Fermi National Accelerator Laboratory

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DIMUON EVENTS*

Benjamin W. Lee

October 1975

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DIMUON EVENTS

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1. Introduction

I planned to talk about the role of anticommuting symmetry transformation in gauge theories.[1] However, I consider the recent discovery of dimuon events[2] in neutrino interactions so momentous that I should report on my understanding of these events, and discuss a preliminary interpretation. No doubt the understanding of this new phenomenon will have a profound impact on the future development of gauge theory of particle interactions and model making.

I shall first describe the reasons why I believe these events represent a new phenomenon, and I shall indulge in a theoretical interpretation on them based on the minimal gauge theory. Experimental data I shall present to you were provided to me by Professor David Cline of the Harvard-Pennsylvania-Wisconsin-Fermilab collaboration.

Table 1 shows the number of dimuon events observed by HPWF. There are altogether 84 dimuon events observed by this collaboration.

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Table 1

Time	Beam	Number of Protons (10^{17})	Number of Dimuon Events
April 1973	400 GeV Bare Target	~0.1	1
Jan. 1974	400 GeV Horn (ν)	0.5	3
July 1974	300 GeV Quadrupole Triplet	0.3	1
Nov. 1974	300 GeV Horn ($\bar{\nu}$)	4.8	11
Feb. 1975	380 GeV Quad. Triplet	7.7	61
April 1975	300 GeV Double Horn ($\bar{\nu}$)	3	7

In addition, the Cal Tech-Fermilab collaboration[3] has observed 4 dimuon events with both muons going through the magnet which is used as a muon spectrometer.

The antineutrino horn beam is an antineutrino-enriched beam. It contains approximately the same number of $\bar{\nu}$'s as ν's. The double-horn antineutrino beam (with a plug) is about 90% pure. The other beams are mostly neutrino beams with about 90% purity.

2. What Is A Dimuon Event?

A typical dimuon event is schematically shown in Fig. 1. This particular event originates in the hadron calorimeter which contains a scintillating material in mineral oil. In this case two muons of opposite signs go through the steel hadron filter and are momentum analyzed in the muon spectrometer.

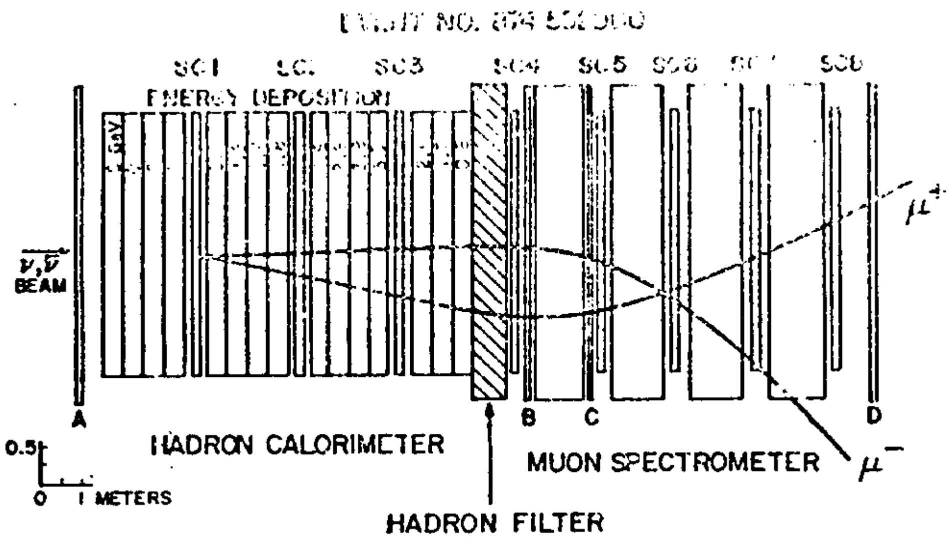


Fig. 1

That the two muons emanate from the same neutrino interaction can be verified by the spatial coincidence of the two muon tracks at the event vertex and the temporal coincidence of the two muon detections.

Figure 2 shows the distribution of dimuon events in the visible energy, E_{vis},

$$E_{vis} = E_H + E_{\mu_1} + E_{\mu_2},$$

where E_H is the hadronic energy deposition in the calorimeter, and $E_{\mu_1} + E_{\mu_2}$ is the sum of muon energies. The rate is proportional to the neutrino event rate, defined as the neutrino flux times the neutrino energy.

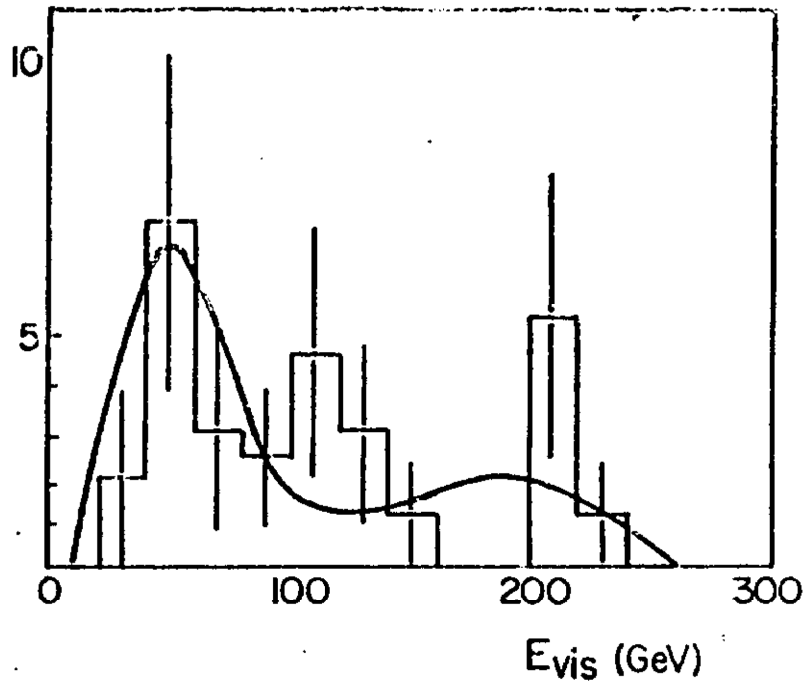


Fig. 2

The basic parameters of the dimuon events are summarized in Table 2. The strongest evidence that the second muon (μ^+ in ν-induced

Table 2

$$\frac{\sigma(\nu \to \mu^-\mu^+)}{\sigma(\nu \to \mu^-)} = 10^{-2}$$

$$\frac{\sigma(\bar{\nu} \to \mu^+\mu^-)}{\sigma(\nu \to \mu^-\mu^+)} = 0.8 \pm 0.6$$

$$\frac{\sigma(\nu \to \mu^-\mu^-)}{\sigma(\nu \to \mu^+\mu^-)} = 0.1$$

reactions, for example) does not come from a mundane source, such as from π or K decays, [redacted] comes from the relative rates of dimuon events per density in the hadron calor[redacted]meter and in the hadron filter. The former is mostly carbon, the latter iron. Since the absorption length of pions (and kaons) differs vastly in the two materials, the relative dimuon event rates would differ vastly if the second muon came from pion/kaon decays. Figure 3 shows a more-or-less constancy of the relative event rates at two different absorption lengths.

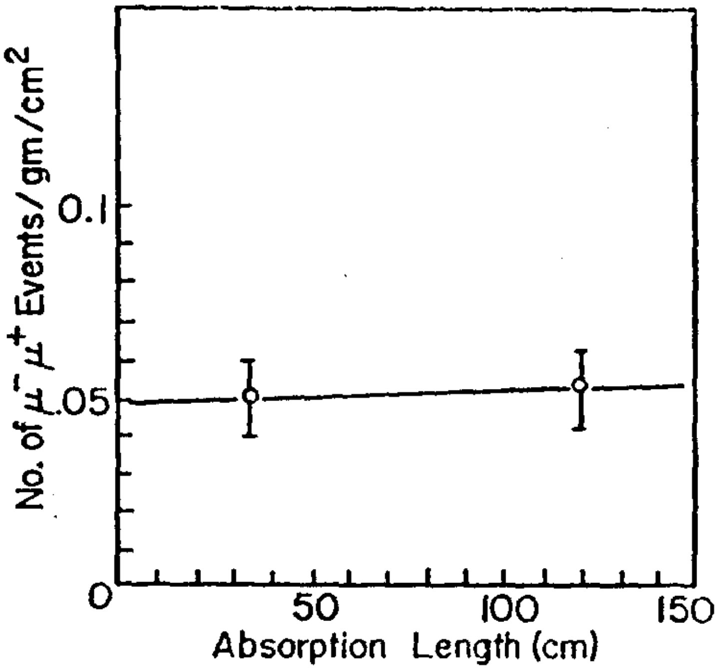


Fig. 3

3. Source of Dimuon Events

The rather large observed rates for dimuon events rule out the possibility that these are four-lepton interactions in nuclear Coulomb field. Figure 4 shows the distribution of ν-induced dimuon events as a function of the μ^- momentum P_- and the μ^+ momentum P_+. The straight line corresponds to $P_+ = P_-$. The numbers attached to events marked by triangles are the hadronic energy depositions for events originating in the hadron calorimeter.

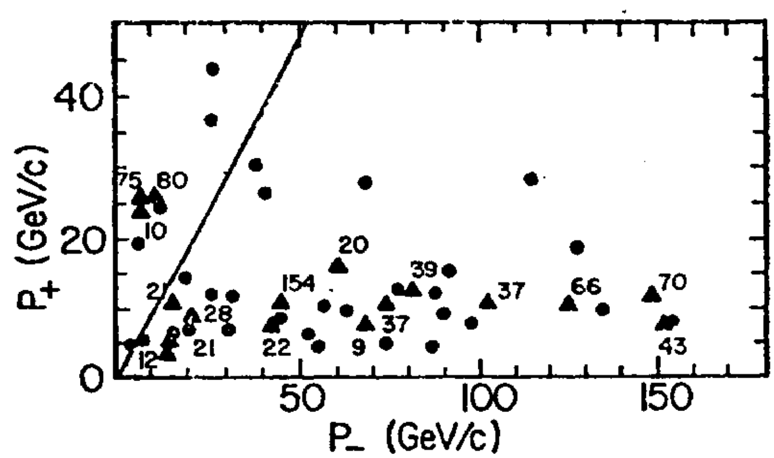


Fig. 4

One notes immediately the preponderance of events in which $P_- > P_+$. This is in opposition to the expectation[4] for the decay of the intermediate boson W^+

$$\nu + N \rightarrow \mu^- + W^+ + N$$
$$\qquad\qquad\qquad\qquad \hookrightarrow \mu^+ + \nu$$

which is produced in nuclear Coulomb field, in which case $P_+ > P_-$, and the hadronic shower is expected to be "quiet".

These events are not likely to come from decays of neutral heavy leptons that might be produced in ν-induced reactions:[5,6]

$$L^0 \to \mu^+ + \mu^- + \nu.$$

In fact, Pais and Treiman[7] considered the ratio $\langle P_- \rangle / \langle P_+ \rangle$ assuming that the opposite sign muons have the same parent and the above decay is described by a local interaction (S, P, T, V, and A). Extremizing the ratio with respect to the velocity and polarization of the parent heavy lepton, they obtained the bounds

$$0.46 \leq \langle P_- \rangle / \langle P_+ \rangle \leq 2.1.$$

This ratio for the events shown in Fig. 4 is

$$\langle P_- \rangle / \langle P_+ \rangle = 3.7 \pm 0.7$$

which is well beyond the upper bound. The HPWF group further notes that it is statistically consistent to assume that events with $P_+ > P_-$ are caused by the $\bar{\nu}$ contamination. Excluding these events, they obtain

$$\langle P_- \rangle / \langle P_+ \rangle = 8.5 \pm 1.7.$$

It is therefore very unlikely that all of the dimuon events arise from the decay of a neutral heavy lepton.

Another piece of evidence, perhaps intuitively more appealing, is the dimuon mass distribution as the incident neutrino energy changes.

If the dimuons came from a common parent of well-defined mass, the mass distribution should be independent of the ν-energy. Figure 5 shows however that the dimuon mass distribution tends to be broadened as E_{vis} increases.

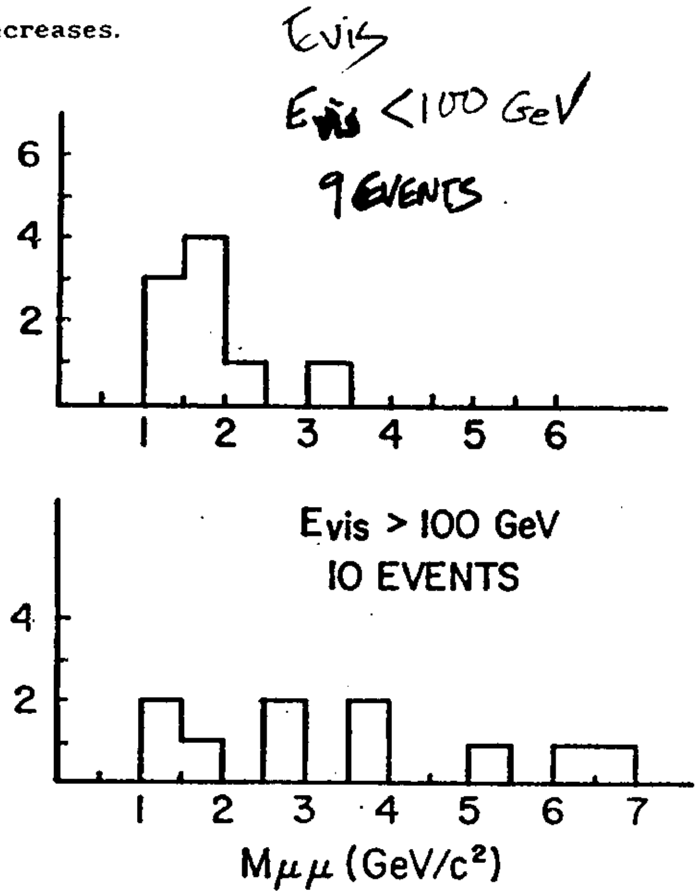


Fig. 5

It is therefore extremely plausible that the extra muon comes from decays of a new particle (or particles) produced at the hadron vertex. To explain the preponderance of opposite-sign dimuons, it is necessary to assume that the new particles carry a new quantum number, which we shall denote by C, and their semileptonic interactions interactions obey the rule $\Delta C = \Delta Q$ in the hadronic sector.

In the minimal model of gauge theory of weak and electromagnetic interactions which is based on the group $SU(2)\times U(1)$[8,9] and incorporates the GIM mechanism[10] with four flavors of quarks, the new particles may be charmed ones. In the deep inelastic region there are various mechanisms for exciting the charm degree of freedom above charm threshold, as we depict in Fig. 6.

We note that the first process, i.e., charm production off valence quarks, is not available for antineutrinos.

4. Issues

In the minimal model interpretation of dimuon events there are three issues we must pay attention to, to understand the gross features discussed in Table 2.

(1) What is the $s\bar{s}$ content of a nucleon?

(2) What is the $c\bar{c}$ content of a nucleon?

(3) What is the inclusive branching ratio of muon-yielding decays of the (generic) charmed particle?

Our knowledge on these matters is not sharp enough to answer these questions definitively. However, it is possible to set reasonable qualitative bounds on these quantities. First, the precise amount of $q\bar{q}$ pairs present in a nucleon is a matter of considerable debate. The

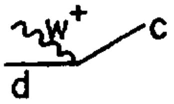
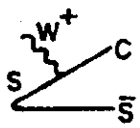
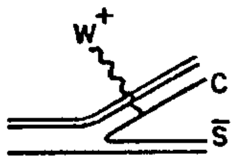
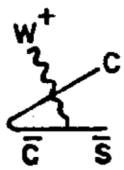
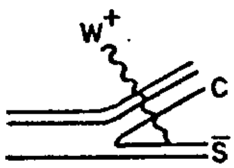
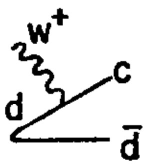
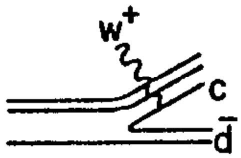
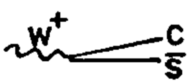
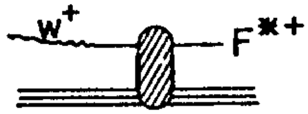
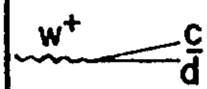
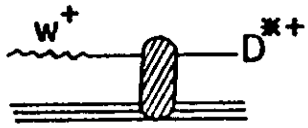
Elementary process	Quark diagram for $\nu + N \rightarrow \mu^- + C + X$	Cabibbo Suppression	Valence or sea quark
		$\sin\theta_C$	valence
		$\cos\theta_C$	sea ($s\bar{s}$)
		$\cos\theta_C$	sea ($c\bar{c}$)
		$\sin\theta_C$	sea ($d\bar{d}$)
		$\cos\theta_C$	diffractive
		$\sin\theta_C$	diffractive

Fig. 6

$s\bar{s}$ content of a nucleon is limited by our preconception that it should not be larger than the $u\bar{u}$ or $d\bar{d}$ contents. However, say 5-10% contamination of $s\bar{s}$ pairs (in terms of the contribution to the F_2 function) in a nucleon seems reasonable and not contradicted by any known facts. We shall use 5% in the following discussion. As for $c\bar{c}$ pairs, we know much less. In the following discussion we will ignore them.

As for the branching ratio into muon channels, Gaillard, Lee, and Rosner[11] gave an estimate of a few percent based on a naive quark model and the notion that the $\underset{\sim}{20}$ piece [in SU(4)] of nonleptonic Hamiltonian is enhanced uniformly by the same amount as the octet piece in nonleptonic decays of hyperons and K-mesons. On the other hand if selective enhancement of a particular nonleptonic channel is not operative, then the branching ratio into muon channels may be considerably bigger. In fact, if there is no selective enhancement, and if all ordinary quark masses can be neglected compared to the charmed quark mass, then the above ratio may be estimated by a simple quark counting:

$$c_\alpha \rightarrow s_\alpha + (u_\beta + \bar{d}_\beta) \qquad \beta = \text{red, blue, white}$$

$$c_\alpha \rightarrow s_\alpha + \mu + \bar{\nu}_\mu$$

$$\rightarrow s_\alpha + e + \bar{\nu}_e$$

where α and β are color indices. Thus,

$$\frac{\Gamma(C \rightarrow \mu + X)}{\Gamma(C \rightarrow \text{all})} = \frac{1}{3 + 1 + 1} = 20\%.$$

We consider this as a loose upper bound. We shall use the figure 10% in the following discussion.

5. Consequences - Predictions

Some of the implications of the assumptions made in the last section on dimuon productions have been discussed by Pais and Treiman,[12] Wolfenstein,[13] and Llewellyn-Smith.[14]

One of the most remarkable features of the dimuon events predicted from these assumptions is that there are two components in these events. The small x component, which reflects the sea $s\bar{s}$ content, yields predominantly $S = \pm 1$, $C = \pm 1$ final states. This component is present both in ν- and $\bar{\nu}$-induced events. The valence component, which arises from the elementary process $W^+ + d \to c$, reflects the valence d-quark distribution, and yields predominantly $S = 0$, $C = +1$ final states. This latter component is present only in ν-induced events.

The ratio of the charm production cross section to the "background" deep inelastic cross section is summarized in Table 3:

Table 3

	ν	$\bar{\nu}$
Small x component $\Delta C = \pm 1,\ \Delta S = \pm 1$	$\sim 5\%$	$\sim 5\% \times 3$
Valence component $\Delta C = \pm 1,\ \Delta S = 0$	$\sim \sin^2\theta_c \sim 5\%$	-
Total	$\dfrac{\sigma(\nu+N\to\mu^-+C+---)}{\sigma(\nu+N\to\mu^-+--)} \approx 10\%$	$\dfrac{\sigma(\bar{\nu}+N\to\mu^++C+---)}{\sigma(\bar{\nu}+N\to\mu^++--)} \approx 15\%$

In this table we have used the empirical fact that

$$\sigma(\bar{\nu} + N \to \mu^+ + ---) = \frac{1}{3}\,\sigma(\nu + N \to \mu^- + ---).$$

In this picture the relative rates of dimuon events are given by

$$\frac{\sigma(\nu + N \to \mu^- + C + ---)}{\sigma(\nu + N \to \mu^- + --)} \times \text{B.R.}\ (C \to \mu^+ + \nu + ---) = 1\%$$

for ν-induced events, and

$$\frac{\sigma(\bar{\nu} + N \to \mu^+ + \bar{C} + ---)}{\sigma(\bar{\nu} + N \to \mu^+ + ---)} \times \text{B.R.}\ (\bar{C} \to \mu^- + \nu + --) = 1.5\%.$$

Further,

$$\frac{\sigma(\bar{\nu} \to \mu^+\mu^-)}{\sigma(\nu \to \mu^-\mu^+)} = 0.5\%.$$

<u>The two-component nature of dimuon events is most important in verifying the present interpretation.</u> In Fig. 7 I have sketched the expected x- and y-distributions of dimuon events.

The experimental data bearing on the x, y distributions are shown in Fig. 8. Because incident neutrino energy is not known, x_{vis} and y_{vis} are defined as

$$y_{vis} \equiv \frac{E_H + E_{\mu_2}}{E_H + E_{\mu_1} + E_{\mu_2}} \le y,$$

$$x_{vis} \equiv \frac{\nu}{y_{vis}} \ge x$$

where $\nu = xy$ can be measured in a flux independent way. Because the data are still statistically poor, I will not draw any conclusions.

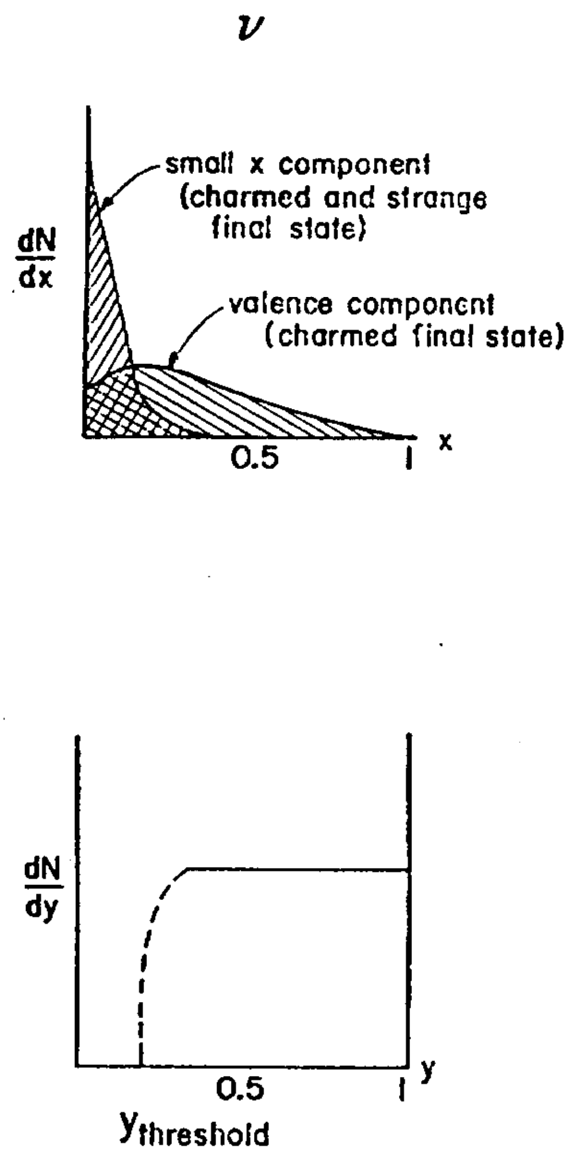

ν
$\bar{\nu}$
small x component
(charmed and strange
final state)
dN/dx
valence component
(charmed final state)
0.5
1
x
small x component
(charmed and strange
final state)
dN/dx
0.5
1
x
dN/dy
0.5
1
y
$y_{threshold}$
dN/dy
0.5
1
y
$y_{threshold}$

Fig. 7

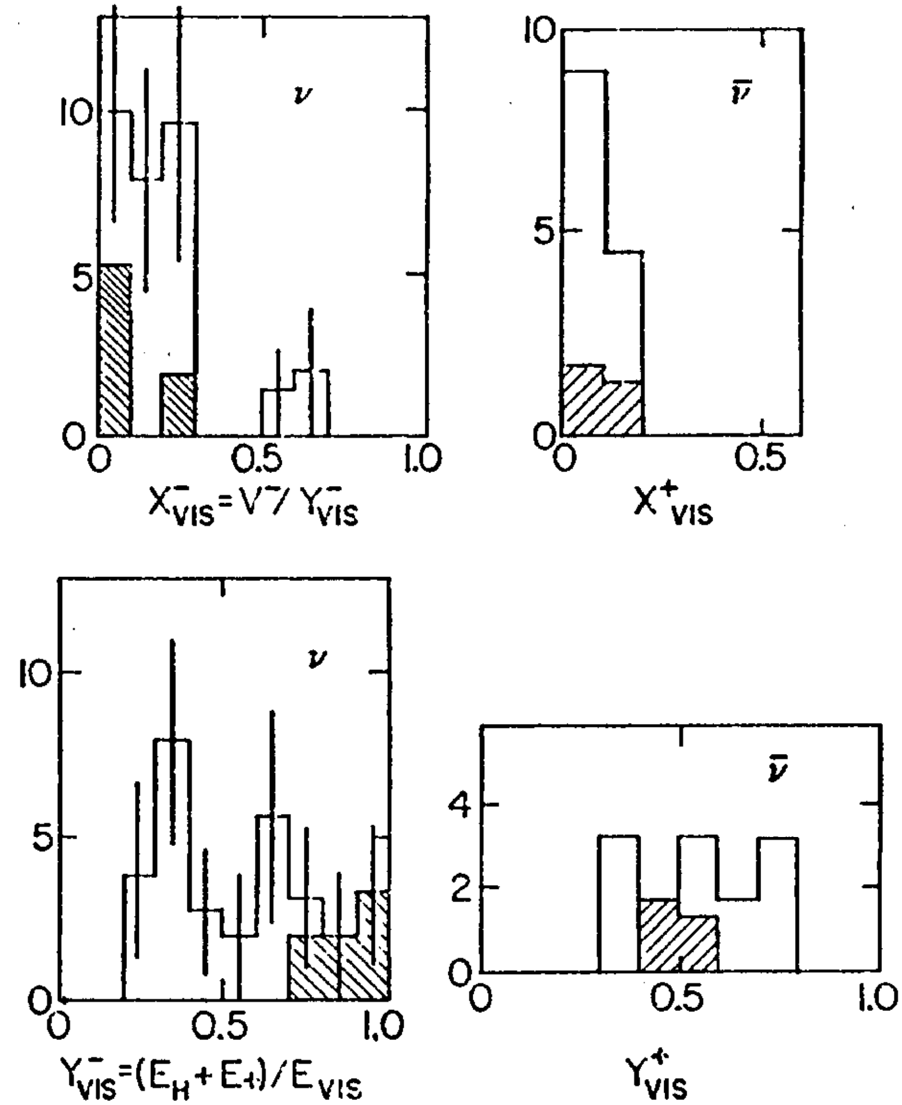

ν
10
5
0
0
0.5
1.0
$X^-_{VIS} = V7/Y^-_{VIS}$
$\bar{\nu}$
10
5
0
0
0.5
X^+_{VIS}
ν
10
5
0
0
0.5
1.0
$Y^-_{VIS} = (E_H + E_{\dagger})/E_{VIS}$
$\bar{\nu}$
4
2
0
0
0.5
1.0
Y^+_{VIS}

Fig. 8

6. Exclusive Channels

There are several exclusive charm producing reactions for which we can make semiquantitative estimates. These processes are of interest in experiments where final state particles are detected and identified, such as in the 15-ft bubble chamber at Fermilab.

Single charmed baryon productions

$$\nu + p \to \mu^- + C_1^{++},$$

$$\nu + n \to \begin{Bmatrix} C_1^+ \\ C_0^+ \end{Bmatrix} + \mu^-$$

have been discussed elsewhere;[11] they are expected to be rather rare. One of these processes may have a bearing on the BNL event[15]

$$\nu + p \to \mu^- + \Lambda + \pi^+ + \pi^+ + \pi^+ + \pi^- .$$

Another class of processes for which one can make quantitative estimates is the charm-strangeness two-body associated productions of the type

$$\nu + p \to \mu^- + K^+ + C_{0,1}^+ .$$

Near threshold, barring the existence of resonances in the hadronic final states, the generalized Born approximation of Adler[16] and Shrock[17] should be fairly reliable. Shrock and I have considered this approach, and concluded[18] that the cross sections for these processes are about 10^{-41} cm^2, around E_ν = 8 GeV. The total cross section for $\nu p \to \mu^- K^+ C_0^+$

is plotted in Fig. 9 (this is preliminary). Since the total νp cross section is about 5×10^{-38} cm^2 at these energies, detection of these processes would be very difficult.

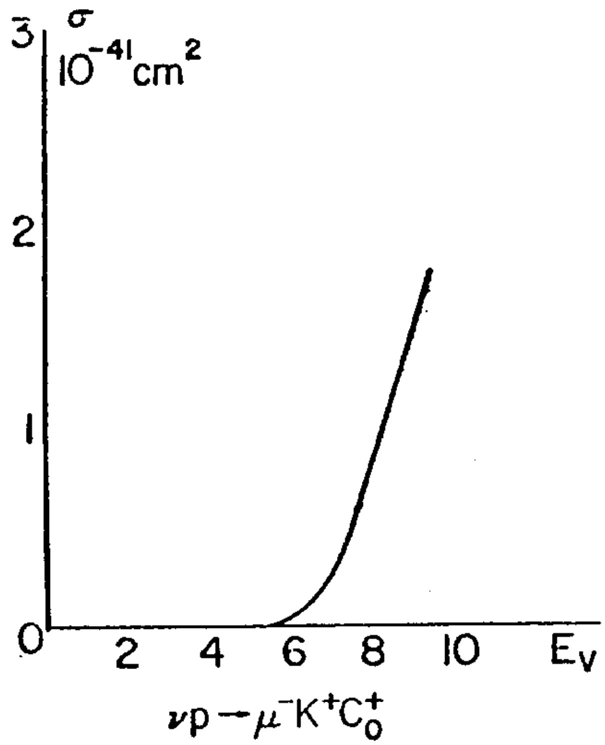


Fig. 9

A process of particular interest is the diffractive production of F^*, which is a 1^- $c\bar{s}$ bound state:

$$\nu + N \rightarrow \mu^- + F^{*+} + N.$$

Many authors have commented on this process and computed its cross section.[11, 19-23] It is given by

$$\frac{d^2\sigma}{dxdy} = \frac{G_F M E_\nu}{\pi} \frac{\cos^2\theta_c}{\gamma_{F^*}^2} \left(\frac{\mu^2}{Q^2+\mu^2}\right)^2$$

$$\frac{Q^2(1-x)}{2\pi}\left[y^2\,\sigma_\perp + 2(\sigma_\perp + \sigma_L)\,\frac{1-y-Mxy/2E_\nu}{1+2xM/yE_\nu}\right]$$

where

M: mass of the nucleon,

μ: mass of F^*,

and $\sigma_\perp$ and σ_L are the transverse and longitudinal F^*N elastic cross sections, and γ_{F^*} is defined by

$$\left\langle F^{*+}(\epsilon)\,\middle|\,J_\mu(0)\,\middle|\,0\right\rangle = \frac{\mu^2}{\gamma_{F^*}}\,\epsilon_\mu .$$

In the following I shall simply assume $\sigma_L = 0$, $\sigma_\perp = \sigma_{el}(F^*N \to F^*N)$. However, there is one effect of extrapolating the initial F^* off the mass shell which is likely to be quite important, viz., the minimal momentum transfer allowed. So we[23] multiply $\sigma_\perp$ by $\exp(b\,t_{min})$ where, in the Bjorken limit,

$$t_{min} \cong \frac{-M^2x^2}{1-x}\left[1 + \frac{1}{2ME_\nu y}\left(M^2 + \frac{\mu^2}{x}\right)\right],$$

and $b \approx 4\,(\text{GeV})^{-2}$.

In Fig. 10 I show a figure from the paper of Gaillard, Jackson, and Nanopoulos.[22] What is plotted is the diffractive vector and axial-vector boson production cross sections as fractions of the total neutrino cross section. Roughly, the ratio of the ρ and F* cross sections is given by[22]

$$\left[\frac{\sigma_{tot}(F^*N)}{\sigma_{tot}(\rho N)}\right]^2 \frac{\gamma_\rho^2}{\gamma_{F^*}^2} = \left(\frac{5\text{ mb}}{26\text{ mb}}\right)^2 \left(\frac{m_\rho}{\mu}\right).$$

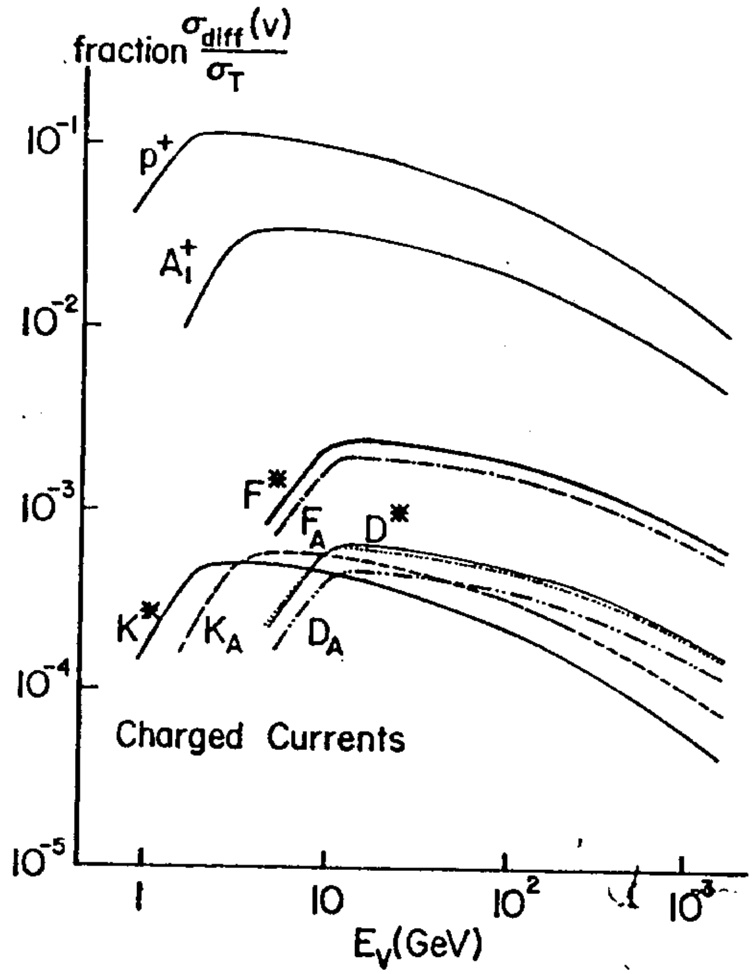


Fig. 10

Thus we expect that the F* diffractive production is about 2×10^{-3} of the total neutrino cross section. However, near the effective threshold of charmed particle production, i. e., at the energy range where deep inelastic, charmed particle production cross section begins to scale, the diffractive F* production may be an important, indeed dominant, source of charmed particles in the final state.

In Figs. 11 and 12 I have plotted the invariant hadronic mass squared (W^2) distribution and the x, y distribution of the diffractive F* production.

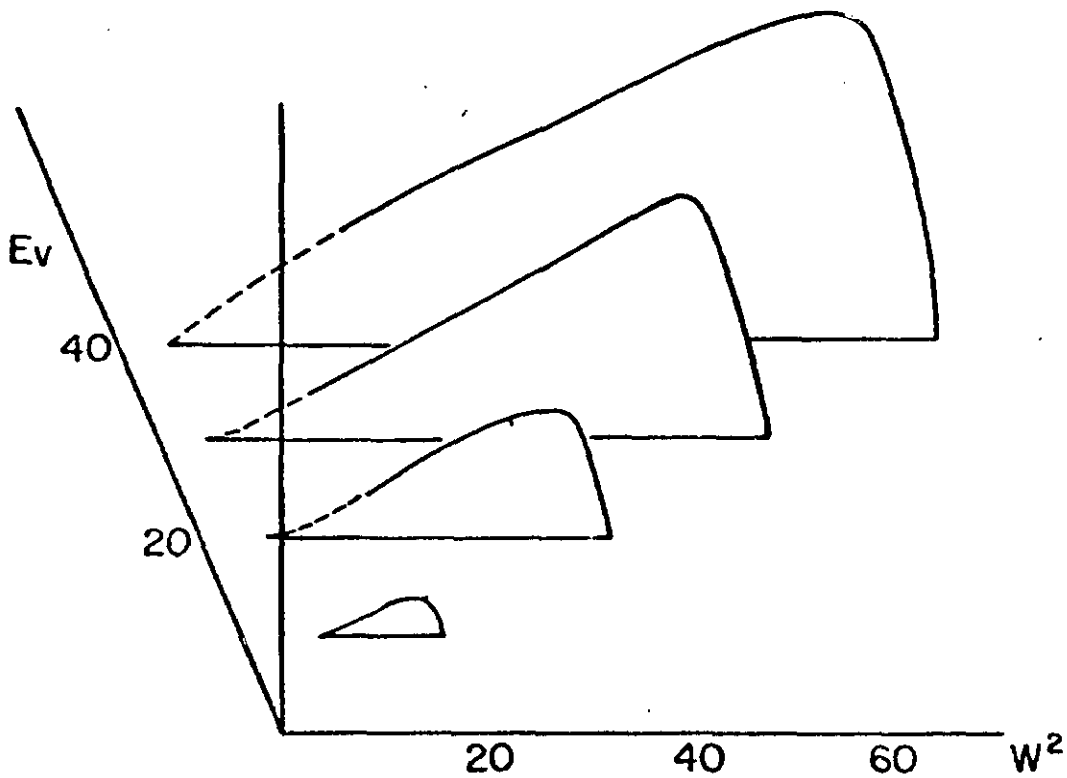


Fig. 11

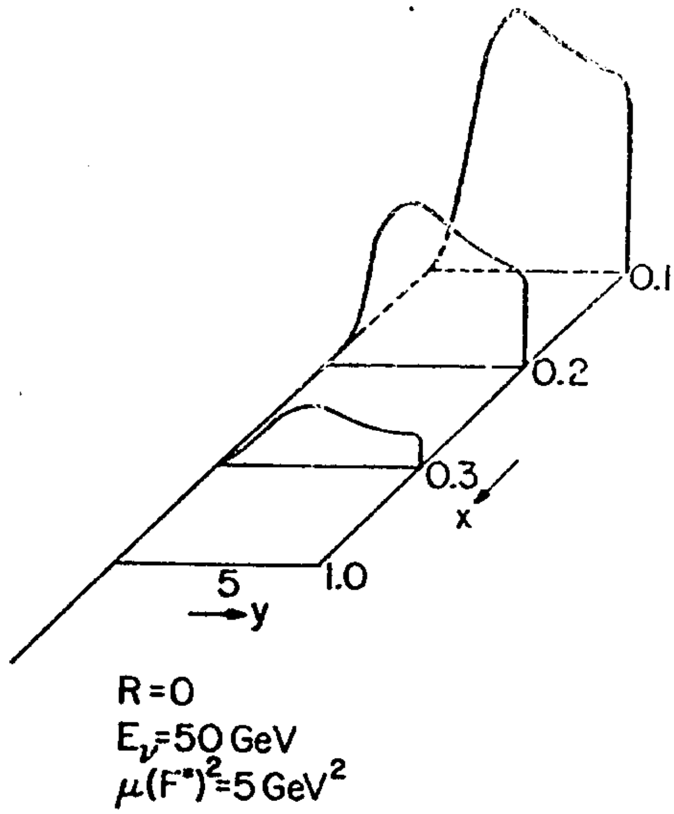


Fig. 12

We have already discussed signatures of F^* production.[11] If F^* is sufficiently heavier than F, then the decays

$$F^* \to F + \eta, \; D + K$$

may be dominant. If these processes are not energetically possible, the electromagnetic decay

$$F^* \to F + \gamma$$

is expected dominant. F^+ would then cascade:

$$F^+ \to \pi^-\pi^+\pi^+,\ K^-K^+\pi^+,\ ---$$
$$\eta \ell^+ \nu,\ X\ell^+ \nu,\ ---.$$

7. Dimuon Events of the Same Sign

In the minimal model, dimuon events of the same sign are explained in terms of associated production of a charmed pair:

$$\begin{array}{l} \nu + N \to \mu^- + C + \overline{C} + --- \\ \qquad\qquad\qquad\qquad\quad \llcorner\!\to \mu^- + \nu + ---. \end{array}$$

While we have no way of estimating charmed pair production in neutrino reactions, strange particle pair production in neutrino reactions is known to be substantial (~ 15%). To explain the ratio $\sigma(\nu \to \mu^-\mu^-)/\sigma(\nu \to \mu^-\mu^+)$ of about 0.1 we must assume that charmed pair production is about 1% of the total neutrino cross section above, say, 40 GeV.

An important corollary of this assumption is that the trimuon events of the type

$$\begin{array}{l} \nu + N \to \mu^- + C + \overline{C} + --- \\ \qquad\qquad\qquad\quad \llcorner\!\to \mu^+ + \nu + --- \\ \qquad\qquad\qquad\qquad\quad \llcorner\!\to \mu^- + \nu + --- \end{array}$$

must exist at the level of 10^{-2} of the dimuon events of opposite signs.

Acknowledgment

I have benefitted greatly from discussions with D. Cline, W. Ford, M. Einhorn, M. K. Gaillard, T. Y. Ling, A. Mann, and S. Treiman on this subject.

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