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PROPOSAL FOR AN EXTENSION OF EXPERIMENT E-545 TO STUDY NEUTRINO INTERACTIONS IN DEUTERIUM IN THE 15-FOOT CHAMBER WITH PLATES AND HIGH RESOLUTION OPTICS USING THE 400 GeV/c WIDE BAND BEAM.

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SUMMARY

We propose an extension of our neutrino-deuterium experiment, E-545, in the 15-foot bubble chamber using the single horn wide band beam at 400 GeV/c. As before, we will make full use of the EMI and the internal picket fence. Important additional features requested are a two-plate system inside the chamber for identifying γ's and $e^{\pm}$, and high resolution optics to find short decay tracks and examine vertices closely. We request 400,000 additional pictures. This will not only enable us to substantially increase the statistics available for our studies of neutrino interactions on neutrons and protons, including charm production and decay, charged and neutral current physics, and hadronic final states, but the presence of plates and high resolution optics will provide a substantial qualitative improvement in our ability to analyze and identify the events.

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I. INTRODUCTION

Experiment E-545, which ran at Fermilab during the winter of 1978-79, was one of the most productive light liquid runs that the 15-foot chamber ever made. 328,000 pictures were taken in deuterium using the 350 GeV/c Wide Band Beam with a working two-plane EMI. The original E-545 proposal requested a run with plates in the chamber to follow a run (E-151/227) without plates. Fermilab, however, approved E-545, with plates, as a substitute for E-151/227. When the test of the 4-plate system turned out to be not completely successful, E-545 was run in the bare chamber. Now, fourteen months since the end of our run, with 2/3 of our data measured, processed and on a DST, and the full and complete DST projected for September 1980, with physics results rapidly emerging and an intense program of analysis mapped out for the coming year, we are proposing an extension of this experiment with a different experimental arrangement.

We propose a 400,000 picture run with two plates in the chamber, high resolution optics and the two plane EMI. The purpose of the plates will be threefold: first, to identify $e^{\pm}$, second , to identify γ's and π°'s through photon conversions, and third , to indicate the lack of π°'s in particular events. The use of the plates as a π° veto or to identify events with single π° emission should substantially increase the number of events which can be fit to exclusive channels.

Since the use of high-resolution optics (HRO) is being seriously proposed for 15-foot operation at Tevatron energies, we request that this development be carried out earlier for this proposed neutrino-deuterium experiment at 400 GeV/c.

The primary purpose of HRO would be to see the decays of charmed particles with observable track length. Given that of the order of five such decays have been seen in the 15-foot with no HRO,[1] we may expect an order of magnitude more if we can obtain a resolution of about 200 microns. The combination of HRO and plates suggests interesting possibilities such as the determination of leptonic and non-leptonic branching ratios of charmed particles. We do not consider HRO an essential part of this proposal, but we think it is important to test and use new higher resolution optical systems. We intend to assist Fermilab in the development and implementation of HRO for the 15-foot bubble chamber.

Our collaboration has long argued the superiority of deuterium as the preferred target for studying neutrino interactions in the 15-foot chamber. In the remaining parts of this proposal, we shall discuss in further detail the progress achieved to date in E-545 and the coming program of analysis; the physics goals which can be achieved in the proposed extension; and the use of plates and high resolution optics as added features for the 15-foot chamber.

If our proposal is approved, we would hope that the run could take place by late 1982. Our collaboration will be prepared, from the Fall of 1980 on, to devote the major part of its strength to this experiment. The experience we have gained in carrying out E-545 will make this proposed extension all the easier for us, since data processing and analyzing systems are now in place and functioning smoothly. The further experience we would gain with plates and HRO would also be excellent preparation for the neutrino-deuterium experiment at Tevatron energies which we are also proposing.

II. SUMMARY OF PROGRESS IN E-545

As stated in the introduction, at the time of writing about 2/3 of the film has been completely processed and all the events found are now on a DST. The other 1/3 of the film has been double-scanned and the events found are now being measured and passed through our geometric and kinematic analysis programs. This work will be finished in September 1980 at which time a full and complete DST for this experiment will exist. The total time elapsed from the run at Fermilab to the complete DST will be about 20 months.

At the same time, we have been pursuing the physics analysis of various topics. Reports on progress from E-545 have been presented at the April 1979 Washington A.P.S. Meeting, at the International Conference Neutrino 79 which took place at Bergen in June 1979, at the International Photon-Lepton Conference at Fermilab in August 1979, at Japanese Physical Society meetings in October 1979 and March, 1980, and at the January 1980 Chicago APS meetings. Further reports will be presented at the 1980 Washington meetings and at international conferences to be held in the summer of 1980, notably the International High Energy Physics Conference in July at Madison. In addition, two papers are now ready to be submitted to letter journals and others are in preparation.

In this section, we briefly report on the present status of our physics analysis with the expectation that more substantial physics results will be available in the near future.

(1) Charged Current Reactions - the n/p ratio and a comparison of the quark distributions $d_n(x)$ and $d_p(x)$

We have determined the value of the ratio $R = \sigma(\nu n \rightarrow \mu^- X)/\sigma(\nu p \rightarrow \mu^- X)$

from our data. The separation of νd interactions into neutron target and proton target events is complicated by the phenomenon of rescattering, in which the products of an interaction with one of the nucleons in the deuteron interact with the other nucleon. The correction for rescattering is important because its effect on νn collisions is to change the topology of an event to that of a νp interaction, while the topology of a νp event in which rescattering occurs remains unchanged. The fraction of νd events which rescatter has been estimated to be 0.094 ± 0.035 in a phenomenological study by extrapolating the rescatter rates observed in pd and πd interactions to νd collisions. This is done by assuming the rescatter rate is a linear function of cross section.

With the present accumulation of data, we find the value of the ratio R to be $R = 1.83 \pm 0.15$. About 1/3 of the error is statistical and 2/3 is due to the uncertainty in the fraction of events which contain rescatters in the deuteron.

In addition we have for the first time, by studying νn scattering, compared the structure functions $d_n(x)$ and $d_p(x)$ for the valence down quark in neutron and proton respectively. The general feature of these distributions (see Fig. 1) is that $d_n(x)$ is considerably broader than $d_p(x)$. The relative broadness of $d_n(x)$ compared to $d_p(x)$ is consistent with the charge symmetric SU(6) breaking effect seen by SLAC when comparing ep with en deep inelastic reactions.[2] Detailed study of the structure functions as a function of Q^2, now in progress, can reflect both QCD and higher twist (primary diquark) effects. In addition, the study of non-singlet cross sections obtained from the difference $\frac{d\sigma}{dx}(\nu n) - \frac{d\sigma}{dx}(\nu p)$, (see Fig. 2, the Feynman-Field fit to our preliminary data), while primarily useful for the study of valence quark properties, can also be used in the small x region to search for asymmetries between $u\bar{u}$ and $d\bar{d}$ in the sea.

The quantity $3[F_1(ep) - F_1(en)] - [F_1(\nu n) - F_1(\nu p)] = 2(\bar{u} - \bar{d})$ is a direct measure of such an asymmetry, which is already suggested from a study of ep and en interactions alone.[3]

Finally, in this neutrino run, we were able, by using the two-plane EMI, to identify $\bar{\nu}_\mu$ interactions, and determine their n/p ratio to be 0.56 ± 0.16.

To obtain information about individual structure functions we can normalize our neutrino flux to our observed number of $\nu - d$ $(I = 0)$ events, using the measured value of $\sigma^{CC}_{TOT}(I = 0)$. We have checked that the flux determined by quasi-elastic events agrees with this method to the statistical accuracy ($\sim$20%) allowed. We shall compare our y distributions with detailed Monte Carlo calculations in order to determine the relative coefficients of terms proportional to 1 and $(1 - y)^2$. Eventually, we will also be able to combine our νd data with $\bar{\nu} d$ data from the BEBC collaboration at CERN.

(2) The Callan-Gross Relation

We have tested the Callan-Gross relation, $F_2(x) = 2xF_1(x)$ in deuterium. The quantity $R = 1 - \frac{f_1}{f_2}$, where $f_1 = \int_o^1 2xF_1(x)dx$ and $f_2 = \int_o^1 F_2(x)dx$, is given in Table I for this experiment as well as for others. We note that the result in deuterium is considerably better than in bubble chamber experiments using heavier liquids and comparable with the CDHS counter experiments. In addition, the use of a deuterium target allows us to test the relation separately for neutrons and protons.

Table I

Test of Callan-Gross Relation

	(n+p)	n	p
This exp. E-545 (D_2)	-0.01 ± 0.07	0.001 ± 0.10	-0.03 ± 0.11
BEBC[(a)]	0.11 ± 0.20		
GGM[(a)]	0.32 ± 0.21		
CDHS[(b)]	-0.03 ± 0.04		
CITFR[(c)]	0.17 ± 0.09		

(a) P.C. Bosetti et al., Nucl. Phys. B142, 1 (1978).

(b) C.D.H.S. Collaboration, XIX Int. Conf. on High Energy Physics, Tokyo (1978).

(c) B.C. Barish et al., ibid.

(3) Neutral Current Interactions

We have found that it is possible to obtain a rather clean sample of ν_μ neutral current events by choosing those events with $|p_{TR}| < 1.0$ GeV/c, where p_{TR} is the transverse momentum relative to the remaining charged particles of the negative particle with the highest transverse momentum relative to the incident beam. In this sample, there exist backgrounds due to ν_μ and $\bar{\nu}_\mu$ charged current interactions where the μ is not identified, $\bar{\nu}_\mu$ neutral current interactions and neutral hadronic induced events. The ν_μ background is corrected for by a Monte Carlo of the p_{TR}^2 spectrum of μ^-, $\bar{\nu}_\mu$ background by using the EMI to identify μ^+, and $\bar{\nu}_\mu$ neutral current events by using known results for $\bar{\nu}_\mu(NC)/\bar{\nu}_\mu(CC)$. The neutral hadronic background is essentially eliminated by the cut $\Sigma p_L > 11$ GeV/c, where p_L is the longitudinal momentum of an outgoing charged particle with respect to the beam direction.

Using our usual methods for separating n from p events, we obtain the following results for the ratios R = NC/CC:

On deuterium	$R_d = 0.29 \pm 0.04$
On protons	$R_p = 0.47 \pm 0.11$
On neutrons	$R_n = 0.19 \pm 0.05$.

Using the results on n and p, and making appropriate experimental corrections, we are able to extract the neutral current coupling constants u_L^2 and d_L^2. A preliminary result is shown in Fig. 3.

(4) Strange Particle Production

At the present time, about 80% of the V° events in our film have been analyzed and we are studying V° production in both charged and neutral current events. In charged current events we find the following overall ratios:

$$\frac{\sigma(K^\circ)}{(\text{all CC})} = 0.132 \pm 0.05; \qquad \frac{\sigma(\Lambda^\circ)}{(\text{all CC})} = 0.057 \pm 0.003;$$

and $\sigma(\overline{\Lambda}^\circ)/\sigma(\text{all CC}) = 0.002 \pm 0.001$. The results are about the same on neutrons and protons. More detailed investigations of the properties of these events are underway. Preliminary results show that the x distribution in the valence region is much broader for neutrons than for protons, as is the case for all charged current events. Striking peaks are also seen at small x indicating that a considerable fraction of the K° and some of the Λ° particles are made in interactions of the neutrino with sea quarks, including

$\nu + s \to c + \mu^-$. This kind of detailed strange particle production data can complement the global sea quark content information provided by counter experiments. Rapidity distributions in the W^+-N center of mass are being studied as a means of separating target from current fragmentation regions. One very exciting prospect is to use the Forward/Backward ratio of Λ° production as a function of Q^2 to set limits on the amount of higher twist contributions present. If a (dd) diquark in a neutron, rather than a single d quark, absorbs the weak current, the probability of forming a Λ° or Σ° in the forward W^+N hemisphere will be enhanced, since the direction of the emitted (ud) diquark and the observed Λ°'s are strongly correlated.

An attempt to analyze our results in terms of the percent of charm production and decay from the valence and sea quark targets is under way. The production of strange resonances K^* and Y^* is also being studied.

(5) Charm Production

For our charmed particle studies, about 80% of our film has now been analyzed for V° events. After cuts used to obtain a clean sample of charged current events we have found 564 K°'s and 481 Λ°'s. The mass resolutions for K°'s and Λ°'s are 5.1 and 1.7 MeV respectively as shown in Fig. 4. We note that for the K°'s, this is more than three times better than the resolution obtained from a neon experiment.

In an inclusive study of the final state combinations $\Lambda\pi^+$, $\Lambda\pi^+\pi^+\pi^-$, $K^\circ p$, $K^\circ p\pi^+\pi^-$, we see evidence for the Λ_c^+ charmed baryon at mass 2.28 GeV (to be submitted to Phys. Rev.) The results are shown in Fig. 5. For the D mesons we see a signal, Fig. 6, but it is clear we need more data.

We have also had success in exclusive events which can be fit with V°s plus charged particles in the final state. Eleven candidates for charmed baryon events have been found, seven for $\Lambda_c^+ \to \Lambda\pi^+$, three for $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$ and one for $\Lambda_c^+ \to K^\circ p$.

Of the seven $\Lambda_c^+ \to \Lambda\pi^+$ events two can be interpreted as $\nu n \to \mu^-\Lambda_c^+$. To confirm the $\Lambda\pi^+$ events further, we show in Fig. 7 the $\Lambda\pi^+$ mass distribution from events which have an exclusive fit for $\Delta S = -1$ with a Λ. We find four excess events above background at the Λ_c^+ mass. An increase in our data by a factor of $\sim 2 - 3$ would give strong evidence for Λ_c production in exclusive reactions.

One event of three $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$ candidates is interpreted as $\nu n \to \mu^-\Lambda_c^+$. The two other events have five pions in the final state and can be fit to $\nu n \to \mu^-\Lambda\pi^+\pi^+\pi^+\pi^-\pi^-$. The first can be interpreted as:

$$\nu n \to \mu^-\Sigma_c^{++}(2486 \pm 19)\pi^-$$
$$\hookrightarrow \Lambda_c^+(2257 \pm 17)\pi^+$$
$$\hookrightarrow Y^{*-}(1382 \pm 3)\pi^+\pi^+$$
$$\hookrightarrow \Lambda\pi^-.$$

The second can be interpreted as

$$\nu n \to \mu^- \Sigma_c^{*\circ}(2509 \pm 13)\pi^+$$
$$\hookrightarrow \Lambda_c^+(2256 \pm 12)\pi^-$$
$$\hookrightarrow \Lambda\pi^+\pi^+\pi^- .$$

The $\Lambda_c^+ \to K^\circ p$ event is fit to $\nu p \to \mu^- p\pi^+ \bar{K}^\circ \pi^- \pi^+$ and can be interpreted as

$$\nu p \to \mu^- \Lambda_c^+(2246 \pm 6)\pi^+$$
$$\hookrightarrow \Delta^{++}(1211 \pm 2) K^{*-}(914 \pm 5)$$
$$\hookrightarrow p\pi^+ \qquad \hookrightarrow \bar{K}^\circ \pi^-$$

Further and more detailed analysis of both the inclusive and exclusive studies of charm production is underway.

(6) Hadron Multiplicity Distributions

We have examined the multiplicity distribution of the final state hadrons produced in charged current νp and νn interactions. In this discussion, all data are corrected for the effects of rescattering within the deuteron, as described in (1) above.

The hadron multiplicity distributions in νN scattering are observed to be similar to those in $\bar{p}p$ annihilations, but systematic differences between neutrino-nucleon and hadron-nucleon multiplicity distributions are noted.

The average charged hadron multiplicity, $\langle n_c \rangle$, is observed to be a linear function of $\ln W^2$, where W is the total hadronic energy, for both νp and νn interactions. The variation of $\langle n_c \rangle$ with W which we observe for

νp interactions is consistent with that reported in two neutrino-hydrogen experiments,[4,5] while $<n_c>$ in νn interactions is systematically lower than the νp values by about half a unit.

The variation of the dispersion of the neutrino-nucleon multiplicity distribution may be parameterized by $D = A <n_c> + B$. The value of the intercept B for νp interactions is found to be different from the value for νn interactions, although the slope parameter A is the same for the two targets. We find $A = 0.34$ for neutrino-nucleon collisions, which is only 60% of the value of A for hadron-nucleon collisions. The result that the intercept B is non-zero is evidence that the data do not obey KNO scaling exactly.

(7) Other Topics in the Hadronic Final States

A variety of problems concerning the final state hadrons are or will soon be under analysis and we expect interesting results within the coming months. We mainly list these topics here as it is still too early to give precise results. Recall that neutrinos provide a uniquely labelled source of quarks and diquarks whose fragmentation properties have been used to describe essentially all of hadron physics. More refined data along these lines for protons and neutrons are very useful for correlating a multitude of strong interaction observations.

a) QCD effects -

We are studying QCD effects which may be observed in final state distributions as well as in structure functions and their moments both for neutrons and protons. Also, in preliminary studies we have found that the distribution of $\langle p_T^2 \rangle$ as a function of W^2 is consistent with QCD predictions. The differences of neutron and proton (n-p) fragmentation distributions are of particular theoretical interest.[6]

b) Jets -

An analysis of jet-like properties of final state particles in terms of the usual parameters of sphericity, spherocity, thrust, etc., is also being carried out.

c) π^- structure function -

By studying νn events in which a slow proton (not the spectator) is produced, one can effectively study $\nu\pi^-$ scattering[7]. We are now beginning this analysis.

d) Charge flow and quark fragmentation -

Forward charge flow in the W^+-N system is being studied along with questions of quark and diquark fragmentation and "leakage" between current and target fragmentation regions.

e) Resonance production -

Studies of production of baryon and meson resonances, both strange and non-strange are underway.

Additional topics slated for study are: comparison of νq with eq scattering, Adler sum rule tests, quasi-elastic $\nu n \rightarrow \mu^- p$ scattering and exclusive reactions with V°'s.

III. PROPOSAL

We propose an extension of experiment E-545, neutrino-deuterium interactions in the 15-foot bubble chamber, which embraces the following features:

Beam - The single horn wide band beam at 400 GeV/c with $\sim 2 \times 10^{13}$ ppp.

Exposure - 400,000 pictures, equivalent to E-545 in total events.

EMI and IPF - The two plane EMI configuration and the enhanced internal picket fence.

Plates - Two large stainless steel plates at the downstream end of the chamber for γ and $e^{\pm}$ identification.

High Resolution Optics - Three additional cameras, adapted for high resolution optics with 200 micron resolution, for the purpose of observing very short decay tracks.

The expected event rates for this proposal are given in Table II. We note that these are realistic rates, in that they are the numbers of events remaining after cuts and efficiency factors (obtained from E-545) are applied.

Physics in this run, and further details of experimental arrangements are discussed in the following sections.

TABLE II

REACTION	Neutrino-Deuterium Event Rates Usable Events* in 400K Pictures at 400 GeV/c
$\nu_\mu p \rightarrow \mu^- X$	4000
$\nu_\mu n \rightarrow \mu^- X$	7200
$\nu_\mu p \rightarrow \nu_\mu X$	1700
$\nu_\mu n \rightarrow \nu_\mu X$	1700
$\nu_\mu \binom{p}{n} \rightarrow \mu^- \Lambda^\circ X$	770
$\nu_\mu \binom{p}{n} \rightarrow \mu^- K^\circ X$	950
$\nu_\mu \binom{p}{n} \rightarrow \mu^- +$ charm	1100 (produced events)
	50 (observed with HRO)
$\nu_\mu \binom{p}{n} \rightarrow \mu^- e^+ X$	60 (e^+ observed in plates)

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* The usable event rates are calculated directly from the direct number of events used in E-545 for analysis by reducing the fiducial volume to 70% of that for the bare chamber, and taking into account the change in the neutrino spectrum in going from 350 to 400 GeV/c. This assumes all applicable cuts as made in CC selection, and efficiency factors will be the same.

IV. PHYSICS IN THE EXTENDED RUN

Experiment E-545 was originally approved for 350,000 pictures at 400 GeV/c, which would have yielded about 40,000 charged current events in the 15-foot chamber. With the application of various cuts and efficiency factors the corresponding observed number would have been about 21,000. Instead, the experimental run was 300,000 pictures at 350 GeV/c resulting in only 13,000 useful CC events. In addition to the overall decrease in the event rate, running at 350 GeV/c instead of 400 GeV/c reduced the number of higher energy events (E_ν > 100 GeV) by a factor of about three. Furthermore, since E-545 was run without plates those features of the experiment which depended on γ and $e^\pm$ identification could not be carried out.

In this section, we discuss the physics results which could be obtained with the added features of plates and high resolution optics, as well as studies which would benefit from increased statistics.

A. Details of Charm Production

As indicated earlier, we are already about to submit the results of our studies on Λ_c production for publication. Nevertheless, the increased statistics to be obtained from the proposed extension will represent a significant improvement in the Λ_c data as well as in the D-meson data.

In addition the use of plates and high resolution optics will provide further advantages in enhancing our ability to study charm production and decay.

In the case of the D mesons we will, with the increased statistics, be able to determine D^+ and D° production rates. These rates, together with the ability to detect e^+ in the two plate system, will allow us to carry out a study of semi-leptonic decay processes for these mesons.[(8)] We stress the point that hadron contamination in electron-like showers from the plates is less than 10^{-3}, which makes this system very suitable for the $\mu^- e^+$ studies. Finally, we point out that the detection of e^+ in the plates will provide us with an enriched sample of neutrino events whose vertices should be examined with the high resolution cameras for short decay tracks.

The ability to detect π°'s through photon conversion in the plates should make it possible in V° events to increase the number of exclusive channel fits which can be interpreted with charmed baryon production and decay. This can be done using the plates as a π° veto, to better isolate final states with only a V° and charged particles, or to find events with only a single π° which can also be fit with no other missing particles.

As has been seen in E-545 and other experiments, it is difficult to study charmed particles in inclusive processes and, at the same time, exclusive events in which they can be identified are rare. Although the plates will improve the situation, it would still be of great benefit to have an additional way to tag those events which contain charm. High resolution cameras would make it possible to do this in a simple way by direct observation of the charmed particle decay tracks. In Section V (B) we discuss an arrangement of the three spare cameras to provide a region of high resolution (about 200 microns) covering about 1/3 of the usual fiducial volume.

In the exposure proposed here, the number of charmed particles produced is expected to be about 900 of which about 200 would be in the high resolution region. If one takes the average momentum of the charmed particles to be about 10 GeV/c then the average distance traveled would be about 750 microns for $D^{\pm}$ (assuming a lifetime of 5×10^{-13} sec) and 200 microns for D° and Λ_c^+ (assuming a lifetime of $1\text{-}2 \times 10^{-13}$ sec)[9]. With high resolution optics we may expect to observe about 50 charm decays with visible tracks. We point out, in addition, that a larger than average fraction of high energy neutrinos, $E_{\nu} > 50$ GeV, will fall within the high resolution region, and that these will produce longer than average charm decay lengths. With the simultaneous presence of the plates, we will be able to sort out, among these events, leptonic from non-leptonic charm decays, and the π° detection ability of the plates will assist in fitting charm decays where a single π° is emitted.

Although information from other experiments is likely to determine charmed particle properties it is important to know how they are produced in neutrino interactions and how the charmed quark, which is primarily produced from a valence quark, hadronizes.

We point out that in experiment E-545, using the two plane EMI, we have at present observed one event which is consistent with the production and visible decay of a D° (after traveling 0.6 mm) in the 15-foot bubble chamber. The event is a candidate for the reaction $\nu n \rightarrow \mu^- p D^{\circ}$,

$D^\circ \to \bar{K^\circ}\mu^+\pi^-$. Some of the characteristics of the event are shown in Figures 8, 9, and 10.

The first figure is a print of the film showing both the production vertex and the K_s° decay. The next figure is an enlargement of the film in the vertex region. The last figure is a plot of the measurements which were produced from digitizations which were not made along the direction of the track but rather were made in a direction perpendicular to each track. This was done to eliminate any measuring bias.

This event, as well as similar ones observed by others in the 15-foot chamber, suggests that HRO will indeed be an effective way to find charm decays.

B. QPM and QCD

Improvements in measuring QPM parameters and testing QCD, will come from the increase in statistics to be achieved (a factor of about two) from the proposed extension as well as from the increased Q^2 and W range available at 400 GeV/c and from the presence of plates in the chamber.

The overall neutron to proton cross section ratio, n/p, is currently limited by the systematic error in the rescattering coefficient, f_d. This parameter, however, can be empirically determined once the BEBC TST experiment has measured n/p in a manner independent of rescattering.[10] By comparing our "raw" n/p ratio with theirs, we will obtain an independent determination of f_d, free of systematic error, which we can then apply in obtaining the neutron and proton structure functions. It will also be of interest to use this to test our present method of determining f_d.

One example of the benefit of increased statistics is in the comparison of neutron and proton structure functions. In the sea region, $x \leq 0.2$, we will be able to look for $\bar{u}$, $\bar{d}$ asymmetries. The Q^2 dependence of the non-singlet structure function, $(d\sigma^n/dx - d\sigma^p/dx)$, in the valence region is also sorely in need of increased statistics.

Similar arguments also apply in the case of the x distributions for strange particle events mentioned in Section II. Interesting possibilities for the strange particle studies exist. Variations with Q^2 of $\Lambda°$ and $\Sigma°$ production in the forward hemisphere could indicate production taking place from ν-diquark scattering and hence be used as a measure of higher twist contributions - a crucial unresolved theoretical and experimental question. The V° events are an area where we can clearly separate final state baryons ($\Lambda°$) from mesons in neutrino events, but to obtain physics from it we must increase the number of events. The plates in the chamber will provide an additional benefit in these studies, since we will be able to distinguish $\Sigma°$ from $\Lambda°$ production about 50% of the time. This could be useful in separating longitudinal and transverse contributions to the deep inelastic amplitudes.[11]

In the hadronic final state we will be particularly interested in studying the current fragmentation region. In the simple QPM, where scaling and factorization hold, the fragmentation functions for the u-quark, $D_u^h(z)$, may be determined for $h = \pi^+$, π^- and $(K°+\bar{K}°)$. QCD predicts a Q^2 dependence of the fragmentation functions, investigations of which are facilitated by using the moments, $D(m,Q^2) = \int_0^1 z^{m-1} D(z,Q^2)dz$, in both their singlet and non-singlet forms.

Although we will not be able to determine z distributions for $\pi°$ mesons, the use of the plates will make it possible to determine the number of $\pi°$

mesons produced in the current fragmentation region. In a simple model of hadronization, the average number of π°'s should be equal to the average number of charged pions, even though the net charge is positive. With the plates we shall be able to test this prediction.

The net charge $\langle Q_F \rangle$ in the current fragmentation region is a measure of the probability γ_u of creating a $u\bar{u}$ pair from the sea. If charm production is neglected it is easily shown that $\langle Q_F \rangle = 1 - \gamma_u$. Since $\gamma_u + \gamma_d + \gamma_s = 1$, if we assume SU(2) symmetry in the sea ($\gamma_u = \gamma_d$) we also obtain $\gamma_s = 1 - 2\gamma_u$ from the net forward charge. An independent measure of γ_s can be obtained by studying the production of K° mesons in the current fragmentation region. The ratio $R = (K^\circ + \bar{K}^\circ)/(\pi^+ + \pi^-)$ is a measure of γ_s/γ_u. This picture assumes the current region consists only of mesons. The presence of baryons can be ascribed to diquark "leakage" from the target to current region (see Fig. 7). In this case $Q_F = 1 - \gamma_u + \Gamma$ where $\Gamma = \Gamma_{uu} - \Gamma_{dd} - \Gamma_{us} - \Gamma_{ss}$. This analysis will be enhanced by the greater W range available at 400 GeV/c and by the increased statistics.

We emphasize that the increased number of high energy neutrinos at 400 GeV/c, the increased (Q^2,W) range this provides, the overall increase in statistics we could obtain, and the use of plates in the chamber, will make us more sensitive to QCD and higher twist effects.

C. Neutral Currents

In E-545 we have obtained NC/CC ratios for νp and νn scattering and shown how these can be used to obtain the neutral current coupling constants u_L^2 and d_L^2 as well as $\sin^2 \theta_W$, as indicated in our preliminary result shown in

Fig. 3. Increased statistics will enable us to make these studies more meaningful.

Up to now, there has been no way to obtain information on the neutral hadronic energy in neutral current events, and therefore parameters such as E_ν, x, y, Q^2, and W cannot be determined on an event by event basis. With two plates in the chamber we expect to observe $\sim$ 60% of all π°'s from charged current events. Since these π°'s tend to be the fast forward ones they carry even a greater percentage of the neutral hadronic energy in pions. Although we cannot measure the individual γ energies well in the plates, we may be able to make a rough estimate of the total neutral hadronic energy in each event. We cannot say at this time how useful or valid any such procedure would be, but we would be able to test it in charged current events where an independent procedure, the Bonn method, is presently used to determine neutral hadronic energy.

V. EXPERIMENTAL ARRANGEMENT

A. Plates

In our original proposal P-545, we proposed a downstream set of four plates inside the 15-foot chamber. A test run of this system was not completely successful due to turbulent conditions in the regions between plates. Therefore the E-545 run took place in the bare chamber. The technical staff at Fermilab has determined that the problem could be cured by trimming back the plates about ten inches on top and bottom. In Appendix A, a detailed analysis of the photon and electron detection capabilities of the trimmed 4-plate system is given.

For this experiment we are proposing a modification of the 4-plate system, namely, that only two plates - the second and third - be used. The total radiation length would be $1.44X_o$. This modification is justified by the following considerations:

(i) We are convinced from experience with other plate experiments that shower multiplication would make the regions behind the 3rd and 4th plates unusable. It will be very difficult to follow tracks through these regions. With only two plates, this would not be a serious problem.

(ii) The technical difficulties which appeared in the 4-plate test would be significantly reduced with only one interplate region instead of three.

(iii) The removal of the first plate will increase the usable fiducial volume from about 60% to 70% of the chamber.

(iv) The reduction in photon and electron conversion efficiency is not great. Overall photon and electron conversion efficiencies will be about 60%. However, the efficiency for catching neutral energy is even greater.

(v) The plates and their mounting supports already exist at Fermilab. The only modification required is the trimming of the top and bottom portions.

(vi) Finally, it should be stressed that the electron identification power for this two plate system is very high ($\sim$93%), with a small hadron contamination ($\lesssim 10^{-3}$).

This is achieved by measuring the highest transverse momentum of the shower particles.

As mentioned earlier, we will use the plates primarily

a) as a π° veto to assist in fitting exclusive channels with no neutrals.

b) to detect events where a single π° is emitted which may then give a constrained fit.

c) to detect electrons and positrons.

d) to assist in separating Σ°'s from Λ°'s.

In addition, the use of plates with a light liquid such as deuterium will result in improved neutrino energy estimates by detecting a major portion of the neutral energy.

B. High Resolution Optics

Recently, tests with high resolution cameras which have taken place in LEBC (Little European Bubble Chamber) and in the SLAC 40-inch chamber have met with considerable success [(12)], achieving resolutions of the order of 50 - 80 microns. It has been proposed at recent workshops on neutrino physics at Tevatron energies [(13)], that the 15-foot chamber also be equipped with high resolution capability by modifying the three spare cameras. Because diffraction limited resolution and the depth of focus of a lens are intimately related, the 50-80 micron resolution referred to above would not be practical in a neutrino beam since the depth of focus is only a few centimeters. A reasonable goal for the 15-foot chamber would be 200 micron resolution which corresponds to a depth of focus of about 30 cm. With the three cameras focussed at different depths, and with their platens modified so as to double the frame length, a region centered on the beam axis about 1 meter in depth and covering the length of the chamber could be observed. (However, with plates in the chamber the platen modification would probably not be necessary). This would correspond to about 1/3 of the usual fiducial volume of the chamber.

We are of the opinion that high resolution optics is technologically and economically feasible for Tevatron running and see no reason why this development could not be carried out earlier. At CERN one camera has recently been modified for high resolution and very good pictures have been obtained.[14]

As part of this proposal, we therefore request a three-camera high resolution system similar to that described. Not only will there be interesting physics to be obtained, but the 400 GeV/c run will provide an excellent test of the system prior to Tevatron running. Our collaboration is prepared to lend considerable assistance to Fermilab in the design, development, and testing of the high resolution cameras.

C. Beam and EMI

We propose to use the two-plane EMI configuration and the enhanced IPF (internal picket fence) with 16 drift chambers (compared to 12 for E-545). We propose to use the single horn wide band beam with 400 GeV/c incident protons.

D. Data Reduction

The four collaborating groups would be able to devote about 25-30 experienced scanners to carry out a double scan and measurement of the film. If high resolution cameras are available then their film would be used to examine the vertex region of those events found in the main scan which fall within the high resolution fiducial volume.

The data processing systems of the group are now working very smoothly and are able to do geometric reconstruction, kinematic fitting and EMI analysis in both Japan and the United States. The only modifications necessary to the package would be those which take into account information on photon and electron conversions in the plates. In addition, for high resolution we would have to incorporate measurements of decay tracks in those views.

The physicists participating in this proposal have also participated in E-545 and therefore we expect the entire experiment, from scanning to final data analysis, to proceed at a rapid rate. We estimate about two years from the experimental run to achievement of a final DST, with physics analysis proceeding as soon as sufficient data is in hand.

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2. E.M. Riordan, et al., SLAC-PUB-1634 (1975); A. Bodek et al., Phys. Rev. D20, 1471 (1979); W.B. Atwood, SLAC-PUB-185 (1975).

3. J. Steinberger, Particles and Fields Division Conference, Montreal, 1979; R.D. Field and R.P. Feynman, Phys. Rev. D15, 2590 (1977) and references therein.

4. J.W. Chapman et al., Phys. Rev. Lett. 36, 124 (1976).

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7. M. Lusignoli et al., Nucl. Phys. B155, 394 (1979).

8. J. Kirkby, in Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Fermilab, Batavia, 23-29 Aug. 1979. Semi-leptonic branching ratios for the D^+ and D° are given to be $(23 \pm 6)\%$ and $<4\%$ respectively.

9. Private Communication - McGill-Ohio State-Toronto-Japan emulsion collaboration (E-531).

10. A Measurement of the Ratio of the Total CC Interaction Cross Sections of High Energy Neutrinos on Neutrons and Protons, BEBC TST Collaboration, Photon-Lepton Conference, 1979.

11. L.F. Abbott et al., Phys. Lett. 88B, 157 (1979).

12. Private communication - G. Kalmus, Rutherford Laboratory.

13. L. Voyvodic, Argonne Workshop on Bubble Chamber Neutrino Physics at the Tevatron, (Oct. 1979), and Fermilab Workshop on Muon and Neutrino Physics at the Tevatron, (Jan. 1980).

14. Private Communication - D.R.O. Morrison, CERN.

15. A.J. Buras and K.J.F. Gaemers, Nucl. Phys. B132, 249 (1978).

FIGURE CAPTIONS

Fig. 1. Bjorken x distributions for neutrino scattering on neutrons and protons. The fits shown are based on expressions from Buras and Gaemers.[15]

Fig. 2. The Feynman-Field fit to $[\frac{d\sigma}{dx}(\nu n) - \frac{d\sigma}{dt}(\nu p)]_{CC}$. The fit is normalized to the data at $x = 0.14$.

Fig. 3. A preliminary result for the neutral current coupling constants u_L^2 and d_L^2. Also shown is the prediction of the Weinberg-Salam model. Note that the νn line intersects the νp line at a greater angle than does the $\nu(I=0)$ line (not shown) making this in principle a more sensitive method than previously used.

Fig. 4. Mass distributions for K° and Λ events yielding resolutions of 5.1 and 1.7 MeV respectively.

Fig. 5. Inclusive mass distributions for (a) $\Lambda\pi^+$, (b) $K^\circ p$, and (c) their sum.

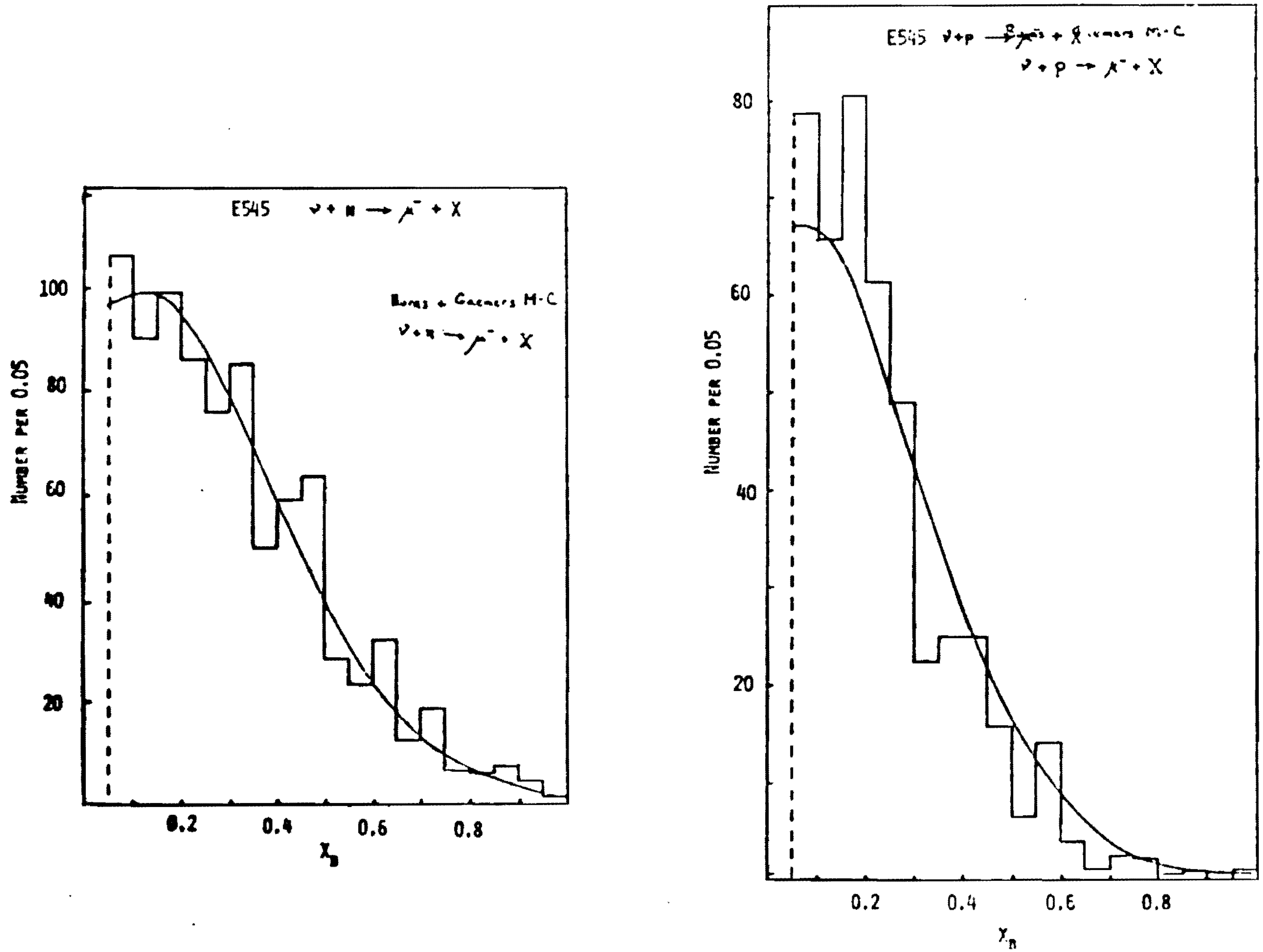
Fig. 6. Inclusive mass distributions for (a) $K^\circ\pi^+\pi^-$, (b) $K^\circ\pi^+ + K^\circ\pi^+\pi^+\pi^-$, and (c) their sum.

Fig. 7. Mass distributions for $\Lambda\pi^+$ from exclusive reactions fit with a single Λ. Also shown is the mass distribution for $\Lambda\pi^+\pi^+$ from these reactions.

Fig. 8. A print of the film containing a candidate for a visible charm decay in the reaction $\nu n \to \mu^- p D^\circ$, $D^\circ \to \overline{K}^\circ \mu^+ \pi^- \nu$.

Fig. 9. An enlargement in the vertex region of the film shown in the previous figure. Lines are drawn to help guide the eye.

Fig. 10. A plot of the measurements on the tracks of the event shown in the previous two figures. Digitizations were not made along the track directions, but perpendicular to them in order to eliminate any measuring bias.



E545 ν + n → μ⁻ + X
Buras + Gaemers M-C
ν + n → μ⁻ + X
Number per 0.05
100
80
60
40
20
0.2
0.4
0.6
0.8
X_B
E545
ν + p → μ⁻ + X
Number per 0.05
80
60
40
20
0.2
0.4
0.6
0.8
X_B

Figure 1

E-545: IIT-MD-SB-Tohoku-Tufts

$$\left[\frac{d\sigma}{dx}(\nu n) - \frac{d\sigma}{dx}(\nu p)\right]_{C.C.}$$

$\langle E_\nu \rangle \cong 55$ GeV

$E_\nu > 15$ GeV

$p_T > 1$ GeV/c

$\Sigma p_\ell > 5$ GeV/c

($f_d = 0.094$)

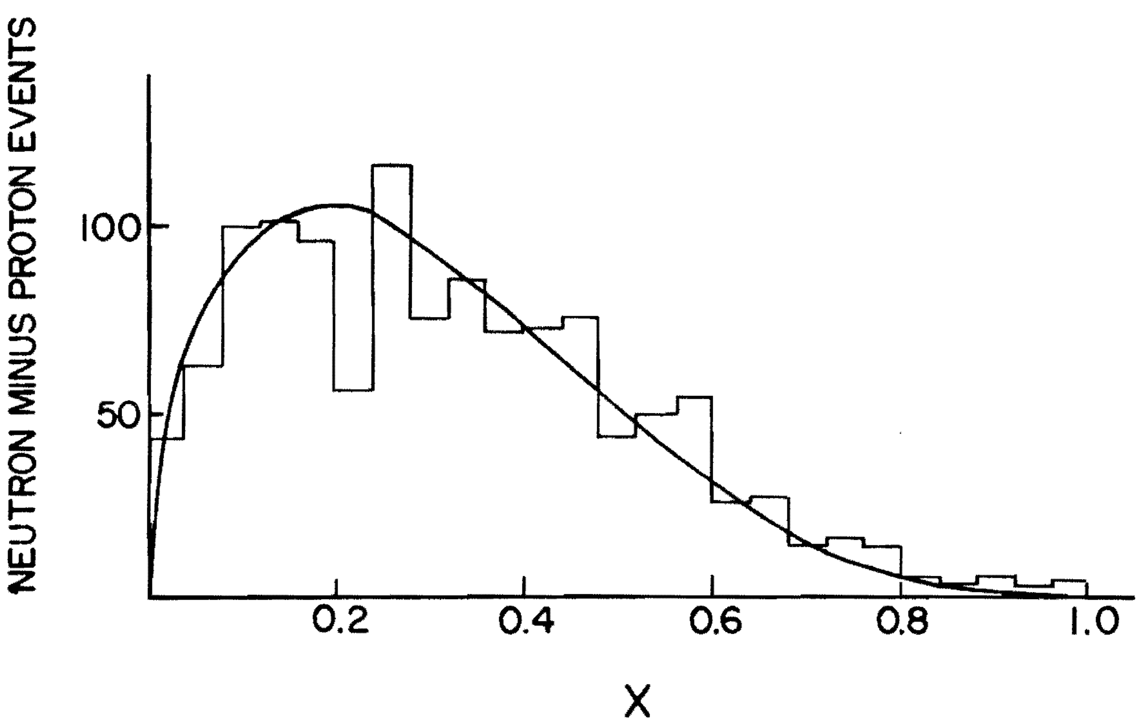


Figure 2

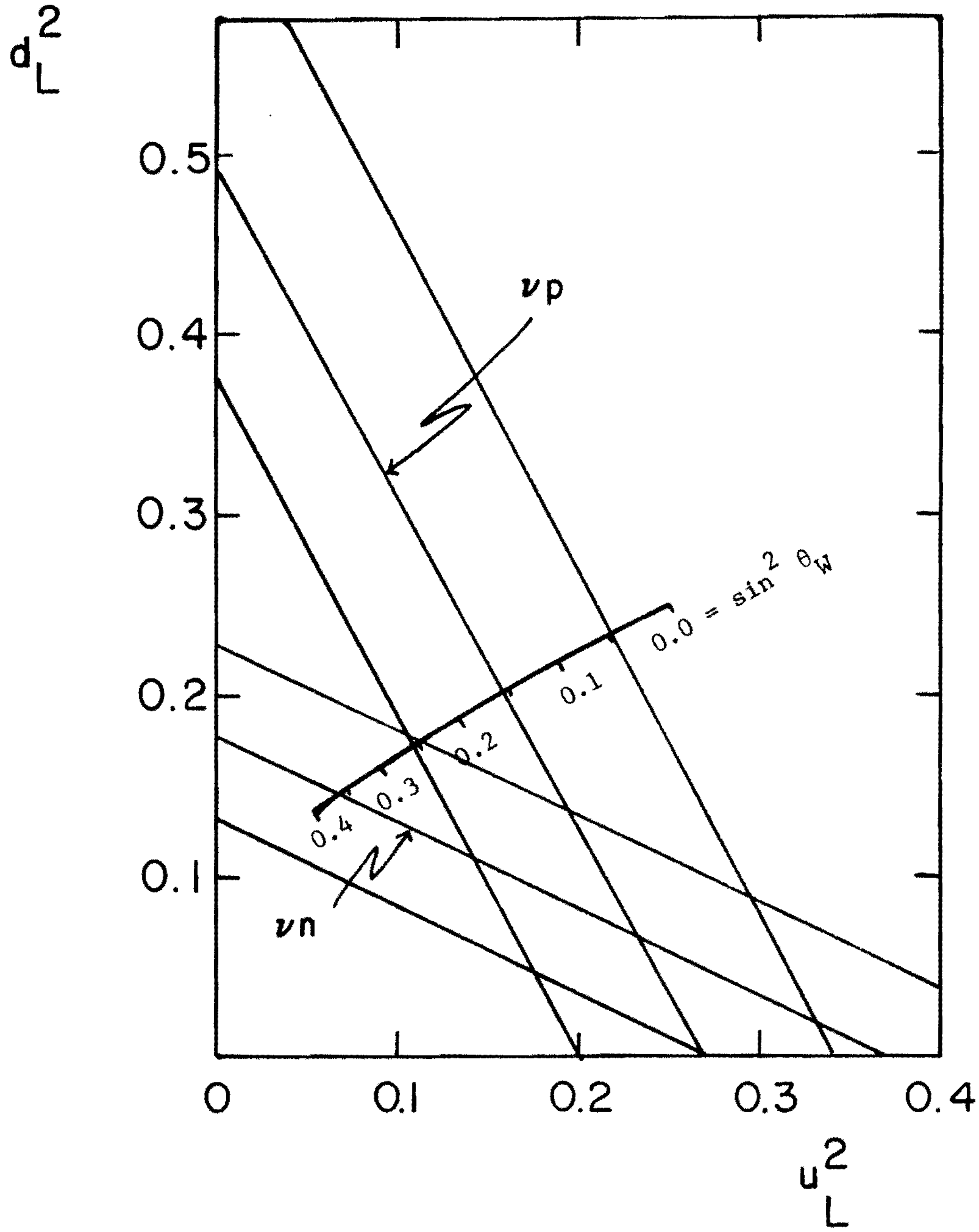

d_L^2
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4
u_L^2
νp
νn
$0.0 = \sin^2 \theta_W$
0.1
0.2
0.3
0.4

Figure 3

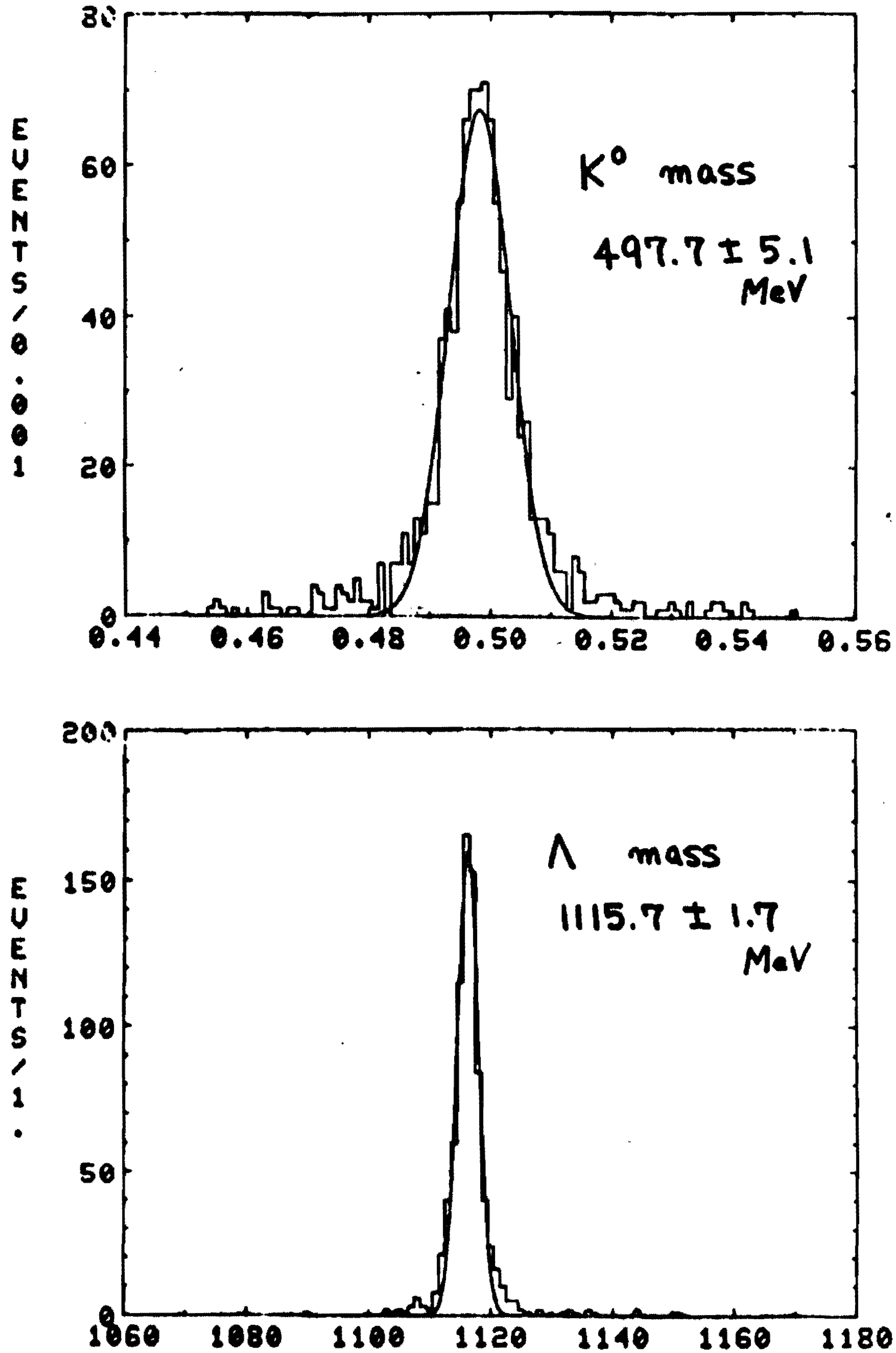
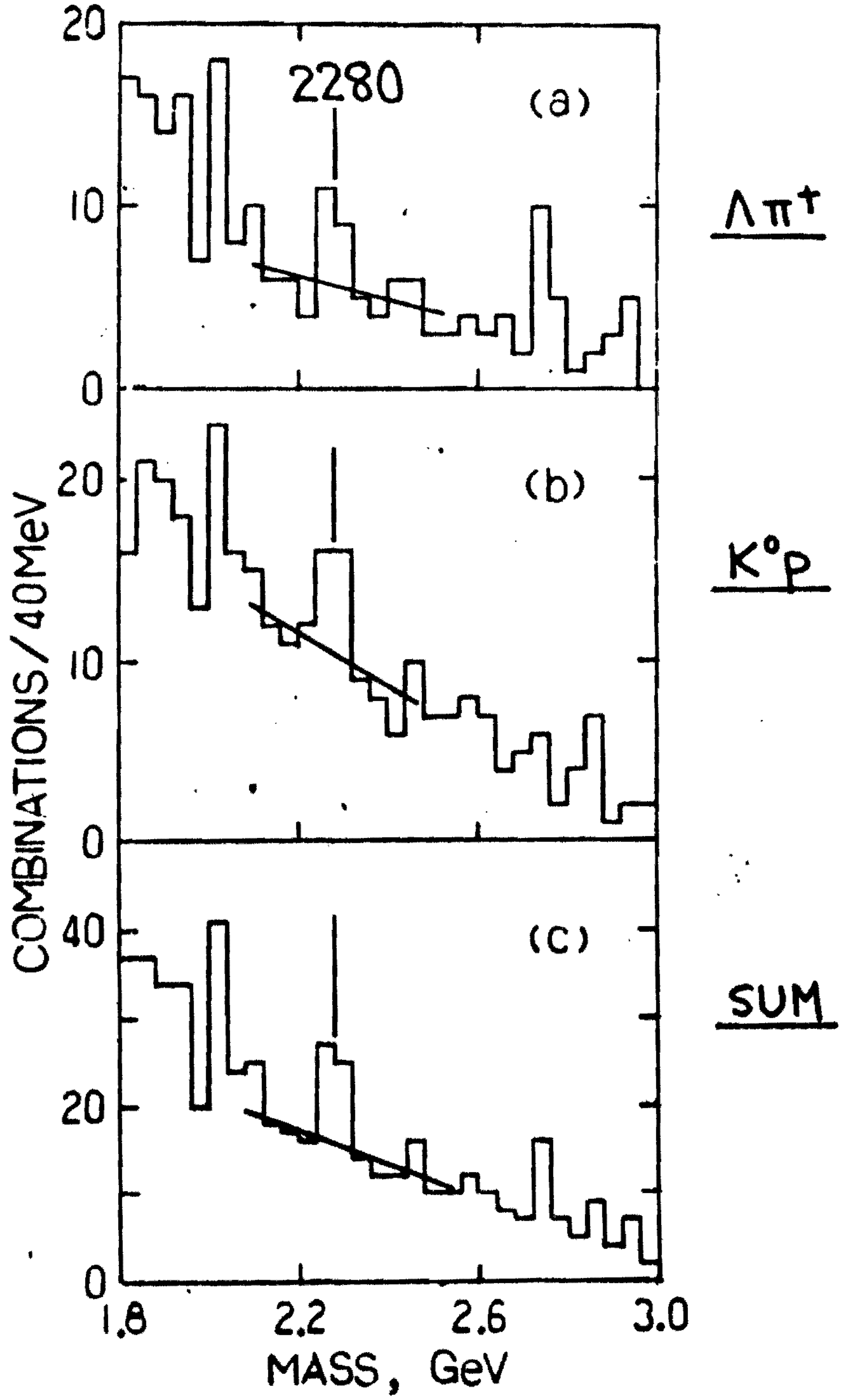

EVENTS/0.001
K^0 mass
497.7 ± 5.1 MeV
0
20
40
60
80
0.44
0.46
0.48
0.50
0.52
0.54
0.56
EVENTS/1.
Λ mass
1115.7 ± 1.7 MeV
0
50
100
150
200
1060
1080
1100
1120
1140
1160
1180

Figure 4



20
10
0
2280
(a)
$\Lambda\pi^+$
20
10
0
(b)
K^0p
40
20
0
(c)
SUM
COMBINATIONS/40MeV
1.8
2.2
2.6
3.0
MASS, GeV

Figure 5

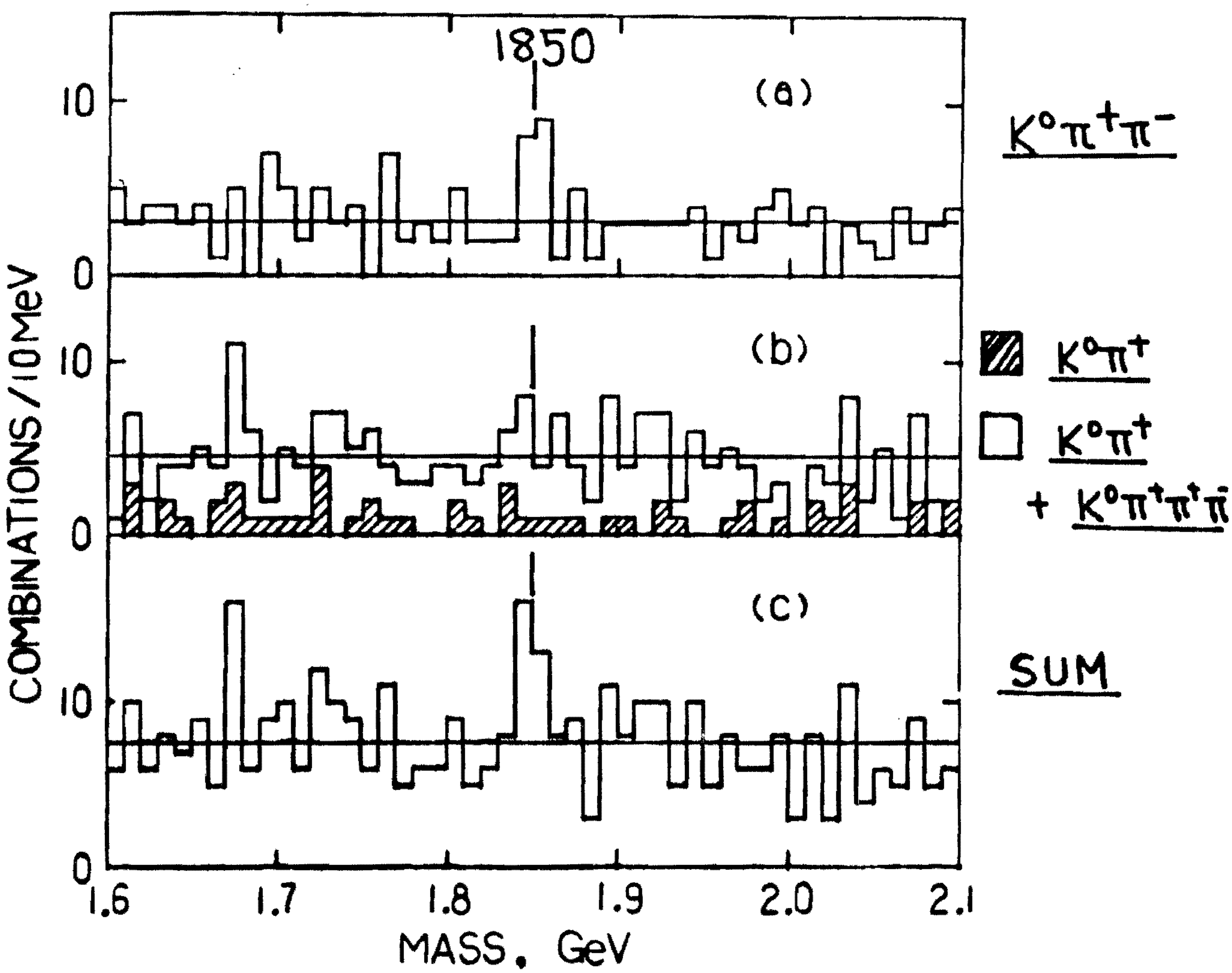

1850
(a)
(b)
(c)
10
0
$K^0\pi^+\pi^-$
$K^0\pi^+$
$K^0\pi^+$
$+ K^0\pi^+\pi^+\pi^-$
SUM
COMBINATIONS/10MeV
1.6
1.7
1.8
1.9
2.0
2.1
MASS, GeV

Figure 6

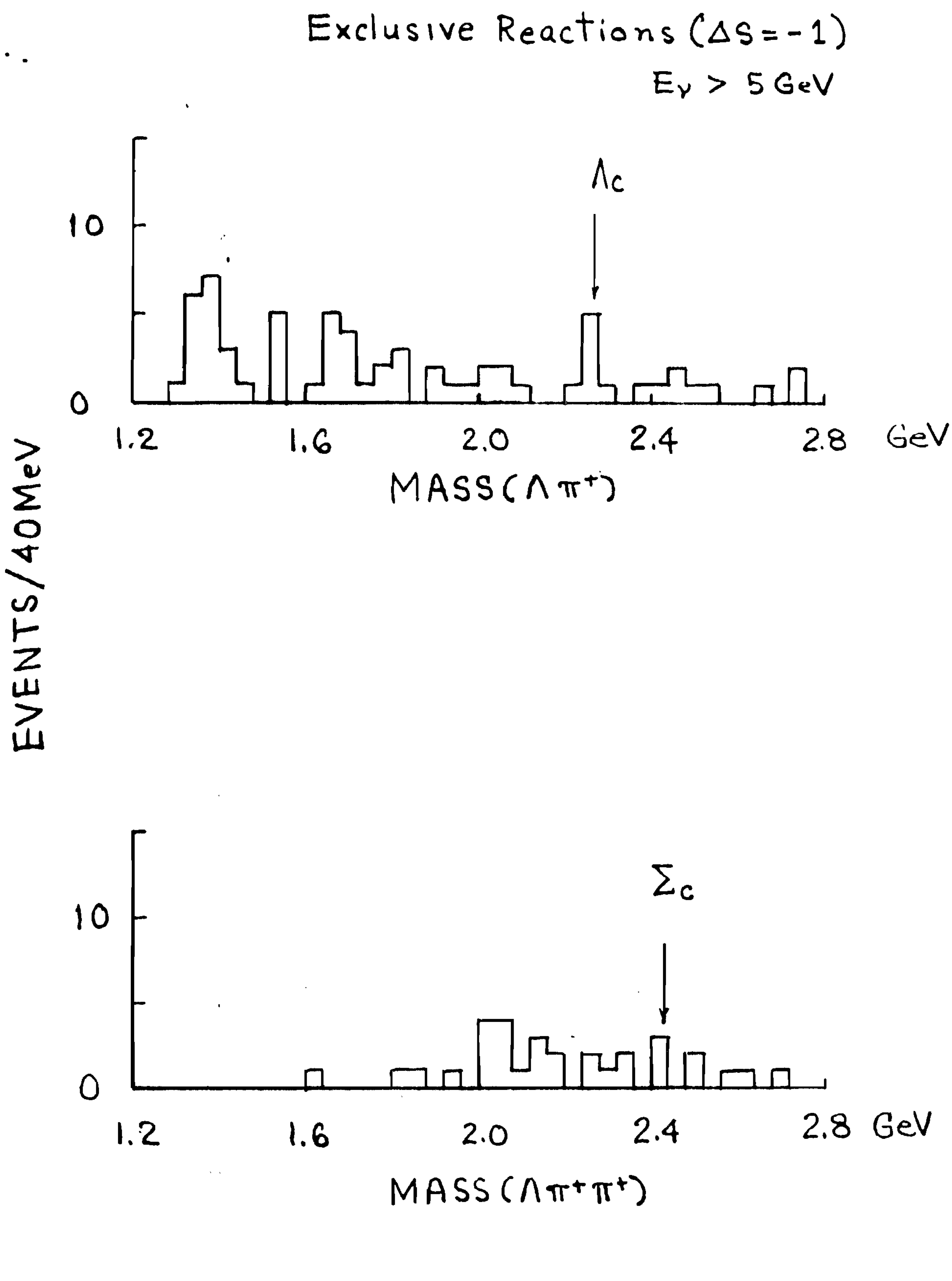

Exclusive Reactions ($\Delta S = -1$)
$E_\gamma > 5$ GeV
Λ_c
10
0
1.2
1.6
2.0
2.4
2.8
GeV
MASS($\Lambda\pi^+$)
EVENTS/40MeV
Σ_c
10
0
1.2
1.6
2.0
2.4
2.8 GeV
MASS($\Lambda\pi^+\pi^+$)

Figure 7

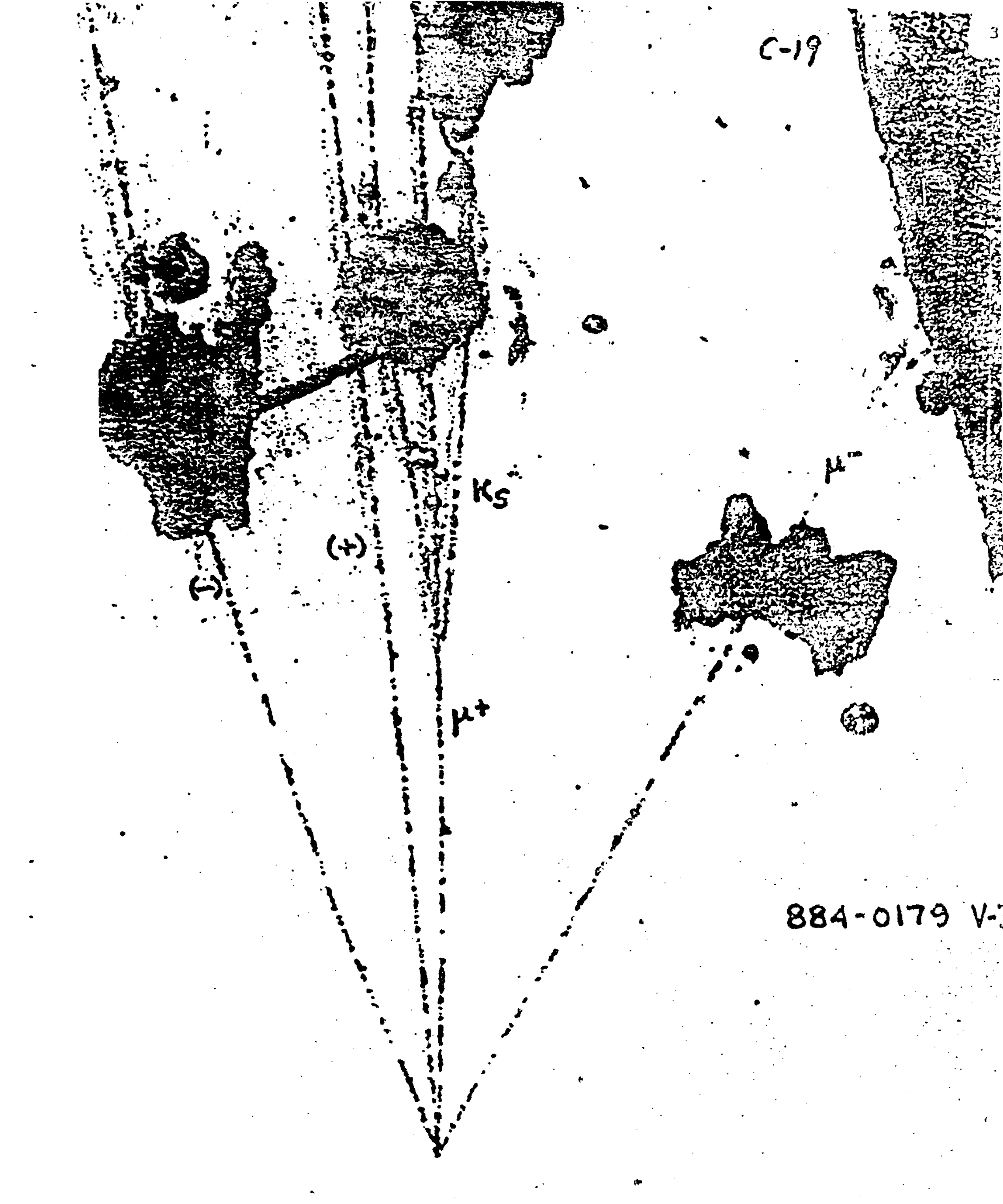


Figure 8

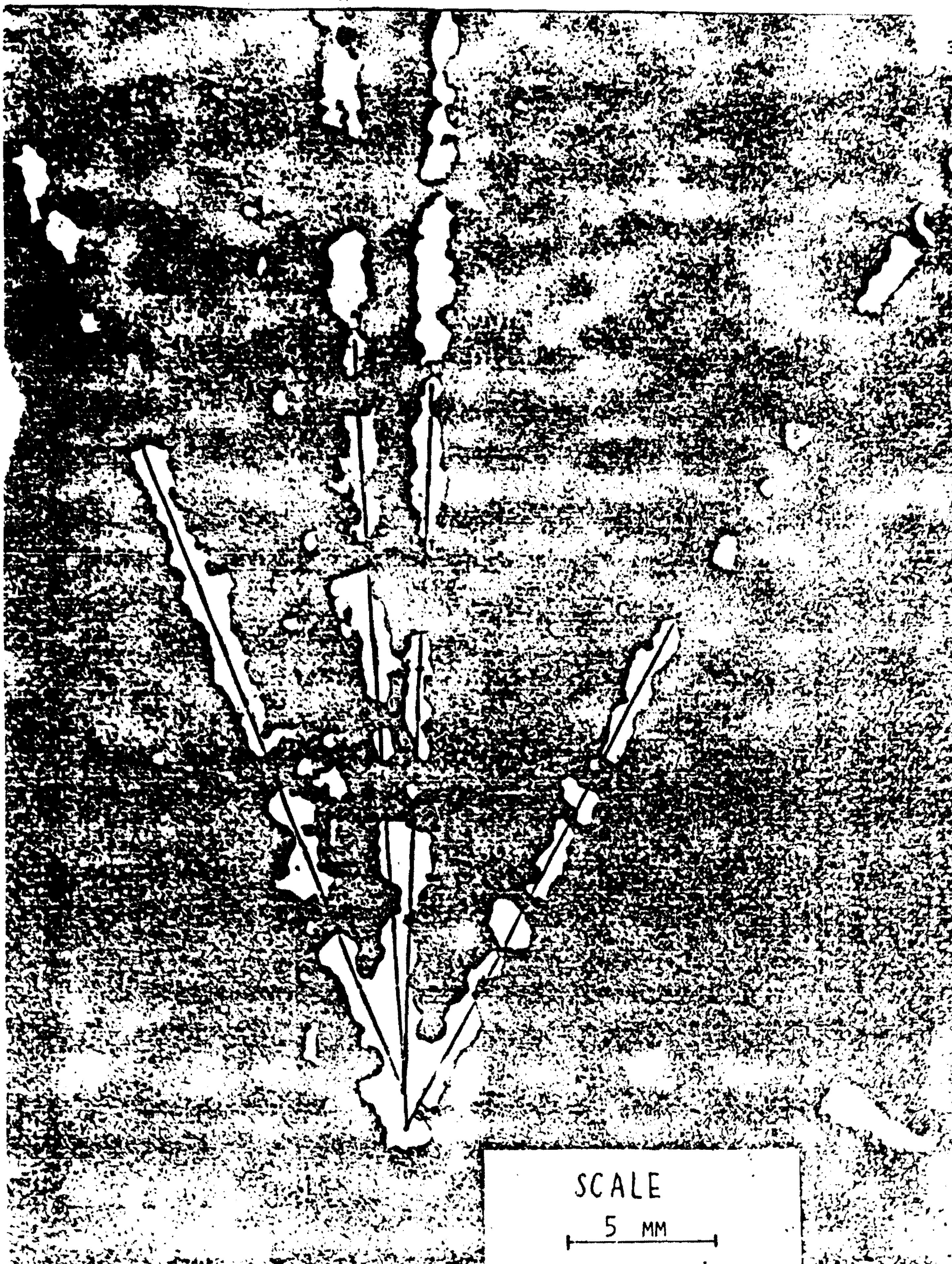


Figure 9

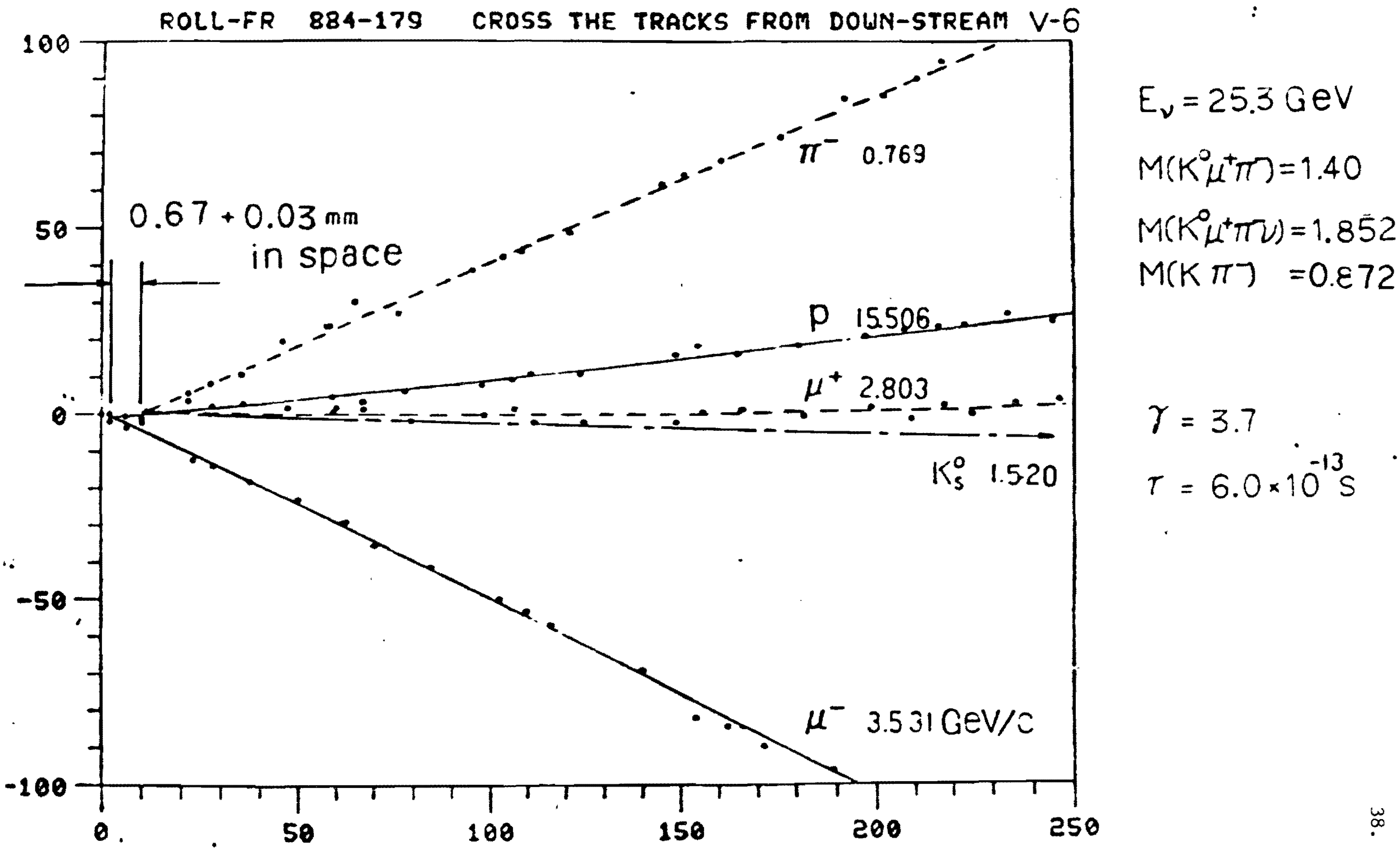

ROLL-FR 884-179 CROSS THE TRACKS FROM DOWN-STREAM V-6
100
50
0
-50
-100
0
50
100
150
200
250
0.67 + 0.03 mm
in space
π⁻ 0.769
p 15.506
μ⁺ 2.803
K°s 1.520
μ⁻ 3.531 GeV/c
Eν = 25.3 GeV
M(K°μ⁺π⁻) = 1.40
M(K°μ⁺π⁻ν) = 1.852
M(Kπ⁻) = 0.872
γ = 3.7
τ = 6.0 × 10⁻¹³ S

Figure 10

APPENDIX A

January 7, 1980

Detection of Neutrino Produced Photons and Electrons by Plates in the 15-ft. Fermilab Bubble Chamber at Tevatron Energies

W.A. Mann and J. Schneps

In 1978 Fermilab approved a test of a downstream plate system inside the 15-foot chamber which was designed for the purpose of detecting photons and electrons from neutrino and antineutrino interactions in hydrogen and deuterium. As it turned out, the plate test was not successful in that the cameras which viewed the regions between plates did not obtain sharp pictures of tracks, and the neutrino-deuterium experiment (E-545) subsequently ran without plates. The antineutrino experiment (E-542) still awaits running time.

According to the Fermilab staff responsible for the plate system (Fig. 1,2), the cure of the problem which led to the difficulty is straightforward. It consists simply in cutting off about ten inches from the top and bottom of the plates so as to eliminate the funneling effect which produced turbulence in the original design. In view of the fact that the plates and their mounting system exist, and that the earlier difficulty can be easily corrected, it becomes evident that reinstallation of the plate system in the chamber may be the simplest and most economical way to achieve good photon and electron detection from neutrino and antineutrino interactions in light liquids. Therefore, it behooves us to examine whether the arguments which would have made the plate system a useful adjunct to the 15-foot chamber at present Fermilab energies still hold true at Tevatron energies, and to compare the plate system to other methods proposed for this purpose.

The advantages of hydrogen or deuterium fills in comparison with heavy liquid fills are the better resolution, the ability to fit exclusive channels, and the reduction of smearing due to Fermi motion and secondary scatters within a heavy nucleus. The disadvantages are in the event rate and the lack of ability to detect photons and electrons in any great number. The plate system can go a long way toward remedying the latter.

We also point out that the use of the plate system reduces the useable fiducial volume of the chamber from $18m^3$ to about $12m^3$, but this is still considerably greater than the $3m^3$ available in the BEBC TST.

We will not review in detail the physics advantages that derive except to point out the following:

1. All information on charmed baryon production in neutrino interactions in bubble chambers comes from the analysis of exclusive channels. With the ability to detect π^0's the number of exclusive charm channels which may be fit may increase substantially. Although much of the charm spectroscopy will be established by the time the Tevatron is available, charm production as a function of neutrino energy and other variables will be of interest.
2. A determination of neutrino energy and the variables x and y depends on a knowledge of the energy and momentum of the neutral particles produced in the interaction. At present a statistical correction is used which results in distributions being smeared. Knowledge of neutral partical momenta will sharpen these distributions.

3. A knowledge of neutral particle energy also makes it possible to achieve a better separation of neutral current interactions and will result in a considerable improvement in neutral current distributions.
4. The hadronization of quarks, particularly of the charmed quarks, is aptly studied in neutrino interactions in light liquids. A proper study should take into account hadronization into neutral as well as charged particles.
5. The reaction $\nu_\mu n \rightarrow p\mu^-$ can be used in deuterium for flux normalization. The plates, used as a γ-ray veto, can rule out background.
6. Using the EMI as a muon detector and the plates as an electron detector, multilepton events in H_2 or D_2 may also be studied.

In 1978 we presented Monte Carlo results on photon and electron detection efficiencies of the "trimmed" plate system for the single horn wide band beam produced by 350 GeV/c protons. For exclusive channel photon production containing π^0's, we used as input real events of the type $\nu_\mu p \rightarrow \mu^- p \pi^+$ and $\nu_\mu p \rightarrow \mu^- p + N\pi$'s, $N = 2-6$, treating the charged pions as π^0's. For inclusive charged current processes we used γ's observed in heavy neon-hydrogen. Simulation of $e^\pm$ production was done using published distributions from the reaction $\nu_\mu N \rightarrow \mu^- e^+ X$. Probabilities for observing γ and $e^\pm$ induced showers in the 13mm steel plates were estimated from shower tables for copper and probabilities for γ conversion in liquid deuterium were determined from hydrogen data.

We have now extended the calculations to neutrino beams produced by protons of 800 and 1000 GeV/c, using the neutrino energy spectra given by H. Mori. The results are shown in the accompanying figures. Figures 3 and 4 show the momentum and production angle distributions for photons from the exclusive final state $\mu^- p\, \pi^0$". Figure 5 shows the number of plates along the line of flight of photons from this final state. Figures 6, 7 and 8 give the same information for inclusive photons from the final states $\mu^- V^0 X + \gamma's$. Figure 9 shows photon detection efficiencies as a function of E_{vis} for both categories of events, and Figure 10shows this as a function of final state photon multiplicity. Finally, Figure 11 shows the capability of the plates for vetoing final states containing π^0's.

At 350 GeV/c we conclude that the detection efficiency is 72% of γ's from inclusive processes and 36% of γ's from the one π^0 channel. The 72% detection efficiency would make it possible to reduce the undetected hadronic energy in inclusive processes to the 10% level. The system's utility for separating fittable exclusive channels is seen from Fig. 11. It is $\gtrsim$ 85% effective as a shield against final states with 2 or more π^0's. In the case of single π^0 final states, the system is $\gtrsim$ 70% effective if one or more charged pions is produced along with the π^0. Only for events where the only pion produced is the single π^0 does the efficiency drop below 50%. At 800 and 1000 GeV/c, as the figures show, the conclusions are almost identical, there being only a slight increase in detection efficiencies.

Up to this point we have emphasized the improvement in the determination of total neutral energy and momentum and in the use of the platesas a π^0 veto. It may also be possible to make some use of the plate information to reconstruct π^0's and use them in exclusive channel fits. Using the predicted uncertainty of $\sim$30% in γ energies, the Purdue group, in a Monte Carlo simulation, found a π^0 mass peak with FWHM of $\sim$80 MeV. Use of the kinematics of the production vertex will improve this.

The efficiency for finding $e^{\pm}$ from the final state $\mu^- e^+ X$ was found to be $\sim 73\%$. It is then necessary to know what kind of background to $e^{\pm}$ events could be caused by $\pi^{\pm}$ incident on the plates. The BC-65 experiment at SLAC, using three tantalum plates of 1.0 radiation length, showed that at 1.6 GeV/c only one $\pi^{\pm}$ in 20,000 caused a fake $e^{\pm}$ shower and at 3.1 GeV/c only one in 100,000 did so, whereas true $e^{\pm}$ tracks caused a good signature $(94 \pm 1)\%$ of the time. The Japanese group at Tohoku, using two tantalum plates each of 1.6 radiation lengths, found one in 10,000 $\pi^{\pm}$ simulated an $e^{\pm}$ shower. The pions came from $\pi^- p$ interactions at 8 GeV/c and the result is consistent with the SLAC data. Based on this data it is estimated that in the proposed 15-foot plate system one $\pi^{\pm}$ in 7000 will fake an $e^{\pm}$ at 1.6 GeV/c and one in 30,000 will do so at 3.1 GeV/c, while $\sim 95\%$ of true $e^{\pm}$ will be identified.

A downstream plate array poses new possibilities and also some problems for identifications and measurement of charged hadrons and muons in neutrino events. It has been pointed out that energetic protons which interact upstream of the plates would, on the average, yield less energetic electromagnetic showers in the plates than would secondary interactions of π^+ mesons, hence the plates would enable some discrimination.(1) The probability that a hadron of several GeV/c momentum undergoes a hadronic interaction in traversing a plate is $\sim 7\%$. For negative tracks, this additional scattering within the visible chamber volume provides discrimination between final state π^-'s and μ^-'s. On the other hand, multiple scattering in the plates and reduction of measurable track length due to strong interactions in the plates will result in reduced momentum resolution for charged tracks. In the available fiducial volume upstream of the plate array, all primary vertices and secondary V° vertices are measured in liquid deuterium where track reconstruction is optimal.

Furthermore, track lengths greater than a meter will be typical. However, improved charged track resolution could be achieved by measuring tracks through the plates. The motivation for doing this is indicated by Figure 12, which shows that, in existing FNAL wide-band exposures, track momenta for charged hadrons and muons are typically 0-20 GeV/c (Figs. 12a, b)[(2)] for which track lengths of 1-2 meters are ideal (Fig. 12c)[(3)]. In neutrino reactions at the Tevatron the muon momentum spectrum will shift upward by tens of GeV/c. In order to avoid substantial deterioration of momentum resolution and in order to associate muon tracks with EMI hits, candidate muon tracks will certainly need to be reconstructed through the plate array; moreover, reconstruction of all charged tracks through the plates should probably be attempted.

FOOTNOTES AND REFERENCES

1. FNAL Proposal E-542, "Proposal for an Extension of E(31)/(390) to Study $\bar{\nu}p/\bar{\nu}n$ Interactions in the 15-Foot Bubble Chamber with γ-Converting Plates", Spokesman: A.F. Garfinkel.

2. Data from $\nu_\mu \cdot N$ Exposures: Fig. 12a. IIT, Maryland, Stony Brook, Tohoku, Tufts Collaboration (E-545). Fig. 12b. Columbia-BNL Collaboration, Thesis by E.E. Schmidt, Jr.

3. Fig. 12c from J. Lach, "Strong Interaction Physics in the NAL Bubble Chamber", in Proceedings of International Conference on Bubble Chamber Technology, Vol. I, p.42, June 1970.

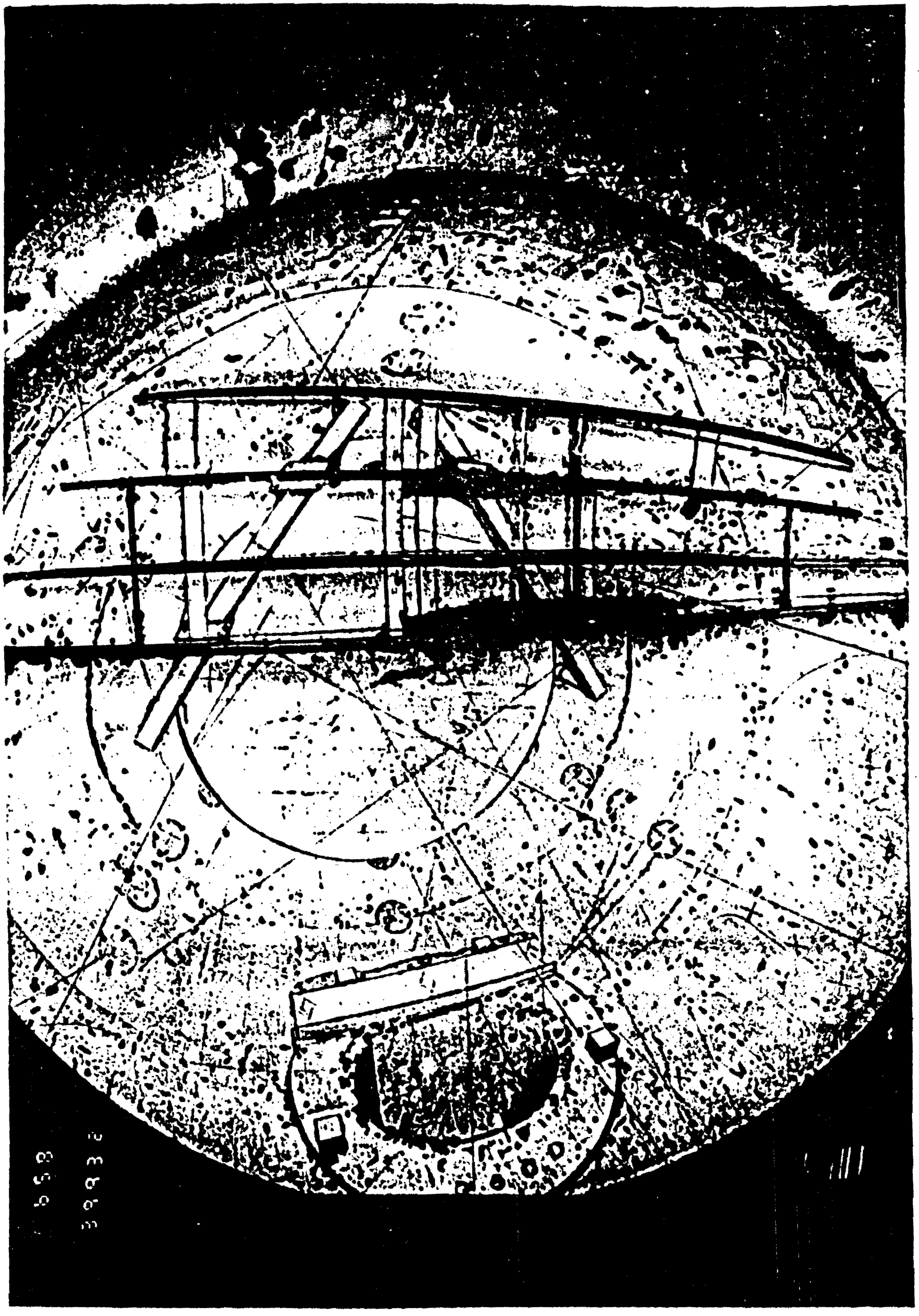
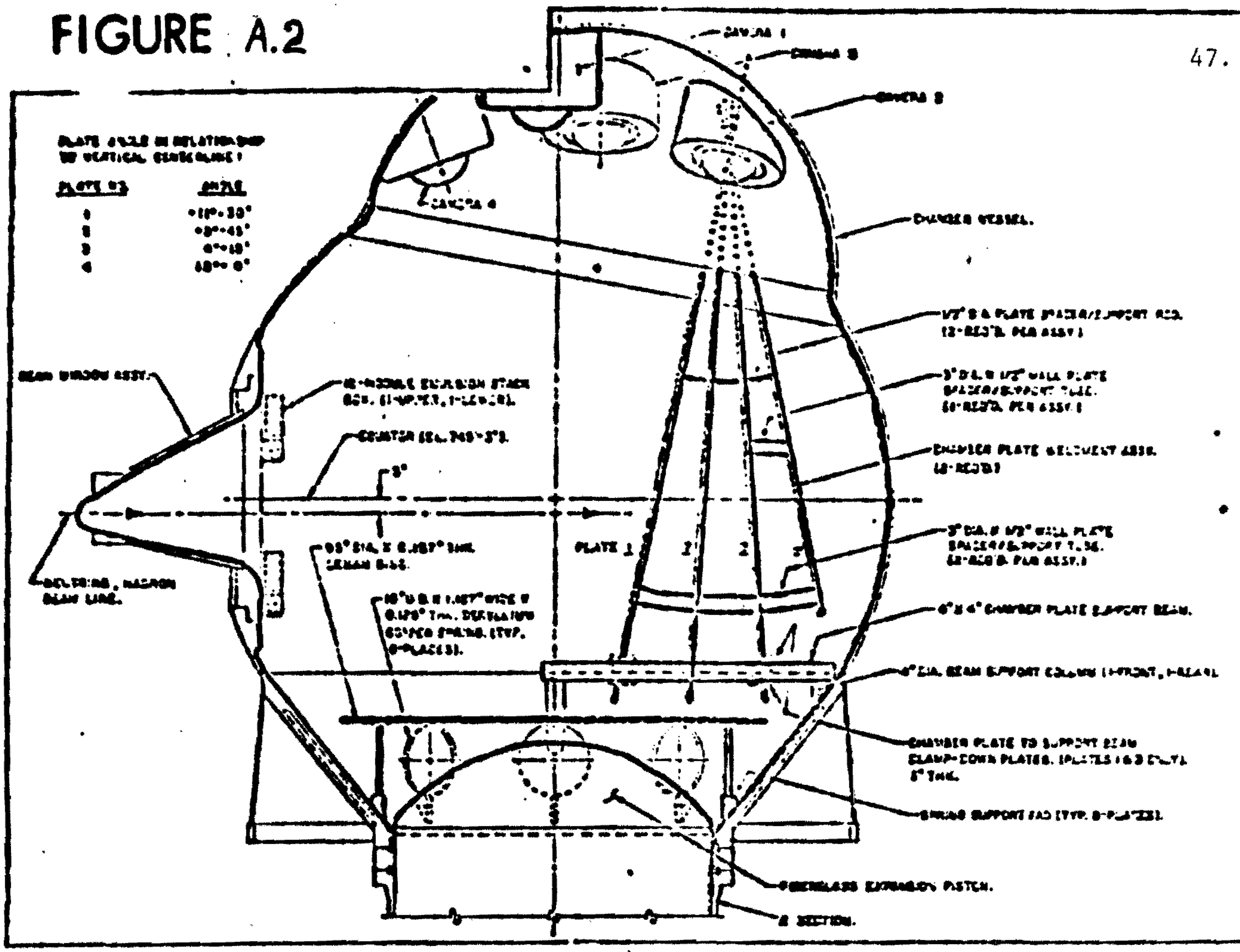


FIGURE A.1

FIGURE A.2



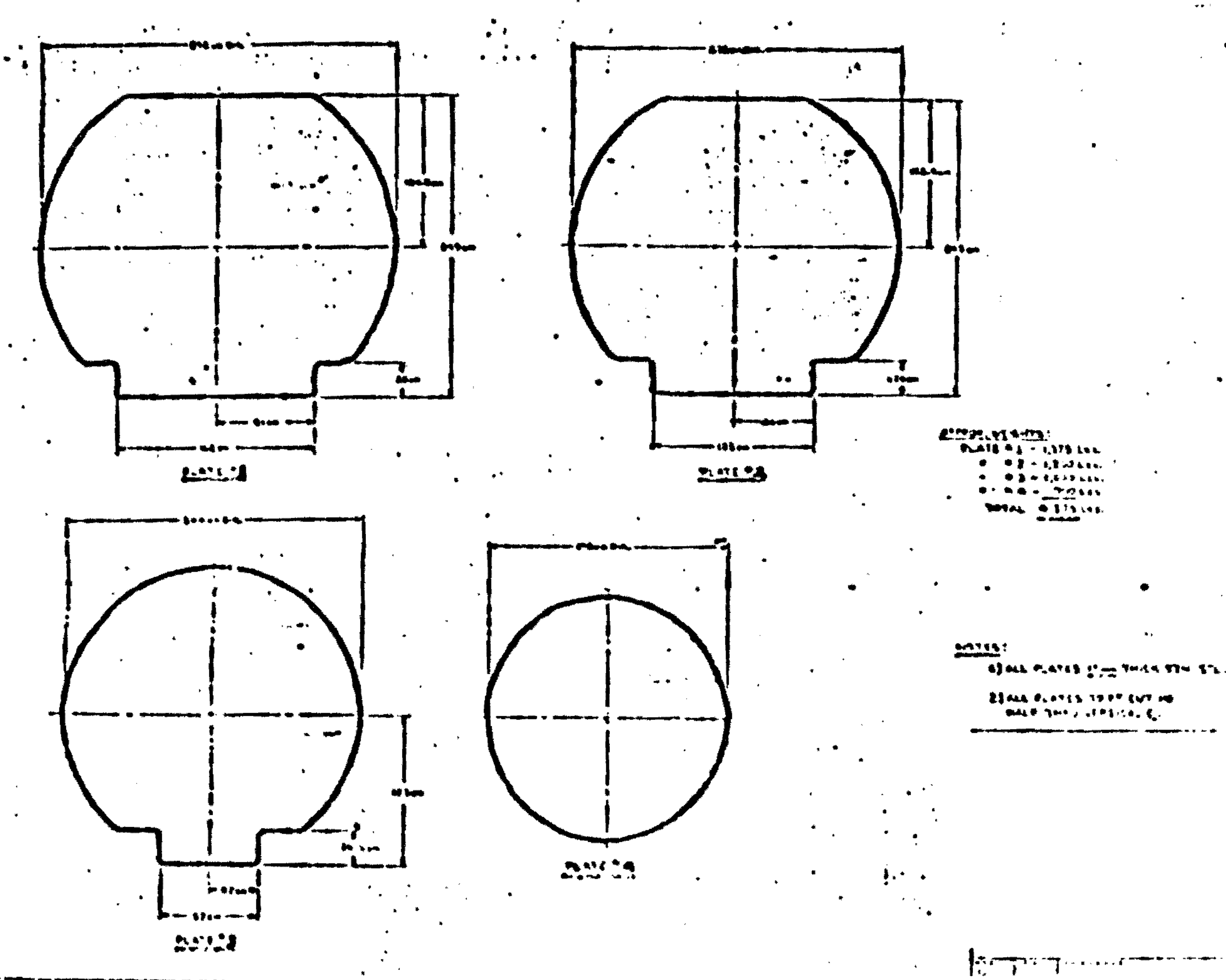


Fig. A.3

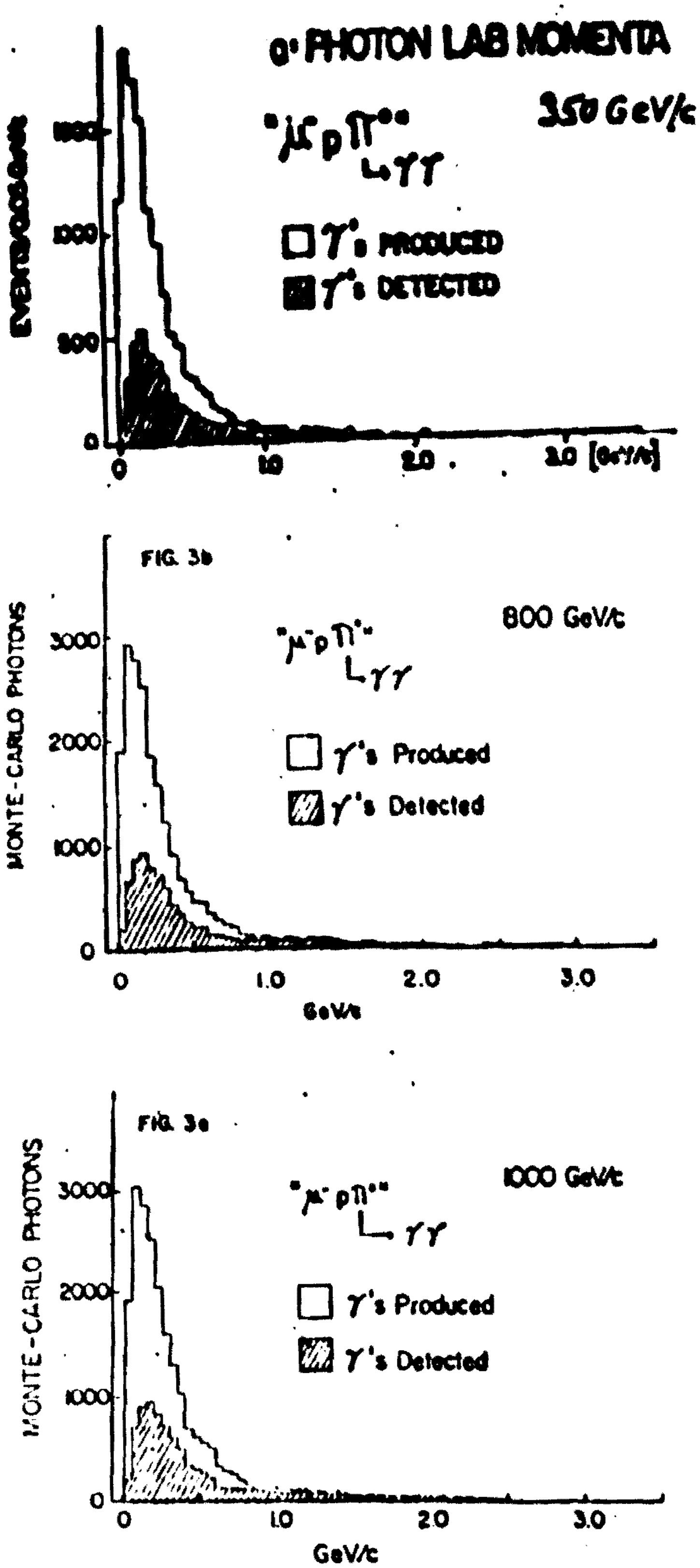

a: PHOTON LAB MOMENTA
350 GeV/c
"$\mu^- p \pi^{\circ}$"
$\hookrightarrow \gamma\gamma$
γ's PRODUCED
γ's DETECTED
0
500
1000
1500
0
1.0
2.0
3.0 [GeV/c]
FIG. 3b
800 GeV/c
"$\mu^- p \pi^{\circ}$"
$\gamma\gamma$
γ's Produced
γ's Detected
MONTE-CARLO PHOTONS
0
1000
2000
3000
0
1.0
2.0
3.0
GeV/c
FIG. 3c
1000 GeV/c
"$\mu^- p \pi^{\circ}$"
$\gamma\gamma$
γ's Produced
γ's Detected
MONTE-CARLO PHOTONS
0
1000
2000
3000
0
1.0
2.0
3.0
GeV/c

Fig. A.4

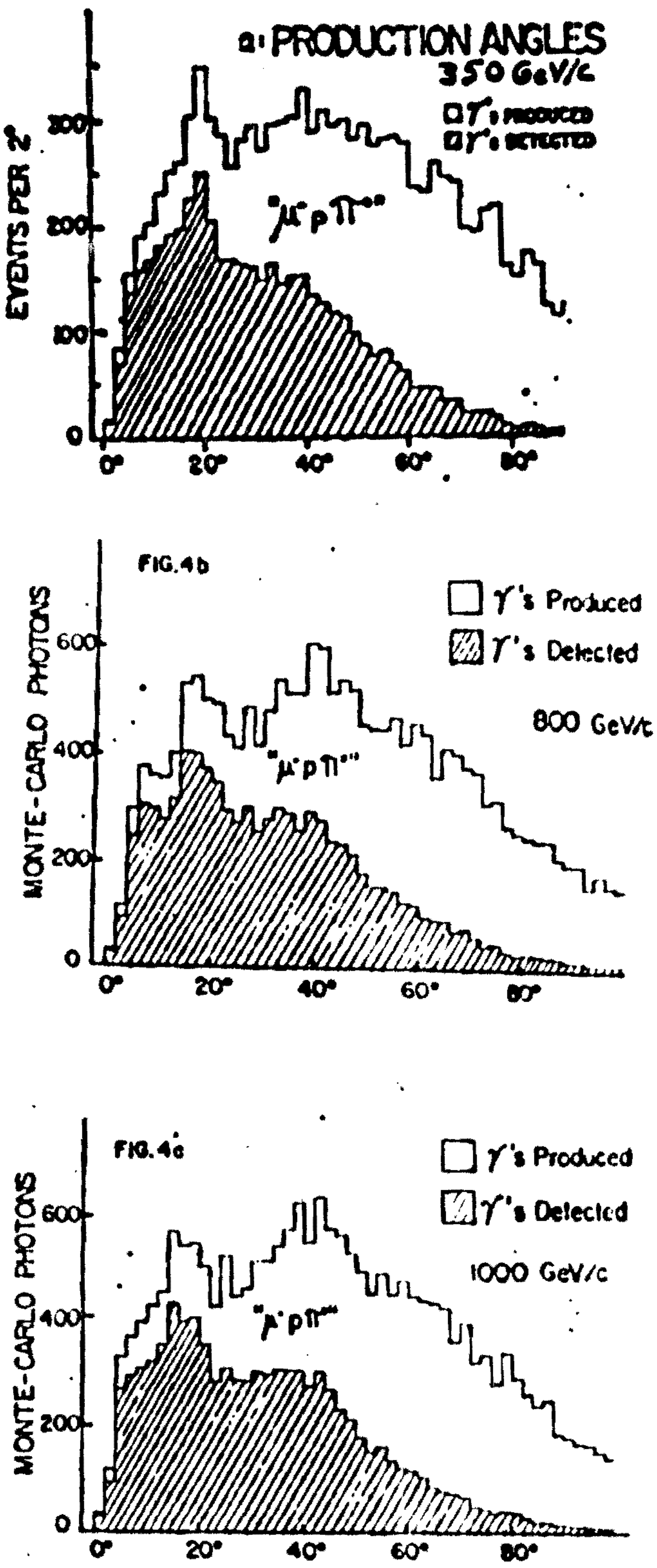

a: PRODUCTION ANGLES
350 GeV/c
γ's PRODUCED
γ's DETECTED
"$\mu^- p \pi^{\circ}$"
EVENTS PER 2°
0
100
200
300
0°
20°
40°
60°
80°
FIG. 4b
γ's Produced
γ's Detected
800 GeV/c
"$\mu^- p \pi^{\circ}$"
MONTE-CARLO PHOTONS
0
200
400
600
0°
20°
40°
60°
80°
FIG. 4c
γ's Produced
γ's Detected
1000 GeV/c
"$\mu^- p \pi^{\circ}$"
MONTE-CARLO PHOTONS
0
200
400
600
0°
20°
40°
60°
80°

Fig. A.5

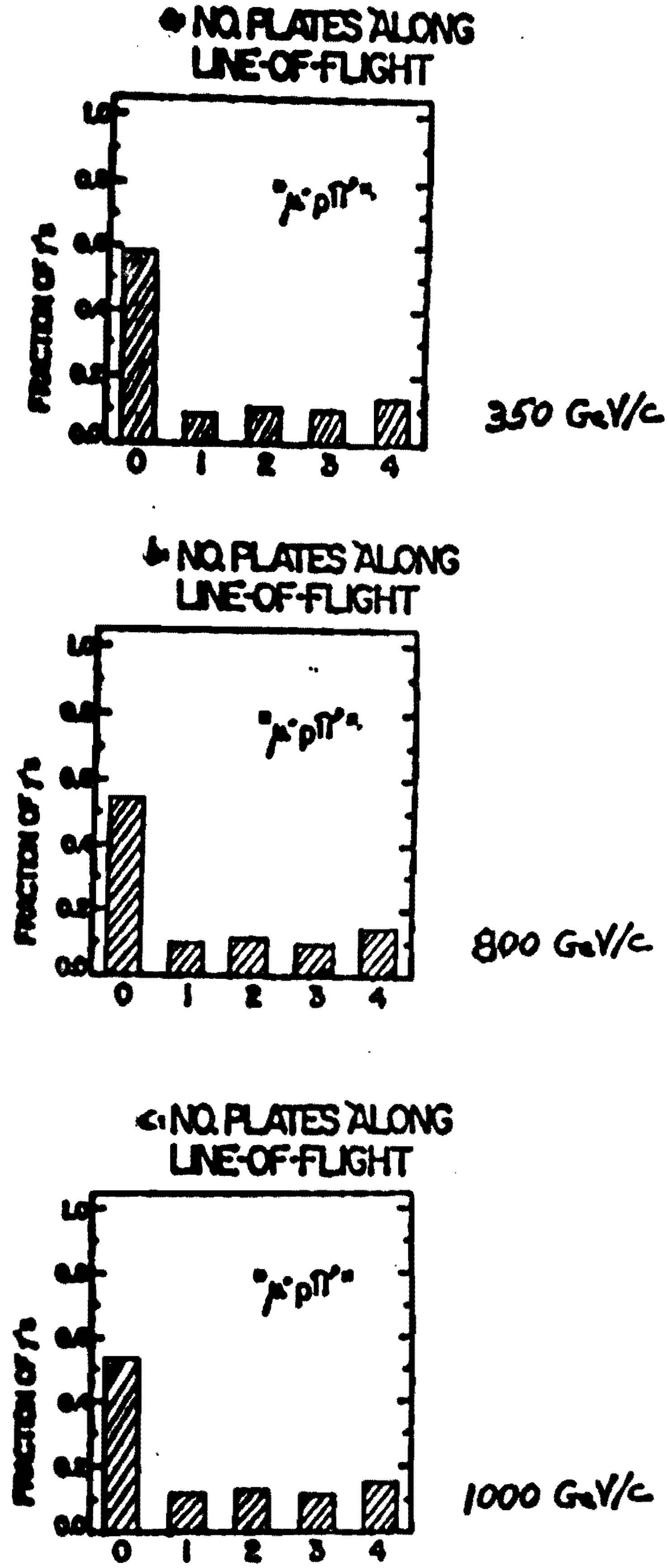

a) NO. PLATES ALONG LINE-OF-FLIGHT
"μ⁺pπ⁺"
FRACTION OF γ's
0 1 2 3 4
350 GeV/c
b) NO. PLATES ALONG LINE-OF-FLIGHT
"μ⁺pπ⁺"
FRACTION OF γ's
0 1 2 3 4
800 GeV/c
c) NO. PLATES ALONG LINE-OF-FLIGHT
"μ⁺pπ⁺"
FRACTION OF γ's
0 1 2 3 4
1000 GeV/c

Fig. A.6

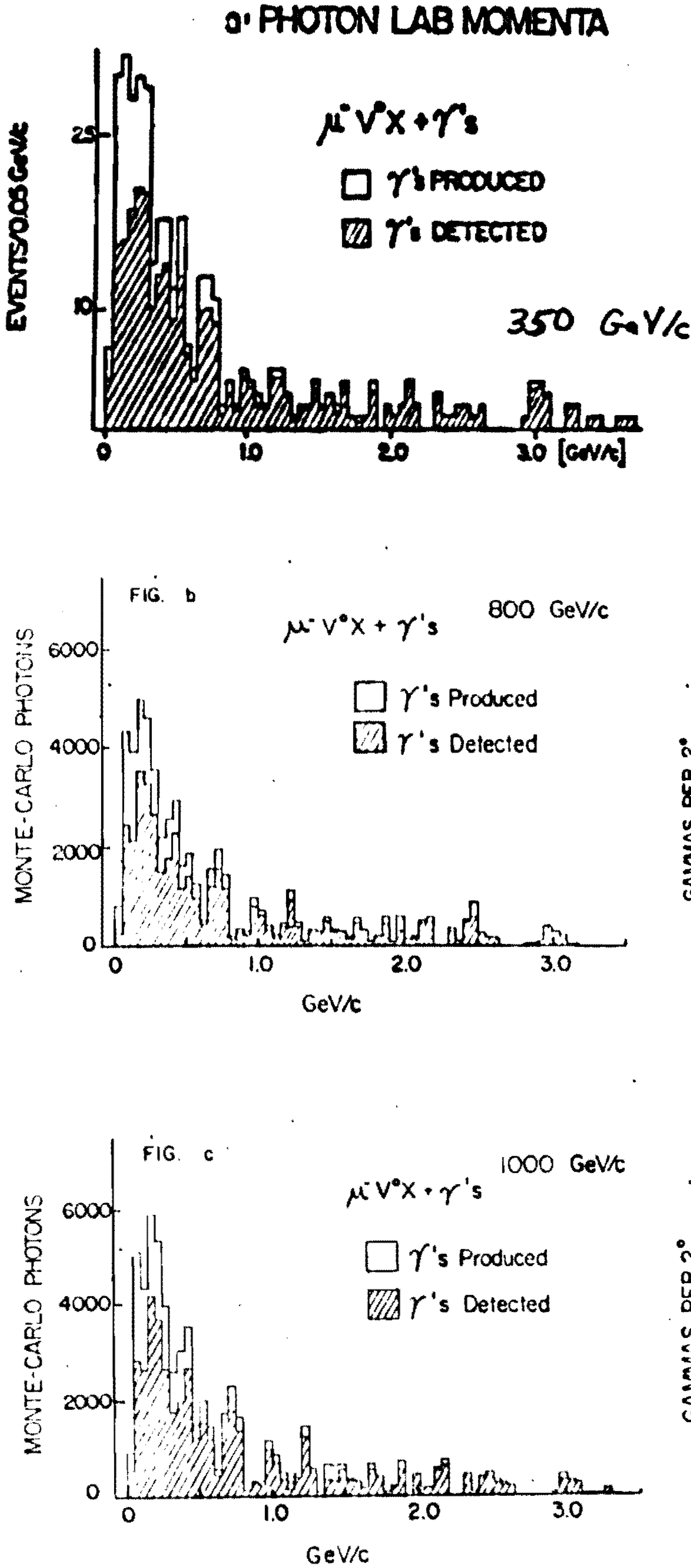

a: PHOTON LAB MOMENTA
$\mu^- V^\circ X + \gamma$'s
γ's PRODUCED
γ's DETECTED
350 GeV/c
EVENTS/0.05 GeV/c
[GeV/c]
FIG. b
800 GeV/c
$\mu^- V^\circ X + \gamma$'s
γ's Produced
γ's Detected
MONTE-CARLO PHOTONS
GeV/c
FIG. c
1000 GeV/c
$\mu^- V^\circ X + \gamma$'s
γ's Produced
γ's Detected
MONTE-CARLO PHOTONS
GeV/c

Fig. A.7

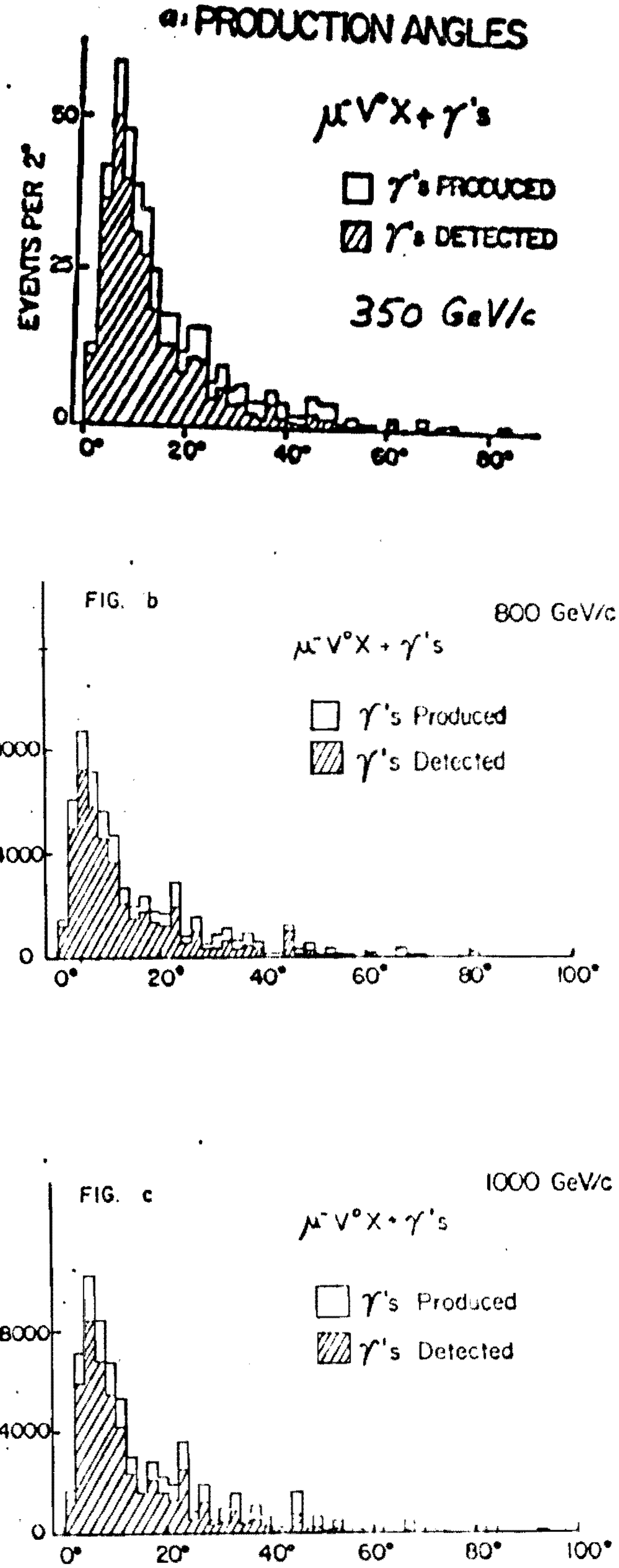
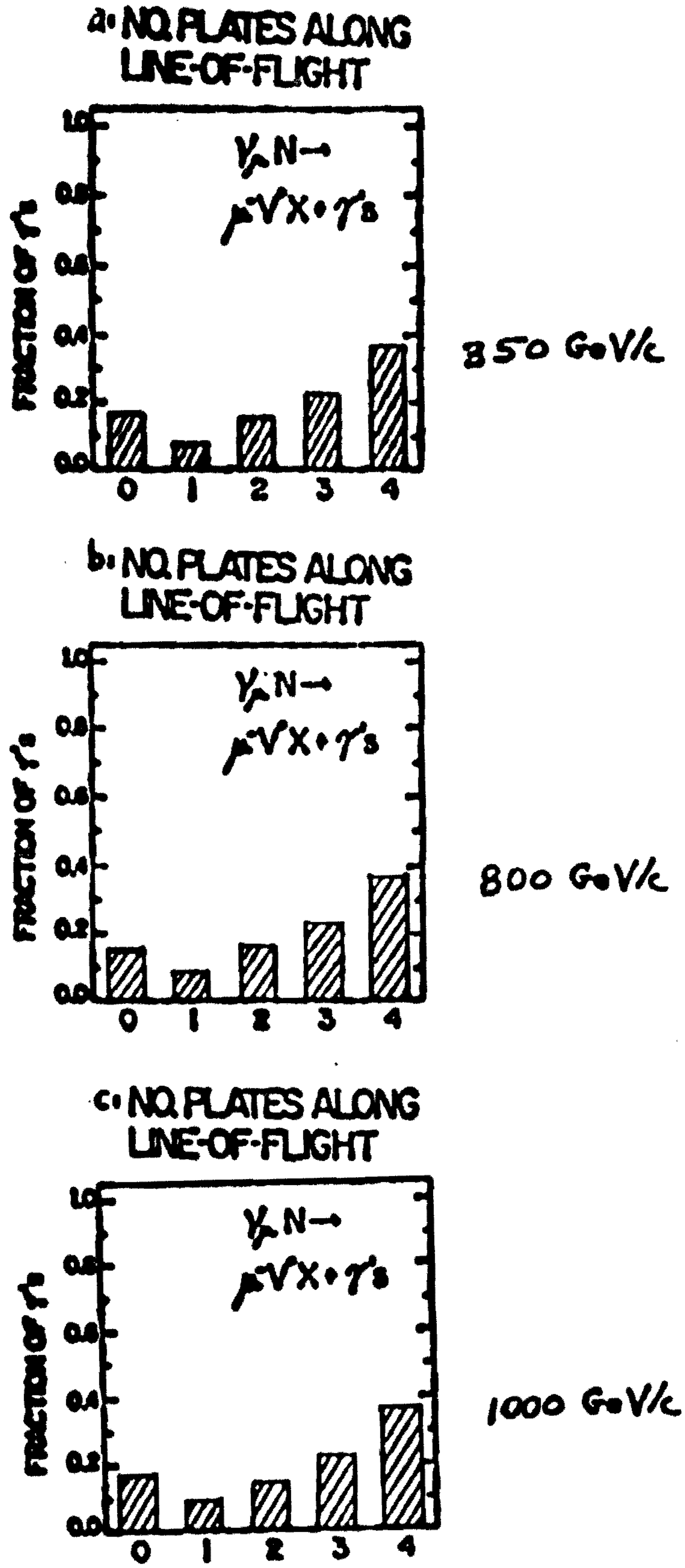

a: PRODUCTION ANGLES
$\mu^- V^\circ X + \gamma$'s
γ's PRODUCED
γ's DETECTED
350 GeV/c
EVENTS PER 2°
FIG. b
800 GeV/c
$\mu^- V^\circ X + \gamma$'s
γ's Produced
γ's Detected
GAMMAS PER 2°
FIG. c
1000 GeV/c
$\mu^- V^\circ X + \gamma$'s
γ's Produced
γ's Detected
GAMMAS PER 2°

Fig. A.8


a. NO. PLATES ALONG LINE-OF-FLIGHT
$\nu_\mu N \rightarrow \mu^- V X + \gamma$'s
FRACTION OF γ's
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
850 GeV/c
b. NO. PLATES ALONG LINE-OF-FLIGHT
$\nu_\mu N \rightarrow \mu^- V X + \gamma$'s
FRACTION OF γ's
800 GeV/c
c. NO. PLATES ALONG LINE-OF-FLIGHT
$\nu_\mu N \rightarrow \mu^- V X + \gamma$'s
FRACTION OF γ's
1000 GeV/c

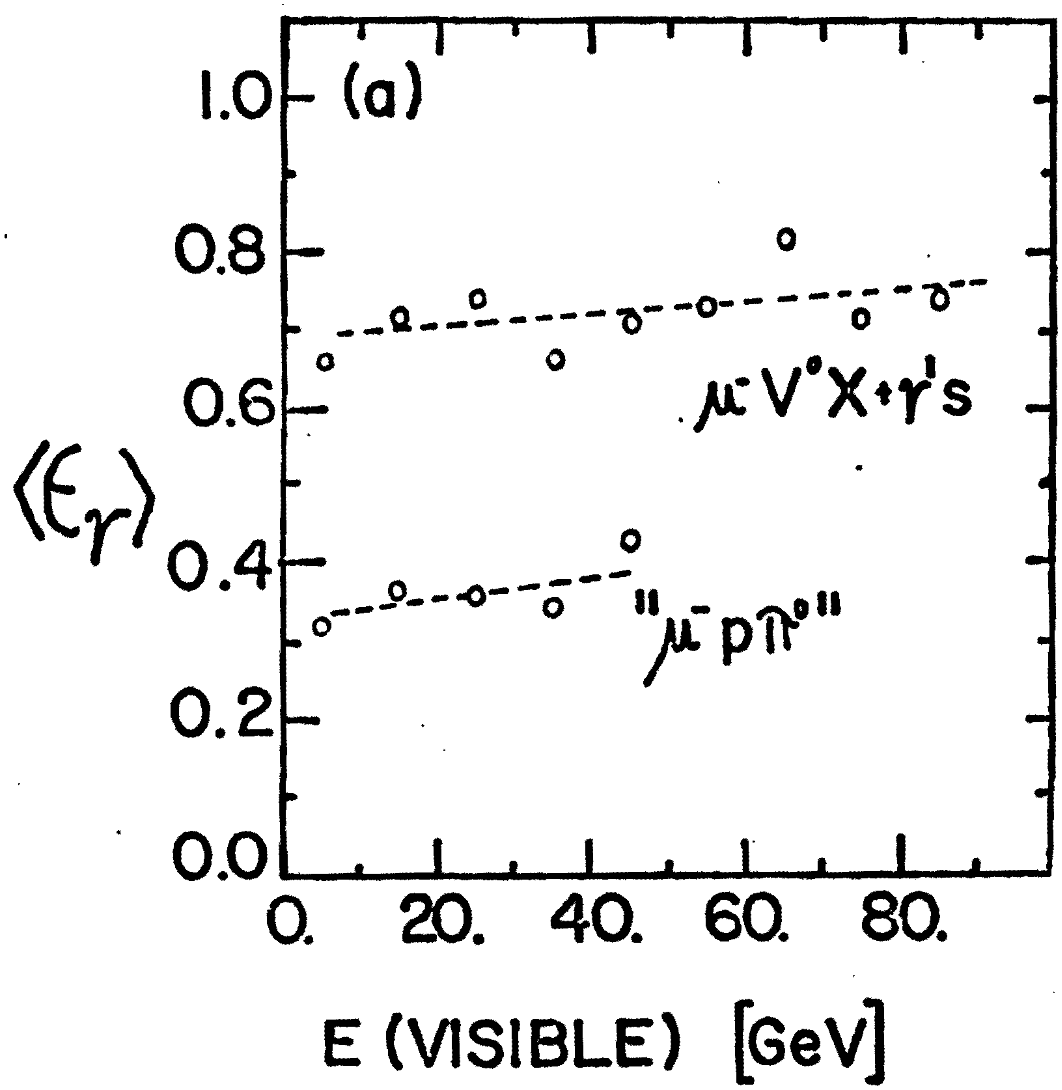


FIGURE A.9

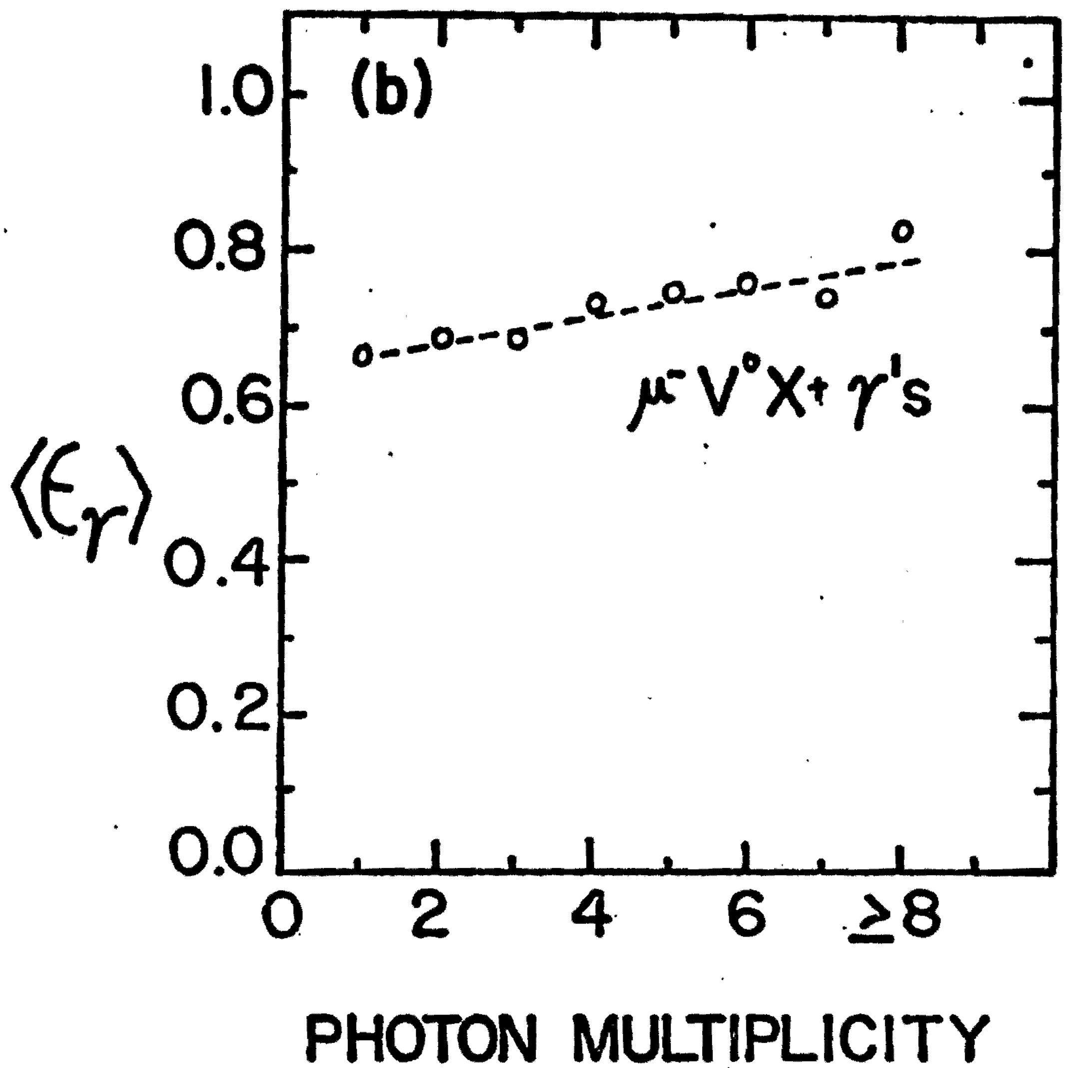
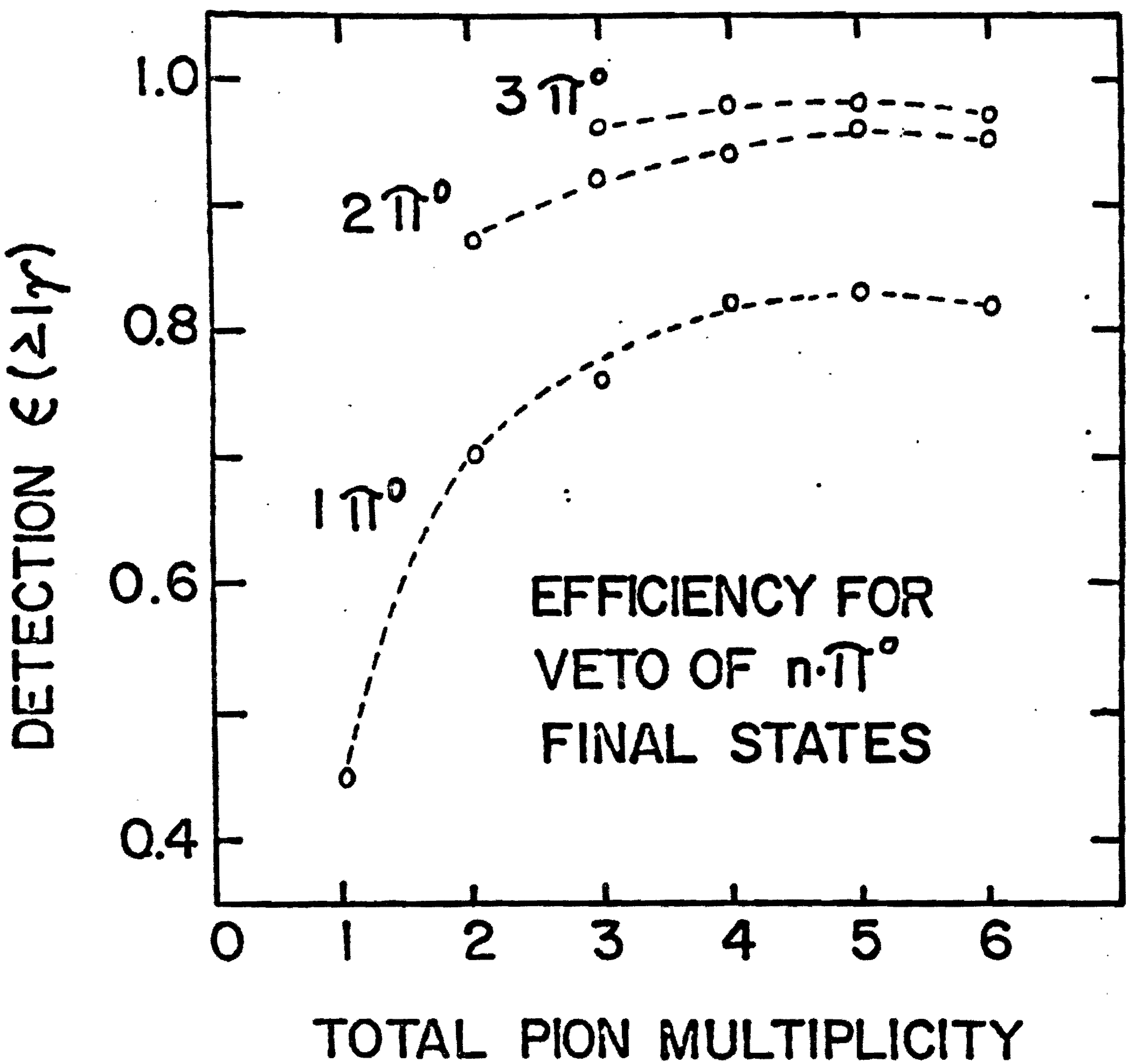

1.0
0.8
0.6
0.4
0.2
0.0
(b)
$\langle \epsilon_\gamma \rangle$
$\mu^- V^\circ X + \gamma$'s
0
2
4
6
≥8
PHOTON MULTIPLICITY

FIGURE A.10



1.0
0.8
0.6
0.4
0
1
2
3
4
5
6
DETECTION $\epsilon(\geq 1\gamma)$
TOTAL PION MULTIPLICITY
$3\pi^0$
$2\pi^0$
$1\pi^0$
EFFICIENCY FOR
VETO OF $n\cdot\pi^0$
FINAL STATES

FIGURE A.11

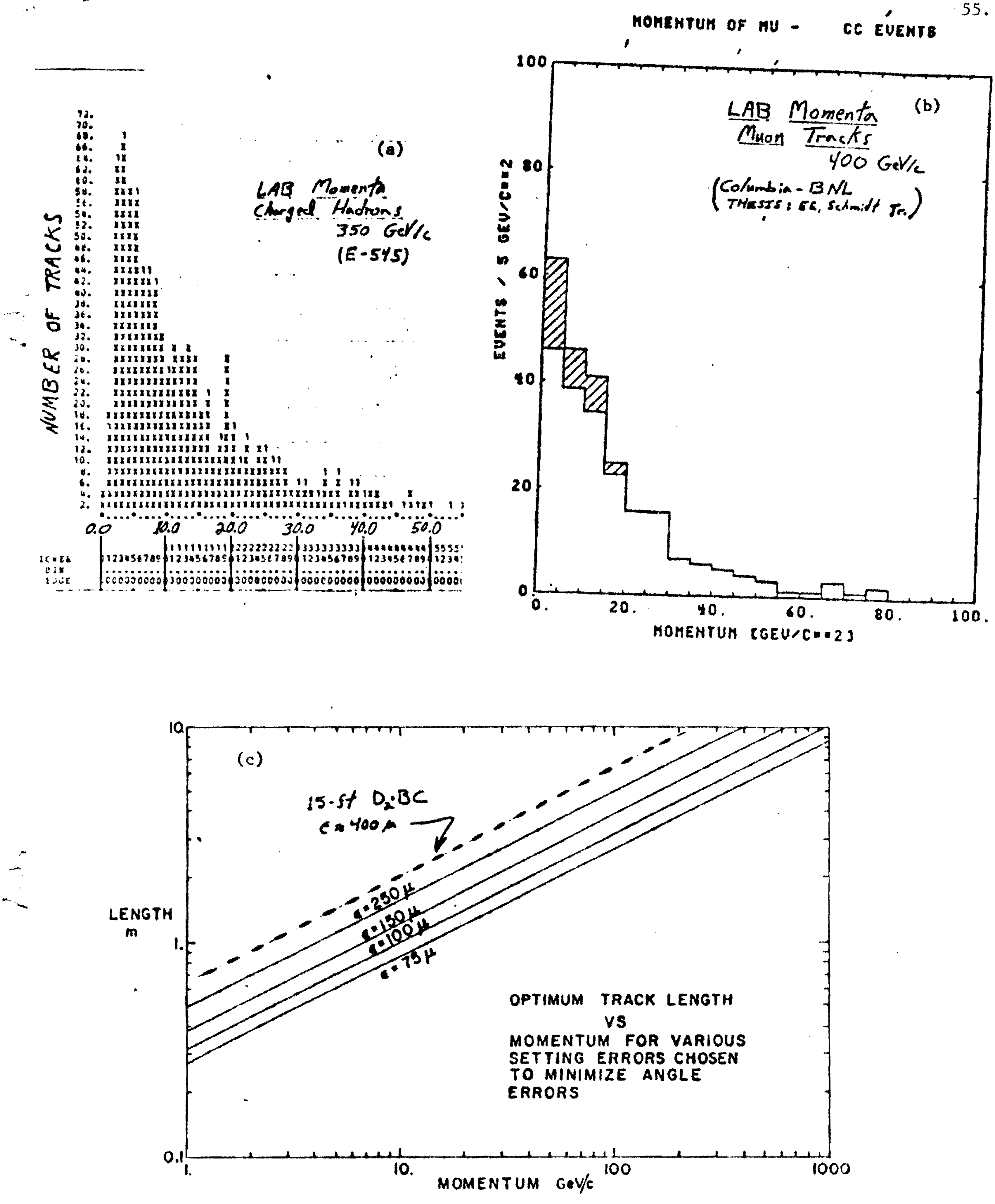

(a)
LAB Momenta
Charged Hadrons
350 GeV/c
(E-545)
NUMBER OF TRACKS
0.0
10.0
20.0
30.0
40.0
50.0
MOMENTUM OF MU - CC EVENTS
(b)
LAB Momenta
Muon Tracks
400 GeV/c
(Columbia - BNL
THESIS : E.C. Schmidt Jr.)
EVENTS / 5 GEV/C**2
MOMENTUM [GEV/C**2]
(c)
15-ft D$_2$BC
ε ≈ 400 μ
ε = 250 μ
ε = 150 μ
ε = 100 μ
ε = 75 μ
LENGTH
m
OPTIMUM TRACK LENGTH
VS
MOMENTUM FOR VARIOUS
SETTING ERRORS CHOSEN
TO MINIMIZE ANGLE
ERRORS
MOMENTUM GeV/c

Figure A.12