \rightarrow \mu^+ X$
	$P_\mu > 10$ GeV	$P_\mu > 15$ GeV
Opposite-sign ($\mu^+\mu^-$)	888	550
($\mu^+\mu^-$) π/K Background	38 (4.3%)	11 (2.1%)
Same-sign ($\mu^+\mu^+$)	128	80
($\mu^+\mu^+$) π/K Background	28 (22%)	4 (5%)

Note that backgrounds for same-sign events are about 25% with a 10 GeV cut, and are reduced to 9% and 5%, for ν and $\bar{\nu}$ respectively, with a 15 GeV cut.

SECTION VII : CONCLUSIONS AND REQUESTS.

The Tevatron quad triplet run will increase current Lab E event statistics by more than an order of magnitude, and will substantially enhance the measurements of structure functions, opposite-sign dimuons, and same-sign dimuons. We request the laboratory to approve us for this four-month run beginning in the fall of 1984.

The quad triplet run will fit smoothly into the current CCFR run plans. We have in fact been planning to have an operating detector during this run period for some time. Now our ideas about how to use the data have become more crystalized, and our plans more specific. These plans do not, we believe, require much additional effort on the part of the laboratory.

The two essential ingredients for the run are 1) the quad triplet beam, and 2) the Lab E detector. The beam should be the quad triplet beam described in section III. The sign-selected triplet beam, which has been suggested in the past, has the strong disadvantage of a lower flux. Since the quad triplet allows one to collect ν and $\bar{\nu}$ data simultaneously, the total flux is more than a factor of two greater with the quad triplet than with the sign-selected triplet (assuming a 50-50 split between ν and $\bar{\nu}$ using the sign-selected triplet). Since the power of a quad triplet run

lies in its high statistics, reducing the flux weakens the chief motivation for the run.

A 1-millisecond spill with a 60-second cycle time, at 10^{13} protons per cycle, seems adequate for this run. However, higher rates can only help us. Moreover, we believe there is a fair amount of uncertainty at this point in exactly what the rates will be. It is difficult to anticipate how much accelerator down-time we will be faced with, and how much the intensity may be limited. It would be to our advantage to have a shorter cycle time (45 seconds) and a longer spill (2 msec), with the same or greater total integrated flux. For example, a 2 msec spill would reduce out deadtime from 36% to 22%, giving a 22% increase in event rate.

Much more work is required to have the detector ready, but this work is progressing well. Under the present schedule, based on the E652 run, we have anticipated having a fully operational detector before the quad triplet run begins. We only need to be sure that the schedule is kept.

Construction work in and around Lab E has been going well, and is scheduled to be completed by February 1984. This is important, since we require a test run in February-May to recalibrate the scintillation counters, to test the new drift chambers in beam conditions, and to check out and debug the new data acquisition system. Fermilab is providing the Lecroy buffered ADCs which will be used in this test run and also in the quad triplet run.

Drift chamber production is a high priority. The

production line in Wilson Hall is fully operational, although turn-on time has been longer than anticipated. Each of the new chambers is being tested in the production line, and they are working as expected. We plan to have at least 20 operational chambers in Lab E by the beginning of the test run.

One of the new TDC modules and its associated data collection electronics has been constructed at Nevis and tested in Lab E (and worked as specified). Delivery of the new modules should begin within the month.

In short, progress has been good and we expect to be ready for the Tevatron quad triplet run on schedule.

The final element that is essential for a good run is the experimenters. The major part of the E616 analysis has been completed (all three thesis students have submitted their theses!). Cross-sections have been published, and papers will be published in the very near future on neutral currents and structure functions (see the appendix). The major part of the E701 oscillation analysis has also been completed, and a paper has been prepared for publication. In other words, the group is free to direct its efforts toward the new experiment.

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