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#45A

NEUTRINO INTERACTIONS ON PROTONS AT FERMILAB ENERGIES

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[Reported by B.P. Roe] Presented at the 1975 Meeting of the European Physical Society.

1. INTRODUCTION

I am reporting some results of the Fermilab-Michigan collaboration concerning the interactions of neutrinos in hydrogen using the Fermilab fifteen foot bubble chamber. These results came from an exposure of the chamber to a broad band one horn neutrino beam using an incident 300 GeV proton beam. We have analyzed 40,000 pictures. The experiment is expected to eventually obtain at least 300,000 pictures, mostly in an improved two horn beam. No external muon identifier (EMI) information is available for this report. The EMI was run during the present exposure and we hope to be merging that information into the present data in the near future. We are only reporting on charged current events at present.

Because of the time allotted to me for this talk I will be forced to select out only a few topics in our results. I will skip or cover only briefly topics already discussed in the review reports of D. Cline and C. Rubbia. It is also necessary to reduce the description of the method of data analysis to a bare minimum.

The data cuts that were made are:

i) Sum of momentum in the neutrino beam direction (ΣP_x) must be greater than 10 GeV/c. ΣP_x is roughly equivalent to visible energy.
ii) The potential track length must be greater than 35 cm.
iii) Fiducial volume cut. The fiducial volume selected was about 20 m^3.
iv) Events had to be measurable in all three views.
v) Scan cuts. We made minor cuts in scanning which should introduce little bias for the purposes of the present discussion.

The fate of the candidates selected according to the above criteria is shown in Table I. Wallons are events originating in the bubble chamber walls. The ΣP_x distribution of the resulting 361 candidates is shown in fig. 1.

Table I
Neutrino Event Disposition

Total frames scanned		40,700
Candidates found		1,502
Candidates rejected in physicist checking		
Cosmic ray events	62	
Wallons	166	
Wallon associated	295	
Low momentum rejects	175	
General rejects	31	
Candidates remaining		773
Candidates rejected in further analysis		
Repeated track failures	27	
Outside fiducial volume	77	
ΣP_x < 10 GeV/c	308	
Final sample of neutrino events		361

2. DATA ANALYSIS

We have three central problems for further analysis. We must decide which particle is the muon, estimate the energy of the incoming neutrino and reject background. The methods we use are based on ideas of G. Myatt, H. Burmeister and D. Cundy. It turns out that the method of estimating neutrino energy also automatically solves the third problem, that of rejecting background. First, what do we do?

i) We pick the negative particle with the highest momentum transverse to the direction of the incoming neutrino to select the muon.
ii) The method of estimating the neutrino energy requires three steps. Firstly, we take the projection of the visible hadronic momentum onto the μ-ν plane. (See fig. 2a). Secondly, we assume the invisible momentum due to unseen neutrals is in the direction of the projected visible hadronic momentum. We can then balance transverse momentum to find the missing momentum and hence the incoming neutrino momentum. Finally, we make sure the results are consistent, that is, that the muon and hadron are not on the same side of the neutrino line. (See fig. 2b). This further reduces the event sample to 287 events.

This defines what we do. We must still ask. How good is this?

We, of course, made extensive monte carlo tests to find a good method of muon selection and test that it introduced little bias. Moreover, we were also able to look at the resultant experimental data and perform several tests which indicated that 85% of our final charged current sample

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were good charged current neutrino events with the muon correctly chosen.

One of these tests was to examine the events and find out how often the highest transverse momentum particle in the reaction is positively charged. This number should be small if the muon is usually the particle with the largest transverse momentum. The results are shown in fig. 3. The monte carlo calculations include an estimate of the effect on the distribution of neutral currents.

Possible sources of background are neutrons and K°, anti-neutrino events, neutral current events and charged current events with the muon incorrectly chosen.

Our studies of the experimental data indicate that no one background component dominates. They are all present in comparable numbers adding up to the 15% total background observed.

The energy reconstruction has played an important role in reducing the background to this level. Our monte carlo results indicate that for charged currents only about 5% of the events fail to reconstruct, but for neutral currents about 2/3 fail to reconstruct. Neutron events are also preferentially failed.

The crucial data feature which allows both the muon selection and the energy reconstruction to work well is that the momentum distribution of the hadrons perpendicular to the overall hadronic axis is narrow. That is the hadrons emerge from the interaction with a jet like structure. This is shown in fig. 4. The data out to .5 GeV/c are fit with an $e^{-bp_\perp^2}$ distribution, where b=9.3 . However, some of the momentum shape just comes from phase space considerations. Monte carlo calculations which weight the phase space distribution by $e^{-bp_\perp^2}$ with b ≃ 5 or 6 give distributions similar to those observed. Calculations from our data indicate

$$< \Delta E\nu/E\nu > \simeq 10\%$$

We can ask how much energy is missing in the reaction on the average. From examining the average fraction of hadronic momentum missing perpendicular to the neutrino axis we conclude that the average fraction of hadronic energy missing is 26%. Since the muon takes about one-half of the neutrino energy on the average the typical event is missing 13% of its energy and we are estimating this fraction by the above method.

3. MULTIPLICITY AND INCLUSIVE DATA

We first examine the multiplicity distributions. We have found that the most important variable effecting the multiplicity is the hadronic effective mass, W. We plot the average multiplicity versus W^2 on a logarithmic scale in fig. 5. It is seen that the data fit a straight line reasonably well. Fig. 6 compares the average multiplicities for electroproduction and photoproduction with our data. Since most of the electroproduction data are for $Q^2 < 2\ (\mathrm{GeV/c})^2$ we have plotted our data for that Q^2 interval (vertical error bars) as well as for all Q^2 (slanted error bars).

The lines drawn through our points are only to guide the eye. Our data are not inconsistent with being on a line parallel to the electroproduction data. Our data are higher but it must be remembered that we produce a doubly charged hadronic system ($\nu p \to \mu^- X^{++}$), whereas the electroproduced hadron system is singly charged.

Fig. 7 compares our results with that obtained from high energy pp singly diffractive interactions. Again our results agree well in shape but are a little higher.

In fig. 8 we plot the rapidity distribution for positive and negative hadrons separately. For positive hadrons about 20% are protons misidentified as pions. This will distort the distribution somewhat. The main point for the present is that there is no evidence for strong leading particle effects. Our x, y, and v distributions are given in the review talk of D. Cline and will not be repeated here.

Our conclusions are:

i) $\langle n_c \rangle = (1.0 \pm .3) + (1.1 \pm 0.1)\ \ln W^2$

ii) $\langle n_c \rangle$ vs W^2 is similar to corresponding γp, e-p, and p-p distributions except $\langle n_c \rangle$ is one-half to one unit higher for the neutrino events. However: $\nu p \to \mu^- X^{++}$ which is doubly charged.

iii) No strong leading particle effects are observed.

4. BARYONIC MASS DISTRIBUTION

We have examined the distribution of the baryonic mass recoiling against the muon. This distribution is shown in fig. 9a. An apparent anamoly is present and shows up more strongly if we make a cut on Q^2. (Fig. 9b, c). Fig. 10 shows the data for prong numbers. For this plot only, a ΣP_x cut of 7 GeV/c was made. The effect seems visible in 3 and 5 prong events, especially at low Q^2, but is not significant in our data at higher prong numbers.

The data are not statistically significant enough to claim a definite effect of this point and these results are shown in the spirit of a progress report. We hope to have about 50% more data in about one month and should be able to confirm or kill the effect at that time.

C. Rubbia in his review talk here has indicated strong negative evidence for this effect since the W distribution in the HPWF experiment does not seem to show such a peak. We note that some caution must be used in making this comparison. The HPWF results are for neutrinos on heavy nuclei. If we assume only that the number of neutrons is approximately equal to the number of protons in his detector, that the neutron cross-section is twice the proton cross-section (naive parton model), and that we have a narrow I-spin $\frac{3}{2}$ resonance, then we would conclude that the ratio of peak to background would be decreased by a factor of $2\frac{1}{4}$ in nuclei compared to hydrogen.

If the resonance is several hundred MeV wide the decay will occur in the nucleus and tend to wash out the peak.

Our conclusion is:

We have some evidence of a peak in X^{++} for $\nu p \to \mu^- X^{++}$ around W=3.4 GeV/c^2. The peak seems to occur for $Q^2 < 5$ and for 3 and 5 prong events. This evidence is not yet strong enough to consider the effect established.

5. STRANGE PARTICLE PRODUCTION

We have examined the behavior of events containing a V°. Fig. 11 shows the fraction of events containing a V° as a function of Σp_x. No strong dependence on Σp_x is seen. Fig. 12 shows the fraction of events containing a V° as a function of charged prong multiplicity. Again no strong effect is observed. Our x and y distributions for strange particle events were shown by D. Cline in his review talk and will not be repeated here. They looked similar to the non strange distributions. No evidence for strong peripheral production was seen. Table II lists the numbers of Λ's, K's, Λ+K, etc. events found and indicates that after corrections for unseen V° 15% ± 4% of our events have a V° associated with them. This does not include strange particle channels without a V° (e.g. $\Sigma^- K^+$) and the fraction of events with any strange particle production is even higher. This ratio seems high compared to earlier theoretical estimates.

Table II

V° Strange Particle Production Yields

	K°	Λ	$\bar{\Lambda}$	Ξ^-	$\Lambda+K^\circ$	Total V°
No. Observed	11 +	11 +	1	0	3	26
No. Corrected#	27.8±11.6*	7.8±9.1	~1.6	-	17.4±10*	54.6±14*
Inclusive No. Corrected#	45.2±12.4*	25.2±7	~1.6	-	-	-

Decay length, neutral branching ratio, scan, 1V°-2V° mixing.
+ Excluding Λ+K° double V° events.
* Assuming $K^\circ_S = K^\circ_L$ and no $K^\circ_S K^\circ_S$ correction.

Relative V° production (Excludes K^+, K^+K^-, $K^+\Sigma^\pm$, etc.)

$$\frac{N_{V^\circ}}{N_\nu} = \frac{54.6 \pm 14}{361 \pm 19} = 0.15 \pm 0.04$$

Next we will discuss limits for $\Delta S = -\Delta Q$ events. We have found no candidates. C. Rubbia in his review talk described our fitting of events without missing neutrals and I will not repeat that here. They were consistent with associated production and inconsistent with single V° production. Our event flux at 13.5 GeV is 15 events/GeV. The BNL flux is .33 events/GeV. We have no $\Delta S = -\Delta Q$ candidates, while BNL has one candidate. I will recapitulate our arguments given in the talk of C. Rubbia to set limits on $\Delta S = -\Delta Q$ events from our numbers of single and double V° events and will add a few more calculations.

We have 11 single Λ, 11 single K°_S, and 3 double $\Lambda+K^\circ_S$ events. We assume the number of K°_S events = the number of K°_L events and that $\Lambda K^+ X^+$ production is one-half the production of $\Lambda K^\circ X^{++}$. (The one-half should be a reasonably conservative guess here.) The expected total number of visible Λ then equals 4.5 times the number of double V° events if we have only associated production. Thus we expect 4.5x3 = 13.5 visible Λ if we have only associated production. We observe 11+3=14. Hence we have no large $\Delta S = -\Delta Q$ signal.

Suppose, however, that our 3 double V° events are a statistical fluctuation and the expected value is smaller. If we have 3 then with a 95% confidence level (C.L.) the expectation value is greater than .8. We replace 3 by .8 and redo the above calculation. We then have 11+.8-.8*1.5 = 8.2 possible single V production events which is about 1/45 of our sample. Hence, at the 95% confidence level less than 1/45 of our events with $\Sigma P_x >$ 10 GeV/c are single Λ production. The BNL rate is 1/5. Finally, suppose we make the speculative assumption that the BNL event can be produced by neutrinos from K decay only. For $\Sigma P_x > 40$ GeV/c our events are heavily weighted by interactions of K decay neutrinos. In this region we have 4 single Λ and 1 Λ+K° out of 87 events total. If we ignore the double V° event completely to get the biggest rate we have $\frac{1}{22}$ for a rate to compare with the 1/5 for BNL.

Our conclusions for this section are:

i) Production of strange particles for $\Sigma P_x > 10$ GeV/c is not a strong function of ΣP_x or of the number of charged prongs at the primary vertex.

ii) About 15% of our events have a V° after correction for those missed. The total strange particle production will be still larger since contributions from non-V° channels (e.g. $\Sigma^- K^+$) must be added.

iii) We have no candidates for $\Delta S = -\Delta Q$ violation but have 50 times the flux that BNL has in the region of energy above 10 GeV/c.

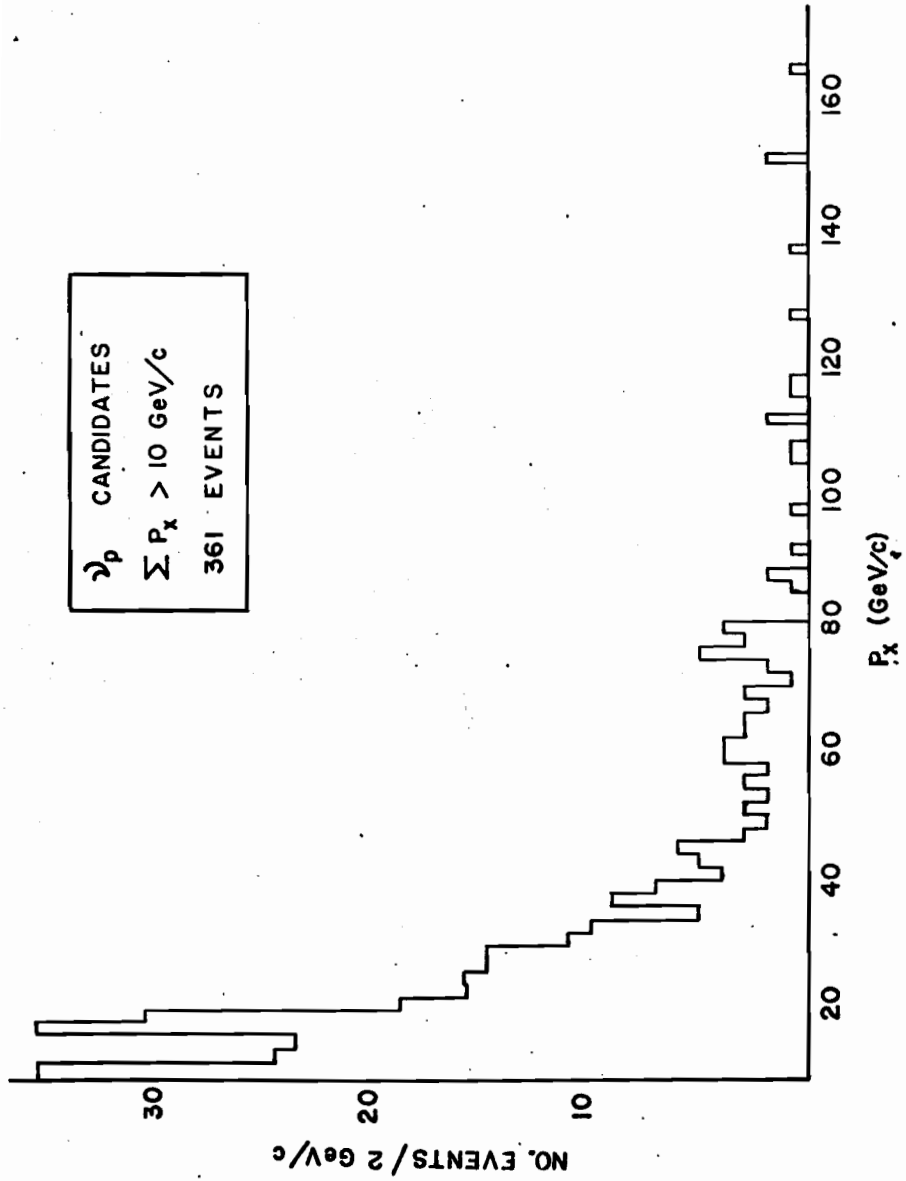
ν_p CANDIDATES
$\sum P_x > 10$ GeV/c
361 EVENTS
NO. EVENTS / 2 GeV/c
30
20
10
20
40
60
80
100
120
140
160
P_x (GeV/c)

Fig. 1

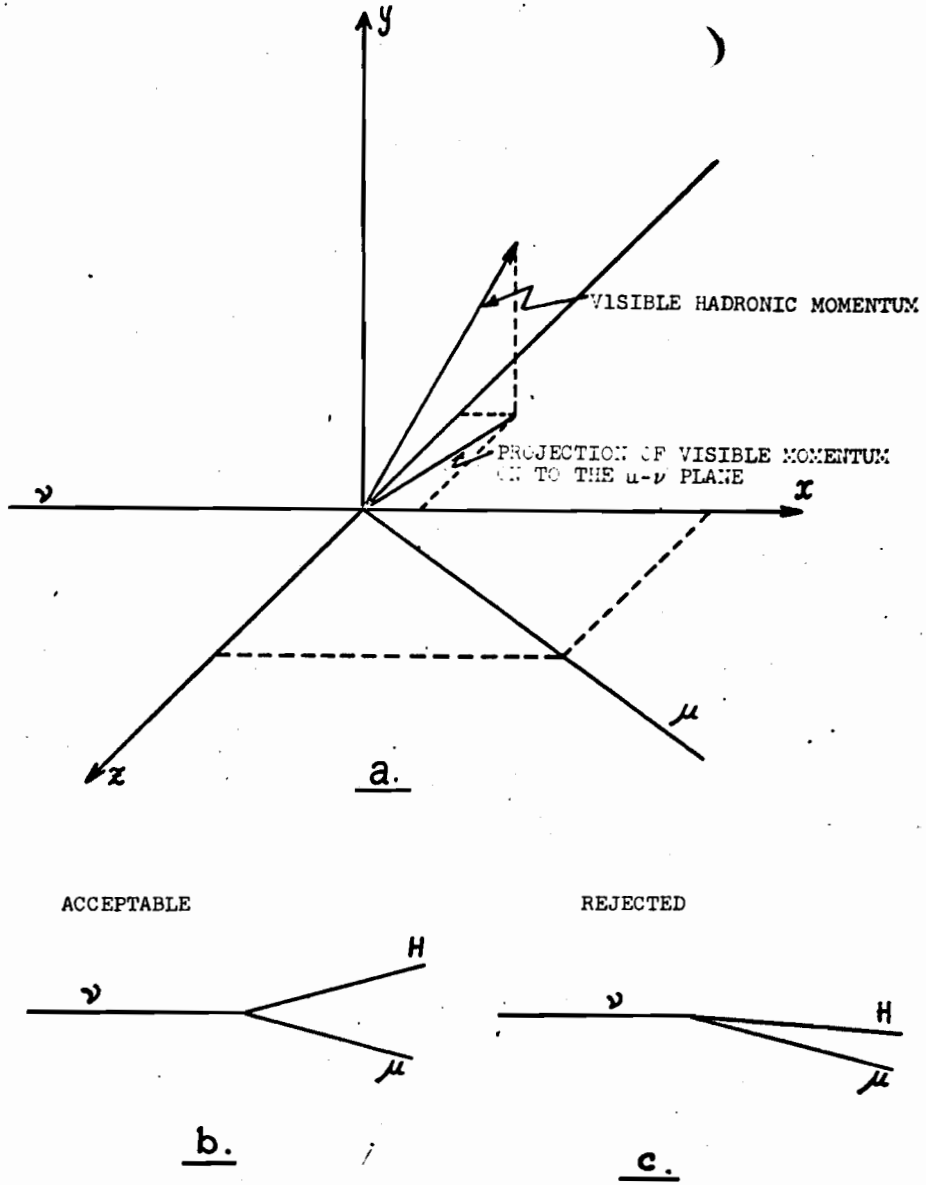
y
x
z
ν
μ
VISIBLE HADRONIC MOMENTUM
PROJECTION OF VISIBLE MOMENTUM ON TO THE μ-ν PLANE
a.
ACCEPTABLE
REJECTED
ν
H
μ
b.
c.

Fig. 2

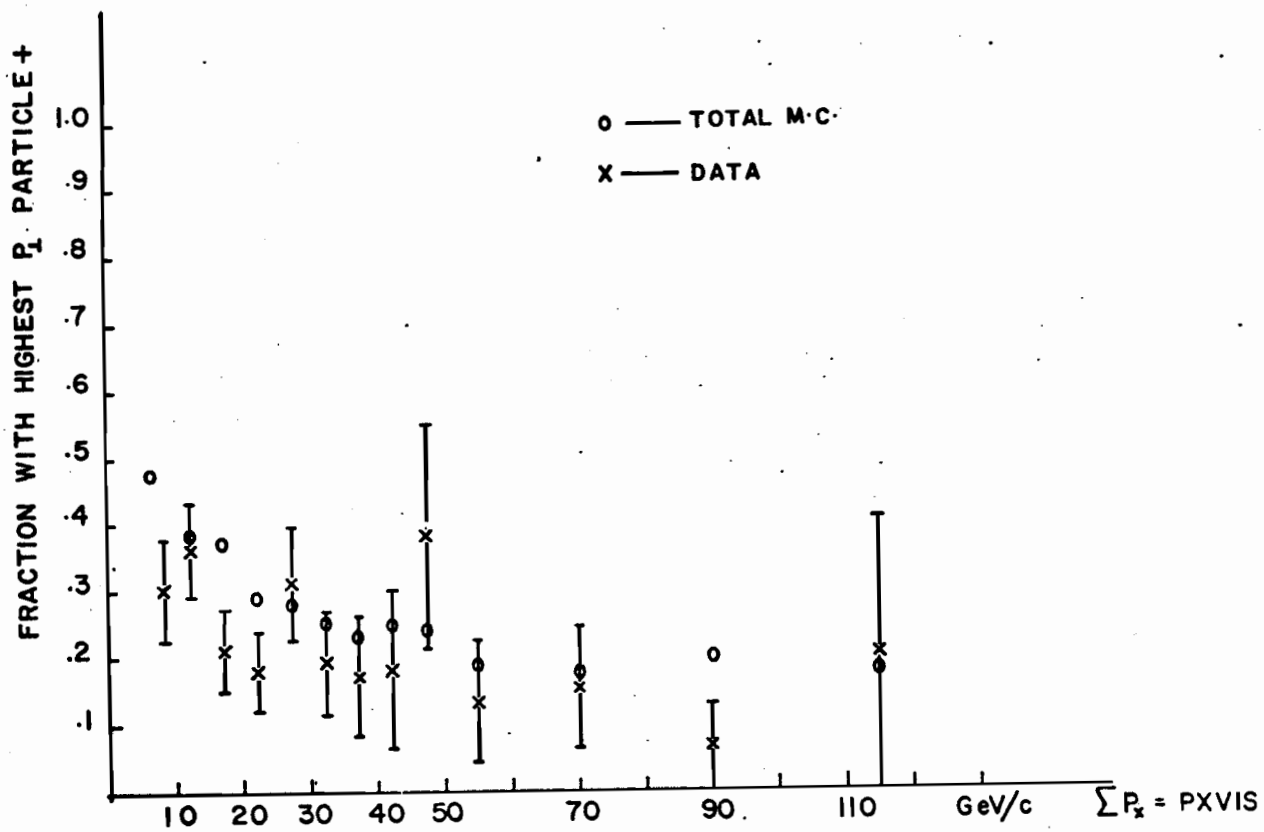
FRACTION WITH HIGHEST $P_\perp$ PARTICLE +
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
o —— TOTAL M·C·
x —— DATA
10
20
30
40
50
70
90
110
GeV/c
$\sum P_x$ = PXVIS

Fig. 3

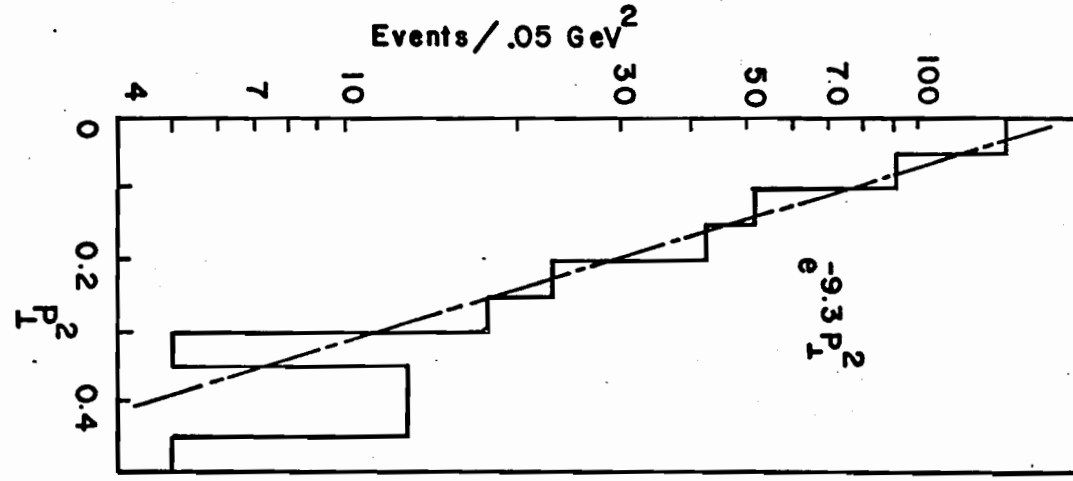
Events / .05 GeV^2
4
7
10
30
50
70
100
0
0.2
0.4
$P_\perp^2$
$e^{-9.3 P_\perp^2}$

Fig. 4

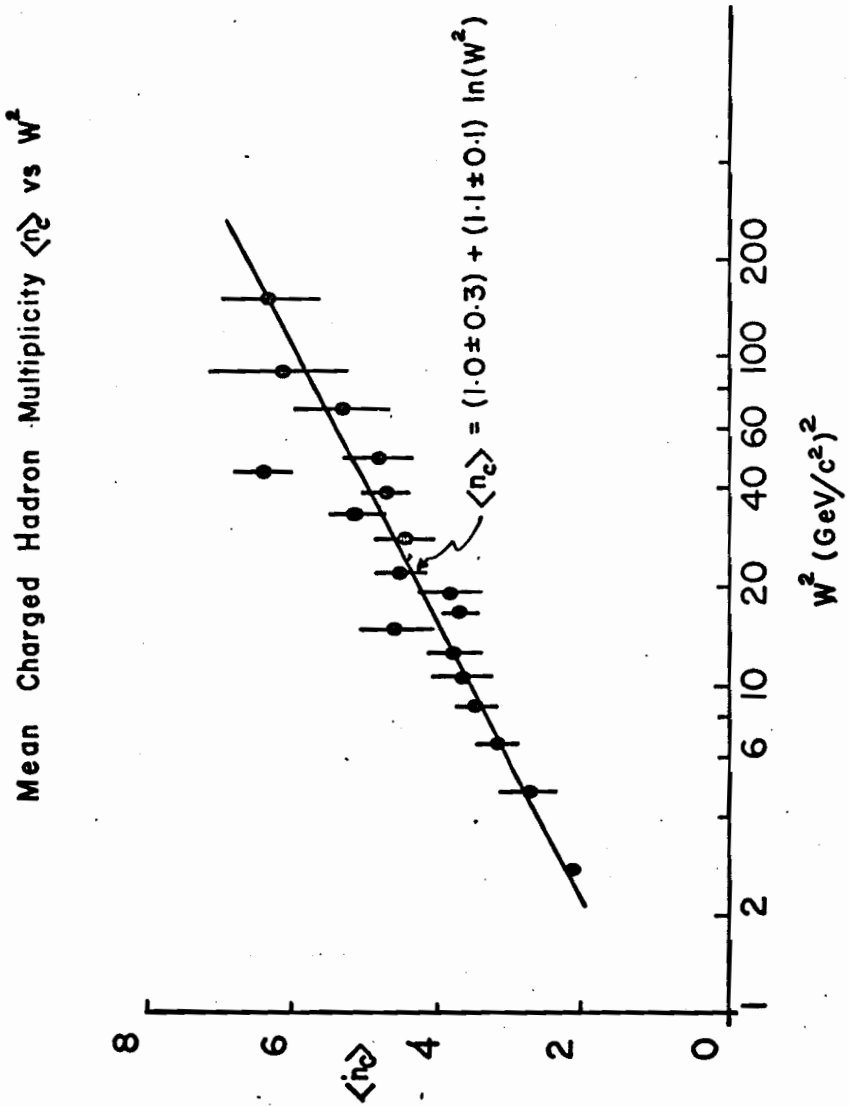
Mean Charged Hadron Multiplicity ⟨n_c⟩ vs W²
⟨n_c⟩ = (1·0±0·3) + (1·1±0·1) ln(W²)
⟨n_c⟩
W² (GeV/c²)²
0
2
4
6
8
1
2
6
10
20
40
60
100
200

Fig. 5

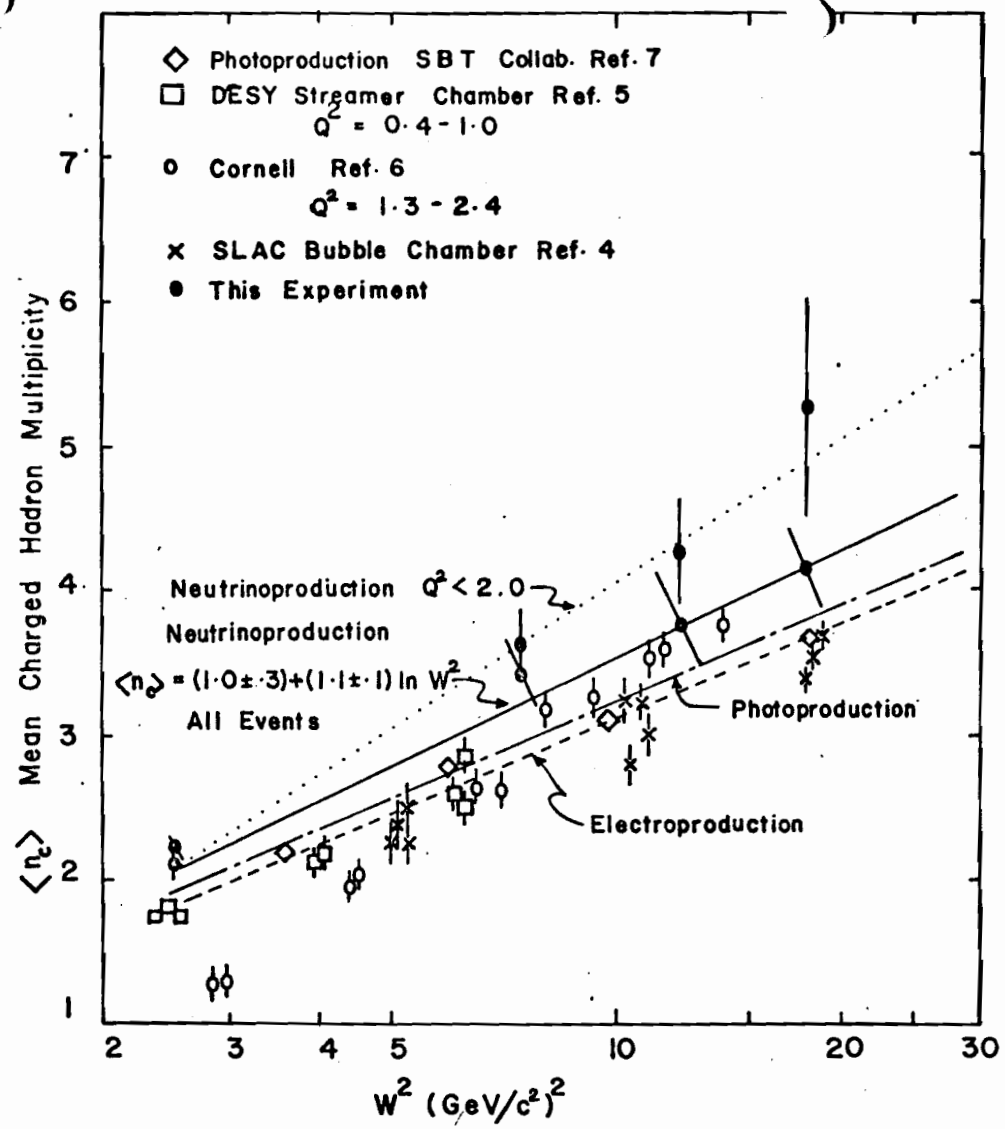
Photoproduction SBT Collab. Ref. 7
DESY Streamer Chamber Ref. 5
Q² = 0·4 - 1·0
Cornell Ref. 6
Q² = 1·3 - 2·4
SLAC Bubble Chamber Ref. 4
This Experiment
Neutrinoproduction Q² < 2.0
Neutrinoproduction
⟨n_c⟩ = (1·0±·3)+(1·1±·1) ln W²
All Events
Photoproduction
Electroproduction
⟨n_c⟩ Mean Charged Hadron Multiplicity
W² (GeV/c²)²
1
2
3
4
5
6
7
2
3
4
5
10
20
30

Fig. 6

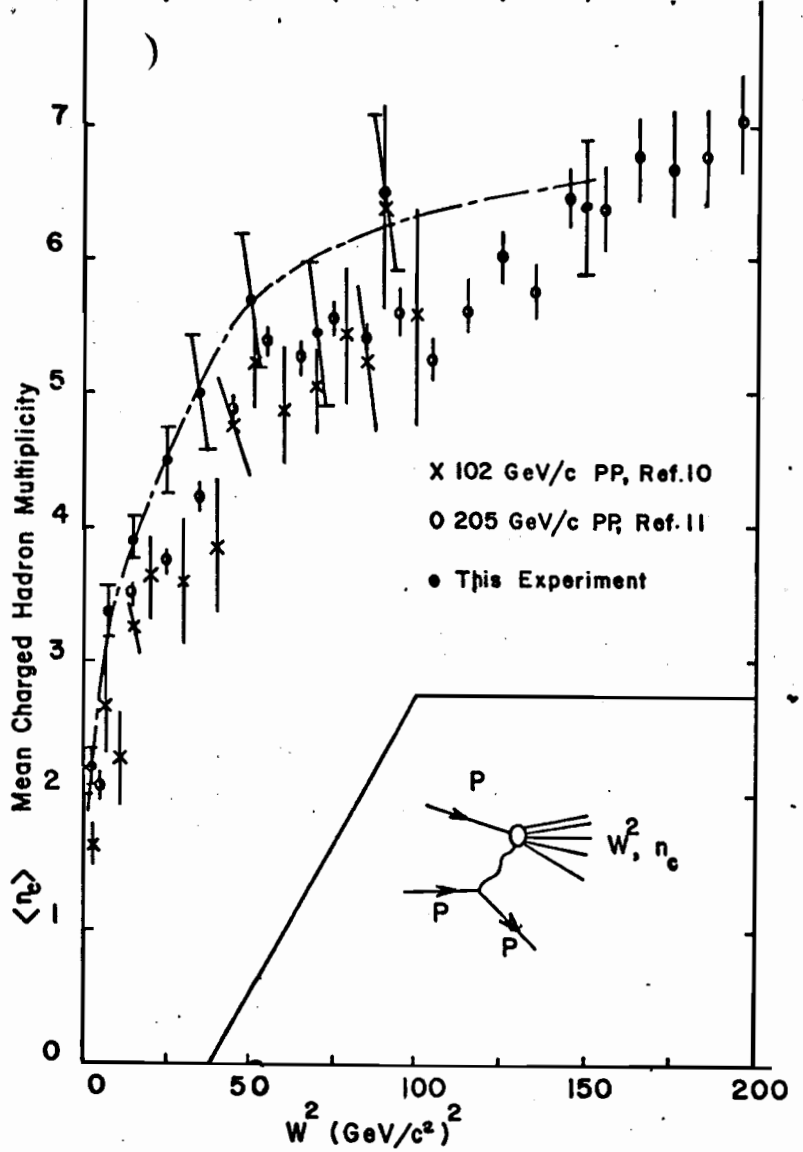
$\langle n_c \rangle$ Mean Charged Hadron Multiplicity
W^2 (GeV/c²)²
X 102 GeV/c PP, Ref.10
O 205 GeV/c PP, Ref.11
• This Experiment
P
P
P
W^2, n_c

Fig. 7

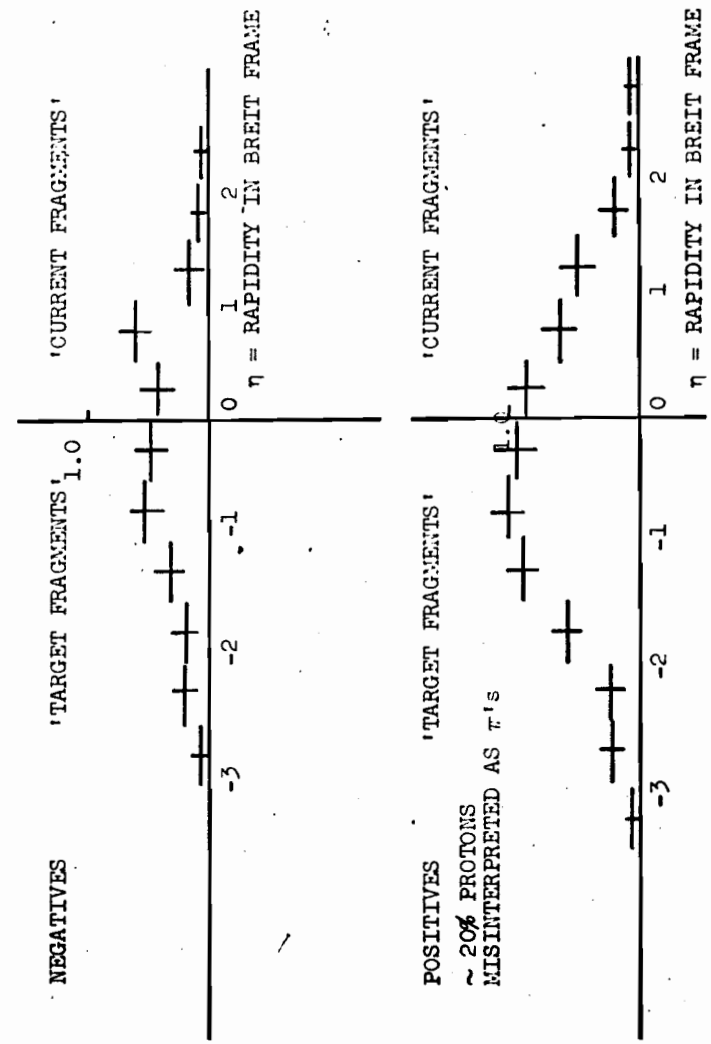
NUMBER OF CHARGED HADRONS/EVENT PER UNIT RAPIDITY INTERVAL
x > 0.1
5 < P < 20 GeV/c
NEGATIVES
'TARGET FRAGMENTS'
'CURRENT FRAGMENTS'
η = RAPIDITY IN BREIT FRAME
POSITIVES
~ 20% PROTONS MISINTERPRETED AS π's
'TARGET FRAGMENTS'
'CURRENT FRAGMENTS'
η = RAPIDITY IN BREIT FRAME

Fig. 8

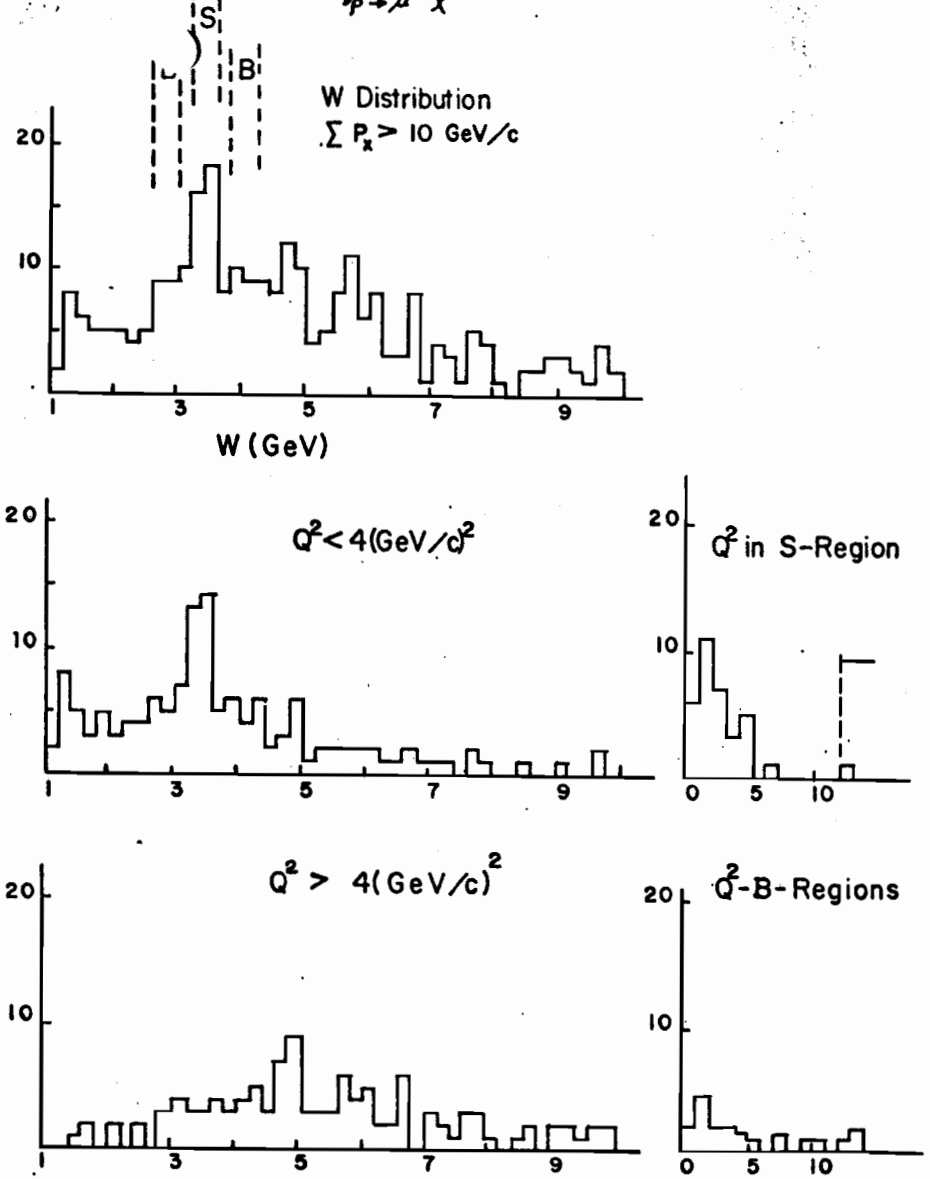
S
B
W Distribution
$\sum P_x > 10$ GeV/c
W (GeV)
$Q^2 < 4 (GeV/c)^2$
Q^2 in S-Region
$Q^2 > 4 (GeV/c)^2$
Q^2-B-Regions

Fig. 9

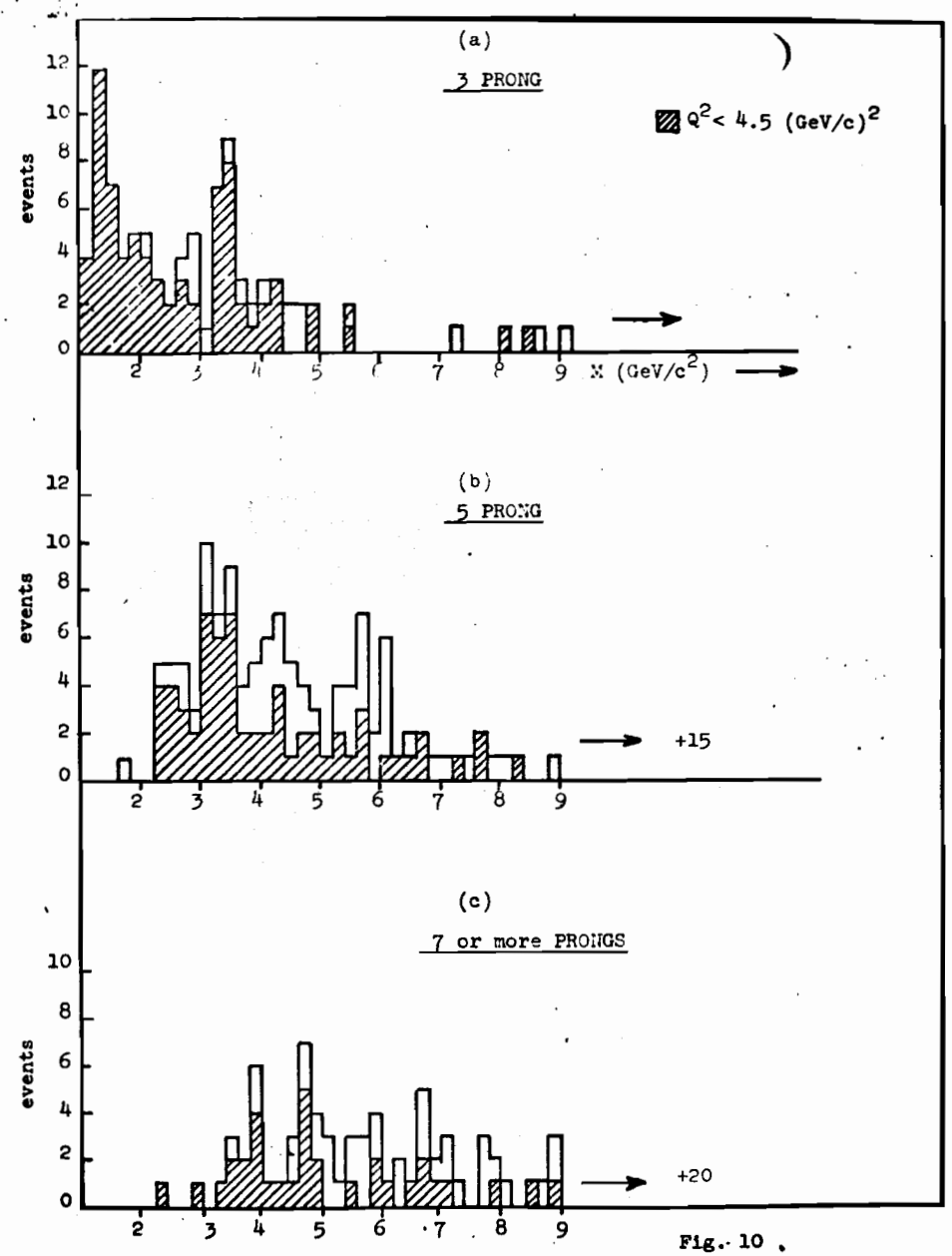
(a)
3 PRONG
$Q^2 < 4.5 (GeV/c)^2$
events
M (GeV/c^2)
(b)
5 PRONG
+15
(c)
7 or more PRONGS
+20

Fig. 10

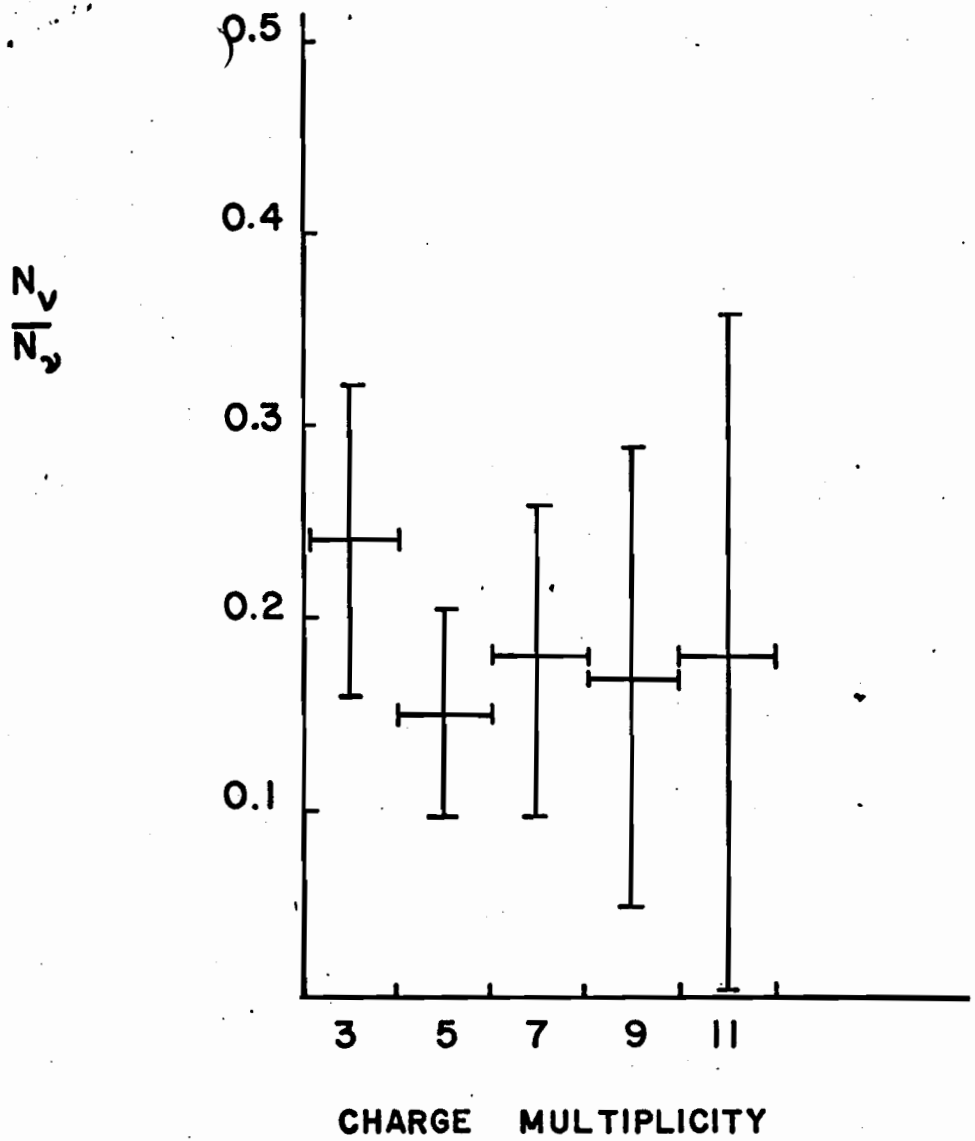
0.5
0.4
0.3
0.2
0.1
N_v / N_ν
3
5
7
9
11
CHARGE MULTIPLICITY

Fig. 11

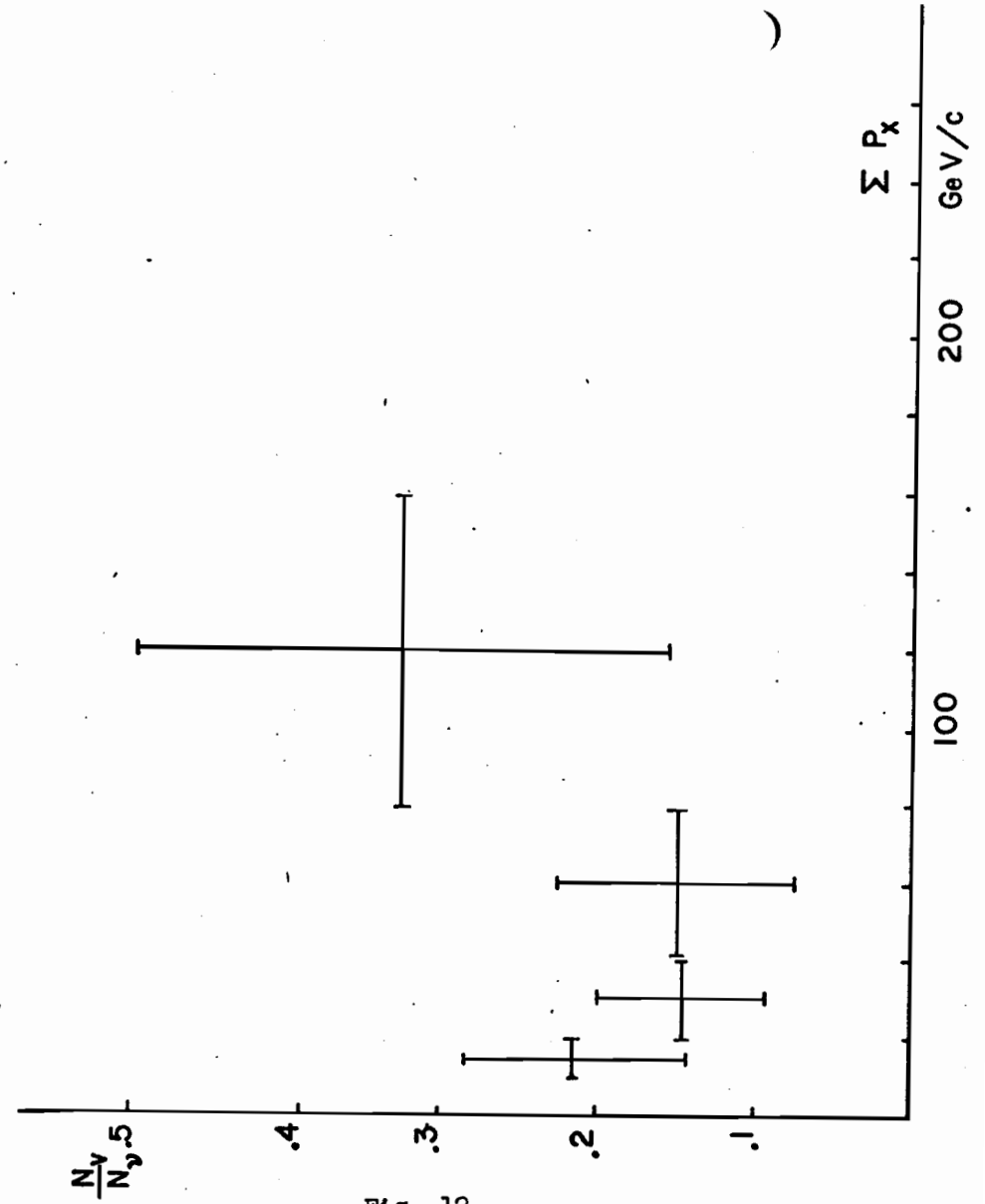
N_v / N_ν
.5
.4
.3
.2
.1
100
200
ΣP_x GeV/c

Fig. 12