PROMPT NEUTRINO RESULTS FROM FERMILAB

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ABSTRACT

Results from a Fermilab experiment to study prompt neutrino production are presented. Assuming the prompt neutrinos come from the decay of charmed mesons we find a total $D\overline{D}$ production cross section of approx. 20 μb/nucleon, in good agreement with previous CERN results. We find a $\overline{\nu}/\nu$ ratio and a ν_e/ν_μ of approx. 1.0. The energy and p_T spectra of the prompt neutrinos are consistent with those expected from $D\overline{D}$ production. Limits on the production of supersymmetric particles have also been obtained.

HISTORICAL INTRODUCTION

In a "conventional" neutrino beam, the production target is followed by a long decay space to give the pions and kaons a chance to decay. The hadrons and muons are then absorbed or ranged out in a massive shield to leave only neutrinos from $\pi+K$ semileptonic decays. In a "prompt" neutrino or beam dump experiment, on the other hand, the hadrons are absorbed in the dump as quickly as possible. Ideally then all the neutrinos come from the decay of very short-lived particles that decay before they get a chance to interact; in practice there is a substantial background of nonprompt neutrinos from pions or kaons which decay before they are absorbed.

The first prompt neutrino experiments were carried out at CERN in 1977.[1-3] These showed that there was an unexpected source of neutrinos which apparently came from the decay of shortlived particles. It gradually became clear that the most likely source was the semileptonic decay of charmed particles. From the neutrino rates the total charm production cross section was inferred to be ~100 μb.
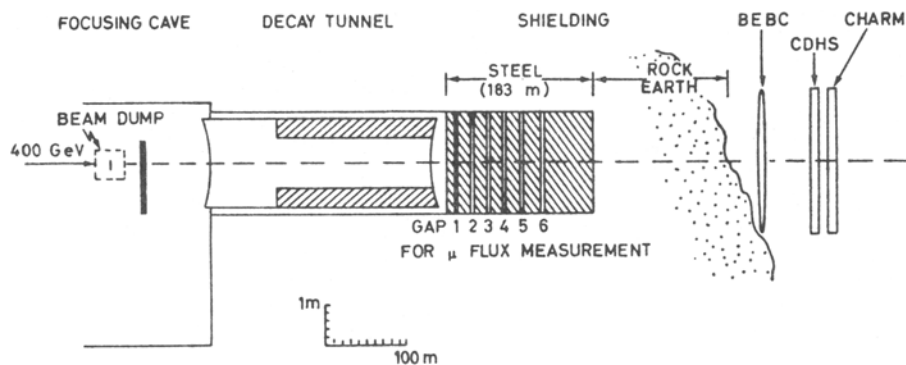
Figure 1.   Second prompt neutrino experiments at CERN

The interest in the results from the first runs led to a second run at CERN in 1979. In that run three detectors took data simultaneously (Figure 1): the Big European Bubble Chamber; CDHS, a huge iron detector; and CHARM, a smaller, more highly segmented detector. The results for the charm production cross section[4-6] generally agreed with the first run's. However there were still some important unanswered questions.

If the prompt neutrinos come from p+N→D+$\overline{D}$+X with the charmed mesons then decaying semileptonically, the flux of neutrinos $\phi(\nu)$ should be equal to that for antineutrinos. The results for $\phi(\overline{\nu})/\phi(\nu)$ were

CDHS[6]: $\phi(\overline{\nu}_\mu)/\phi(\nu_\mu) = 0.46 {+0.21 \atop -0.16}$

BEBC[4]: $\phi(\overline{\nu}_\mu)/\phi(\nu_\mu) = 0.79 \pm 0.62$
$\phi(\overline{\nu}_e)/\phi(\nu_e) = 0.65 \pm 0.33$

CHARM[5]: $\phi(\overline{\nu}_\mu)/\phi(\nu_\mu) = 1.3 \pm {+0.6 \atop -0.5}$

Now this ratio is really not very fundamental. The D and $\overline{D}$ momentum spectra need not be the same, so $\phi(\nu)=\phi(\overline{\nu})$ only if integrated over energy and angle. We also have to assume D$^+$=D$^-$ and D$^\circ$=$\overline{D}^\circ$, which need not be the case. However this ratio is an important one in testing charm production models, and it would be nice to know what it is.

If the prompt neutrinos come from the semileptonic decays of massive particles we expect $\phi(\nu_e)\cong\phi(\nu_\mu)$. In this case the three experiments agree quite well,

CDHS[6]: $\phi(\nu_e)/\phi(\nu_\mu) = 0.64 \pm {+0.22 \atop -0.15}$

BEBC[4]: $\phi(\nu_e)/\phi(\nu_\mu) = 0.59 {+0.35 \atop -0.21}$

CHARM[5]: $\phi(\nu_e)/\phi(\nu_\mu) = 0.48 \pm 0.16$

If this ratio were significantly different from one, it would be a very important result. Possible explanations range from the mundane: e.g. - a contamination from nonprompt neutrinos (mostly ν_μ) from proton beam interactions upstream of the beam dump; to the exotic:

e.g. - neutrino oscillations which transform ν_e to ν_τ or another species of neutrino.

In addition, the CHARM group[5] reported a 2.4 std. deviation excess of muonless events with visible energy < 20 GeV. The CDHS group saw no effect but their energy threshold was somewhat higher.[6]

Immediately following the first CERN prompt neutrino experiment our group proposed that a new beam specifically designed for prompt neutrinos be installed at Fermilab. This has been done in the area historically called the Meson Laboratory. The CERN neutrino beam was originally designed for neutrinos from pion and kaon decays which are produced at quite small angles to the proton beam. The detectors therefore can be quite far away. Prompt neutrinos (presumably) are from the decays of much more massive particles like D mesons and are produced with a much larger angular spread, so that the CERN detectors are not well matched to the prompt neutrino beam. Ideally one should use a detector with much larger transverse dimensions for prompt neutrinos or move the detector much closer to the production target. The only realistic solution for us was the latter. This was made possible through the use of a magnetized iron beam dump described below.

PROMPT NEUTRINO BEAM AND DETECTOR

The prompt neutrino beam and detector are shown schematically in Figure 2. A beam of 400 GeV protons with intensity about 2×10^{12} per beam pulse is incident from the left. The proton beam passes through a vertical pitching magnet and strikes one of several targets: tungsten, copper, or beryllium with either normal density or about one-third normal density. Only the tungsten data have been analyzed so far. The target is immediately followed by 11 m of magnetized iron with the magnetic field horizontal. Thus muons are deflected vertically. Hadrons are absorbed in the dump, and most of the muons are ranged out or deflected away from the detector which is only 60 m from the target.
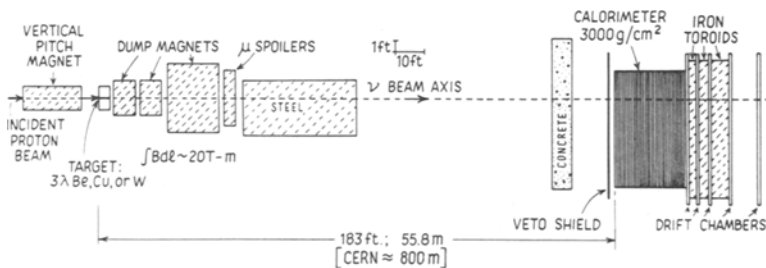

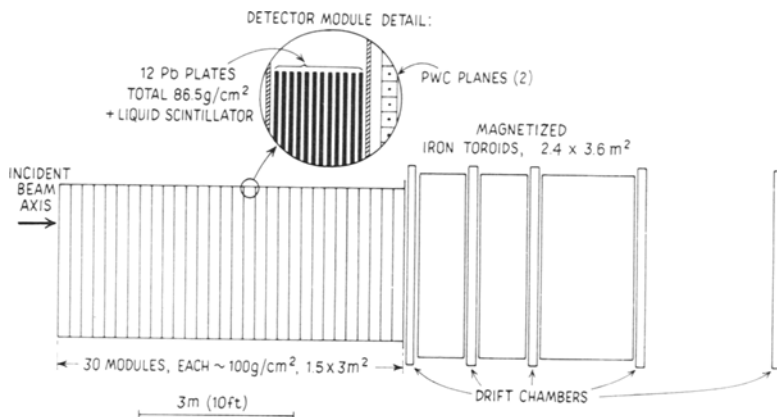Figure 2. Fermilab prompt neutrino experiment

Figure 3. Fermilab prompt neutrino detector

The detector is preceded by a triple wall of veto counters which are used to prevent triggers from charged particles entering the detector. The detector is shown in somewhat more detail in Figure 3. The sensitive volume consists of a calorimeter with lead plates. The total mass is about 150 tons and the fiducial mass is about 80 tons. The lead is divided into 30 modules, each with 12 lead plates . (See inset of Fig. 3). The modules are divided vertically into 5 cells. The lead plates are covered with teflon and immersed in liquid scintillator. Scintillation light travels by total reflection at the liquid-teflon interface and is brought to photomultiplier tubes at either end of each cell. There are a total of 300 phototubes on the calorimeter, each with its own analog-to-digital readout. Each of the 30 calorimeter modules is followed by two PWC planes, one with wires horizontal, the other with wires vertical. The wires are on 2.54 cm centers and have individual analog readouts[7] with a total of 6000 wires.

The calorimeter is followed by a muon spectrometer with solid iron magnets and drift chambers to track the muons from ν_μ charged-current events and measure their momenta.

The decision to trigger the event readout was based on the pulse-height information from the calorimeter phototubes. Minimum pulse-height requirements were imposed on overlapping groups of phototubes. Typically about 24 triggers were recorded per one-second long beam spill. Of these ≈6 were due to cosmic rays, and most of the rest came from muon interactions in the floor or roof blocks. In addition, approx. 6 cosmic ray triggers were recorded during a one-second "beam off" period; this provided a sample of cosmic ray triggers which allowed corrections for any cosmic ray events which faked real neutrino events. About one in 500 triggers yielded a neutrino event within the fiducial volume.

The triggering efficiency was mapped out as a function of energy deposited and position in the calorimeter by making use of the interactions of muons traversing the calorimeter. The solid curve in Fig. 4 is the unbiased energy loss spectrum observed when we trigger on muons traversing the detector. The lower two curves are the
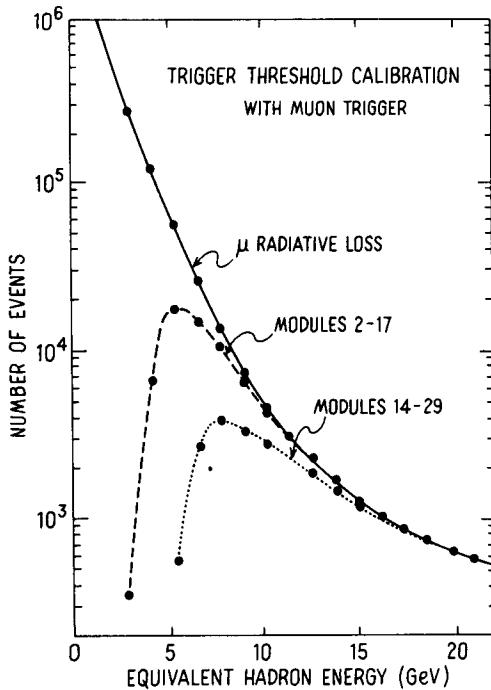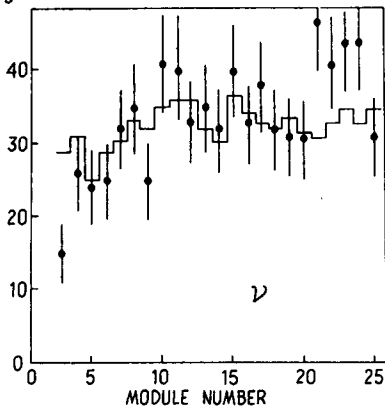
Figure 4. Trigger efficiency
calibration

spectra for muons which satisfy the trigger requirement. (A higher energy threshold was imposed for modules 14-29 in the calorimeter.) The ratio of muons which satisfy the energy trigger requirement to all muons at any energy gives the triggering efficiency. The trigger efficiency averaged over the entire detector was >50% above about 6.5 GeV for the front half of the detector and above 9 GeV for the back half.

CHECKS AND CORRECTIONS

One worry in a neutrino experiment is that the sample is contaminated by events initiated by neutrons or K°'s coming from the shielding upstream of the detector. This would show up as an excess of events in the front part of the detector. Figure 5 compares the observed distribution of vertices with a Monte Carlo estimate of the expected distribution for ν and $\bar{\nu}$ events. If anything, there is a slight deficit of events in the first module.

As a direct check on possible contamination of nonprompt neutrinos from upstream sources, we had a pitching magnet just upstream of the production target (Fig. 2). Because of this, the prompt events should be centered vertically in the detector, while neutrinos from sources upstream of the pitching magnet would be centered about 25 cm lower. Figure 6 shows the observed distribution of vertices as seen looking toward the target. There is no sign of any excess of events in the lower half of the detector.
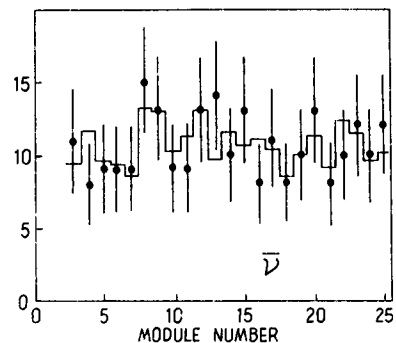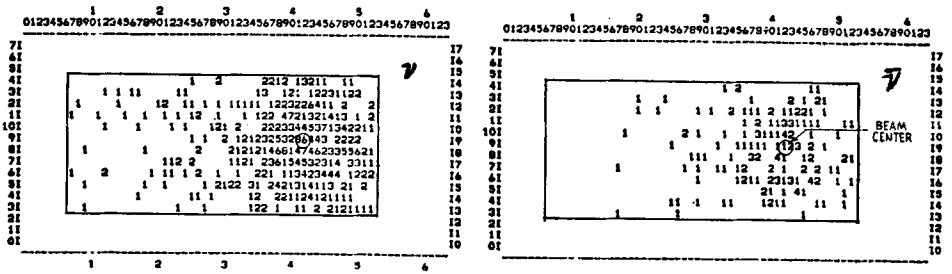

Figure 5. Vertex distributions

Figure 6.   Scatter plots of vertex distributions (looking into beam)

As further evidence that we are looking at neutrinos we can look at the Bjorken x and y distributions of the events.   Figure 7 compares the observed $x_{BJ}=Q^2/(2m_p(E_\nu-E'_\nu))$] distributions for ν and $\bar{\nu}$ with those expected.   The y distributions observed are also consistent with those expected.   Thus we conclude we are looking at "garden-variety" ν's and and $\bar{\nu}$'s.

The data contain a significant fraction of nonprompt ν's from pion and kaon decays.   We expect our nonprompt background to be generally lower than those observed in the CERN experiments because our detector subtends a much larger fraction of the prompt neutrinos.
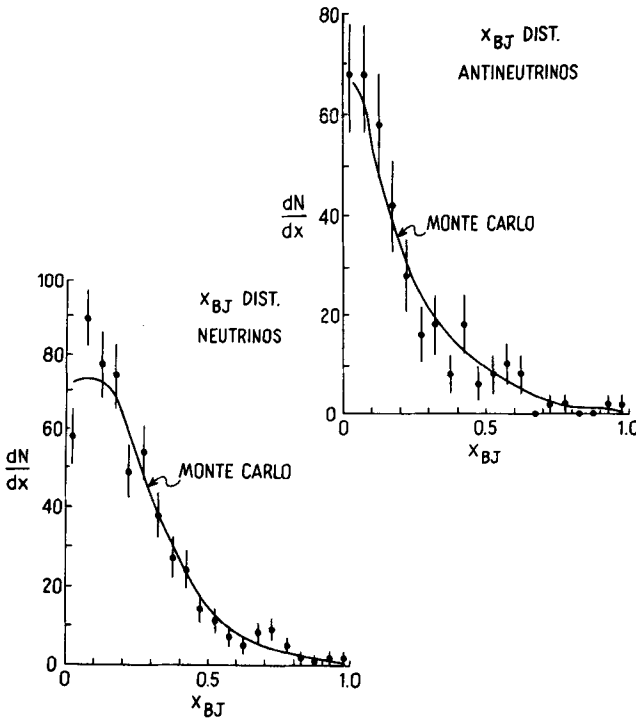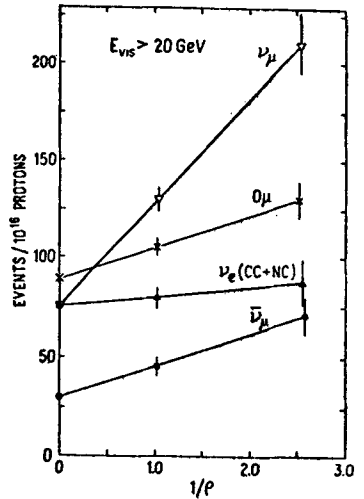

Figure 7.   Bjorken
x distributions

Figure 8.   Extrapolation to
infinite target density

The conventional way of subtracting the nonprompts is to extrapolate the rate to infinite target density. It is easy to show that the nonprompts go linearly to zero as $1/\rho \to 0$. Figure 8 shows the extrapolation for various subsets of our data. The "0μ" events contain the $\nu_e + \bar{\nu}_e$ events plus the ν_μ and $\bar{\nu}_\mu$ neutral current events. If the $\nu_\mu + \bar{\nu}_\mu$ neutral current events are subtracted we can isolate the ν_e contribution. As expected, the nonprompt background in the ν_e sample is quite small; the only significant source of nonprompt ν_e is the semileptonic decays of K's, which are suppressed by long lifetimes or small branching ratios. Figure 9 shows the extrapolation for the CERN experiments for which the prompt signal is considerably smaller.

We took great precautions with our proton beam line to minimize and understand any beam scraping which could be a source of what appear to be prompt neutrinos. Over 30 loss monitors were situated all along the beam line. These monitors were calibrated directly in counts/(interacting proton) by introducing foils of known thickness at various places in the beam and by improving or worsening the beam vacuum. A very convenient way of calculating the upstream background is in terms of the nonprompt background from the target. Both come from essentially the same mix of pion and kaon decays. The calculation is something like

$$\frac{\text{Upstream Background}}{\text{Nonprompts from Tungsten}} \cong \sum_{\substack{\text{beam} \\ \text{line}}} \left(\frac{\text{Interacting Protons}}{\text{Total Protons}} \right)$$

$$\cdot \left(\frac{\text{Decay Path}}{\text{M.F.P. in Tungsten}} \right) \cdot (\text{Solid Angle Factor})$$

where M.F.P. is the mean free path for hadrons and the solid angle factor is readily calculable from the geometry. We concluded that no significant contribution came from the beam line upstream of the last bend, mainly because of the solid angle factor. The result was that
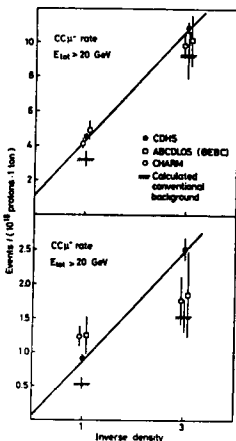

Figure 9. Extrapolation for CERN experiments.

$$\frac{\text{Upstream Background}}{\text{Nonprompts from Tungsten}} = 0.5\% \pm 0.25\%$$

or typically <1% of the prompt signal.

In addition there is a calculable background from vacuum windows, air, etc. just upstream of the target. This was approx. 16% of the prompts from tungsten.

RESULTS AND DISCUSSION

Once we have the prompt neutrino signal isolated, the next step is to calculate the neutrino flux. This is straightfoward and noncontroversial. The ν and $\bar{\nu}$

interaction cross sections are well known. The rest involves triggering and geometric efficiencies. Corrections have been applied for scanning losses, etc. The total number of interacting protons comes from a secondary emission monitor calibrated frequently by standard foil activation techniques.

To go from neutrino fluxes to charm production cross sections does involve a number of assumptions. These are worth spelling out in detail:

(1) Source is $p+N \to D+\bar{D}+x$ (not $\Lambda_c \bar{D}$, etc).
(2) Because the target is thick, we can get significant contributions from secondary hadrons. To account for this we assume the $D\bar{D}$ cross section varies as $s^{1.3}$ and the proton elasticity is 0.3.
(3) To get the cross sections for nucleons from that for tungsten, the A dependence of charm production must be known. Conventional wisdom suggests that for central production of $D\bar{D}$ pairs, an $A^{1.0}$ dependence is to be expected. This is roughly what is observed for ψ/J production off nuclei. We therefore assume an $A^{1.0}$ dependence independent of x and P_T.
(4) The dependence of the cross section on Feynman x and P_T is assumed to be

$$E \frac{d^3\sigma}{dp^3} = C \ (1-|x|)^n \ e^{-bP_T}$$

This factorized form is found to be only a fair approximation for other processes.
(5) The branching ratio of $D \to \mu+\nu_\mu+X$ is taken to be .082. This is the average of D^+ and D° as compiled by the Particle Data Group.

Given these assumptions we can compute a total charm production cross section and compare it with the CERN results. This comparison is made in Table I with the same assumptions used in all cases.

It is evident from Table I that the charm production cross sections are in good agreement if the same assumptions are used. By way of comparison, if we use a model suggested by J. Leveille[8] in which $E \ d^3\sigma/dp^3 \propto (1-|x|)^5 \ e^{-3.45 m_T}$ with $m_T \equiv (m_D^2+p_T^2)^{1/2}$, then our cross section goes up to 25.7±5.5 mb.

Historically it has been very difficult to reconcile the charm production cross sections observed at 400 GeV with the much larger cross sections observed at the CERN ISR. However, F. Halzen at the Paris Conference[9] pointed out that if an $A^{2/3}$ dependence for charm production is assumed, the heavy target results rise significantly, and much better agreement is obtained. Figure 10 taken from his talk is a nice summary of the situation. The curve is a nonperturbative QCD model calculation by Halzen, Keung, and Scott.[10] As can be seen, with an $A^{2/3}$ dependence all the data are in very good

TABLE I

σ(·DD̄) From Beam Dump Experiments

$$\left[\text{Assuming } E \frac{d^3\sigma}{dp^3} = C \ s^{1.3} \ A^{1.0} \ (1-|x|)^3 \ e^{-2P_T} \right]$$

Group	Angle Covered	Particle Detected	σ(DD̄) (μb/nucleon)
This exp't	0-37 mr	ν_μ	17.1 ± 4.7
CHARM	0-2	ν_e, ν_μ	14 ± 5
BEBC	0-2	ν_μ ν_e	45 ± 15 26 ± 15
CCFRS	0-40 (350 GeV)	μ	15 ± 5 (18 at 400 GeV if $s^{1.3}$)

agreement with each other and the model. It is worth noting that the difference between $A^{1.0}$ and $A^{2/3}$ is a factor of 5.7 for tungsten and 4.0 for copper. The uncertainty in the A dependence is thus the largest uncertainty in extracting the nucleon-nucleon cross section from the beam dump experiments. We hope to answer this important question when our copper and beryllium data are analyzed.

Another important question in testing the charm production models is the ratio of $\bar{\nu}$ and ν fluxes. Table II compares our results so far with the CERN results.
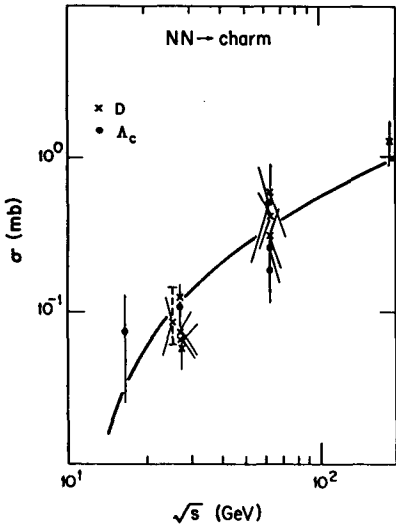

Figure 10. (From F. Halzen[9])- Total charm production vs √s assuming an $A^{2/3}$ dependence.

TABLE II

This exp't: $\bar{\nu}/\nu = 1.01 \pm 0.24$

CDHS[6]: $\bar{\nu}_\mu/\nu_\mu = 0.46 \ {}^{+\ 0.21}_{-\ 0.16}$

BEBC[4]: $\bar{\nu}_e/\nu_e = 0.65 \pm 0.33$

CHARM[5]: $\bar{\nu}/\nu = 1.3 \ {}^{+\ 0.6}_{-\ 0.5}$

Thus our result is consistent with unity, which is as expected in models with central DD̄ production. The error is still relatively large, but will go down significantly when the remainder of our data is analyzed.
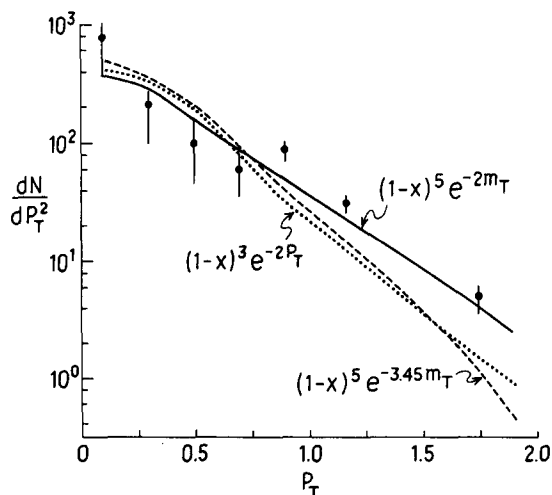
Figure 11. Observed p_T spectrum of ν_μ compared to predictions of charm production models.

Another important test of the production models is to determine whether the energy and P_T spectra of the prompt neutrinos agree with those predicted. Figure 11 compares the observed P_T spectrum for prompt ν_μ with those predicted for three production models. The $(1-x)^3 e^{-2P_T}$ and Leveille models predict very similar spectra which fall off somewhat faster than the data. The $(1-x)^5 e^{-2m_T}$ curve is an example of a form which agrees with the data at large P_T. In Fig. 12 we compare the prompt $\nu_e + \bar{\nu}_e$ energy spectrum with predictions of two models. The energy spectrum is consistent with n between 3 and 5. A substantial contribution of diffractive production with a flat spectrum in x or one which is peaked at $|x| \gtrsim 0.5$ would not be consistent with the data.

A very important question is the ratio of prompt ν_e to ν_μ which seems low in the CERN results. (See introduction.) Figure 13 shows our preliminary result for the ratio as a function of neutrino energy. Only statistical errors are shown. Below $E_\nu = 30$ GeV, systematic errors are likely to be substantial, so the low ratio there should not be taken seriously. Indeed we have discovered effects which may raise the ν_e/ν_μ ratio significantly, but this new analysis is not complete. Above 30 GeV the ratio is consistent with one.[11]

In addition to prompt neutrinos per se, beam dumps are a favorite hunting ground for new, relatively weakly interacting particles which can penetrate lots of shielding. One example would be the supersymmetric counterpart of the photon, the photino $\tilde{\gamma}$. These might be produced from the decay of gluinos. The photinos can interact in our detector to produce muonless events with unusually large P_T. The absence of such anomalous events allows us to set rather stringent limits on the existence of gluinos of mass < 4 GeV/c^2 which decay into photinos or Goldstinos. Unfortunately the limits are different for every gluino production/lifetime/decay
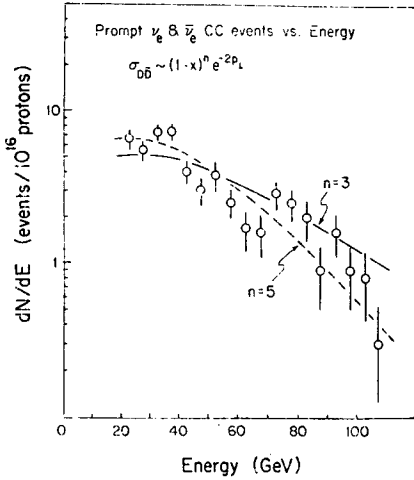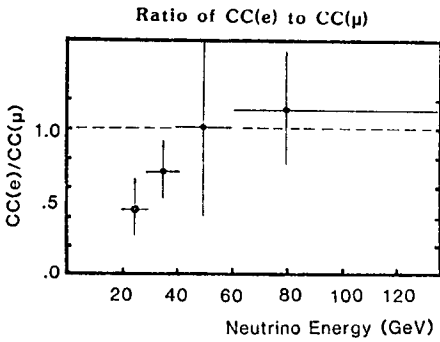
Figure 12. Observed E_ν spectrum of prompt ν_e.

scenario, and it is hard to give a concise summary. Figure 14 gives one example, that of gluinos which decay quickly to $\tilde{\gamma}\,q\bar{q}$ with the $\tilde{\gamma}$ long-lived. As is typical, the limits depend on some unknown parameter in the theory. In this case it is m_ϕ, the mass of the lightest scalar quark, which is supposed to be less than the mass of the Z°. For further details, see Reference 12.

Figure 13. Ratio of prompt ν_e to prompt ν_μ vs energy (preliminary)
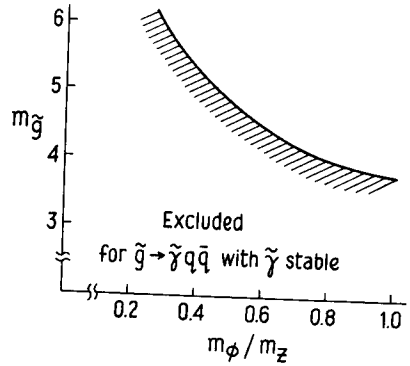

Figure 14. Example of limit on supersymmetric particles.

SUMMARY AND PROGNOSTICATION OF THINGS TO COME

In summary, we find

(1) A charm production cross section of approx. 20 μb/nucleon (assuming an $A^{1.0}$ dependence), in good agreement with the CERN prompt neutrino experiments.

(2) $\bar{\nu}/\nu \cong 1.0$ as expected for $D\bar{D}$ production.

(3) $\nu_e/\nu_\mu \cong 1.0$ which implies no exotic sources (or sinks!) of either neutrino species.

(4) P_T and E_ν distributions consistent with reasonable charm production models (though a possible "excess" at large P_T).

(5) No sign of gluinos, etc. ($m_{\tilde{g}} \gtrsim 4$ GeV/c^2).

(6) Charm production models with a large component with a flat x dependence [or harder] are not consistent with the neutrino energy spectrum.

The results given here are based on data from our 1981 run. When the analysis of data from the 1982 run is complete we will be able to reduce the statistical and systematic errors considerably. We also have data yet to be analyzed for beryllium and copper targets which should answer the question of the A dependence. The analysis of events with $E_\nu < 20$ GeV is difficult because backgrounds are higher and efficiencies are lower. When this is complete, we hope to be able to shed some light on the excess of events seen by the CHARM group for $E_\nu \lesssim 20$ GeV.

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