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Review of Neutrino Physics at Brookhaven

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I. Introduction

This is an interesting point in time to discuss the neutrino physics program at Brookhaven. Firstly because the Brookhaven neutrino beam is the last operating medium energy beam, and, secondly because the program here is in transition. The first round counter experiments are winding down to a successful conclusion and a major new experiment has been approved and is expected to begin taking data in late 1979. No attempt will be made to review all the current physics here. Rather a few topics will be discussed to illustrate both the problems inherent in medium energy neutrino physics and the future prospects here at Brookhaven. An alternative discussion of the Brookhaven program may be found in the HEDG talk by P. Sokolsky(1) while a complete review of the neutral current results is contained in the Tokyo review talk by C. Baltay.(2)

The event rates in the Brookhaven neutrino beam will be discussed and then a brief review of the current experiments will be presented. The physics topics to be discussed are mainly neutral current interactions; elastic neutrino scattering from electrons and protons, and single pion production. Finally the search for charmed baryon production and the associated search for dilepton events will be presented.

Apart from BNL, medium energy neutrino physics results have come from the CERN PS beam and the Argonne ZGS. The PS beam was very similar to the Brookhaven beam. Physics there was dominated by the heavy liquid bubble chamber GARGAMELLE. From millions of pictures in freon and propane many neutrino and antineutrino results have been extracted. However, as will be apparent later, the combination of bubble chamber and heavy liquids is inherently limited in the accuracy one can obtain. Furthermore, since GARGAMELLE has been moved to the SPS, no additional data will be available. The only other PS neutrino experiment was a counter experiment mounted by an Aachen-Padua collaboration. This produced results on νe and νp elastic scattering and dileptons, and these will be considered later. The Argonne ZGS neutrino program has also terminated. The ZGS neutrino beam had maximum flux at $\sim$ 0.7 GeV (the BNL spectrum peaks at $\sim$ 1.5 GeV). The program consisted of only neutrino running with the ANL 12' bubble chamber filled with hydrogen or deuterium. At ZGS energies the dominant production is quasi-elastic $\nu n \to \mu^- p$ and single pion $\nu N \to \mu N' \pi$ final states.

II. Rates and Spectrum

Since neutrino flux calculations are somewhat unreliable, it is perhaps better to discuss rates and energy spectra in terms of the observed events in the 7' bubble chamber. These calculations are based on the recent D_2 running where with 8×10^{12} protons per pulse on target and a restricted fiducial volume of $4 m^3$ (0.55 mtons) 1 neutrino interaction was detected every 210 pictures. If one assumes that normal running conditions are 10^{13} ppp at a 1.4 sec rep. rate, then the number of events per metric ton per day (NEMD) assuming the 7' bubble chamber scanning efficiency to be 90% is 600. In general this must be corrected for the efficiency of the neutrino line (say 90%) and the location of the experiment. This latter factor is essentially the ratio of the solid angle subtended by the experiment from the center of the pion decay tunnel to the solid angle subtended by the bubble chamber. At best this factor will be $r \lesssim 1/2$. Consequently, for an apparatus of mass M metric tons the number of charged current events detectable per day at BNL is $\cong 540 \times M \times r$. It should be noted that the equivalent rate at FNAL (based on Exp. 53A data of 0.6 events per pulse for 20 mton fiducial volume with 8×10^{12}ppp and a 10 sec rep. rate is $\sim 300 \times M \times r$ where at FNAL $r \gtrsim 1$.

There has been little antineutrino running in the BNL bubble chamber. However, since at BNL energies the ratio of π^+ to π^- production is approximately 2 to 1 and $\sigma^{\bar{\nu}}_{TOT} \sim 0.38 \times \sigma^{\nu}_{TOT}$, the corresponding calculation for the number of charged current antineutrino interactions per day is $\sim 100 \times M \times r$.

The observed energy distribution for charged current events in the 7' bubble chamber(3) is shown in Fig. 1. The spectrum peaks at $\sim$ 1.5 GeV but 14% of events have energies greater than 4 GeV. This is significant in that the threshold for charmed baryon production ($m_c \sim 2.2$ GeV) is in this region.

The recoil hadron mass $W^2 = m_p^2 + 2m_p(E_\nu - E_\mu) - Q^2$ distribution for D_2 events in the 7' bubble chamber is shown in Fig. 2. The predominant final states are the quasi elastic channel $\mu^- p$ and the single pion final states $\mu^- N\pi$. However, 23% of the events are above threshold for strange particle production.

From the energy and recoil mass distributions it is clear that the neutrino cross section at BNL is the sum of a few exclusive channels. And to the extent that one intends to study exclusive processes one would prefer to use simple targets (H_2 or D_2) and, where applicable, to use kinematic fitting to isolate the desired final state. This would argue for the bubble chamber as the ideal detector and for the study of constrained charged current processes (e.g. $\nu n \to \mu^- p$, $\nu p \to \mu^- p \pi^+$, $\nu n \to \mu^- C^+$ etc.) this is certainly true. However, for low cross-section processes or low charged multiplicity final states this is not so obvious. For example, to measure an exclusive proton ($N_p/N \cong 1/2$) channel ($\nu p \to \mu^- X^{++}$) whose cross section is 10^{-2} of the total cross section and for which the expected detection efficiency is 10^{-1}, the expected number of events per metric ton per day is only $540 \times 1/2 \times 1/2 \times 10^{-3} = 0.14$. Thus, to observe one event per day, a 10 mton fiducial volume is required.

The dilemma of studying exclusive channels in neutrino interactions is then to use the bubble chamber with H_2 or D_2 and be limited by rate or, in some cases, background or to use a heavy target to yield an acceptable rate but to suffer from a reduced detection efficiency and ultimately from nuclear corrections which serve to mix the final states produced in the original reaction. This problem is perhaps best illustrated by the study of single pion final states (Sect. IV) and is somewhat minimized in the study of elastic scattering (Sect. V, Sect. VI).

III. Detectors

A. 7' Bubble Chamber (H_2,D_2 fill)

The 7' bubble chamber has operated very reliably over the past few years and an average of 50,000 pictures per day is a reasonable estimate of its present capabilities. However, the present BNL scanning capacity is ∿ 400,000 pictures per year, so without a large increase in personnel one could expect to analyze at most ∿ 1 million pictures (∿7,000 charged current neutrino interactions) in the next few years. This is reasonable for the study of the dominant charged current channels and should yield a number (Sect. VII) of identified charmed particle decays. For neutral current studies four 2" thick 6'x5' stainless steel plates have been inserted in the back third of the chamber. This provides a π^- identification efficiency of ~50% and provides an adequate neutral current sample for many investigations. However, apart from rate there are some inherent limitations in the use of the bubble chamber. Since the lifetime of the chamber is ~ msecs, there is no timing information. In particular, beam produced slow neutrons provide an almost unsurmountable background ($np \rightarrow np$) for the study of elastic neutrino proton scattering ($\nu p \rightarrow \nu p$). It should be noted that the high energy ($P > 0.8$ GeV/c) neutron background is well understood by detecting the constrained fit neutron channel ($np \rightarrow \pi^- pp$) and using the relevent neutron cross sections to estimate backgrounds in unconstrained channels (eg. $np \rightarrow np\pi^+\pi^-$). The other fundamental limitation is the scanning and detection efficiency for single charged prong final states (eg. $\nu p \rightarrow \nu n\pi^+$, $\nu p \rightarrow \nu p\pi^o$). There is little hope for a detailed study of single pion production by neutral currents.

B. 7' Bubble Chamber Heavy Neon-H_2 mixture (64% Neon by volume)

The 7' bubble chamber has recently run with a heavy Ne/H_2 mixture. A total of 220,000 ν-pictures and 300,000 $\bar{\nu}$-pictures were taken. These should yield approximately 4,500 charged current ν-events and 1,025 $\bar{\nu}$-events. The major advantage of this neon mixture is that the radiation length is ~40 cms and for a reasonable fiducial volume there is excellent electron and γ-detection. There is also reasonable neutron detection efficiency. The basic problems here are the limited statistics, lack of kinematics, large neutron background due to the chamber lifetime and the fundamental problem of nuclear corrections in the study of exclusive channels. In general the physics available to this experiment is similar to the GARGAMELLE experiments, however, the systematics are different and there is likely to be less neutron background.

C. Columbia - Illinois - Rockefeller

The original CIR detector (Fig. 3) was a 26 ton detector comprising 26 optical spark chamber modules of 6'x6'x1/4" Al with interspersed scintillation counters to give timing and dE/dx measurements. Since each optical spark chamber was a fraction of a radiation length this was a good shower detector. The experiment originally concentrated on neutral current single π^o production[4] (Sect. IV) and later produced the first measurement on elastic neutrino proton scattering.[5] To reduce background from prompt neutrons the apparatus was mounted in an air house far removed from potential massive sources for background neutrino interactions. However, the experiment was then sensitive to the sea of lower energy beam associated neutrons and this led to large backgrounds in the original measurement. In the course of the original analysis of π^o production, the group was led to the conclusion that there were some $\mu^- e^+ + \ldots$ events in the sample where the e^+ was not obviously from asymmetric Dalitz pairs.[6] This led to a new detector (Fig. 4) which, in addition to the original optical spark chamber, contained a magnet and a section of magnetized toroids for dimuon identification. In addition, the new detector is contained in a partial blockhouse with a heavy concrete roof to isolate the apparatus from the primary sea of beam produced slow neutrons. When fully analyzed this new detectors' data should yield a few hundred elastic νp and $\bar{\nu} p$ events and extrapolating from the few $\mu^- e^+$ events about 100 dilepton events are expected.

D. <u>Harvard - Pennsylvania - Wisconsin - Brookhaven</u>

The HPWB detector (Fig. 5) was 33 tons composed primarily of liquid scintillator modules 2.6 m x 2.6 m x 20 cms with the final cells alternated with drift chambers to give angular measurements for some fraction of the detector. In general, though, the detector has poor angular resolution and poor granularity as track segments were only defined to be in 20 cms cubes of liquid scintillator (The position along the scintillator cell was determined from the time difference between the phototubes at each end of the cell). The apparatus was completely enclosed in a concrete blockhouse. While this eliminated the flux of slow beam associated neutrons, it provided a potential source for fast neutrino produced neutrons from the blockhouse wall. The group argues that these neutrons can be eliminated to a satisfactory degree by timing. The physics from this detector has been elastic neutrino and antineutrino proton scattering[7] and the first measurement of the q^2 distribution for these processes

IV. Single Pion Neutral Current Production

The study of single pion neutral current production is probably the best example of the problems inherent in the study of exclusive final states. These are important processes for establishing the isospin properties of the neutral current. More specifically, if the neutral current is a mixture of isovector and isoscalar components, then three amplitudes (the isovector $I_z = 1$, $I_z = 0$ and the isoscalar) must be determined. A good measurement of the exclusive channels a) $\nu p \to \nu p \pi^o$, b) $\nu p \to \nu n \pi^+$, c) $\nu n \to \nu n \rho^o$, d) $\nu n \to \nu p \pi^-$ allows a determination of the isospin. For example, (Table I) if the isospin is pure isovector or isoscalar some simple relations must be satisfied.

Only the GARGAMELLE group has attempted to measure all four cross sections.[8] They observe a number of events in each final state and then calculate the number initially created by neutrino interactions from the equations

$$\vec{N}_\pi^{OBS} = \alpha \Sigma_i W_i S(A_i) T(A_i) \; \vec{\sigma}_{FREE}$$

where $\vec{N}_\pi^{OBS}$ is the number of events observed in the channels a---d listed above, W_i is the fraction by weight of H, C, F, Br in the bubble chamber liquid, $T(A_i)$ is the probability of finding a proton or neutron in the element A_i, $\vec{\sigma}_{FREE}$ is the set of cross sections to be determined and $S_{jk}(A_i)$ is for each element A_i a matrix such that the jk element is the probability for the element A_i that the $(N\pi)_j$ final state in the original neutrino interaction is observed, because of nuclear corrections, as the final state $(N\pi)_k$. The observed and corrected ratios (Table I) suggest a mixture of isovector and isoscalar components. Since only relatively light elements are in the chamber mixture and events with observed nuclear breakup are not used the correction factors calculated are always less than 1.5. However, the estimated systematic uncertainty in the calculations is $\sim$(20-30)% and it is not clear if better statistics were available, how to reduce the systematics.

An alternative approach to the study of isospin would be to search for the $\Delta(1236)$, which is strongly excited in charged currents, in neutral current final states such as $\nu p \pi^o$. Two results, one from GARGAMELLE[8] and one from the CIR group at BNL, have been reported. GARGAMELLE (Fig. 6) claims an even stronger $\Delta(1236)$ signal in the neutral current channel $\nu p \pi^o$ than in the charged current channel, $\mu^- p \pi^o$, which is somewhat unexpected. In addition, there is about a 30% neutron background contamination in the plot. The CIR analysis yields a different picture. Their total neutral current sample (Fig. 7a) suggests a $\Delta(1236)$ signal. However, they claim this is likely to be charged current punch through since it is predominantly in the sample where the $p\pi^o$ is forward $\theta p\pi^o < 20^o$ and, therefore, the muon is slow and at wide angle and in this case can be easily missed in the detector.

The only light liquid bubble chamber measurement of single pion production is from the Argonne 12' chamber filled with D_2.[9] In the analysis of about 750,000 pictures 7 candidates for $\nu n \to \nu n\pi^+$ and 7 for $\nu p \to \nu p\pi^o$ were obtained. This gave the cross section ratios

$$R_o = \frac{\sigma(\nu p \to \nu p\pi^o)}{\sigma(\nu p \to \mu^- p\pi^+} = 0.51 \pm 0.25 \text{ for } P_p < 1 \text{ GeV}$$

$$R_+ = \frac{\sigma(\nu p \to \nu n\pi^+)}{\sigma(\nu p \to \mu^- p\pi^+)} = 0.17 \pm 0.08 \text{ for } P_{\pi^+} < 400 \text{ MeV.}$$

Again, it is difficult to see how one can obtain the statistics required to precisely determine the isospin of the neutral current.

A totally different approach is to study the ratio of two pion production

$$R_2 = \frac{\nu n \to \nu n\pi^+\pi^-}{\nu p \to \nu p\pi^+\pi^-} .$$

Both reactions are easy to study in the 7' and reasonable statistics will be accumulated in the near future. At present, based on 25 events the measured ratio is

$$R_2 = 0.49 \pm 0.21.$$

If the neutral current isospin is pure isoscalar or isovector, then R_2 should be identically one.

V. Neutrino and Antineutrino Elastic Proton Scattering

There are two separate arguments for measuring neutrino proton scattering. First, it is the simplest hadronic neutral current interaction and with a few quite reasonable assumptions one can determine the Weinberg angle in the standard SU(2) x U(1) model. However, to do this one needs precise neutrino and antineutrino data. As can be seen in Fig. 8 even a precise measurement of νp scattering will at best determine a range of $\sin^2\theta_w$, not a specific angle. The combination of νp and $\bar{\nu} p$ data (Fig. 9) can in principal yield a unique solution. However, the quality of the current data is such that while the neutral current being pure vector or axial-vector is ruled out at the 2-3σ level, no precise determination of the coupling is possible.

Secondly, it is an important ingredient in some model independent analyses of the neutral current couplings. If one assumes the neutral current is only a mixture of vector and axial vector currents, then only four couplings corresponding to right and left handed u and d quark transitions (u_L, u_R, d_L, d_R) need be determined. These model independent analyses[10,11] use as input

a) Deep inelastic neutral current inclusive scattering data which determines the strengths $(u_L^2 + d_L^2)$ and $(u_R^2 + d_R^2)$

b) Inclusive neutral current pion production

$$\nu N \rightarrow \nu\pi^{\pm}---, \ \bar{\nu}N \rightarrow \nu\pi^{\pm}---$$

c) Neutral current single pion exclusive production

d) νp, $\bar{\nu}p$ elastic scattering total cross sections

e) νp, $\bar{\nu}p$ Q^2 distributions.

The earliest analyses relied heavily on the pion production data but more recently Clandson, Paschos and Sulak[11] have shown that the inclusive production (a) coupled with the elastic scattering (d) and the measured Q^2 distributions (e) can be used to determine the couplings if one accepts some general qualitative features of the single pion data. This is significant in that improvement in the proton measurements is possible but the same is not obviously true for the pion data. The current analysis is clearly limited (Fig. 10) by the present antineutrino data.

There are now four separate measurements of νp elastic scattering (Table II) and one of $\bar{\nu}p$ elastic scattering. The most precise measurement is by the HPB group at BNL. Their estimate[7] is that there is a possible systematic error of $\sim$20% which is comparable to the present statistical error.

Since a detailed study of νp and $\bar{\nu}p$ scattering is particularly suited to the BNL beam, one could seriously entertain constructing a major new detector to make a precise study of these hadronic channels. This, in part, was the motivation for the recently approved Exp. No. 734[12] which will be discussed in the following section. There are a number of obvious ways to improve the current measurements. First, a more massive detector is required. This would not only yield better statistics but allow the selection of a small fiducial volume isolated by the bulk of the detector from possible background neutron sources. Second, finer target segmentation for more frequent dE/dx sampling, frequent track detectors for better angular and spatial resolution would provide superior π,p separation, an improved Q^2 range and rejection of some multiprong background events. Third, the nuclear corrections can at least be minimized by working with a light nuclear target such as liquid scintillator.

The design of Exp. No. 734 was primarily dictated by the challenge of measuring elastic electron scattering ($\nu e \to \nu e$, $\bar{\nu}e \to \bar{\nu}e$). However, the major improvements required for an improved measurement of νp, $\bar{\nu}p$ scattering are implicit in the design, and current estimates are that an improvement of at least a factor of four in the systematic error of the first round BNL experiments will be attained.

VI. Neutrino Electron Elastic Scattering

Theoretically, neutrino electron elastic scattering is the simplest process to analyze. However, from an experiment viewpoint, it is extremely difficult. Since the cross section is proportional to the target mass

$$\sigma(\nu e \to \nu e)/\sigma(\nu N \to \mu^- X) \;\alpha\; m_e/m_n \sim 1/2000$$

and No.e^-/No.N $\sim$ 1/2 even with a 50% e^- detection efficiency and r = 1/2 the number of detected events per day per mton is

$$\text{No}(\nu e \to \nu e)/\text{day/mton} = 540/2000\text{x}8 = 0.03.$$

Consequently, with a 70 mton fiducial 2 events/day would be observed. Fortunately since $\sin^2\theta_w \simeq 1/4$ $\sigma(\nu e \to \nu e) \simeq \sigma(\bar{\nu}e \to \bar{\nu}e)$ so one would expect $\sim$ 1 ($\bar{\nu}e \to \bar{\nu}e$) event detected per day.

There are a number of reasons why one might do this experiment at BNL. As was noted earlier (Sect. 2), the number of events per day per mton is similar here and at FNAL. In addition, a reasonable ($\sim$10 mrad) angular resolution on the electron measurement is sufficient at BNL. The fundamental signature for νe scattering is a single electron in the forward direction. For elastic scattering with a fixed neutrino energy the electron angle (θ_e) and energy (E_e) are correlated. However, for a broad band beam one can show that $E_e\theta_e^2 \leq 2m_e = 1$ MeV. This implies (Table III) that the typical angles at BNL are 70 to 10 mrad, while at FNAL the range is 10 to 1 mrad. Last, the backgrounds at BNL energies are well understood. In fact, the dominant background is $\nu n \to \nu n\pi^o$ where one γ from the π^o decay goes forward while the second γ and neutron escape detection. From the measured $\nu n\pi^o$ cross section one concludes that with reasonable 2nd γ detection ($\sim$50%), neutron detection

($\sim$33%) and some γ-e discrimination ($\sim$x5) this background will constitute only a few percent of the signal. At FNAL it is not so apparent what the major backgrounds will be and how to handle them.

A proposal[(12)] from a BNL-Brown University-University of Pennsylvania collaboration to study neutrino electron and neutrino proton scattering was recently approved and is expected to begin taking data with $\sim$1/3 of the detector in place in Oct. 1979. The completed detector will be 150 tons with 90% of the mass as Liquid Scintillator. There will be 130 modules each 4m x 4m and roughly 15.5 cms long in the beam direction. Each module will contain a vertical plane of 16 liquid scintillation counters (4m x 25 cms x 7.5 cms), a X-plane of 64 proportional drift tubes (PDT) each 4 m x 4 cm x 8 cms, and a Y-plane of PDT's. Pulse height, crude position and the event time will be determined from the scintillator cells. The drift time and pulse height will be measured in the PDT's. Test beam studies have shown that position resolution of < 1 mm with adequate pulse height resolution can be achieved. This will yield the required angular resolution and γ-e discrimination for the $\nu e, \bar{\nu} e$ scattering experiment. Monte Carlo simulations indicate that with the proposed detector the $\nu n \pi^o$ background will be $\lesssim$ 7%.

The primary objective of this experiment is to detect $\gtrsim$ 100 events in each of the elastic channels $\nu e \rightarrow \nu e$ and $\bar{\nu} e \rightarrow \bar{\nu} e$. The expected error on the cross section ratio $R = \sigma(\nu e \rightarrow \nu e)/\sigma(\bar{\nu} e \rightarrow \bar{\nu} e)$ should then be $\sim$15% and this will produce a determination of $\sin^2\theta_W$ to 10%.

In addition, as was discussed in the previous section, this detector will greatly improve the measurement of νp and $\bar{\nu} p$ elastic scattering.

VII. Charm Production at BNL

A. <u>Hadronic Charm Decays</u>

In the conventional GIM quark scheme there are three distinct ways to produce strange particles in neutrino interactions. Since charged current neutrino interactions have a μ^- in the final state, the charge change (ΔQ) in the quark transition must be $\Delta Q = +1$. The allowed quark transitions are from Q = -1/3 quarks/or antiquarks) to Q = +2/3 quarks (or antiquarks). The dominant transitions are then $d \rightarrow u$ or $s \rightarrow c$ with amplitudes proportional to

$\cos^2\theta_c$ where θ_c is the Cabibbo angle ($\tan^2\theta_c \sim 0.06$) while the transitions $d \to c$, $s \to u$ are suppressed as these amplitudes are proportional to $\sin^2\theta_c$. Strange particle production can then occur from[13]

i) Associated production where an $s\bar{s}$ pair is excited from the sea

$$\nu d \to \mu^- u s \bar{s} \qquad \text{e.g.} \quad \nu n \to \mu^- K^+ \Lambda$$

which has a rate proportional to $d(x)\cos^2\theta_c\ F(s\bar{s})$ where $F(s\bar{s})$ is the probability of exciting an $s\bar{s}$ pair

or ii) $\Delta S = +\Delta Q$ strange particle production

$$\nu\bar{u} \to \mu^- \bar{s} \qquad \text{e.g.} \quad \nu p \to \mu^- K^o p \pi^+$$

$$\nu s\bar{s} \to \mu^- u\bar{s}$$

which has a rate proportional to $\bar{u}(x)\sin^2\theta_c$ or $s(x)\sin^2\theta_c$. It is important to note that a $\bar{s}$ is always produced so $\Delta S = +\Delta Q$

or iii) Apparent $\Delta S = -\Delta Q$ strange particle production

Since the dominant charm decay is $c \to s$ if one produces a c-quark from a d-quark the final state will almost always contain an s-quark

$$\nu d \to \mu^- c \ (c \to s) \qquad \text{e.g.} \quad \nu n \to \mu^- \Lambda_c^+$$

The rate in this case is proportional to $d(x)\sin^2\theta_c$ and since the final state contains only an s-quark and not an $\bar{s}$-quark, it is an apparent $\Delta S = -\Delta Q$ transition.

In general then one expects more $\Delta S = -\Delta Q$ production than $\Delta S = +\Delta Q$ since

$$\text{Rate}\left(\frac{\Delta S = -\Delta Q}{\Delta S = +\Delta Q}\right) \sim \frac{d}{\bar{u} + s} > 1$$

but associated production dominates both the other mechanisms.

The BNL neutrino beam and the 7' chamber are well suited to the study of strange particle production since one has good efficiency for separating the three mechsnisms for strange particle production. Since the beam energy is relatively low, the produced particles are in general slow and one can successfully use kinematic fitting[14] to distinguish associated production events (e.g. $\mu^- K^+ \Lambda$) from single strange particle production (e.g. $\mu^- \pi^+ \Lambda$). For identified single strange particle production one can separate $\Delta S = -\Delta Q$ events from $\Delta S = +\Delta Q$ events in one of two ways. If the strange particle is a Λ, then since a Λ has $S = -1$, it must have been $\Delta S = -\Delta Q$ production. For

K^o production there is no trivial solution. However, if the K^o is from a $K^{*-} \rightarrow K^o\pi^-$ decay and the x-value for the event is consistent with valence production ($\Delta S = +\Delta Q$ events are always produced from sea quarks), then there is a high probability that the K^o is actually a $\overline{K}^o$ and the event is charm production. The threshold for $\mu^-\Lambda_c^+$ is $E_\nu = 2.5$ GeV while for $\mu^- D^o p$ it is 4.0 GeV, so at BNL one would expect exclusive charm baryon production to be the dominant charm channel.

The ability to identify charm by searching for its $\Delta S = -\Delta Q$ is a unique attribute of the BNL beam and chamber. With higher energy beams and heavy liquid chambers, this approach becomes at best unlikely to succeed. And the conventional approach in these cases of plotting all effective mass combinations (e.g. $\Lambda\pi^+\pi^+\pi^-$, $K^o p$---) and searching for narrow peaks is proving to be quite tedious.[15]

To date, 2 $\Delta S = -\Delta Q$ events have been observed in the 7' chamber. The The first event[16] published shortly after the discovery of the J/ψ was identified as

$$\nu p \rightarrow \mu^-\Sigma_c^{++}$$
$$\hookrightarrow \Lambda_c^+\pi^o$$
$$\hookrightarrow \Lambda\pi^+\pi^+\pi^-$$

and determined the mass of the Σ_c^{++} to be 2426 ± 12 MeV and $m_{\Lambda_c^+} \cong 2260$

A second event (Fig. 12) has recently been found.[17] It is identified as

$$\nu n \rightarrow \mu^-\Lambda_c^+$$
$$\hookrightarrow K^{*-}p\pi^+$$
$$\hookrightarrow \overline{K}^o\pi^-$$

where $m_{\Lambda_c^+} = 2254 \pm 12$ and if one accepts that the Λ_c^+ mass has already been established, the probability that this event is not charm production is $< 10^{-3}$. The importance of this event is that it establishes the $\overline{K}^o$ decay mode of the Λ_c^+ and with 2 events observed in 4,500 charged current neutrino interactions, it allows a reasonable estimate for the rate at which charmed baryons can be expected to be detected in the 7' chamber. For example, the BNL spectrum (14% of events have $E_\nu > 4$ GeV) together with the assumptions that $\Lambda_c^+ \rightarrow$ visible

$\Lambda \to p\pi^-$ or a visible $K^o \to \pi^+\pi^-$ 1/3 of the time, and 1/4 of the time $\Lambda_c \to$ all charged tracks and no neutrals are produced with the Λ_c^+ (i.e. not $\mu^-\Lambda_c^+\pi^o$ production) one calculates a charmed baryon production rate of ~4% in agreement with the Cabibbo angle prediction.

The present rate of one identified charmed baryon event in 250,000 pictures implies that with the present scanning facilities some 5-10 events could be found in the next few years. Clearly a major commitment with additional support could increase the number substantially since the present limitation is not taking film but analyzing it.

While the projected rate for observing charmed baryons at BNL is modest, it is not obvious how well other searches will proceed. At present there are two other results on charmed baryon production. A FNAL photoproduction experiment(18) has reported a significant peak in the $\bar{\Lambda}\pi^-\pi^-\pi^+$ effective mass spectrum at 2.26 GeV which they identify as the $\bar{\Lambda}_c$. More recently(19) the same group working with a substantially modified apparatus has confirmed the original observation. They have not as yet been able to observe the Λ_c. In e^+e^- collisions at SPEAR a significant threshold in $\bar{p}$ and Λ production is observed(20) in the region of E_{cm} = 4-4.5 GeV. This is suggestive of the onset of charmed baryon production. The observed rate of $p + \bar{p}$ production is ~ 8 times the $\Lambda + \bar{\Lambda}$ production. If $e^+e^- \to B\bar{B}$ is the dominant production, this would argue for charmed baryons predominantly decaying into K^o's and not Λ's. If the process $e^+e^- \to B\bar{M}p$ (i.e. a charmed baryon, anticharmed meson and a baryon) is competetive with $e^+e^- \to B\bar{B}$, this conclusion is weakened considerably. However, it should be noted that to date no specific charmed baryon decays have been observed in e^+e^- collisions. An alternative arena for the study of charmed baryon decays is neutrino interactions at high energy. No events have been reported yet(21) and the success of this search will depend critically on the ratio of charmed meson to charmed baryon production at high energies, the ratio of $B \to \Lambda$ compared to $B \to K^o$ (kinematic constraints are more definitive for Λ^o final states in light liquids) and the ratio of two body to multibody decay modes (in effective mass plots two body decays will be on the tails of phase space distributions whereas multibody decays lie near the peak).

B. Dilepton Production

Since charm particles decay semileptonically, dilepton events (μ^-e^+ or $\mu^-\mu^+$) should be produced at BNL. Indeed the CIR group at BNL and the

GARGAMELLE and Aachen-Padua groups working in the CERN PS neutrino beam have reported the observation of dileptons. The first and certainly the clearest result was from the GARGAMELLE group.(24) They observed 14 μ^-e^+ and 3 $\mu^-e^+V^o$ events but no μ^-e^- events above background. The presence of only μ^-e^+ events, the momentum spectrum of the e^+ and the V^o content are all consistent with charm production. Neither of the counter experiments are magnetic detectors so the charges of the leptons are not determined. The CIR group(6) has observed 7 μe events where the momentum of the e is greater than 2 GeV and the rate $\mu e/\mu$ is $\sim 3 \times 10^{-4}$. The source of these events is not understood. The Aachen-Padua group(25) has searched for final states which contain only a μ, an e and possibly recoil stubs. They find 14 of these events with a calculated background from asymmetric Dalitz and close pair conversion from π^o decay of 4 events. The effect is most pronounced for electron energies over 2 GeV. They argue that these events are inconsistent with charm production and argue for a heavy lepton M^o as the possible source.

Therefore, while dilepton events have been observed in medium energy beams the number of events is small, the momentum cut in the counter experiments is high and there is some contention as to the source or sources of these events. If one accepts that the rate of dilepton production at these energies is $\sim 3 \times 10^{-4}$, then the new BNL experiment (#734) will detect 1 μe event approximately every 2 hours. In addition, the ability to detect second photons from π^o decays and to discriminate γ's from e's provides good rejection against conventional apparent e-sources like π^o decays. Consequently, there is every expectation that with the improved statistics one can investigate in some detail the production of dileptons at moderate neutrino energies.

VIII. Conclusion

The high event rate and relative simplicity of the produced final states are the unique features of neutrino physics at Brookhaven which make it particularly suitable for the study of many topics of current interest. This not only applies to exclusive charged current studies, which are the province of the 7' bubble chamber program but to the elastic scattering from protons and electrons which is the focus of the recently approved experiment. Also, interesting results on multipion neutral current production and charm baryon production can be expected from the 7' chamber in the not too distant future.

References

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13. Strange particles can also occur via charm production from an s-quark

$$\nu s\bar{s} \to \mu^- c\bar{s} \quad (c \to s) \qquad \text{eg.} \quad \nu n \to \mu^- D^+ \Lambda$$

However, the threshold for this is high enough that it is unlikely to contribute at BNL energies.

References (cont'd.)

14. Approximately 60% of all the strange particle events observed in the 7' bubble chamber yield unique 3c-fits.

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Figure Captions

1[illegible]78	Fig. 1	Neutrino energy distribution for observed 7' bubble chamber events.
12-72-78	Fig. 2	Recoil hadron mass distribution for observed 7' bubble chamber events.
12-265-78	Fig. 3	Original Columbia-Illinois-Rockefeller detector.
12-264-78	Fig. 4	New Columbia-Illinois-Rockefeller detector.
12-266-78	Fig. 5	Harvard-Pennsylvania-Wisconsin-BNL detector.
12-263-78	Fig. 6	Effective $p\pi^o$ mass distributions for $\mu^- p\pi^o$ and $\nu p\pi^o$ final states as observed in GARGAMELLE experiment.
12-267-78	Fig. 7	Effective $p\pi^o$ mass distribution for $\mu^- p\pi^o$ and $\nu p\pi^o$ final states as observed in the CIR experiment.
12-69-78	Fig. 8	Measurements of $R_\nu = (\nu p \rightarrow \nu p)/(\nu n \rightarrow \mu^- p)$ and comparison to Weinberg-Salam model prediction.
12-71-78	Fig. 9	Measurements of R_ν and $R_{\bar{\nu}}$ and comparison to Weinberg-Salam model prediction.
12-73-78	Fig. 10	Q^2 distributions for νp and $\bar{\nu} p$ elastic scattering. Measurement from HPWB experiment.
12-75-78	Fig. 11	Effective mass distributions for BNL 7' bubble chamber strange particle events.
10-1339-78	Fig. 12	Picture of 2nd 7' bubble chamber charmed baryon event as seen in View 2.

Table Captions

Table I.	Isospin Relations for Single Pion Production
Table II.	Elastic Scattering on Protons
Table III.	Electron Energy and Angle Correlation

TABLE I.

Isospin Relations for Single Pion Production

	$\nu p \to \nu p \pi^o$;	$\nu p \to \nu n \pi^+$;	$\nu n \to \nu n \pi^o$;	$\nu n \to \nu p \pi^-$
$\Delta I = 0$	1	2	1	2
$\Delta I = 1$	2	1	2	1
GARGAMELLE Data	248	141	99	134
After Corrections	$\sim 3/2$	1	3/4	1

TABLE II.

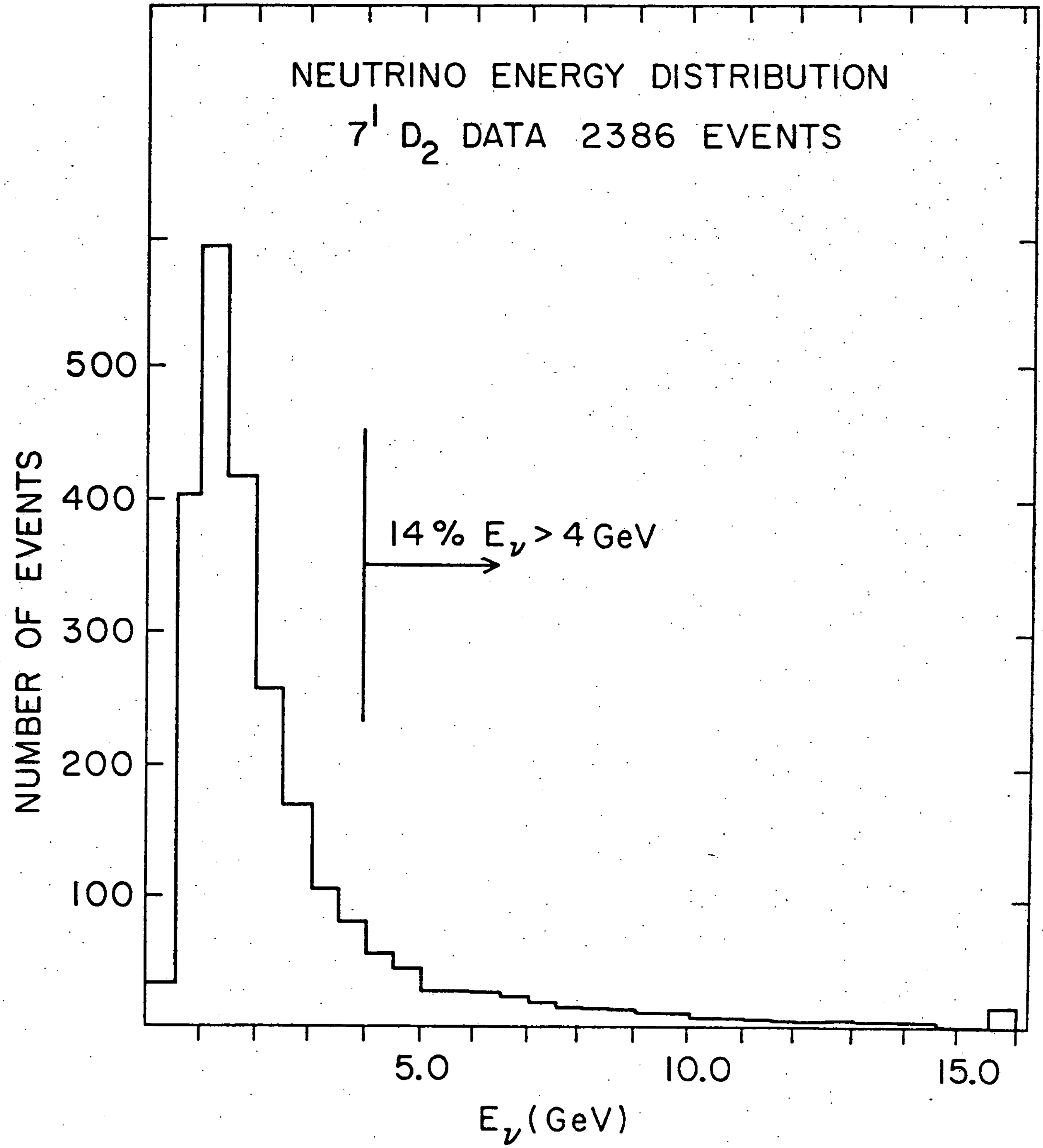
Elastic Scattering on Protons

Exp.	$\nu p \to \nu p$ Events	Back-ground	$\frac{\nu p \to \nu p}{\nu n \to \mu^- p}$	$\bar{\nu} p \to \bar{\nu} p$ Events	Back-ground	$\frac{\bar{\nu} p \to \bar{\nu} p}{\nu p \to \mu^+ n}$
HPB	255	88	0.11±0.02	69	28	0.19±0.05
CIR	71	30	0.20±0.06			
Aachen-Padua	155	110	0.10±0.03			
GARGAMELLE	100	62	0.12±0.06			

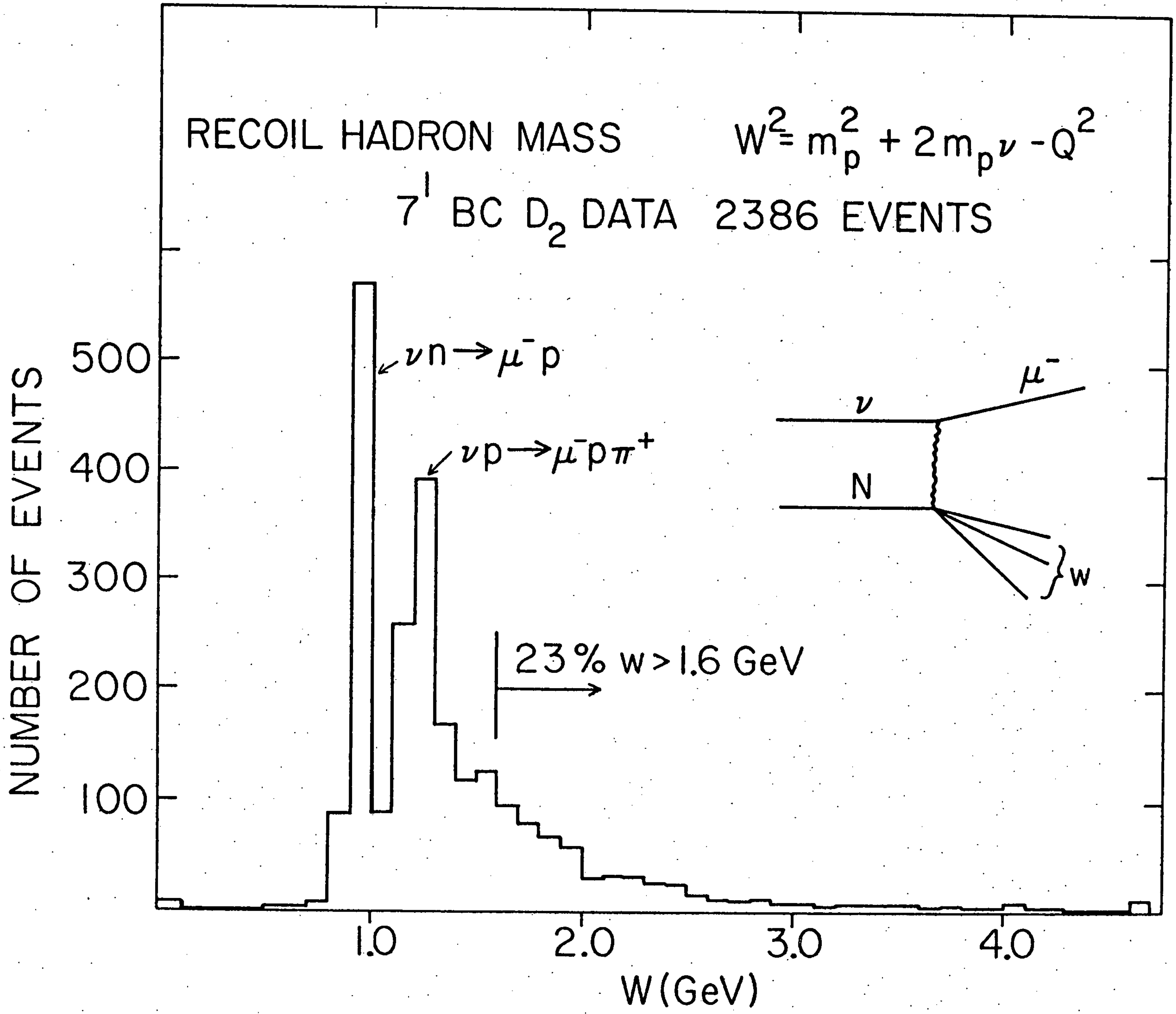
TABLE III.

Electron Energy and Angle Correlation

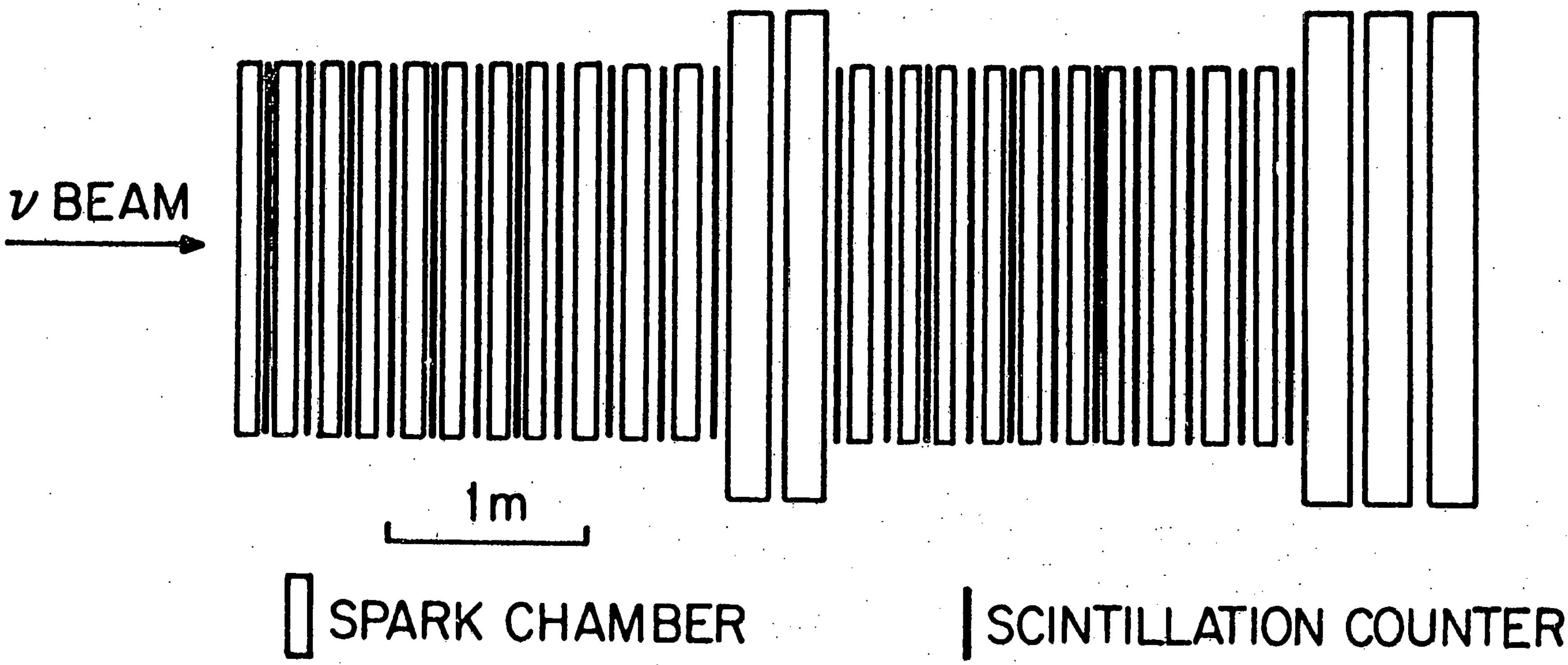
E_e (GeV)	θ_{mrad}	
.2	71	
.5	45	← BNL
1.0	32	
10.0	10	
20.0	7	← FNAL

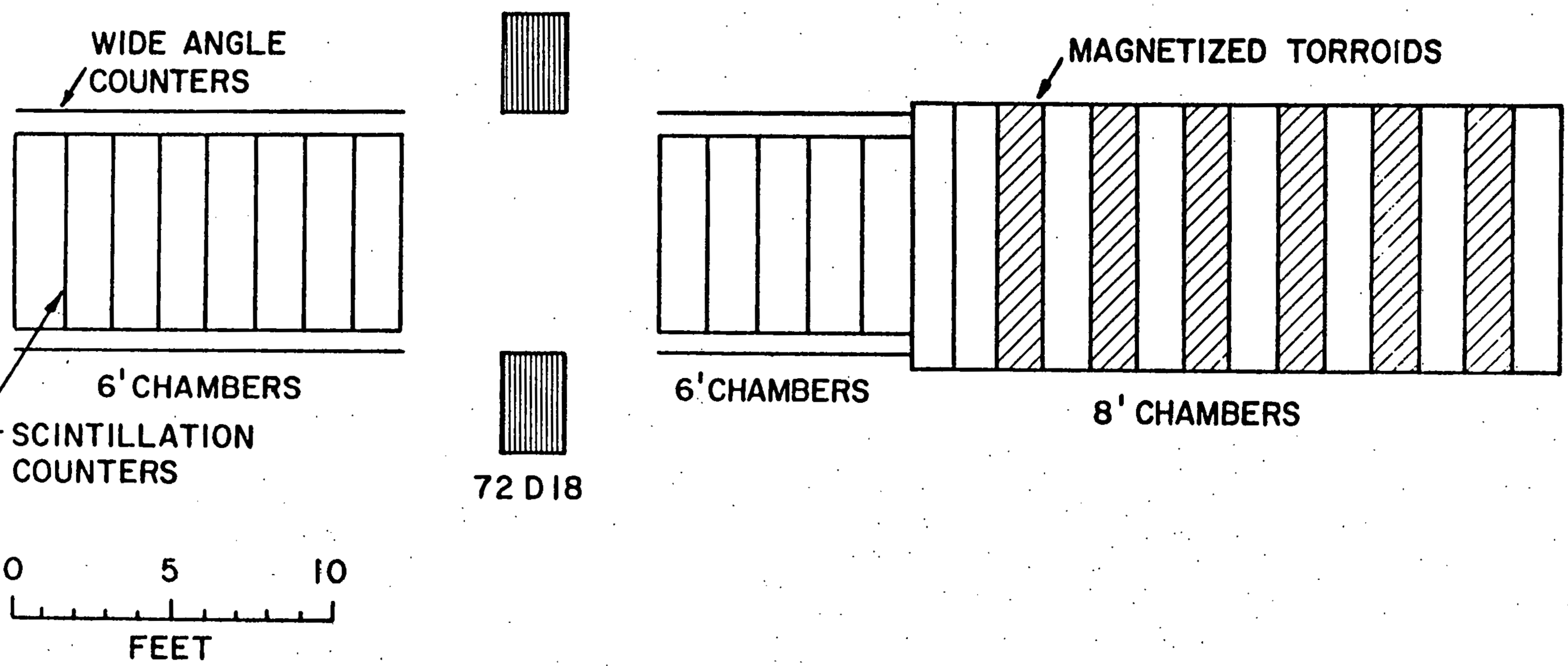


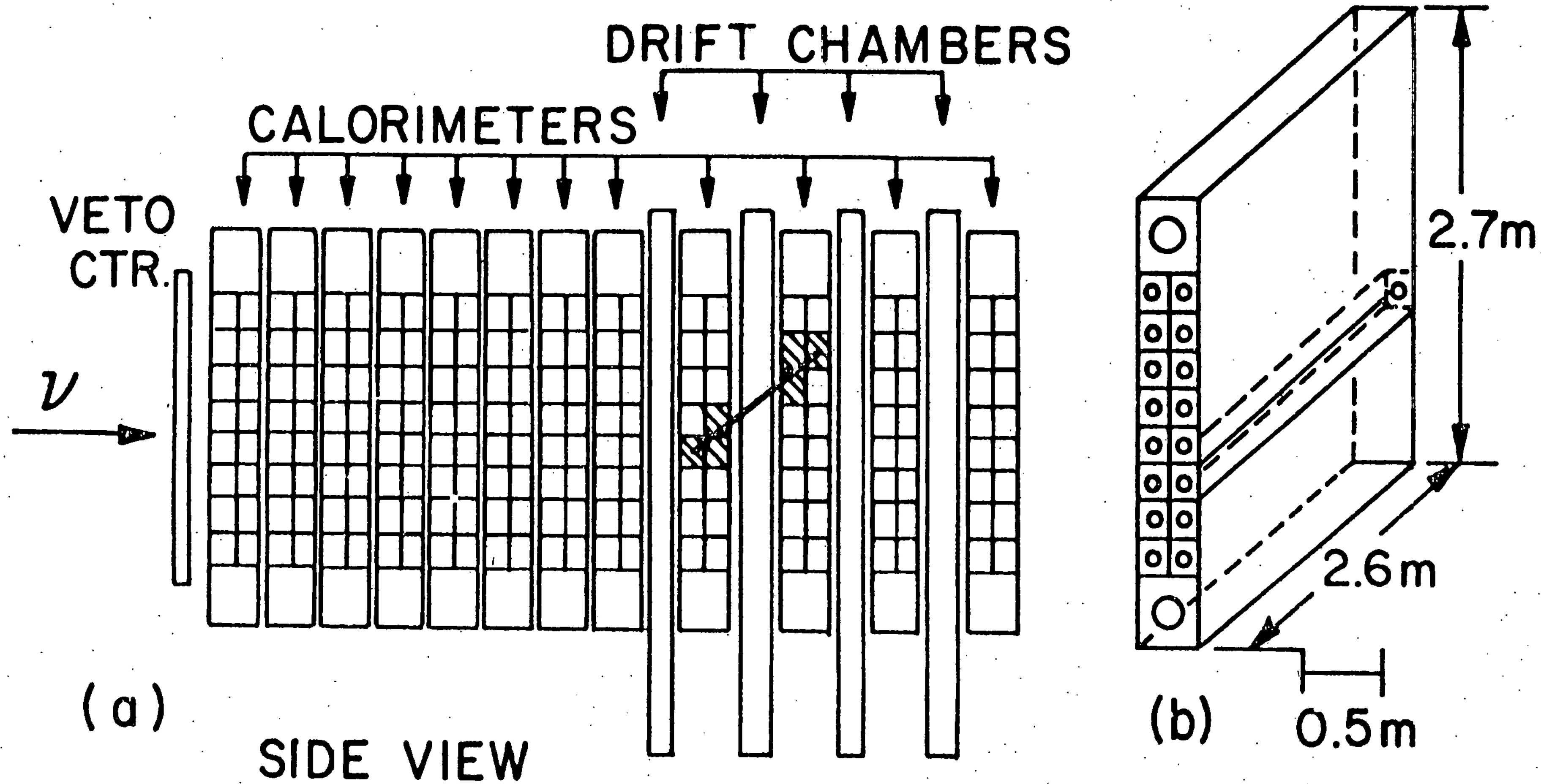
NEUTRINO ENERGY DISTRIBUTION
7' D2 DATA 2386 EVENTS
14% Eν > 4 GeV
NUMBER OF EVENTS
100
200
300
400
500
5.0
10.0
15.0
Eν (GeV)

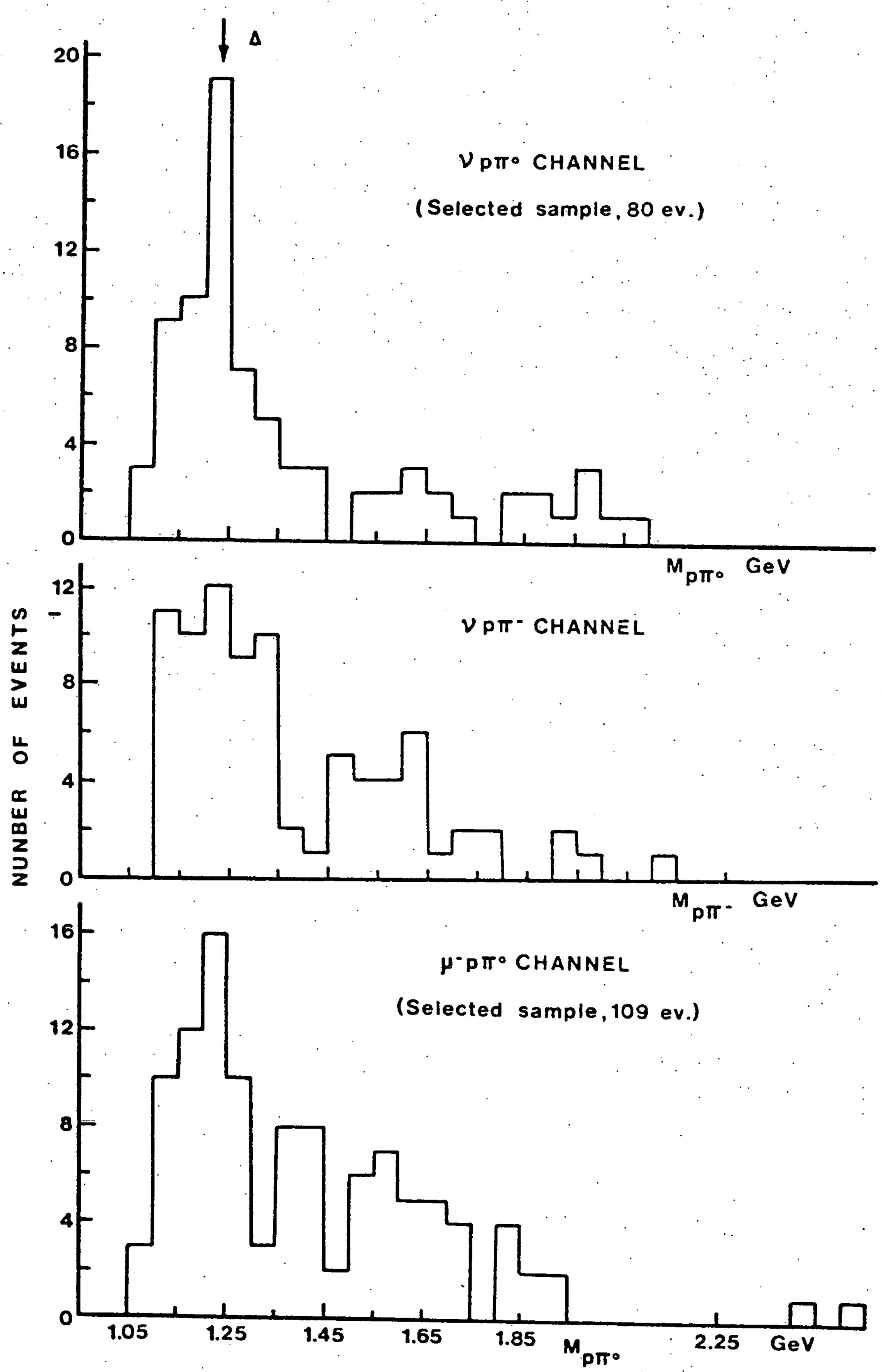


RECOIL HADRON MASS
$W^2 = m_p^2 + 2m_p\nu - Q^2$
7' BC D_2 DATA 2386 EVENTS
NUMBER OF EVENTS
500
400
300
200
100
$\nu n \rightarrow \mu^- p$
$\nu p \rightarrow \mu^- p \pi^+$
23% w > 1.6 GeV
ν
μ^-
N
w
1.0
2.0
3.0
4.0
W(GeV)

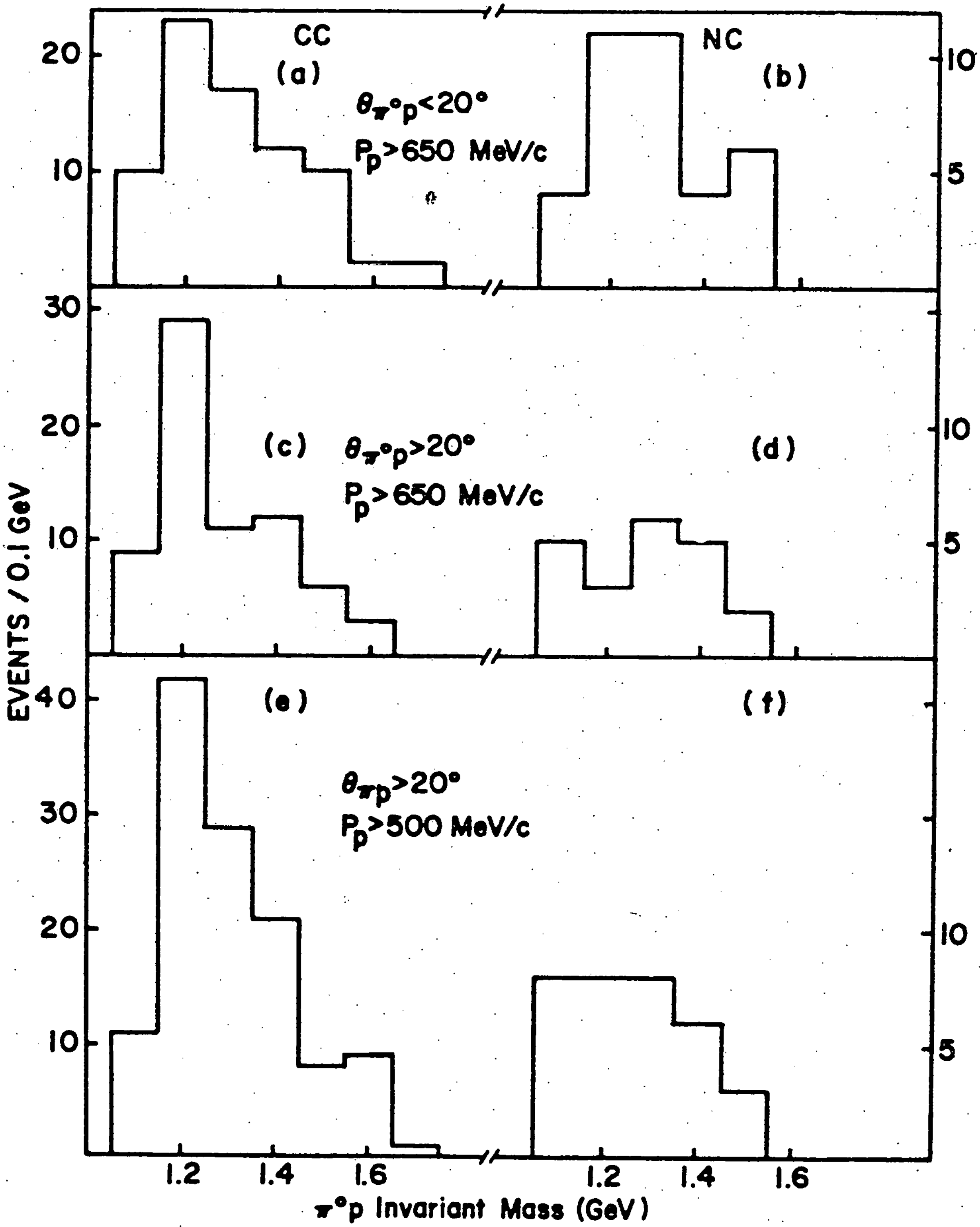

ν BEAM
1m
SPARK CHAMBER
SCINTILLATION COUNTER

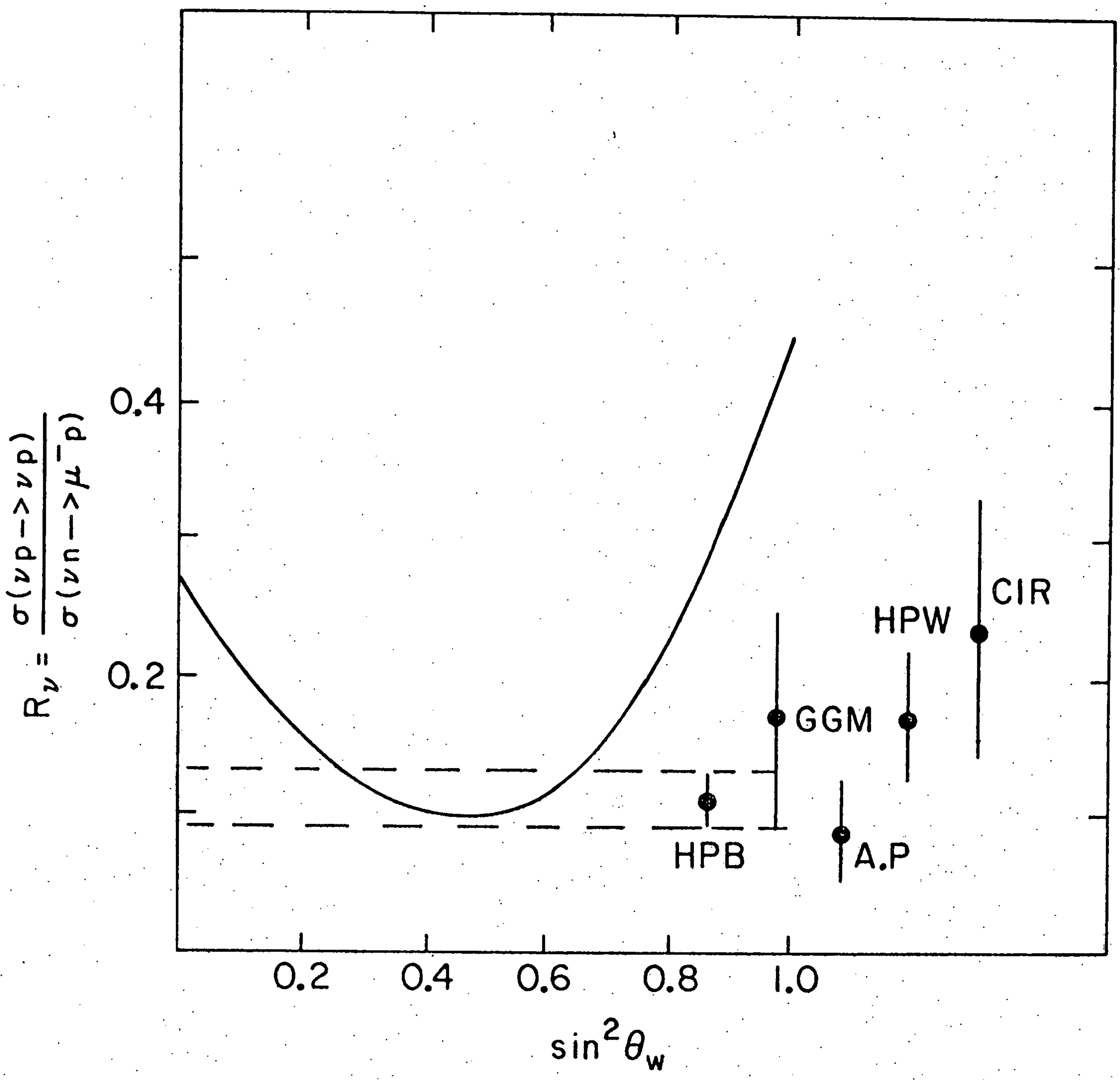

WIDE ANGLE COUNTERS
MAGNETIZED TORROIDS
6' CHAMBERS
SCINTILLATION COUNTERS
72 D 18
6' CHAMBERS
8' CHAMBERS
0
5
10
FEET


DRIFT CHAMBERS
CALORIMETERS
VETO
CTR.
ν
(a)
SIDE VIEW
2.7m
2.6m
(b)
0.5m

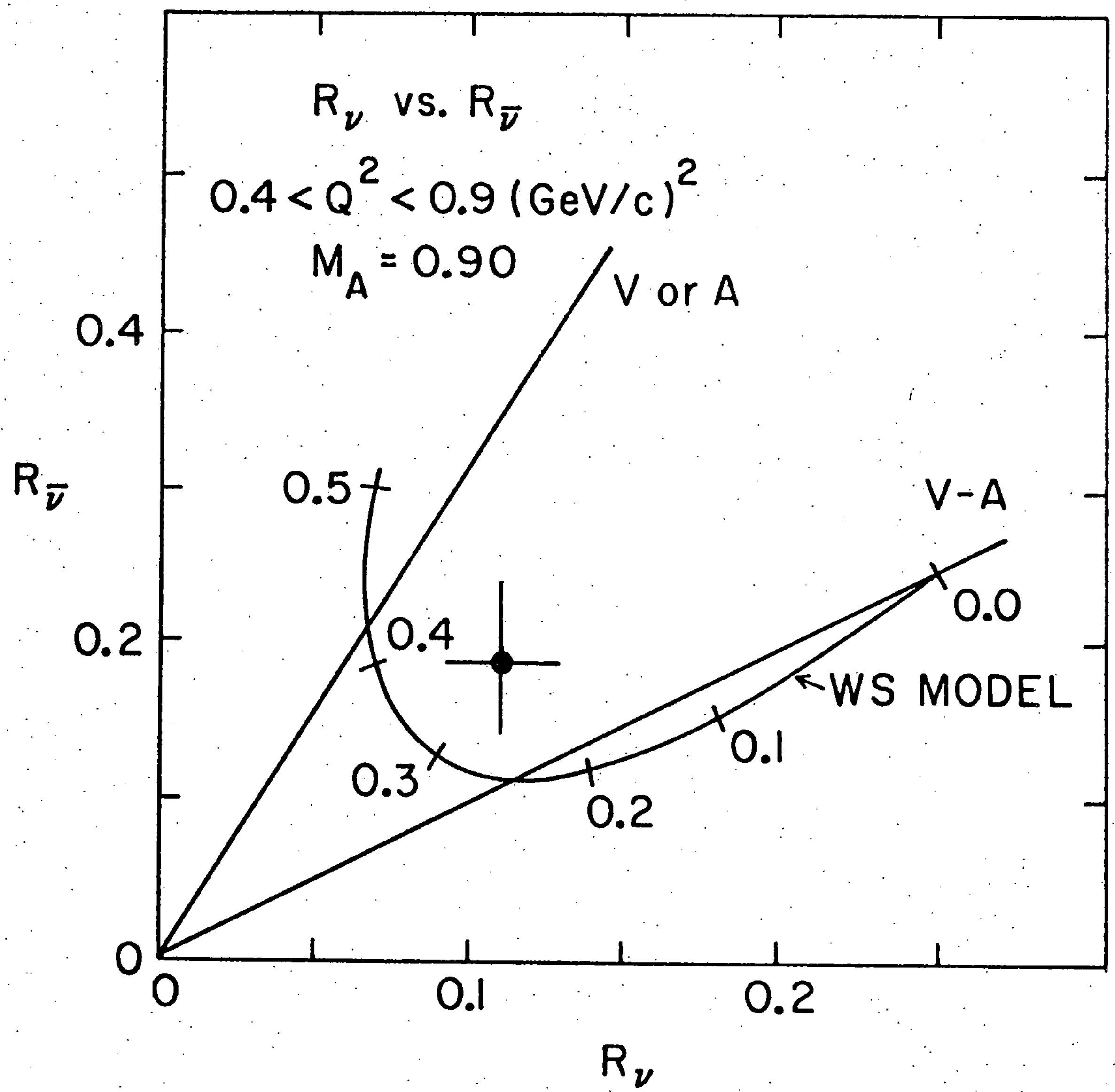


Δ
ν p π° CHANNEL
(Selected sample, 80 ev.)
$M_{p\pi^0}$ GeV
ν p π⁻ CHANNEL
$M_{p\pi^-}$ GeV
μ⁻ p π° CHANNEL
(Selected sample, 109 ev.)
NUNBER OF EVENTS
1.05
1.25
1.45
1.65
1.85
$M_{p\pi^0}$
2.25
GeV

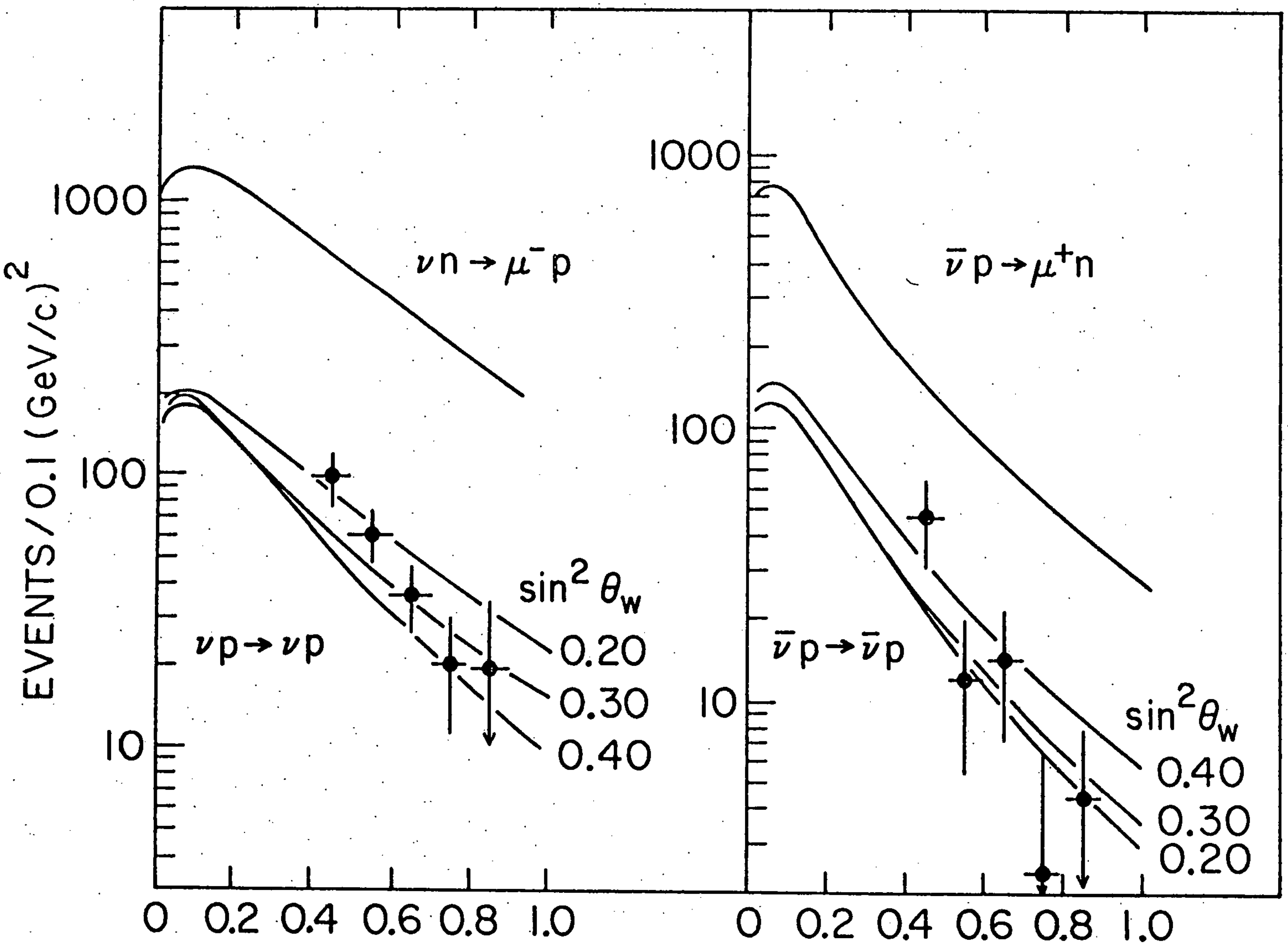

CC
(a)
$\theta_{\pi^\circ p}$<20°
P_p>650 MeV/c
NC
(b)
(c)
$\theta_{\pi^\circ p}$>20°
P_p>650 MeV/c
(d)
(e)
$\theta_{\pi p}$>20°
P_p>500 MeV/c
(f)
EVENTS / 0.1 GeV
$\pi^\circ p$ Invariant Mass (GeV)



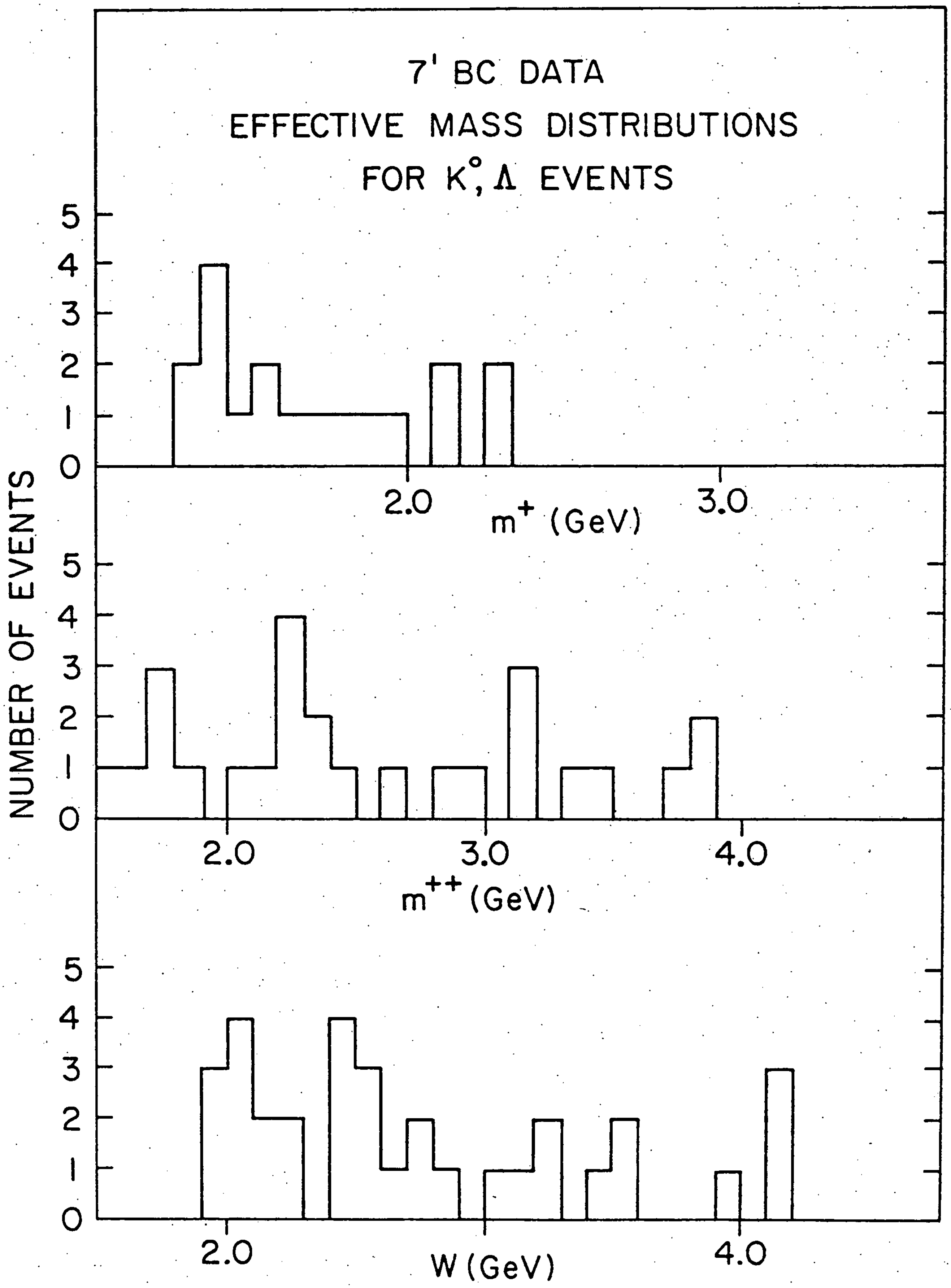
0.4
0.2
$R_\nu = \frac{\sigma(\nu p \to \nu p)}{\sigma(\nu n \to \mu^- p)}$
0.2
0.4
0.6
0.8
1.0
$\sin^2\theta_W$
HPB
GGM
A.P
HPW
CIR

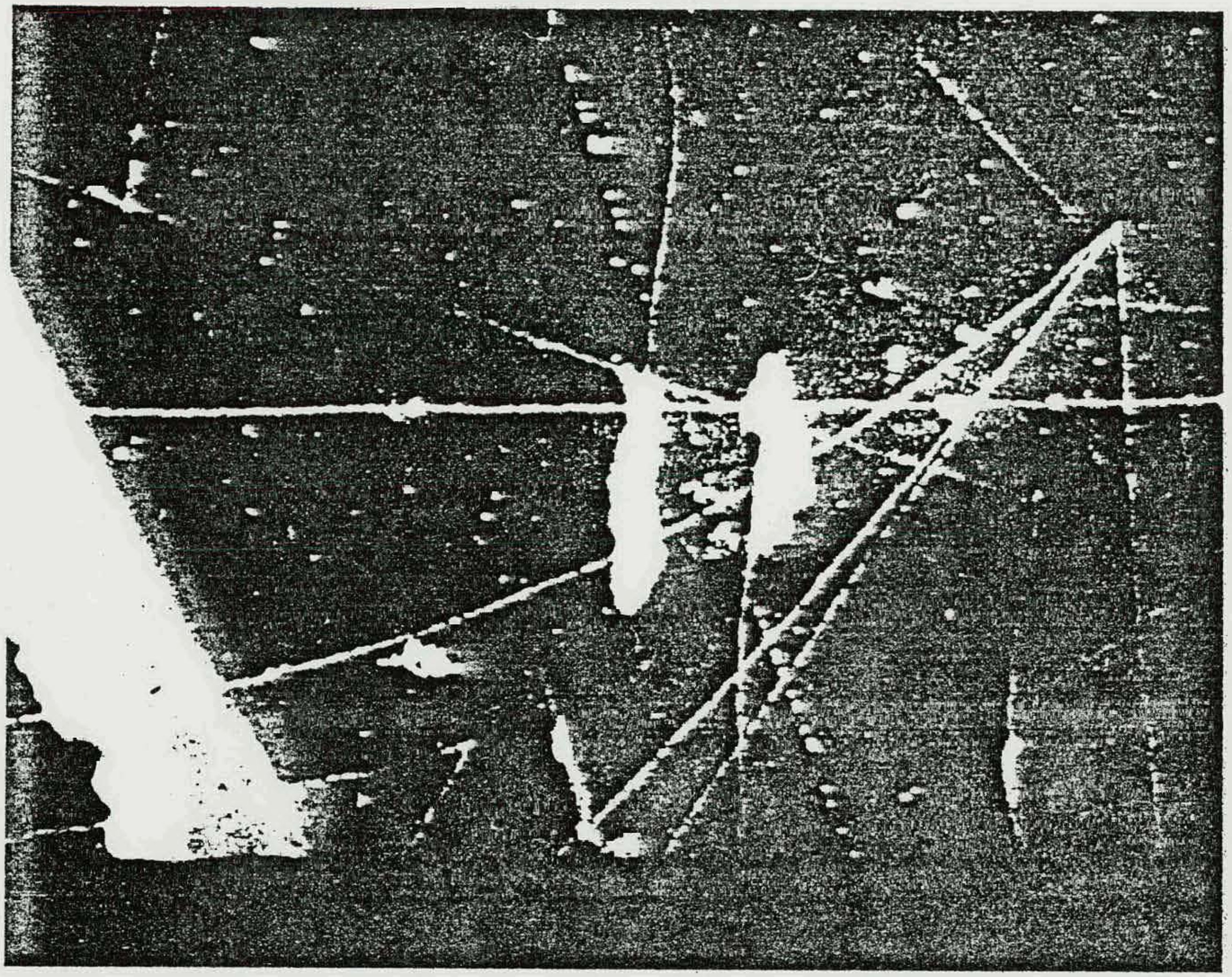


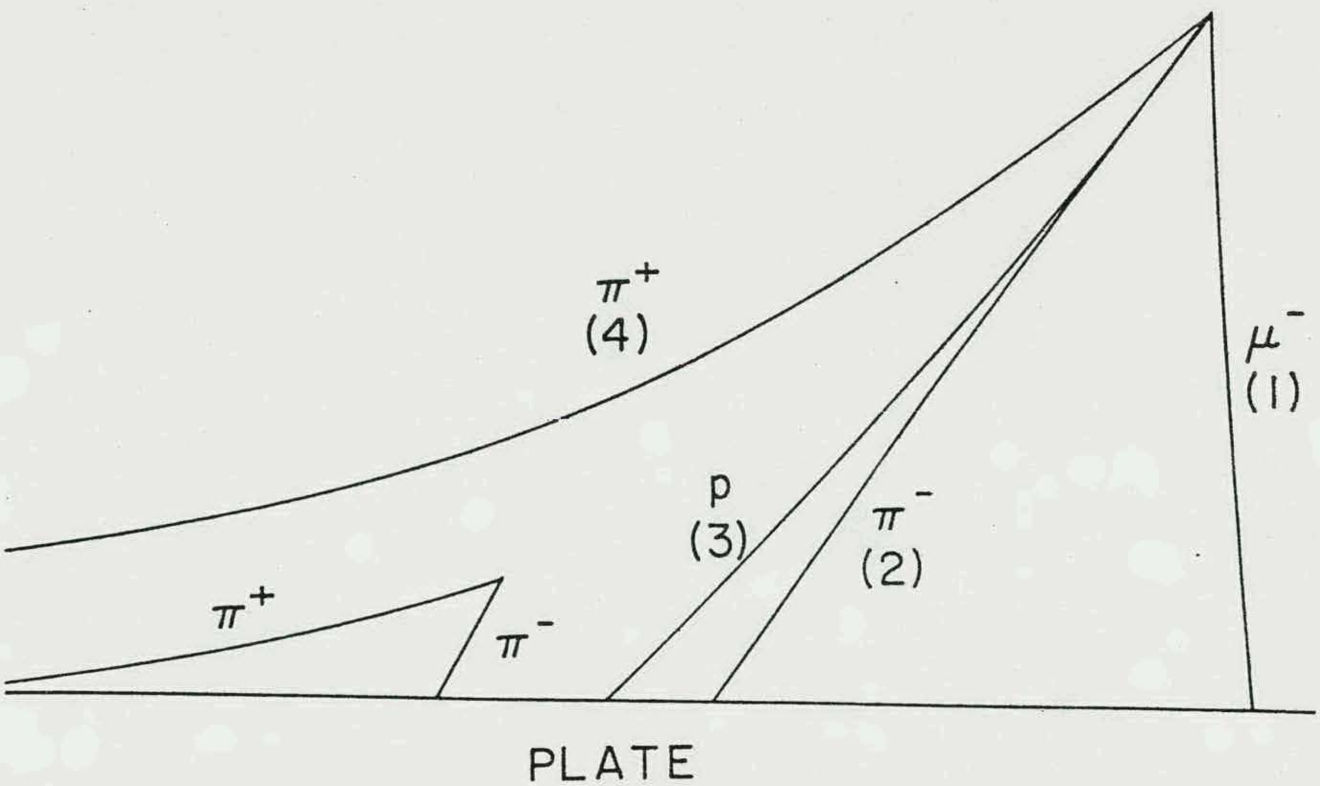
R_ν vs. R_ν̄
0.4 < Q² < 0.9 (GeV/c)²
M_A = 0.90
V or A
V-A
WS MODEL
0.5
0.4
0.3
0.2
0.1
0.0
R_ν̄
R_ν
0
0.1
0.2
0.4



EVENTS/0.1 (GeV/c)^2
1000
100
10
$\nu n \rightarrow \mu^- p$
$\nu p \rightarrow \nu p$
$\sin^2\theta_W$
0.20
0.30
0.40
0 0.2 0.4 0.6 0.8 1.0
1000
100
10
$\bar{\nu} p \rightarrow \mu^+ n$
$\bar{\nu} p \rightarrow \bar{\nu} p$
$\sin^2\theta_W$
0.40
0.30
0.20
0 0.2 0.4 0.6 0.8 1.0


7' BC DATA
EFFECTIVE MASS DISTRIBUTIONS
FOR K°, Λ EVENTS
NUMBER OF EVENTS
0
1
2
3
4
5
2.0
3.0
m+ (GeV)
4.0
m++ (GeV)
W (GeV)





π^+
(4)
μ^-
(1)
p
(3)
π^-
(2)
π^+
π^-
PLATE