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PROMPT PRODUCTION OF MUON NEUTRINOS AND MUON ANTINEUTRINOS IN PROTON-TUNGSTEN COLLISIONS

The Ohio State University

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300 N. Zeeb Road, Ann Arbor, MI 48106
PROMPT PRODUCTION OF MUON NEUTRINOS AND MUON ANTINEUTRINOS IN PROTON-TUNGSTEN COLLISIONS.

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

Jan Sigve Hoftun, Cand. mag., M. Sc.

* * * * *

The Ohio State University

1983

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CHAPTER I
INTRODUCTION

In 1974 new experimental results from two separate experiments stirred up a lot of interest because they could best be explained by a model with a new quark carrying the quantum number charm.

The charm quark idea was first proposed in a paper by Bjorken and Glashow in 1964 [1]. In 1970 Glashow, Iliopoulos and Maiani showed that lepton-hadron symmetry was possible by including the charm quark in a weak-isospin doublet with a combination of the down quark and the strange quark [2].

One of the experiments mentioned above was performed at SLAC where they looked at the ratio of cross sections for $e^+e^- \rightarrow \text{hadrons}$ and $e^+e^- \rightarrow \mu^+\mu^-$ [3]. They found an increase in this ratio at about 3.7 GeV center-of-mass energy, consistent with reaching the threshold for producing a new quark with electric charge $2/3$ of an electron charge, and a sharp peak at about 3.1 GeV. Another experiment, at Brookhaven National Laboratory using proton-nucleon
collisions, also found a sharp resonance at 3.096 GeV [4]. In the quark model this resonance, named $J/\psi$, consists of one charm quark and one anticharm quark.

This discovery led to a series of new experimental efforts to investigate all possible states of charmed particles. These included colliding beam experiments (either pp or $e^+e^-$) to study the $J/\psi$ family and search for new states with even more exotic quantum numbers and high resolution bubble chamber and hybrid emulsion-spectrometer experiments to study the life time of these extremely short-lived particles.

Still another type of experiment motivated in part by this discovery was the "beam dump" experiment. In a beam dump experiment a beam of particles from an accelerator strikes a large target. All the beam particles interact in the target, and both these primary and most of the secondary particles are absorbed by the target. This reduces the number of decay products from relatively long-lived particles like $\pi$-mesons and K-mesons, offering an excellent opportunity to study the "prompt" particles, those produced in or very near the primary interaction. This allows us to learn about the production of short-lived particles in the target. Several experiments to look for neutrinos from such a beam dump were initiated. The first results from these
experiments were reported in 1978 [5] [6] [7].

These early experiments did not agree on the production cross section for prompt neutrinos. The results ranged from 30 to 400 \( \mu b \) per nucleon. The observed event ratio of antineutrinos to neutrinos was \( 0.22 \pm 0.02 \) [8]. The experiments were not equipped to do extrapolation to infinite target density. However, the observed ratio was significantly higher than the ratio expected from \( \pi \)-meson and K-meson decay (\( 0.146 \pm 0.015 \)). Later results from the same experiment found a prompt antineutrino flux consistent with zero by doing target extrapolation [9]. (See section 3.1 for the technique of target extrapolation.)

Since there were many unanswered questions, it was clear that definitive experiments needed to be done. A collaboration to perform an experiment to answer some of these questions was formed by physicists from University of Michigan, the Ohio State University, University of Washington and University of Wisconsin. Their proposal was accepted by Fermi National Accelerator Laboratory (Fermilab) and assigned experiment number 613. Later the group was joined by experimenters from University of Florence, Italy. To speed up the completion of the experiment, it was decided to use already existing lead/liquid-scintillator modules as the neutrino detector (see chapter on apparatus).
The milestones in the history of the experiment were as follows:

1. Proposal submitted .................. September 1978
2. Proposal accepted ................... November 1978
4. Housing for detector .............. February 1980
5. Half of detector installed .......... April 1980
6. Test run ................................ June 1980
7. Rest of detector installed .......... November 1980
8. First running period ............... February-May 1981

In the following chapters, the theory behind prompt neutrino production and neutrino detection, the apparatus as actually built, the off-line analysis and the final results are described.
Since neutrinos were postulated to explain the $\beta$-decay spectrum of radioactive nuclei, they have been the focus of much experimental and theoretical interest. The first direct evidence for their existence came in 1953 [10].

2.1 Standard Model of Quarks and Leptons.

The current view of the world of elementary particles is best described in the quark model. Quarks were hypothesized by Gell-Mann and Zweig independently in 1964 to explain the large number of strongly interacting particles observed at that time [11] [12]. These particles form multiplets which could be explained by postulating that they were the bound states of either three quarks (baryons) or a quark and an antiquark (mesons). The various types of quarks were named up, down and strange (u,d,s). For example, a proton consists of two up quarks and one down quark in this picture (uud). The quarks are all fermions with spin 1/2 in units of $\hbar$ and have electric charge of either 2/3 or -1/3 of an
elementary electron charge. One of the successes of this model was the $\Sigma^-$-particle (sss) which was found with the mass that it was predicted to have.

As explained in the introduction, another quark, the charm quark, was added to the picture in 1974. The quarks then made up two isospin doublets or generations, the up-down doublet and the charm-strange doublet. These generations were parallel to the lepton $e^-\nu_e$ and $\mu^-\nu_\mu$ generations. This picture has since been expanded to include a new generation, the top-bottom quark doublet and the corresponding $\tau^-\nu_\tau$ lepton doublet. Direct evidence for the top quark and $\nu_\tau$ has yet to be found. The whole picture can be summarized by writing the generations together:

\[
\begin{align*}
\text{quarks} & \quad [u] \quad [c] \quad [t] \\
\text{leptons} & \quad [e] \quad [\nu_e] \quad [\nu_\tau] \quad [\tau]
\end{align*}
\]

The bottom quark was established by the discovery of a sharp resonance, the $T$-particle, at 9.46 GeV [13]. The $\tau$-lepton was discovered at SLAC in 1975 [14]. They found many events in the channel $e^+e^- \rightarrow e^\pm + \mu^\mp + \geq 2$ undetected particles. This could not be explained by the production of
any known particles, but it was consistent with the production and decay of a pair of heavy leptons. Efforts to find the top quark by looking for an increase in \( R(e^+e^- \rightarrow \text{hadrons}/e^+e^- + \mu^+\mu^-) \) have been unsuccessful up to 36 GeV, the maximum available center-of-mass energy at \( e^+e^- \) machines (PETRA at DESY in Hamburg, Germany).

2.2 Prompt Neutrino Production in the Standard Model.

In the standard model, the explanation for prompt neutrinos is that they come from semi-leptonic decay of D-mesons, which are particles carrying the charm quantum number and having the following properties [15]:

- Valence quarks: \( D^+ = (c\bar{d}), D^- = (\bar{c}d), D^0 = (c\bar{u}), D^{*0} = (\bar{c}u) \).
- Mass: \( D^+ = 1869.4 \text{ MeV}, D^0 = 1864.7 \text{ MeV} \).
- Life-time: \( D^+ = 9.1 \times 10^{-13} \text{ sec}, D^0 = 4.8 \times 10^{-13} \text{ sec} \).

Although the predominant decay mode of D-mesons is into K-mesons, about 20% decay into electrons, and about 20% into muons.

If all the prompt neutrinos and antineutrinos came from the decay of D-mesons, there would be an equal number of each produced. This is because the D-mesons are produced associatively, i.e. as \( D\bar{D} \) pairs, in proton-nucleus
collisions. This means that there are the same number of $D$ and $\bar{D}$ produced. Since a $D$ decays into $\mu^+ \nu_\mu$ and a $\bar{D}$ into $\mu^- \bar{\nu}_\mu$, this yields the same number of neutrinos and antineutrinos. The decay process can be illustrated with Feynman diagrams (Fig 1).

Other processes could also contribute to the production of prompt neutrinos and antineutrinos, especially the production and decay of the charmed baryon $\Lambda_c$. It has the following properties [15]:

Valence quarks: $\Lambda_c^+ (cud)$.

Mass: 2282.2 MeV.

Life-time: $1.1 \times 10^{-13}$ sec.

The early experiments on $\Lambda_c$ production at the CERN ISR found a cross section in the range 65-80 μb [16] [17] [18], which was higher than the measured cross section for $D$ production (30-40 μb) [19]. In proton-nucleus collisions more $\Lambda_c^+$ than $\Lambda_c^-$ are produced because there are more quarks than antiquarks in the nucleons. To conserve charm, a $D$-meson is produced together with the $\Lambda_c^+$. The quark model does not predict much about the decay of the $\Lambda_c$, and not much is known from experiments. The $\Lambda_c$ is produced diffractively, i.e. it is peaked in the forward direction, but the branching ratio for it to decay into leptons (4.5%) is lower than that for $D$-mesons (20%). The energy spectrum
of the decay products from the $\Lambda_c$ may also be different from
the spectrum from $D$-meson decay. Considering these
differences, all that can be concluded is that the
production of neutrinos may be different from the production
of antineutrinos in this process.

2.3 Neutrino-nucleon Inelastic Scattering.

Because neutrinos only interact via the weak interaction,
they are very suitable for so-called "deep inelastic"
scattering experiments. In these experiments, a lepton
interacts with a nucleon in such a way that it probes the
inner structure of the target particle. The first
experiments of this kind gave important evidence for an
inner structure of point-like particles in the nucleons.

Because of lepton-number and charge conservation, the
only charged-current interactions involving a up or a down
quark are the following:

$$\nu_\mu d + \mu^- u \quad (\text{Fig 2})$$
$$\bar{\nu}_\mu u + \mu^+ d \quad (\text{Fig 3})$$
Neutrino interactions can then be used to probe the quark content of nucleons. The result from such experiments showed that the nucleons did not consist of only three quarks: there seemed to be an antiquark contribution of 8% as well [20]. This has been explained as a "sea" of quark-antiquark pairs.

2.3.1 Differential and Total Cross Sections.

Several variables have been introduced to describe neutrino interactions. The Bjorken scaling variables \( x, y \) will be used here. They are defined

\[
x = \frac{q^2}{2M(E-E')} \]

\[
y = \frac{E-E'}{E} \]

where \( q^2=2EE'(1-\cos\theta) \) is the square of the 4-momentum transfer,

\( E \) is the incoming neutrino energy,

\( E' \) is the outgoing lepton energy,

\( M \) is the nucleon mass, and

\( \theta \) is the scattering angle (angle of outgoing lepton with respect to the neutrino direction)
Using these variables and the structure functions, the differential cross sections can be written:

\[
\frac{d^2g^{\nu,\bar{\nu}}}{dxdy} = G^2ME\left[F_2^{\nu,\bar{\nu}}(x,q^2)(1-y\frac{Mx\nu}{2E}) + 2xF_1^{\nu,\bar{\nu}}(x,q^2)\frac{y^2}{2} + xF_3^{\nu,\bar{\nu}}(x,q^2)\cdot y(1-y)\right]
\]  

(2.1)

where \( G \) is the Fermi-coupling constant, + is for neutrinos and - is for antineutrinos. It is hypothesized that the structure functions \( F_1,2,3(x,q^2) = F_1,2,3(x) \) asymptotically at high \( q^2 \) and high \( E-E' \). This is known as Bjorken scaling [21]. Experimentally this has been verified to be almost true at the available energies.

Assuming scaling and \( E\gg M \), and integrating (2.1) over \( x \) and \( y \), the total cross sections follow:

\[
\sigma^{\nu,\bar{\nu}} = \frac{G^2ME}{\pi} \left[\int_0^1 \frac{1}{2} F_2^{\nu,\bar{\nu}}(x)dx + 1/6 \int_0^1 2xF_1^{\nu,\bar{\nu}}(x)dx + 1/3 \int_0^1 xF_3^{\nu,\bar{\nu}}(x)dx\right]
\]

(2.2)

which is directly proportional to \( E \). This is well-established experimentally [22].
In this context, these properties of neutrino interactions will be used to calculate and correct for the geometric acceptance and trigger biases of the detector.

2.3.2 Data from Neutrino Experiments.

E-613 was not an experiment to study deep inelastic neutrino scattering. Several other high statistics experiments have been performed for this purpose \cite{23} \cite{24} \cite{25}. These experiments have focused on the structure functions and the distributions of events as functions of $y$ and $x$. The early beam dump experiments found that the prompt neutrinos also followed the same distributions. This only meant that the prompt neutrinos were of the same kind as the ones generated by decay of $\pi$-mesons and K-mesons. After corrections for apparatus acceptance, the measured distributions from E-613 should then be the same as the ones found by the deep inelastic scattering experiments. The previously measured $x$- and $y$-distributions were used as input for the Monte Carlo calculations of the apparatus acceptance to generate the division of the total energy into a muon part and a hadron part and to generate the angle between the direction of the outgoing muon and the direction of the neutrino.
3.1 Technique of Beam Dump Experiments.

Beam dump experiments are constructed to maximize the flux of penetrating particles produced near the interaction of a beam particle with a target nucleus. These particles must be detected after having traversed a length of material acting as a shield or filter. Among the experimentally known particles, muons and neutrinos are the only candidates. The ideal beam-dump target would have infinite density and be infinitely long. With such a target, all long-lived particles like π-mesons and K-mesons would be absorbed before they could decay. In practice, this target is impossible to build, and another technique must be used to extract the number of prompt particles produced very near the interaction point. The technique most often used involves two targets made of the same material but of different densities. If these two targets are long enough so that most of the beam particles interact in them, they both yield the same number of prompt particles. The number
of non-prompt particles produced is proportional to the inverse of the density since it only depends on the available decay space.

If the number of prompt particles is $N_p$, and if the total observed number of particles for a target with density $d_i$ is $N_i$ ($i=1,2$), then

$$N_1 = N_p + a/d_1$$  \hspace{1cm} (1)$$
$$N_2 = N_p + a/d_2$$  \hspace{1cm} (2)$$

where $a$ is a constant.

Subtracting (1) from (2) and solving for $a$,

$$a = \frac{d_1(N_2 - N_1)}{d_1/d_2 - 1}$$

and from equation (1),

$$N_p = \frac{dN_1 - N_2}{d - 1}$$  \hspace{1cm} (3.1)$$

where $d=d_1/d_2$.

From (1) we see that $N_i + N_p$ as $d_i \to \infty$.

When the observed particles are neutrinos, two special considerations must be made. First, because of lepton number conservation, a muon is always created together with the muon neutrino. These muons cannot be allowed to hit the
neutrino detector since it has to be very sensitive in order to detect as many neutrinos as possible.

The second consideration is that the detector itself must be massive enough to detect neutrinos with a reasonable probability. This requires heavy material and repetition of a basic structure.

The early experiments at CERN had made use of already existing neutrino-beam facilities and neutrino detectors and had used a long earth shielding to range out the muons produced together with the neutrinos. Consequently the neutrino detectors had been very far from the target and therefore had covered a very small solid angle and small range in transverse momentum. By placing the detectors closer to the target, the transverse momentum range could be extended and solid angle could be increased, and therefore a larger number of events could be collected with the same number of incident protons. However, with the reduced earth shielding, the detector could not accept the flux of muons without too much dead time. But since muons have electric charge while neutrinos are neutral, magnets could be used as active shielding to bend the muons away from the direction of the detector.
The comparison between the beam dump experiments done at CERN and E-613 is made in the following table:

**TABLE 1**

**COMPARISON OF BEAM DUMP EXPERIMENTS**

<table>
<thead>
<tr>
<th>EXPERIMENT</th>
<th>TARGET</th>
<th>SHIELD</th>
<th>DUMP-DETECTOR DISTANCE (m)</th>
<th>ACTIVE MASS (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN (BEBC,CHARM, CDHS)</td>
<td>Cu</td>
<td>PASSIVE Fe</td>
<td>830 (on average)</td>
<td>12.5, 100, 500</td>
</tr>
<tr>
<td>E-613 (Cu,Be)</td>
<td>MAGNETIZED + PASSIVE Fe</td>
<td>55</td>
<td></td>
<td>64</td>
</tr>
</tbody>
</table>

3.2 Beam Line.

E-613 was located in the M2 beam line of the Meson Area at Fermilab. (Fig 4)

The protons were accelerated in the linear accelerator, booster, and main ring to 400 GeV/c and then directed to the experimental areas by the switchyard. Each of the two beams of protons directed to the Meson Area ordinarily struck a target before being separated into beams of different
particles and momenta. The M2 line was built to be used as a beam of secondary protons produced in interactions in one of these targets (named M-center). But for E-613, as many as possible of the primary protons, those which did not interact in the M-center target, were transmitted to the beam-dump target.

Downstream of the M-center target, two strings of dipole magnets bent the beam in the horizontal plane. They were tuned to pass 400-GeV/c protons. Neutral particles and lower momentum charged particles produced upstream did not get by these magnets in the direction of the detector. The beam line also had a number of quadrupole magnets to control the position and size of the beam. All the beam line magnets were controlled from a console in the area of the detector. (Fig 5)

Ionization chambers were placed at various positions along the beam line to help in the tuning of the magnets. These halo and loss monitors indicated how many particles were on the outside of the vacuum pipe. High counting rate in these monitors meant that either the beam was not positioned correctly or that it was "out of focus". A system was set up on the experimental computer to check these readings and suspend data-taking if any of them were consistently too high (or too low).
The data from all the beam monitors also went through an extensive off-line analysis to determine whether a given spill could be used or not. The spill was used if fewer than three out of twelve beam-line monitors and none of the beam-on-target monitors downstream of the beam-dump target were outside pre-set limits. The limits were set by histograming all the data for a specific monitor for each setting of the high voltage.

Further downstream, a short dipole magnet pitched the beam vertically so that it hit the center of the detector. This also helped prevent unwanted particles from reaching the detector. Directly downstream of this bending magnet the protons went through a secondary emission monitor (SEM). It generated a signal proportional to the number of particles passing through it. This provided the measurement of the number of protons used in the experiment. The SEM was calibrated by placing a thin copper foil in the beam for a certain length of time and accumulating the reading of the SEM. By measuring the radioactivity of the foil, the number of protons that passed through it was determined [26]. Finally the beam passed through a position monitor (SWIC) for the fine tuning onto the beam-dump target.
During the running, the cycle time of the accelerator varied from eight to fifteen seconds, and E-613 received on the average $2 \times 10^{12}$ protons per pulse, spread over a one second spill time.

3.2.1 Beam Cleanliness.

The halo and loss monitors were calibrated by placing known amounts of material in the path of the beam and measuring how much the readings changed. This was used to find out how much of the beam interacted with the residual air or with material in the beam line. When the protons interacted, $\pi$-mesons were produced and subsequently decayed into muons and muon neutrinos. These neutrinos, produced upstream of the beam-dump target, constituted a non-prompt background which did not depend on the target density and their number should therefore be minimized.

3.3 Beam Dump Target and Muon Shield.

To learn about the dependence of prompt-neutrino production on the target material, a total of six different targets were used. They were mounted in a block of copper for water-cooling purposes. This block rested on a carriage
that could be moved vertically and horizontally to position the desired target in the beam. The targets were all approximately three interaction lengths long. (An interaction length is the length of material in which all but 1/e of a beam of hadrons interacts.) There were three different materials, tungsten (W), copper (Cu) and beryllium (Be), with two different "densities" for each. The densities were labeled "full" and "partial", where the full density targets were solid blocks of material and the partial density targets were made by spacing discs of the material with air gaps. (Fig 6)

The results reported here are from the runs with the tungsten targets. This is the material yielding the most prompt neutrinos relative to background neutrinos because of its high atomic number. Most of the running period from February to May 1981 was on tungsten of full and partial density. In 1982 (March to May) an equal amount of running on tungsten was done. For tungsten, the ratio of the full density to the partial density was 2.7.

The readout of the position of the target was calibrated by surveying before anything in front of the target was put in place. The fine tuning of the target position was done while the beam was hitting it by using readings from monitors further downstream to tell how close to the center
The target, because of its length, served as the primary beam dump: most of the beam stopped in the target. Immediately downstream of the target, active and passive shielding stopped or bent away all particles except neutrinos that were generated in the interactions between the beam protons and the target nuclei.

The upstream part of the shielding consisted of two solid iron magnets. These stopped most hadrons that punched through the target. Muons were deflected vertically out of the beam direction. These magnets and the target assembly were housed in a steel cave to shield the outside against radiation.

Downstream of this steel cave, there was a larger solid iron magnet that had been used by another experiment in the same beam line. It was repositioned to deflect particles vertically. This magnet bent the muons even farther away from the neutrino-beam direction. Two smaller magnets were placed immediately downstream to deflect away the muons that had been bent back by the return yoke of the large magnet. Some muons still "leaked" through this system of magnets close enough to the neutrino-beam direction to reach the detector, so a large amount of steel was added behind the
active dump to stop the low energy part of this flux. (Fig 7)

3.4 Neutrino Detector.

The E-613 neutrino detector was placed in a separate building 180 feet (55 m) from the beam-dump target (Fig 8,9). The building was large enough so that the apparatus could be assembled and serviced in it, and it housed all the electronics needed in the experiment (Fig 10).

3.4.1 Calorimeter.

The main part of the detector was the lead/liquid-scintillator calorimeter. It served both as a neutrino-interaction target and as a device to trigger on and to measure the ionization energy deposited by the particles created in the neutrino interaction. It consisted of thirty modules, each a steel box containing twelve 1/4-inch thick vertical lead plates with liquid scintillator between them. This system sampled the hadron shower every 1.2 radiation lengths. The liquid was mineral oil with a scintillating chemical compound (NE235) dissolved in it. The photons generated when a charged particle passed through
the liquid scintillator were detected at each end of the module by photomultiplier tubes. The tubes used were 2-inch diameter XP2202's made by Amperex. The lead plates were coated with reflective Teflon sheets to enhance light collection. Total internal reflection occurred at the Teflon-scintillator interface since the index of refraction of Teflon (n=1.33) is lower than that of the scintillator (n=1.47). This means that more photons than just the ones with straight line paths to the phototubes were detected. Each module was separated into five horizontal cells by internal spacers, for a total of 150 cells, or 300 phototubes.

The signal from each of these phototubes was proportional to the amount of light that reached it and, therefore, proportional to the energy deposited in the cell. The sizes of the signals were measured by a system of analog-to-digital converters (ADC). The same signals were used to trigger the apparatus.

The ADC system had to have a very large dynamic range to accurately measure small energy depositions, such as those from minimum ionizing particles, as well as very large ones from neutrino interactions. This required good control of the gain and pedestals for each of the 300 channels, and a LeCroy 2285 system was chosen. Before data collection,
average values of the pedestals were stored in the ADC memory by running a lot of dummy triggers into the system. To monitor any drift in the pedestal values during data collection, one dummy trigger was taken between each pulse from the accelerator.

The calorimeter was calibrated by using muons generated in the beam-dump target and further upstream and leaving the active shielding magnets off. A muon deposited a small amount of energy in each cell it went through. This was measured to be, on the average, 150 MeV. The high voltages supplied to the phototubes were regulated to keep the signal from muon deposits at forty counts in the ADC channels. The final conversion from ADC counts to energy was done by using the result of placing some of the modules in a beam of μ-mesons of known momentum. This was needed because a hadronic shower of a certain energy deposits more of its energy in one cell due to nuclear interactions than a muon of the same energy does. Each type of particle was given a calibration number to convert from ADC counts to energy deposited. The resolution of the calorimeter modules was also measured in this beam of μ-mesons. The average value for the resolution was found to be \(0.52/\sqrt{E}\) where \(E\) is the energy of the hadron shower (Fig 11).
3.4.2 Proportional Wire Chambers.

In each gap between two calorimeter modules, there were two planes of proportional wire chambers (PWC's), one with horizontal wires and one with vertical wires [27]. They consisted of 1-inch by 1-inch square tubes of extruded aluminum with a 0.002-inch wire in the center. There were thirty planes of 136 5-foot long vertical wires and thirty planes of 64 12-foot long horizontal wires, for a total of 6000 PWC wires in the entire system. The tubes were filled with a mixture of 80% argon and 20% carbon dioxide.

The wires were kept at +2000V to attract electrons generated by collisions in the gas. At this voltage the number of electrons was proportional to the number of particles passing through the tube and therefore to the energy deposited. The readout electronics consisted of an amplifier, a storage capacitor and an analog switch for each wire. Eight wires were served by one analog multiplexer which gated the signals onto the readout bus at the appropriate times. The signals on the bus were compared to a pre-set minimum voltage and, if they were above this minimum, digitized by a 12-bit ADC and stored in a random access memory. The readout of the system by the computer was handled through CAMAC.
3.4.3 Muon Spectrometer.

Downstream of the calorimeter-PWC detector, a muon spectrometer was used to measure the momentum of the muons coming from charged-current muon neutrino interactions. It consisted of three solid-iron magnets with approximately toroidal fields and five sets of drift chambers. The magnets had transverse dimensions of twelve by eight feet. The two upstream ones were thirty-five inches thick and the third one seventy inches thick in the beam direction. The magnets were constructed from 8 (or 16) individual plates, and the top and bottom halves were separated by iron spacer plates. A hole was left in the middle so that coils could be put around the top and bottom halves. (Fig 12) The current supplied to the magnets was high enough (1000A) to drive the iron into saturation with a field strength of about twenty kilogauss. Each set of drift chambers had five planes, two with thirty-six vertical wires each, two with twenty-four horizontal wires each and one with thirty-six wires making an angle of 30° with the vertical. The vertical wire chambers were labeled X and X'; the horizontal, Y and Y'; and the angled wire chambers, U. The primed chambers were upstream of the unprimed in both cases and staggered \( \frac{1}{2} \) cell width with respect to them. The sum of the drift times in the primed and unprimed chambers add up to a constant which was used to determine which side of
the wire the particle passed (Fig 13).

The five planes made up what was known as a superplane, and they were labeled # 1 through # 5 with # 1 directly downstream of the calorimeter.

The drift chambers had to cover a large area, and their resolution had to be better than the limit set by the multiple scattering in the iron magnets. A construction method using aluminum I-shaped beams to form 4-inch wide cells was chosen. A 0.004-inch gold-plated tungsten wire was strung in the middle of each cell. By having negative high voltage on the I-beams and positive on the wire, the field in one cell was approximately uniform. This gave the electrons knocked loose from gas molecules by passing charged particles a constant drift velocity towards the wire.

A single plane was made up of several smaller modules, four for X, three for Y, and six for U. These modules were mounted in a frame which had holes to position each module in its correct place. Tracks on the floor and wheels on the frames were used to take the frames out from the gaps between the magnets for service.
The gas used in the chambers was 50% argon and 50% ethane. Each module had a separate gas connection to a distribution system with flowmeters, manifolds and shut-off valves. The exhaust gas went through individual oil bubblers to prevent air from diffusing back into the modules. Each module also was connected to a power supply for the amplifiers and to high voltage supplies for the wires and the I-beams.

The electronics used to record the drift times was of the same construction as that used by a previous experiment at Fermilab (E-531, Hybrid emulsion-spectrometer experiment to measure lifetimes of charmed particles) [28].

The first stage in the electronics consisted of fast amplifiers mounted on the chamber modules. The analog pulses from the wires were amplified by a factor of 100. To minimize the width of the pulse, they were shaped by filtering through a network of capacitors and resistors. The input impedance of the amplifier was matched to the impedance of the wire. To further reduce the widths of the pulses, the wires were terminated at the end away from the amplifier by resistors matching the impedance of the wire in series with capacitors to isolate the high voltage on the wire. This prevented reflections of the signals from
arriving at the amplifier a little later than the real signals and making the real signals look wider than they really were. The amplified signal was fed into a fast discriminator mounted on the same board. It had a variable threshold and gave a signal of fixed voltage with a duration equal to the time the real signal was below threshold (negative pulse).

The signals were transmitted from the discriminators to the input of the recording electronics on coaxial cables of equal length. The idea for the time measuring electronics was taken from a basic design by W. Sippach (Nevis Labs) [29]. The layout is shown in Figure 14. The first stage consisted of a series of time recorder modules (TR's), each having 8 inputs. They used four-bit phase code in parallel with three-bit gray code, driven by a 83\(^{-}\) MHz clock. The phase code and gray code made interpolation between the counts of the clock possible to an accuracy of 1.5 nsec. with redundancy in the counting, allowing the system to recover some errors.

The codes for all the signals that arrived at the TR's were stored in a local memory that was fourteen words deep for each input channel. When the apparatus was triggered, a signal was generated, delayed and used as a common stop for all the TR's. The delay ensured that the signal from the
The longest possible drift time could reach the TR. The on-line PDP-11 computer communicated with this system through a CAMAC interface which was connected to the super controller (SC) of the recording electronics via a multi-conductor cable. The SC had a pre-programmed memory and controlled the flow of signals from the TR's to the computer. The SC and the TR's were connected through CAMAC encoders (CE) and time encoders (TE), one of each for each crate of TR's. The TE's converted the difference between the signals and the stop pulse into a number of clock counts (each count 1.5 ns.) by using the stored codes for the signals and the stop pulse.

To test this system as used in E-531, a special diagnostic program had been written. Since the computers used were not the same in the two experiments, much of this program had to be rewritten. This mainly involved making sure that the program communicated through CAMAC properly.

A small number of drift chamber modules were brought to Fermilab in July 1979 and tested in the M5 beam line. Resolution, linearity and efficiency were studied (Fig 15, 16, 17).
The efficiency plateau for the voltage on the wire was found to start at 3400 V, and the chambers became noisy at 3700 V. Therefore a running voltage of 3500 V was chosen. The voltage on the I-beams did not influence the efficiency very much, and -4000 V was chosen.

A physical survey of the drift chambers was done before the data taking started (and after the data taking was over in 1981). The positions of the individual modules were determined before the superplanes were placed in the gaps between the magnets, and the positions of the superplanes were recorded after they were in their "permanent" positions. Most of the surveys were only accurate to 1/8 inch and had to be improved for the actual use in the reconstruction programs. This was done by taking data with the magnetic field turned off and triggering on muons traversing all of the detector. By fitting straight lines to these tracks, the final numbers for the survey constants were found. Many tracks had to be used for each set of constants to compensate for the multiple scattering in the iron toroids.
3.5 Triggering Electronics.

3.5.1 1981 Trigger.

During the 1981 running period, one trigger scheme was used to look for neutrino interactions. This scheme used the signals from the phototubes as inputs. Whether it fired or not was determined by the total energy deposited, and it was called the energy trigger or ETRIG for short. The basic units in ETRIG were groupings or "segments" of sixteen phototubes, eight deep in the beam direction and two high in the vertical direction, all on the same side of the detector with respect to the beam direction. These segments overlapped and were repeated symmetrically on the other side of the detector (Fig 18). The signals from these sixteen tubes were summed linearly and then split into two equal parts that were used as inputs for two discriminators. The threshold levels in the two discriminators were set a factor of four apart. A combination of three of the total of four discriminators (two segments on each side of the detector) generated a signal from a coincidence circuit and determined the characteristic W-shaped response of the trigger as a function of the position across the calorimeter (Fig 19). The signal from the twenty-four segments were combined and
sent to a coincidence circuit in which they, timing gates and signals from the veto counters in front formed the final trigger signal. The timing gates were generated by signals coming from the accelerator and kept the apparatus alive only during the spills. An additional gate, separate from the beam gate, was used to monitor the number of cosmic ray triggers. About one-third of the triggers were cosmic rays during normal running. The front veto counters prevented the apparatus from triggering on the many muons that came along with the neutrinos. The counters had an efficiency of 99.99996%. Since the counting rate in these counters was quite high (500,000 counts per spill), it created dead time in the apparatus. Each muon turned the apparatus off for a time long enough to make sure that the calorimeter signals from that muon had been processed in the rest of the triggering electronics. The rate at which the computer could write events to magnetic tape was also lower than the actual rate of triggers, thus increasing the dead time. Depending on the target used (partial density tungsten yielded more muons than full density) and the beam intensity, the dead time varied from about 20% to about 40%.
3.5.2 1982 Triggers.

For the 1982 running period, an electronic scheme to eliminate the W-shaped response was added to ETRIG. It multiplied the signal coming from the sixteen phototubes in a segment by the signal from the segment on the opposite side of the detector. This produced a signal proportional to the square of the energy deposited. By discriminating this signal, all energy deposits above a fixed level were accepted. To pick out the product of the two signals coming from the energy deposit, ETRIG as described above was used as a pre-trigger for the multipliers. The multipliers were rather slow and had to be gated with a long gate. This meant that signals from different particles passing through the scintillator were multiplied together as well as the two signals coming from a real energy deposit. The four discriminators in ETRIG were set at the same threshold, making the response V-shaped instead of W-shaped, but the multipliers flattened this out (Fig 20).

An additional trigger was implemented in 1982 to increase the acceptance for charged-current muon neutrino interactions. It used two walls of plastic scintillation counters, one between PWC plane # 30 and drift chamber superplane # 1 and the other between superplane # 4 and superplane # 5. Coincidences between signals from these two
walls of counters and signals from a combination of the eight downstream modules in the calorimeter, constituted a trigger for muons traversing the entire muon spectrometer. The front veto counters and timing gates were used as in the case of ETRIG. This trigger scheme was known as CCTRIG to distinguish it from ETRIG.

These two triggers were run simultaneously in 1982, but because the passive shielding in front of the detector had been improved since 1981, the total number of triggers did not increase. Since the beam intensity was slightly higher in 1982, the dead time stayed at 30-40%. The dead time was continuously monitored by using a high-rate counter placed in the flux of muons coming from the active shielding. The count rate in this counter tracked the total beam intensity including variations within the spill. Both the total number of counts while the apparatus was alive and the total number over the spill were recorded. The ratio of these two numbers is a good measure of the live time of the apparatus (live time is equal to one minus dead time). The count rate in the SEM was multiplied by this live time for every spill. Using this, the corrected number of protons was calculated for each target.
3.5.3 Muon Trigger.

To take calibration and alignment data, an alternate trigger scheme was devised. It used coincidences between two walls of counters in the front of the detector to trigger on muons. In addition, vertical counters were used to pick out muons going through certain regions of the detector, and coincidences between module # 1 and the sum of modules # 27-30 were used to pick out muons going through the same cell in all modules. By including counters downstream of the third magnet, the trigger could be limited to the muons with high enough momentum to traverse all of the muon spectrometer.

3.6 On-line Data Acquisition.

After a trigger was satisfied, a signal was sent to the on-line PDP-11 computer. It processed this signal at interrupt level, stopping whatever else it was doing to record data for the trigger. The computer communicated with the recording electronics via CAMAC (computer assisted measurement, and control). The recording devices for the PWC's, calorimeter and drift chambers were interrogated in a fixed sequence, giving them time to finish recording data before it was sent to the computer.
The program MULTI ran on the computer. MULTI, a general purpose data acquisition program, was modified and supported by the Fermilab Computing Department for use in high energy physics experiments [30]. Extra features, like graphic display of events and data unpacking routines for histograming, were added for this specific experiment. MULTI also checked voltage supplies, magnet currents and beam line monitors and suspended data-taking if any of these fell outside pre-set limits. The data for these checks were read in from special recording devices between each spill from the accelerator. Scalers, used to monitor total beam intensity and the number of triggers in each segment of the detector, were also recorded between spills.

During normal running, the highest priority task for the computer was to process triggers and write the data to magnetic tape. Some of the data were also passed to a different part of the program for histograming or display.

3.6.1 Trigger Composition.

The trigger schemes that were used allowed a lot of unwanted triggers. These came from cosmic rays, from stray muons that did not fire the veto counters or that came in from the side, from showers from interactions in the
concrete below or above the detector, or from neutral hadrons in the beam. Thirty triggers were recorded, on the average, for each beam pulse and a neutrino interaction was expected in only one out of 200 of them. The charged-current muon neutrino events that are of interest here were expected in about 30% of the total number of neutrino interactions. That number comes from assuming a 1:1 ratio of electron neutrinos to muon neutrinos in the beam and from the fact that 1/3 of neutrino interactions are neutral-current interactions [31].
4.1 Event Sample Selection.

As explained in section 3.6.1, about 600 triggers were written to tape for each real charged-current muon neutrino interaction. The charged-current events had a characteristic signature since the outgoing muon was very penetrating and, in most cases, showed up in the drift chamber system. A reduced sample was made by excluding most unwanted triggers from the data with a computer program known as a cutting program. The final selection was done by human intervention through scanning. The computer formed a picture of the event showing the hit wires in the PWC's and drift chambers and the hit cells in the calorimeter on a screen (Fig 21, 22). The operator kept the events corresponding to signatures for real neutrino interactions. This was done in two iterations, with looser requirements for keeping events in the first pass. In the second iteration, a physicist looked at the event display to make sure it was consistent with a neutrino interaction.
4.2 Event Reconstruction.

The final sample of events was run through a computer program that fit the tracks in the PWC system to straight lines and did the momentum reconstruction in the muon spectrometer.

The first step in the reconstruction was to find the interaction point (vertex) for the neutrino. This was done by finding the calorimeter module with the largest energy deposit. The reconstructed vertex was then placed in the middle of the module immediately upstream of the one with the maximum deposit. Since the hadron shower did not develop very much in the module where the interaction actually occurred, this was the best estimate for the vertex position in the z-direction. (The z-axis was horizontal and parallel to the neutrino beam direction, the y-axis was vertical and the x-axis was horizontal and perpendicular to the beam direction.) In the transverse directions (x and y) the reconstructed vertex position was found by calculating the centroid of the hadron shower in the PWC plane downstream of the vertex module. Figure 23 shows the vertex distribution in the transverse coordinates x and y. The distribution is centered at the beam center which means that the events mainly came from interactions in the beam-dump target. Neutrinos produced upstream of the last vertical
bending magnet would be centered several inches below the indicated beam center. Figure 24 and 25 show the longitudinal vertex distributions for antineutrinos and neutrinos. The neutrino distribution show a slow rise towards the downstream end of the detector as expected since the muon acceptance increased when the muon was created closer to the muon spectrometer. The antineutrino distribution shows a peak followed by a hole in the upstream ten calorimeter modules. Even though the statistics was low, the effect seems to be statistically significant. A detailed study showed that the effect was due to events which fired the CCTRIG, and it was therefore not due to the calorimeter modules. The best explanation is that some effect like noisy chambers made the vertex determination place the vertex too far upstream. Since the number of events in this region is small, the effect is hard to measure.

The PWC tracks were found by searching for connected segments of a minimum length. The angle of the track was calculated from a fit to a straight line through the positions of the wires. These tracks in the PWC's were also projected to drift chamber superplane.# 1 and used as a starting point for the trackfinding in the drift chambers.
In the drift chambers, the double layers of chambers (X,X' or Y,Y') were used to determine which side of the wires the particle passed as explained in section 3.4.3. Furthermore, the x- and y-coordinates were matched by using the hits in the U-chambers. The collection of positions found in this way was passed to the momentum fitting program which made the final selection of points on the track. The fitting started with a very high momentum, and by calculating the differences between a projected track and the positions of the hits it found new values of the parameters. It used this process to minimize the chi-square function for the fit, and the process was repeated until a value close to the real minimum was found. See Appendix A for a more detailed description of the programs used in the drift chamber trackfinding and momentum fitting. The errors in these fits are as expected from multiple scattering in the iron magnets (Fig 26).

After this reconstruction all events were examined with an expanded version of the event-display program. It displayed the fitted tracks, the total energy deposited in the calorimeter and the muon momentum from the fit on the picture. The events with bad muon-momentum fit were marked and, after the hits that did not belong to the track had been removed, these events were refitted. The "bad" hits were removed by using a graphics-cursor on an interactive
terminal. Also the vertex position was checked and corrected with the graphics cursor. The files output by this process contained events with fit information set up for use by data-summary programs.

Several samples and control samples of charged-current events were made. For the 1981 data, the main sample was collected by a program that accepted events with some energy deposition in the calorimeter and hits in both of the two drift chamber superplanes closest to the calorimeter. It excluded tracks entering the calorimeter from the top, bottom, front or sides. To these were added events found by two other programs, one that mainly looked at the energy deposition and one that did simple trackfinding in the drift chambers and the PWC's. The last one followed tracks from the back and checked whether they "stopped" in the detector or not. For the 1982 data, the trackfinding program was updated and used on events which fired the CCTRIG, while the energy-deposition program was run on all the data. Two samples with considerable overlap were generated this way and later combined to form one major sample.
4.3 Corrections to the Final Event Sample.

Several cuts were imposed on the reconstructed sample of events by the data-summary programs to make sure that as many as possible of the background events were excluded and that only events in regions where the apparatus acceptance was higher than 3% were included.

First, events with vertex in the outer edges of the detector were excluded. This is often called the fiducial volume cut, and events with vertex less than eight inches in from the edge of the lead plates in the horizontal or the vertical direction were cut. Furthermore, only events in calorimeter modules # 3-25 inclusive were accepted. The cut on calorimeter modules was done to exclude the muons entering from the front which failed to give a signal in the front veto counters and to exclude events with hadron showers extending beyond the end of the calorimeter. In addition, events in which the neutrino direction made an angle of more than 35 mrad with the beam direction were cut.

The momentum of the outgoing muons could only be reconstructed if they traversed enough magnetic field to be bent a measurable distance. This was assured by only accepting events with muons giving signals in at least superplane # 1-3. After reconstruction this cut was
augmented by cutting events in which the muon momentum at the vertex was less than 6 GeV/c. This ensured that the data and the acceptance calculation had the same requirements.

Events with bad momentum fit were also excluded by requiring that the fractional error in the fit was less than 60%. This mainly cut events with low momentum tracks and signals in only three superplanes.

The reconstruction of the track in the muon spectrometer was most difficult around the hole in the center of the toroidal magnets. The magnetic field was not known very well in this region. For each event, the fraction of the total distance traversed in the spectrometer that the muon travelled through a region of four inches by fifty-four inches was calculated. (The hole was 2 1/4 inches by 48 inches.) If this fraction was greater than .60, the event was excluded. This cut was also imposed on the Monte Carlo events.

When the reconstructed neutrino energy was greater than 200 GeV, the event was cut. This was because the programs reconstructing the hadron shower energy and the muon momentum were inaccurate at high energies. The one dealing with the hadron shower energy missed parts of showers that
extended outside the volume looked at by the phototubes. The muon track reconstruction program did not have accurate enough information about the positions of the wires to deal with the very straight tracks at high muon momenta.

A cut was imposed on all events with neutrino energy of less than 20 GeV because ETRIG was inefficient and the acceptance was low for such events. The acceptance was low since many of these events had vertices close to the edge of the detector or had muon tracks that were too short to be reconstructed.

4.3.1 Scanning Loss, Cutter Loss.

To fully normalize the final data, the efficiencies of all the programs used to process the data and of the scanning had to be measured. This was done in several different ways. Part of the data was scanned before having passed through a cutting program. This was a very direct way of getting the program efficiencies, but it was very slow because of the high ratio of background to real events. Another way involved collecting a sample of events with one cutting program and using it to test the others. Since several cutting programs were developed, this was easily done. These events were also put randomly in data to be
scanned and thereby the scanning efficiencies were determined. Double scanning (two persons scanning the same data independently) also gave numbers for this efficiency. The efficiencies are summarized in Table 2.

TABLE 2

CUTTER AND SCANNING EFFICIENCIES

<table>
<thead>
<tr>
<th>Year</th>
<th>Cutter</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981</td>
<td>Cutters</td>
<td>98%</td>
</tr>
<tr>
<td>1982</td>
<td>ETRIG Cutter</td>
<td>89%</td>
</tr>
<tr>
<td>1982</td>
<td>CCTRIG Cutter</td>
<td>92% (includes hardware)</td>
</tr>
<tr>
<td>Scanning</td>
<td></td>
<td>100%</td>
</tr>
</tbody>
</table>

The 1982 CCTRIG cutter efficiency given above was for events with vertex in modules # 3-20. Events with vertex in module # 21-25 was missed by this program when they had a hadron shower extending towards the end of the calorimeter. The program could then not find the muon track, but these events were picked up by the ETRIG program which looked at all the data.
4.3.2 Reconstruction Loss.

The event reconstruction was not 100% efficient. The vertex finding and trackfinding in the PWC's did not directly exclude events from the sample if they were inefficient. Only when fiducial volume cuts were imposed did this effect the number of events in the sample. The only real inefficiency came from the trackfinding and momentum fitting in the drift chambers. The efficiencies are summarized in Table 3.

<table>
<thead>
<tr>
<th>Year</th>
<th>Data Type</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981</td>
<td>All data</td>
<td>86%</td>
</tr>
<tr>
<td>1982</td>
<td>ETRIG only data</td>
<td>84%</td>
</tr>
<tr>
<td>1982</td>
<td>CCTRIG only data</td>
<td>94%</td>
</tr>
<tr>
<td>1982</td>
<td>Both triggers</td>
<td>90%</td>
</tr>
</tbody>
</table>

4.3.3 Geometric Acceptance of the Detector.

The acceptance for each event was calculated by generating 200 accepted or 600 total (whichever came first) Monte Carlo events with the same total energy and vertex position as the real event but with varied ratio of hadron
energy to muon momentum and with varied muon azimuthal angle. The events were weighted with the inverse of this acceptance. Figures 27, 28, 29, 30 show the acceptance as function of energy or neutrino (antineutrino) polar angle. The graphs were made by histograming the acceptance as it was calculated and normalize to the number of entries in each bin. A smooth curve was drawn through the points with a polynomial fit to guide the drawing for the low energy part and the whole angle range. The acceptance improved between 1981 and 1982 due to the addition of CCTRIG.

In addition there was one more acceptance that had to be calculated since the detector only covers part of the solid-angle out to 35 mrad. This acceptance was calculated as a function of the neutrino polar angle by determining the fraction of a full circle circumference that fell within the detector at a given angle (Fig 31). As seen from the graph, this acceptance was quite low beyond 15 mrad. For the results in which this was included as a weight, a few events at large angles contributed more than their share in the final numbers.

The effect of the acceptance can be seen by looking at the difference between measured and weighted distributions (Fig 32, 33, 34, 35). The azimuthal acceptance had a big effect, as can be seen from the graphs. Since the
statistics at low energy was low for the 1981 data due to low acceptance the weighting procedure did not correctly model the real distribution.

To check the accuracy of the acceptance calculations, histograms of the kinematic variables described in Ch. 2 and of all of the directly measured quantities were compared with the Monte Carlo-generated ones. Care was taken to generate the same number of integrated entries in the measured histograms and the corresponding Monte Carlo histograms so that the two histograms could be compared directly. All the figures referred to in the following paragraphs came from the 1982 data. This was because it had better statistical precision than the 1981 data.

Distributions in hadron-shower energy for antineutrinos and neutrinos are shown in Figures 36 and 37. The agreement between the histograms from the data and the Monte Carlo was very good for hadron energy. A double peak appeared in the distributions, especially in the neutrino case, because the data included events from both triggers. The peak at zero came from events that fired only the CCTRIG, and the peak at 10 GeV came from events that fired only the ETRIG.
Figures 38 and 39 show the distributions in muon momentum. The agreement between the data histograms and the Monte Carlo histograms was very good for muon momentum as well. In tracing the Monte Carlo events the survey constants were only used to determine whether the muon reached the position of superplane # 3 or not. Therefore no bias from the momentum fitting influenced the Monte Carlo generation of muon momentum, and this was a good indicator of the accuracy of the fitting procedure.

Muon angle distributions are shown in Figures 40 and 41. The angle between the direction of the neutrino and that of the outgoing muon was calculated from the scalar product of the direction vector to the vertex position and the muon momentum vector. The vertex was measured with an accuracy of about three inches in the transverse directions and of about five inches along the beam direction. The direction of the muon was determined as the direction between the vertex position and the position of the hit in the first drift chamber plane. The angle from the fit in the muon spectrometer was used when the angle was less than 30 mrad. Because of multiple scattering of the muon in the lead and the coarse granularity of the PWC system, the determination of this angle was inaccurate, resulting in the lack of agreement between the measured angles and the Monte Carlo generated ones.
The distributions in the Bjorken scaling variables $x$ and $y$ are shown in Figures 42 and 43. The scatter plots show the region of observed values for $x$ and $y$. The outlines drawn on each graph are the limits of Monte Carlo generated distributions.

The $y$-variable combines the measurements of hadron energy and muon momentum. Taking the resolution of these two measurements into account, the agreement between data and Monte Carlo histograms is very good.

The $x$-variable depends strongly on the muon angle and the slight discrepancy between the data and the Monte Carlo histograms came from the errors in the measured angle. For the Monte Carlo events, $x$ was generated from measured distributions from other experiments and used to calculate the muon angle.

4.4 Neutrino Background and Target-length Corrections.

The neutrinos from protons interactions upstream of the beam-dump target (described in section 3.2.1) showed up as background in the prompt sample since their production did not depend on the beam-dump target (refer to equation 3.1). In 1981 this background was measured to be less than 1% of
the total signal from the full density target, and in 1982 it was measured to be less than .5% due to improved vacuum. Proton interactions in the material just upstream of the beam-dump target (SEM, SWIC, air) produced a larger background. The number of neutrinos from the decay of $\pi$- and K-mesons from these interactions was calculated as a function of energy by using known production spectra [32] and life-times and branching ratios from other experiments [15]. The following table summarizes the percentage of upstream background in the total number of observed events.

**TABLE 4**

**UPSTREAM BACKGROUND**

<table>
<thead>
<tr>
<th></th>
<th>1981</th>
<th>1982</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full</td>
<td>Partial</td>
<td>Full</td>
<td>Partial</td>
</tr>
<tr>
<td>Antineutrinos:</td>
<td>2.6%</td>
<td>1.9%</td>
<td>1.8%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Neutrinos:</td>
<td>4.4%</td>
<td>2.8%</td>
<td>3.3%</td>
<td>2.0%</td>
</tr>
</tbody>
</table>
The full density tungsten target was four interaction lengths long while the partial density target was three interaction lengths long. Physically the partial density target was longer over-all than the full density one because of the air gaps between the discs. Since they did not contain equal amounts of material, a different number of particles "punched through" the backs of the targets. The full density target was followed by solid copper while the partial density target was followed directly by the first solid iron magnet. This gave a different yield of neutrinos. Those effects were calculated numerically by using energy and transverse momentum spectra [32], dependence on atomic number of the target [33] and $K_S$ production [34] from other experiments. The calculations were repeated for targets of "infinite" length but with the same density as the physical targets. The ratio of the number of neutrinos that hit the detector from the physical target to the number from the infinitely long full density target then gave the inverse densities which were used to do the infinite density extrapolation. The result of the calculation was given as a function of either neutrino energy or neutrino transverse momentum. The average value for the full density target was 1.07 and the average for the partial density target was 2.66 for neutrinos and 2.68 for antineutrinos.
CHAPTER V

RESULTS

5.1 Rates of Prompt Neutrinos.

The process for calculating the number of prompt particles leading to equation 3.1 is equivalent to an extrapolation to infinite density. For use in this chapter, equation 3.1 is rewritten as:

\[ N_p = \frac{d_t N_f - d_f N_t}{d_t - d_f} \]  (5.1)

where

- \( N_p \) is the number of prompt events,
- \( N_f \) is the number of events yielded by the full density target (after subtraction of upstream background),
- \( N_t \) is the number yielded by the partial density target (after subtraction of upstream background), and
- \( d_f \) and \( d_t \) are the inverse densities (for the full and partial density targets (see sect. 4.4)).
The numbers of events, after normalizing to $10^{17}$ protons on the target, are summarized in Table 5 and 6 where the errors are statistical only. Corrected means that apparatus acceptance and the efficiencies from Table 2 and 3 were used in the correction and that the upstream background was subtracted. The numbers where the azimuthal weights were included also included the above corrections.

**TABLE 5**

1981 DATA

<table>
<thead>
<tr>
<th></th>
<th>Full density</th>
<th>Partial density</th>
</tr>
</thead>
<tbody>
<tr>
<td>uncorrected</td>
<td>173±16</td>
<td>283±41</td>
</tr>
<tr>
<td>$\overline{v}$ corrected</td>
<td>376±40</td>
<td>597±99</td>
</tr>
<tr>
<td>w/ azimuthal weight</td>
<td>739±108</td>
<td>977±216</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Full density</th>
<th>Partial density</th>
</tr>
</thead>
<tbody>
<tr>
<td>uncorrected</td>
<td>526±28</td>
<td>875±73</td>
</tr>
<tr>
<td>$\nu$ corrected</td>
<td>1025±61</td>
<td>1796±168</td>
</tr>
<tr>
<td>w/ azimuthal weight</td>
<td>1767±153</td>
<td>3090±423</td>
</tr>
</tbody>
</table>

| Protons          | $0.6630 \times 10^{17}$ | $0.1658 \times 10^{17}$ |
TABLE 6

1982 DATA

<table>
<thead>
<tr>
<th></th>
<th>Full density</th>
<th>Partial density</th>
</tr>
</thead>
<tbody>
<tr>
<td>uncorrected</td>
<td>245±19</td>
<td>336±39</td>
</tr>
<tr>
<td>( \nabla ) corrected</td>
<td>360±29</td>
<td>490±60</td>
</tr>
<tr>
<td>w/ azimuthal weight</td>
<td>710±80</td>
<td>911±147</td>
</tr>
<tr>
<td>uncorrected</td>
<td>569±29</td>
<td>1025±69</td>
</tr>
<tr>
<td>( \nabla ) corrected</td>
<td>948±51</td>
<td>1750±125</td>
</tr>
<tr>
<td>w/ azimuthal weight</td>
<td>1969±154</td>
<td>3365±342</td>
</tr>
</tbody>
</table>

Protons \( \cdot 6974 \cdot 10^{17} \) \( \cdot 2175 \cdot 10^{17} \)

From these numbers and eq. 5.1, the total prompt production rate follows:

TABLE 7

PROMPT SIGNAL

<table>
<thead>
<tr>
<th></th>
<th>1981</th>
<th>1982</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\nabla} ) w/o azimuthal weight</td>
<td>232±92</td>
<td>274±62</td>
</tr>
<tr>
<td>( P_{\nabla} ) w/ azimuthal weight</td>
<td>583±228</td>
<td>578±164</td>
</tr>
<tr>
<td>( P_{\nabla} ) w/o azimuthal weight</td>
<td>500±153</td>
<td>402±121</td>
</tr>
<tr>
<td>( P_{\nabla} ) w/ azimuthal weight</td>
<td>861±388</td>
<td>1013±350</td>
</tr>
</tbody>
</table>
For the 1982 data without azimuthal weights, the dependence of the event rate on the inverse density and the extrapolation to infinite density from that are shown graphically in Figure 44.

It was possible to improve the statistical errors in these results by using more of the information from the calculations of the non-prompt neutrino production in the beam-dump target. To do this, the calculated spectra for the two targets for antineutrinos and neutrinos were normalized to the integral of the full density neutrino spectrum. The data was grouped in bins of varying width to avoid problems with low statistics in the high energy (or transverse momentum) region. The results are then described by equations of the form:

\[ N_{ij} = P_{im} f_{ij} K \]

where \( N_{ij} \) is the number of neutrinos from full density \((j=1)\), neutrinos from partial density \((j=2)\), antineutrinos from full density \((j=3)\) or antineutrinos from partial density \((j=4)\), \( i \) runs over the number of bins used in the fit (5 for the results given here), \( P_{im} \) is the prompt neutrino signal for \( m=1 \)
(j=1,2) or the prompt antineutrino signal for
m=2 (j=3,4),

K is the normalization for the non-prompt
neutrino signal from the full density target,
and

\( f_{ij} \) is the shape of the non-prompt signals (see
sect. 4.4) normalized as described above.

This way of writing the result is a constraint on the
shape of the non-prompt spectra and gave more equations than
unknowns, and by doing a least-squares fit to this system of
equations, the \( P_{im} \)'s and K were found.

The results are shown in Figure 45 and 46 for the energy
distributions and in Figure 47 and 48 for the transverse
momentum distributions. The transverse momentum
distributions are plotted as \( dN/dp^2_\perp \) to avoid the kinematic
limit of zero events at zero transverse momentum. All these
plots are for the data without azimuthal weights because
these weights are large and the errors then becomes large as
well. Table 8 gives the results after adding up the entries
in the different bins, where the errors also include the
correlations between the bins.
5.2 Ratio of Prompt Antineutrino to Neutrino Flux.

5.2.1 Corrections for Non-isoscalar Neutrino Target.

To compare the production of antineutrinos with the production of neutrinos, the observed numbers of prompt events must be converted to flux. Other experiments have measured the total cross section for neutrino interactions on different targets. The best number for the antineutrino
The cross section is $(0.30\pm0.01)\cdot E \cdot 10^{18}$ cm$^2$, and the best number for the neutrino cross section is $(0.63\pm0.02)\cdot E \cdot 10^{18}$ cm$^2$ where $E$ is the neutrino energy [35]. These numbers are for so-called isoscalar targets (i.e. targets with the same number of protons and neutrons). The lead in the calorimeter was the neutrino target in E-613, and the cross sections must be corrected for the neutron excess in lead. The ratio of cross sections for antineutrinos on neutrons and on protons has been measured to be $0.515\pm0.028$. For neutrinos this ratio has been measured to be $2.05\pm0.14$. [36] From this the cross sections can be calculated:

$$
\sigma_{\nu p} = (0.396 \pm 0.015) \cdot E \cdot 10^{18} \text{ cm}^2
$$

$$
\sigma_{\bar{\nu} n} = (0.204 \pm 0.014) \cdot E \cdot 10^{18} \text{ cm}^2
$$

$$
\sigma_{\nu p} = (0.413 \pm 0.023) \cdot E \cdot 10^{18} \text{ cm}^2
$$

$$
\sigma_{\bar{\nu} n} = (0.847 \pm 0.075) \cdot E \cdot 10^{18} \text{ cm}^2
$$

To calculate the ratio of fluxes from the measured ratio of prompt antineutrino rate to prompt neutrino rate, the ratio of antineutrino to neutrino cross sections has to be used. For lead it is given by:
\[ r = \frac{Z^* \sigma_{\nu p}(A-Z) \cdot \sigma_{\nu n}}{Z^* \sigma_{\bar{\nu} p}(A-Z) \cdot \sigma_{\bar{\nu} n}} = 0.418 \pm 0.032 \]

where \( Z = 82 \) is the atomic number of lead and \( A = 207 \) is the mass number of lead.

5.2.2 Corrected Flux Ratio.

The ratio of antineutrino to neutrino flux is now:

\[ \frac{P_{\bar{\nu}}}{P_{\nu}} = \frac{1}{R} \]

The ratios are calculated using the numbers without azimuthal acceptance and are:

<table>
<thead>
<tr>
<th>Extrapolation</th>
<th>Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981:</td>
<td>R = 1.11 \pm 0.46</td>
</tr>
<tr>
<td>1982:</td>
<td>R = 1.63 \pm 0.61</td>
</tr>
</tbody>
</table>

The ratio of antineutrino to neutrino flux was calculated as a function of energy (Fig 49). The measured ratio falls towards higher energies. This could be due to limited statistics in the antineutrino data at high energies. The
ratio was also calculated as a function of transverse momentum of the neutrino (Fig 50). Both these calculations used the data from the constrained fits as input.

5.3 Error Analysis.

5.3.1 Statistical Errors.

Since the probability for the occurrence of a particular event was uniform in time and small, and since the number of time intervals was very much larger than the number of events, the real binominal distribution can be approximated with a Poisson distribution [37]. The Poisson distribution has a standard deviation equal to the square root of the number of observed events. In calculating the statistical errors, the weighting and normalization must be taken into account.

The statistical error becomes

\[ s = \frac{w}{p\sqrt{N}} = \frac{W}{p\sqrt{N}} \]

where \( w \) is average weight per event,

\( W \) is the weighted number of events,
N is the observed number of events, and 
p is the number of protons used to obtain N events.

From equation 5.1 the error in the number of prompt events

\[ s_p = \frac{1}{d_t - d_f} \sqrt{[(d_t - s_f)^2 + (d_f - s_t)^2]} \]  

(5.2)

where \( s_p \) is the error in the prompt signal, 
\( s_f \) is the error in the measured number from the full density target, and 
\( s_t \) is the error in the measured number from the partial density target.

The number of events from the two targets are statistically independent. This formula was used to calculate the errors given in tables 3 and 4.

5.3.2 Systematic Errors.

The systematic errors were much harder to determine than the statistical ones. The major sources are discussed below.
i. Efficiencies.

The first sources of error were the calculations of the efficiencies described in sections 4.3.1 and 4.3.2. If they were independent of all measured quantities and variables derived from them and equal for neutrinos and antineutrinos, they would not enter the calculation of the ratio of antineutrino to neutrino flux. This was true for all multiplicative corrections to the data. The efficiencies of the cutting programs for the 1981 data were found to have a very small energy dependence which has been ignored. For the 1982 data, the efficiencies from Table 2 and 3 were included in the Monte Carlo calculations of acceptance since the triggers were run simultaneously. The scanning efficiency was low at low neutrino energy, which is an argument for only using events with total neutrino energy above 20 GeV. The scanning efficiency for charged-current events was uniform above this energy. The trackfinding and momentum-fitting efficiency had a modest momentum dependence.
ii. Effective densities.

The calculation of effective densities described in section 4.4 also introduced systematic error. For an error of 5% in the effective densities the ratios from extrapolations are:

\[
R_-=1.81 \quad R_+=1.50 \text{ compared to } R=1.63 \text{ (1982)}
\]

Figure 51 shows the variation of the flux ratio and the statistical errors when the inverse density of the partial density target is varied. The variation is the same when the inverse density of the full density target is varied because only the ratio of the densities enters the calculations as can be seen from eq. 5.1 and eq. 5.2.

When the coefficient of the exponential fit to the non-prompt calculated spectra was varied by 5%, the ratios from the fit became:

\[
R_-=1.38 \quad R_+=1.37 \text{ compared to } R=1.35 \text{ (1982)}
\]
iii. Misidentification.

Some neutrinos may have been identified as antineutrinos and vice versa. This might change the ratio since more neutrinos than antineutrinos were actually observed. This effect was largest at high muon momentum where the momentum-fitting algorithm had difficulties determining the direction of the bending because of survey errors and miscalculations of the magnetic field. These events all had weights very close to one, and the net number of misidentified events increased the observed number of antineutrinos. Setting the increase for antineutrinos to $a_f$ and to $a_t$ for the two targets and assuming that 10% of the events above 80 GeV/c muon momentum were misidentified, i.e. $a_f=10$ and $a_t=19$. Using the numbers of events corrected for this in equation 5.1 and calculating the corrected ratio yields $R_c=1.61$ for the 1982 data compared to $R=1.63$. From the constrained fit $R_c=1.41$ compared to $R=1.35$.

iv. Errors in measured quantities.

All measured quantities had errors. The deposit of energy in the calorimeter was a statistical process, and therefore the final measured energy had resolution smearing. The resolution for hadrons was measured to be $0.52/\sqrt{E}$. It was
put in the acceptance Monte Carlo as a smearing. But the energy measurement might also have had errors due to drift in the high voltage supplies and to fluctuations in the amount of light collected for a given amount of energy deposited. The high voltages were monitored closely during the run, and the calibrations were checked regularly by running muons through all the cells. Since the energy spectra for neutrinos and antineutrinos were quite similar, the remaining uncertainty in the energy measurement has been ignored.

The measurement of muon momentum had errors as well. Multiple scattering in the iron toroids dominated all other effects at momenta below 80 GeV and introduced a smearing which did not give any systematic effects.

5.4 Comparison with Results from other Experiments.

This experiment clearly has a positive signal for prompt antineutrinos. As stated in the Introduction, this was not true for the CDHS beam dump experiment at CERN. The BEBC group found the ratio of antineutrino to neutrino flux to be $0.79 \pm 0.63$ [38] and the CHARM group found the ratio $1.3 \pm 0.5^{+0.4}_{-0.2}$ (statistical and systematic errors) [39]. Both these results are in agreement with the result from E-613.
5.5 Conclusions.

The weighted average of the total prompt antineutrino and neutrino signals was used to calculate the average result for the ratio, and the result is:

\[ R = 1.42 \pm 0.42 \quad \text{(from extrapolations)} \]

\[ R = 1.38 \pm 0.29 \quad \text{(from fits)} \]

The number from the fits shows a possible excess of antineutrino events, but when systematic errors are included the significance is very small. This means that the data is consistent with the theory that all the prompt neutrinos come from the central production and decay of D-meson pairs. There is no direct evidence for diffractive production of \( \Lambda_c \)'s in this experiment. This production mechanism cannot be totally ruled out, however, it may be suppressed enough from the property \( \Lambda_c \) decay mentioned in section 2.2 to disappear in the large errors of the measurement.
A.1 Method of trackfinding.

The x-coordinates of the points on a track in the PWC's were fitted to a straight line and projected to drift chamber superplane #1 which follows the calorimeter. The match with hits in the X,X'-chambers were then used as a starting point for the trackfinding. y-coordinates were also matched in a similar way. In both X- and Y-chambers the double layer of staggered planes were used to resolve ambiguities and the U-chambers were used to match x- and y-coordinates.

The x-coordinates in the downstream drift chamber superplanes were determined by the hits which satisfy the requirement that the sum of the drift times in X- and X'-chambers be within a window centered on the maximum drift time. For non-normal incident tracks, a correction for this sum was made by using the angle calculated by projecting the
track from the preceding superplane. The y-coordinates of the track were then determined in the same way. A further constraint was introduced by finding 3-fold X-Y-U matches in the downstream four superplanes.

A.2 Tuning of survey constants

A large number of constants were used to determine the positions of the wires and the correct conversion from measured number of clock counts to distance from the wires.

A.2.1 Definitions of constants

POS: Position of reference target on a module within each plane (east module for X- and U-chambers, lowest module for Y-chambers).

DPOS: Rotation of the whole superplane.

TMOD: Position and rotation angles for the individual modules.
DOFF: Offset of prime chambers.

ZPOS: Position of superframe in z (beam direction).

DZPOS: Difference in z-position within one superplane.

DCUP: Delay from particle passage to stop in the Sippach system. The signal provides start and a signal delayed DCUP ns provides stop, such that real drift time was: TIME=DCUP-DATA.

DCORR: Corrections to DCUP due to time of flight and other effects making one superplane different from another.

DRFTIM: Conversion from time to real distance. (498 ns/inch)

TDCNS: Conversion from TDC counts to nanoseconds (=1.5).

A.2.2 Method of tuning

Initial values were taken from results of the testing in
M5 and survey of the chambers. Then histograms of variables directly or indirectly dependent on these constants were used to tune them.

The position of the first superplane was tuned to match the PWC's. This can be done accurate to .05 inches and with a width corresponding to the resolution due to the PWC wire spacing.

Straight-through muon tracks were fitted to a straight line using the angles from PWC tracks to give a first guess of the slopes for the line. The points found this way were then fitted internally to a straight line. The deviations from this fitted line were used to tune the positions of superplanes and modules within superplanes.

DCUP was tuned mainly by looking at the low edge of the distribution of measured drift times. It was made to line up on zero. DCORR was tuned in the same way.

See histograms for examples of:

i. Matching in x-coordinate between PWC's and drift chambers. (Fig 53)

ii. Matching in y-coordinate between PWC's and drift chambers. (Fig 54)
iii. Sum of distances measured in Y and in Y' minus DOFF. (Fig 55)

iv. Difference in y-coordinate from X and U and from Y. (Fig 56)

v. Low edge of measured times in one superplane. (Fig 57)

A.3 Momentum fitting.

A.3.1 Method of momentum fitting.

Given the angles and the x,y coordinates of a track entering the first drift chamber superplane, the momentum of the track was found by an iteration procedure. For the first iteration an essentially infinite momentum was chosen. The chi-square function and its partial derivatives with respect to the parameters of the fit were then found numerically. By inverting the matrix of these derivatives, a new set of parameters which gave a value of the chi-square function closer to its minimum was found. These values then were used in the next iteration. This process was repeated until a value closer to the minimum than a convergence limit was found or until a maximum number of iterations had been tried. The fit was accepted if the chi-square per degree of freedom was less than 5.0. Otherwise certain methods of trying more points or a new track were tried.
A.3.2 Fitting efficiency.

By using the criteria stated above, it was found that about 80% of the events could be fitted on the first pass. After hand selecting the points on the track this was brought up to about 90%. For tracks known to go all the way through the spectrometer this final efficiency was 94%. Reasons for no fit were (in order of importance):

1. Chamber inefficiencies.

2. Trackfinder picking the wrong hit in one superplane due to many hits.

3. Very straight tracks combined with survey errors.

4. Ambiguities not resolved.

This was slightly biased towards high momentum tracks, but the cut on total neutrino energy of 200 GeV took away most of this bias.
Figure 58 gives the chi-square for the fitting of muons from special MUTRIG runs.

A.4 Description of subroutines

In this section the different subroutines used to do the trackfinding and momentum fitting are described.

The subroutines used were:

1. DCUPK
2. DCCLR
3. DCSIFT
4. MUDC1
5. MUDRFT
6. DCTRCK
7. DCUMAT
8. MUMOM
   a. BFIELD
   b. DEDX

A.4.1 DCUPK
Purpose: To unpack data into chamber-information and spatial coordinates.

Call: CALL DCUPK(JJ,HIT,IHIT)

JJ: Data to be unpacked
HIT: Array to hold raw data (1), position of wire (2),
distance from wire to hit (3), z-position
of wire (4), slope of wire in x-y plane (5),
slope of wire in z (6) and reference where HIT(2)
was given (in y for X-chamber) (7).
IHIT: Array to hold mark (1), superplane (2),
plane within superplane (3), wire-number
within plane (4) and raw TDC-COUNTS (5).

Commonblocks: DCCOM, DCSURV

A.4.2 DCCLR

Purpose: To clear arrays and preset values for use in track finding.

Call: CALL DCCLR
Commonblock: DCCOM

A.4.3 DCSIFT

Purpose: To set up a map of hits in superplanes and planes.

Call: CALL DCSIFT

Commonblocks: DCCOM, fills DCMAP (explained in 4.9)

Bank: DDAT

A.4.4 MUDC1

Purpose: To match a found track in x-coordinates from PWC's with a hit in X or X' in the first superplane.

Call: CALL MUDC1

Commonblocks: DCCOM, DCMAP, DCSURV

Banks: DDAT, PXMU, lifts DMUL
A.4.5 MUDRFT

Purpose: To act as a setup for calls to the track-finding and momentum-fitting routines.

Call: CALL MUDRFT

Commonblocks: DCCOM, DCMAP, DCSURV

Bank: DDAT

A.4.6 DCTRCK

Purpose: To do trackfinding in x-(or y-)coordinate by looking at the sum of drift times in the two chambers making up the total X-(or Y-)plane.

Call: CALL DCTRCK(XDC, XARR, XFLAG, IXARR, DSLO, IFIRST, ILAST, THE1, IOFF, ZARR)

XDC: Returned array of good hits.
XARR: Returned array of all possible coordinates.

XFLAG: Returned array of number of entries in XDC.

IXARR: Returned array of number of entries in XARR.

DSLO: Returned array of wire slopes for entries in XDC and XARR.

IFIRST: First superplane to use.

ILAST: Last superplane to use.

THE1: Incoming angle into superplane 1.

IOFF: View to trackfind (=0 for x, =2 for y).

ZARR: Returned array of z-positions of wire-centers.

Commonblocks: DCSURV, DCMAP

A.4.7 DCUMAT

Purpose: To use U-chamber to match x- and y-coordinates.
Call: CALL DCUMAT(IFIRST, ILAST)

IFIRST: First superplane to be matched

ILAST: Last superplane to be matched

Commonblocks: DCCOM, DCSURV, DCMAP

Bank: DDAT

A.4.8 MUMOM

Purpose: To fit momentum to a found track by making an educated guess of a momentum-value and trace the muon through the toroids. This repeated until chi-square was minimized. If any coordinate was ambiguous it will use the best one in the fit.

Call: CALL MUMOM(IPAR)

IPAR: Number of parameters to be used. IPAR=3 was standard and the parameters were momentum and incoming angles. IPAR=1 was used for short
tracks and only the momentum was a parameter of the fit.

Commonblocks: DCCOM, DCSURV

Banks: PXMU, PYMU, lifts DMU2

It calls:

A.4.8.1 BFIELD

Purpose: To find the magnetic field at a given point.
The field map was made by using the POISSON group of programs.

Call: CALL BFIELD(X,Y,Z,B)

(X,Y,Z): coordinates of point.

B: Array for field components (dimensioned B(3) )

Commonblocks: FIELD
A.4.8.2 DEDX

Purpose: To calculate energy loss by a particle passing through matter. It updates the momentum components.

Call: CALL DEDX(PX,PY,PZ,DS,MATL,ISTOP)

(PX,PY,PZ): Momentum components.
DS: Archlength of travel (in cm.)
MATL: Material; 1=iron, 2=solid scintillator, 3=lead.
ISTOP: Flag set if particle ranged out.

A.4.9 COMMONBLOCKS

DCCOM: Coordinates and markers from trackfinding.

DCSURV: Survey constants.

DCMAP: Map of hits in superplanes and planes. The map consists of two arrays JLOC and JCNT both dimensioned (5,5) where the first index indicates plane and the second was the superplane number. JLOC gives location within
bank of data (DDAT) for the first hit in a given plane and superplane. JCNT gives the number of hits on the plane and superplane.

FIELD: Magnetic field map.
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D-meson Decay

HIGHER ORDER GRAPHS

Figure 1. Semileptonic decay of D-mesons into muons
NEUTRINO–NUCLEON SCATTERING

Figure 2. Neutrino–nucleon scattering
ANTINEUTRINO-NUCLEON SCATTERING

Figure 3. Antineutrino-nucleon scattering
Figure 4. The Fermilab accelerator
Figure 5. M2 beam line
Figure 6. Beam-dump targets
Figure 7. E-613 target and dump magnets
Figure 8. E-613 experiment - overall plan view
Figure 9. E-613 detector - plan view
Figure 10. E-613 detector building layout
HADRON ENERGY RESOLUTION

Figure 11. Hadron energy resolution
Figure 12. Toroid construction
Figure 13. Drift chamber staggered cells

\[ t_1 + t_2 = T \]
WHERE \( T \) IS A CONSTANT
Figure 14. Drift chamber readout
Figure 15. Drift chamber resolution
Figure 16. Drift chamber linearity
EFFICIENCY vs. HIGH VOLTAGE

GAS: 50% Ar, 50% ethane  
DISC. LEVEL 15 mv  
I-BEAM VOLTAGE -42 Kv

Figure 17. Drift chamber efficiency
Figure 18. Trigger logic
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Figure 25. z-coordinate of vertex for neutrinos
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AZIMUTHAL ACCEPTANCE vs NEUTRINO POLAR ANGLE

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HADRON ENERGY FOR ANTINEUTRINOS

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Figure 46. Prompt neutrino energy spectrum
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Figure 50. Ratio of antineutrino to neutrino flux as a function of neutrino transverse momentum
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MATCHING IN x-COORDINATE BETWEEN DC AND PWC

Figure 52. Matching in x-coordinate between PWC's and drift chambers.
MATCHING IN Y-COORDINATES BETWEEN DC AND PWC

Figure 53. Matching in y-coordinate between PWC's and drift chambers
Figure 54. Sum of distances measured in $Y$ and $Y'$ minus DOFF
DIFERENCE IN Y-COORDINATES (Yxu - Y)

Figure 55. Difference in y-coordinate from X and U and from Y
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Figure 57. Chi-square distribution from momentum fits
MEASURED POSITION MINUS PROJECTED POSITION
SUPERPLANE #2

Figure 58. Measured-fit for superplane #2
MEASURED POSITION MINUS PROJECTED POSITION
SUPERPLANE # 3

Figure 59. Measured-fit for superplane # 3
MEASURED POSITION MINUS PROJECTED POSITION
SUPERPLANE # 4

Figure 60. Measured-fit for superplane # 4
Figure 61. Measured-fit for superplane #5