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Neutrino and Antineutrino New Data and Vectorlike Models

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Abstract

A detailed assessment of recently reported neutrino and antineutrino "new physics" data at high energies is carried out in a strictly vectorlike quark-parton model. The model is found to be in very good agreement with the data, with a sea quark contribution as little as 10% or less, relative to the valence contribution. Various other advantageous features of the vectorlike model, compared to the standard four-quark model, are pointed out. The implication is that besides the charmed quark c, other heavy quarks could exist, and are probably already being excited at the presently available high neutrino energies.

1. *Introduction*

Among various effects that have been observed in recent inclusive neutrino and antineutrino interactions at high energies (Roe, 1976; Mann, 1976; Benvenuti et al., 1976a–c), and that do not seem to have been satisfactorily accounted for within the standard GIM quark-parton model (Glashow et al., 1970), one may list the following:

(i) Strong increase in the ratio of the inclusive charged current antineutrino to neutrino cross section, $\sigma_c^{\bar{\nu}N}/\sigma_c^{\nu N}$, at high energies, compared to low-energy value of $\frac{1}{3}$.
(ii) High y anomaly observed in the antineutrino single-muon inclusive scattering data.
(iii) A substantial rise in $\langle y\rangle^{\bar{\nu}N}$ at high energies.

In addition, there is the problem of explaining the origin and production rates of dimuons ($\mu^+\mu^-$; $\mu^\pm\mu^\pm$), as well as the more recently discovered trimuon events ($\mu^+\mu^+\mu^-$; $\mu^-\mu^-\mu^+$): (Barish et al., 1976).

In an earlier paper (Ndili and Chukwumah, 1977), hereafter referred to as Paper I, we attempted to explain these strong features of the neutrino-antineutrino data, in terms of the GIM four-quark model. While we achieved a certain measure of success, we were compelled to use a rather large proportion of sea quark contribution relative to the valence quarks. On the other hand, within the last year or so, various models containing more than the conventional four quarks have been proposed (Fritzsch et al., 1975; Wilczek et al., 1975; Rujula et al., 1975a; Achiman et al., 1975; Gursey and Sikivie, 1976; Pakvasa et al., 1975). Some of these multiquark models possess the theoretically appealing feature of being purely vectorlike. As a result, various attempts have been made to work out the consequences of such multiquark models and compare with high-energy data for both colliding beam and neutrino processes. (Barnett, 1976; Rujula, 1976a, b; Barger and Nanopoulos, 1976; Lee, 1976; Albright and Oakes 1976; Abe et al., 1977; Nandi, 1976; Minkowski, 1976; Fritzsch and Minkowski, 1975, 1976; Inoue et al., 1976; Harari, 1976; Fritzsch, 1977; Das, 1976).

In this paper, we shall approach the problem of explaining the "new physics" neutrino and antineutrino data from the same point of view as in our Paper I, except that we use here a purely vectorlike six-quark model instead of the conventional four-quark GIM model. We shall also calculate the average y distribution, which is becoming an important part of experimental data. Similar calculations have been reported by various authors (Albright and Shrock, 1977; Barger et al., 1976; Kaplan and Martin, 1976; Graham et al., 1976).

2. *Vectorlike Models*

It is known that in order to make the hadronic weak current vectorlike, at least six kinds of quarks or flavors have to be used. In a strictly vectorlike model, every quark sits in a right- and left-handed doublet, and the doublets are given as follows:

Model (*a*):

$$\begin{pmatrix} u \\ d_\theta \end{pmatrix}_L, \quad \begin{pmatrix} c \\ s_{\theta,\phi} \end{pmatrix}_L, \quad \begin{pmatrix} t \\ b_\phi \end{pmatrix}_L, \quad \begin{pmatrix} u \\ b \end{pmatrix}_R, \quad \begin{pmatrix} c \\ s_\psi \end{pmatrix}_R, \quad \begin{pmatrix} t \\ d_\psi \end{pmatrix}_R$$

where

$$\begin{aligned} d_\theta &= d \cos \theta_c + s \sin \theta_c \\ s_\theta &= -d \sin \theta_c + s \cos \theta_c \\ s_{\theta,\phi} &= s_\theta \cos \phi + b \sin \phi \\ s_\psi &= s \cos \psi + d \sin \psi \\ d_\psi &= -s \sin \psi + d \cos \psi \\ b_\phi &= -s_\theta \sin \phi + b \cos \phi \end{aligned}$$

and c, t, and b stand for "charm," "beauty (bottom)," and "truth (top)," respectively, with charges $+\frac{2}{3}, +\frac{2}{3}, -\frac{1}{3}$. The right-handed quarks are rotated through an angle ψ.

The other theoretically appealing models are as follows.

(b) *The FMG Model* (Fritzsch et al., 1975) *and the WZKT Model* (Wilczek et al., 1975). For these, $\psi = 0$ so that the charm-changing currents are obtained from

$$\begin{pmatrix} c \\ s_\theta \end{pmatrix}_L, \quad \begin{pmatrix} c \\ s_\theta \end{pmatrix}_R, \quad \begin{pmatrix} t \\ d \end{pmatrix}_R, \quad \begin{pmatrix} u \\ b \end{pmatrix}_R$$

(c) *The DGG Model.* This model is due to De Rujula et al. (1975a,b). The mixing angle is taken as $-\pi/2$. The charm-changing threshold W_c is assumed to be associated with the c-quark production, and W_b and W_t are related by

$$W_b = W_t > W_c$$

The couplings are given by

$$\begin{pmatrix} c \\ s_\theta \end{pmatrix}_L, \quad \begin{pmatrix} c \\ d \end{pmatrix}_R, \quad \begin{pmatrix} u \\ d_\theta \end{pmatrix}_L$$

and

$$\begin{pmatrix} c \\ s_\theta \end{pmatrix}_L, \quad \begin{pmatrix} c \\ d \end{pmatrix}_R, \quad \begin{pmatrix} u \\ b \end{pmatrix}_R, \quad \begin{pmatrix} t \\ -s \end{pmatrix}_R, \quad \begin{pmatrix} u \\ d_\theta \end{pmatrix}_L$$

(d) *The AKW Model.* This model was suggested by Achiman et al. (1975). The couplings are given by

$$\begin{pmatrix} u \\ d_\theta \end{pmatrix}_L, \quad \begin{pmatrix} c \\ s_\theta \end{pmatrix}_L, \quad \begin{pmatrix} u_\phi \\ b \end{pmatrix}_R$$

(e) *The G–S(B) and G–S(C) Models.* These two models were introduced by Gürsey and Sikivie (1976), and the current couplings are given, respectively, by

$$\begin{pmatrix} u \\ d_\theta \end{pmatrix}_L, \quad \begin{pmatrix} c \\ s_\theta \end{pmatrix}_L, \quad \begin{pmatrix} u \\ b_\phi \end{pmatrix}_R, \quad \begin{pmatrix} c \\ s \end{pmatrix}_R$$

and

$$\begin{pmatrix} u_\alpha \\ d_\alpha \end{pmatrix}_L, \quad \begin{pmatrix} c_\alpha \\ b_\alpha \end{pmatrix}_L, \quad \begin{pmatrix} u \\ b_\phi \end{pmatrix}_R, \quad \begin{pmatrix} c \\ s \end{pmatrix}_R$$

There is also a model proposed by Pakvasa et al. (1975).

We shall work in the strictly vectorlike quark–parton model (a). The weak charged current in this model is given by

$$\begin{aligned} J_\mu^+ &= \bar{u}\gamma_\mu(1+\gamma_5)d_\theta + \bar{c}\gamma_\mu(1+\gamma_5)S_{\theta,\phi} \\ &\quad + \bar{t}\gamma_\mu(1+\gamma_5)b_\phi + \bar{u}\gamma_\mu(1-\gamma_5)b \\ &\quad + \bar{c}\gamma_\mu(1-\gamma_5)s_\psi + \bar{t}\gamma_\mu(1-\gamma_5)d_\psi \end{aligned} \tag{2.1}$$

That is,

$$
\begin{aligned}
J_\mu^+ = {} & \bar{u}\gamma_\mu(1+\gamma_5)d\cos\theta_c + \bar{u}\gamma_\mu(1+\gamma_5)s\sin\theta_c \\
& - \bar{c}\gamma_\mu(1+\gamma_5)d\sin\theta_c\cos\phi + \bar{c}\gamma_\mu(1+\gamma_5)s\cos\theta_c\cos\phi \\
& + \bar{t}\gamma_\mu(1+\gamma_5)d\sin\theta_c\sin\phi - \bar{t}\gamma_\mu(1+\gamma_5)s\cos\theta_c\sin\phi \\
& + \bar{t}\gamma_\mu(1+\gamma_5)b\cos\phi + \bar{u}\gamma_\mu(1-\gamma_5)b \\
& + \bar{c}\gamma_\mu(1-\gamma_5)s\cos\psi + \bar{c}\gamma_\mu(1-\gamma_5)d\sin\psi \\
& + \bar{t}\gamma_\mu(1-\gamma_5)d\cos\psi - \bar{t}\gamma_\mu(1-\gamma_5)s\sin\psi
\end{aligned}
\tag{2.2}
$$

where the first row is the conventional $SU(3)$ weak charged current while the rest are the charm-changing weak currents.

3. *Neutrino and Antineutrino Cross Sections*

In order to obtain the cross sections for various inclusive neutrino and antinuetrino interactions, both below and above heavy quark thresholds, we shall proceed as in Section II of our Paper I, classifying our event topologies as follows.

(a) Single-muon events:

$$\nu + N \to \mu^- + X$$

to which three event types,

(a)-(i), (a)-(ii), and (a)-(iii)

contribute (see Paper I).

(b) Dimuon events:

$$\nu + N \to \mu^- + \mu^+ + X$$

assumed to be signatures for heavy-quark excitation, accompanied by semileptonic decay.

(c) Like-sign dimuon and trimuon events:

$$\nu + N \to \mu^\mp + \mu^\mp + X$$

and

$$\nu + N \to \mu^\mp + \mu^\mp + \mu^\mp + X$$

assumed also to be due to associated "charmed" hadron production.

We shall assume further the so-called slow rescaling and introduce a threshold-modified variable ξ, whenever we are above a heavy-quark production threshold. Making these assumptions and using the vectorlike quark model current coupling of equation (2.1), we obtain the following cross sections:

Events of Type (a)-(i). The contributing elementary processes specified with respect to the proton and the neutrino are:

$$\nu + d \to \mu^- + u, \qquad \nu + s \to \mu^- + u$$
$$\nu + \bar{u} \to \mu^- + \bar{d}, \qquad \nu + \bar{u} \to \mu^- + s$$

The differential cross sections are

$$\frac{d\sigma^{\nu N}}{dxdy} = \frac{G^2ME}{\pi} x \{(u(x) + d(x)) \cos^2\theta_c + \alpha[(\bar{u}(x) + d(x))(1-y)^2 + 2s(x)\sin^2\theta_c]\} \quad (3.1)$$

$$\frac{d\sigma^{\bar{\nu} N}}{dxdy} = \frac{G^2ME}{\pi} x[(u(x) + d(x))(1-y)^2 + \alpha\{(\bar{u}(x) + \bar{d}(x))\cos^2\theta_c + 2s(x)\sin^2\theta_c\}] \quad (3.2)$$

where α is a free parameter measuring the percentage contribution of the "sea" quarks to the "valence" quarks, with $(0 \leqslant \alpha < 1)$.

Events of Type (a)-(ii). The differential cross sections are

$$\begin{aligned}\frac{d\sigma^{\nu N}}{dxdy} = {} & \frac{G^2ME}{\pi} x \{(x) + d(x)) \cos^2\theta_c \\ & + \alpha[(\bar{u}(x) + \bar{d}(x))(1-y)^2 + 2s(x)\sin^2\theta_c]\} \\ & + \frac{G^2ME}{\pi} \alpha \cdot 2x(1-y)^2 \bar{c}(x)\cos^2\phi \\ & + \frac{G^2ME}{\pi} \alpha \cdot 2x(1-y)^2 \bar{t}(x)\sin^2\phi \\ & + \frac{G^2ME}{\pi} \alpha \cdot 2x[c(x) + t(x)] \end{aligned} \quad (3.3)$$

$$\begin{aligned}\frac{d\sigma^{\bar{\nu} N}}{dxdy} = {} & \frac{G^2ME}{\pi} x \{(u(x) + d(x))(1-y)^2 \\ & + \alpha[(\bar{u}(x) + \bar{d}(x))\cos^2\theta_c + 2\bar{s}(x)\sin^2\theta_c]\} \\ & + \frac{G^2ME}{\pi} \alpha \cdot 2x(1-y)^2 [c(x)\cos^2\phi + t(x)\sin^2\phi] \\ & + \frac{G^2ME}{\pi} \alpha \cdot 2x[\bar{c}(x) + \bar{t}(x)] \end{aligned} \quad (3.4)$$

where we are using the following notations: $t(x)$, $t(\xi)$, $b(x)$, $b(\xi)$, $c(x)$, $c(\xi)$ for heavy-quark densities, and $u(\xi_Q)$ for u quark density above threshold for producing Q-type heavy quark.

Events of Type (a)-(iii). The contributing elementary processes specified with respect to the neutrino and the proton are as follows.

$(V-A)$ Couplings:

$$\begin{aligned}
&\nu+d \to \mu^- + c\\
&\nu+s \to \mu^- + c\\
&\nu+b \to \mu^- + t\\
&\nu+d \to \mu^- + t\\
&\nu+s \to \mu^- + t\\
&\nu+b \to \mu^- + c
\end{aligned}$$

$(V+A)$ Couplings:

$$\begin{aligned}
&\nu+\bar{u} \to \mu^- + b\\
&\nu+d \to \mu^- + t\\
&\nu+s \to \mu^- + t\\
&\nu+s \to \mu^- + c\\
&\nu+d \to \mu^- + c
\end{aligned} \tag{3.5}$$

Then for the production of heavy hadrons Y, with "new" quantum numbers, we have for the neutrinos

$$\begin{aligned}
\frac{d\sigma^{\nu N}}{dxdy} = \frac{G^2ME}{\pi} \{&\xi_c\,[u(\xi_c) + d(\xi_c)] \sin^2\theta_c \cos^2\phi\, Y_c^+ (1 - B_\nu{}^c)\\
&+ 2s(\xi_c)\xi_c \cdot \alpha \cdot \cos^2\theta_c \cos^2\phi\, Y_c^+(1 - B_\nu{}^c)\\
&+ 2b(\xi_t)\xi_t \cos^2\phi\, Y_t^t(1 - B_\nu{}^+)\alpha\\
&+ \xi_t\,[u(\xi_t) + d(\xi_t)]\ \sin^2\theta_c \sin^2\phi\, Y_t^t(1 - B_\nu{}^t)\\
&+ 2s(\xi_t)_t \cdot \alpha \cdot \cos^2\theta_c \sin^2\phi\, Y_t^t(1 - B_\nu{}^t)\\
&+ 2b(\xi_c)_c \sin^2\phi\, Y_c^+\alpha(1 - B_\nu{}^c)\\
&+ \alpha \cdot \xi_b\,[\bar{u}(\xi_b) + \bar{d}(\xi_b)]\ Y_b^+(1 - B_\nu{}^b)\\
&+ \xi_t\,[u(\xi_t) + d(\xi_t)]\ Y_t^-\cos^2\varphi(1 - B_\nu{}^t)\\
&+ \alpha \cdot 2s(\xi_t)\xi_t Y_t^- \sin^2\varphi(1 - B_\nu{}^t)\\
&+ 2s(\xi_c)\xi_c \cdot \alpha \cdot Y_c^- \cos^2\varphi(1 - B_\nu{}^c)\\
&+ \xi_c\,[u(\xi_c) + \bar{d}(\xi_c)]\ Y_c^- \sin^2\varphi(1 - B_\nu{}^c)\}
\end{aligned} \tag{3.6}$$

where

$$\begin{aligned}
\xi_Q &= x + \frac{m_Q{}^2}{2MEy}\\
Y_Q{}^+ &= 1 - \frac{m_Q{}^2}{2ME\xi_Q}\\
Y_Q{}^- &= (1-y)^2 + (1-y)\frac{m_Q{}^2}{2ME\xi_Q}\\
B_\nu{}^Q &= \frac{\Gamma(Y^Q \to \text{hadrons})}{\Gamma(Y^Q \to \text{all})}
\end{aligned} \tag{3.7}$$

Similarly,

$$\frac{d\sigma^{\bar{\nu}N}}{dxdy} = \frac{G^2ME}{\pi}\{[\alpha\xi_c(\bar{u}(\xi_c) + \bar{d}(\xi_c))\sin^2\theta_c\cos^2\phi Y_c{}^+(1 - B_{\bar{\nu}}{}^c)$$

$$+ 2\xi_c\alpha\bar{s}(\xi_c)Y_c^+\cos^2\theta_c\cos^2\phi]\,(1 - B_{\bar{\nu}}{}^c)$$
$$+ 2\bar{b}(\xi_t)\xi_t\alpha Y_t^+\cos^2\phi(1 - B_{\bar{\nu}}{}^t)$$
$$+ \alpha\xi_t[\bar{u}(\xi_t) + \bar{d}(\xi_t)]\,Y_t^+\sin^2\theta_c\sin^2\phi(1 - B_{\bar{\nu}}{}^t)$$
$$+ \alpha\cdot 2\bar{s}(\xi_t)\xi_t Y_t{}^+\cos^2\theta_c\sin^2\phi(1 - B_{\bar{\nu}}{}^t)$$
$$+ \alpha\cdot 2\bar{b}(\xi_c)\xi_c Y_c^+\sin^2\phi(1 - B_{\bar{\nu}}{}^c)$$
$$+ \xi_b[u(\xi_b) + (\xi_b)]\,Y_b^+(1 - B_{\bar{\nu}}{}^b)$$
$$+ \alpha\xi_t[\bar{u}(\xi_t) + \bar{d}(\xi_t)]\cos^2\psi(1 - B_{\bar{\nu}}{}^t)Y_t^-$$
$$+ \alpha\cdot 2\bar{s}(\xi_t)\xi_t\sin^2\psi Y_t{}^-(1 - B_{\bar{\nu}}{}^t)$$
$$+ \alpha\cdot 2\bar{s}(\xi_c)\xi_c Y_c{}^-\cos^2\psi(1 - B_{\bar{\nu}}{}^c)$$
$$+ \alpha\cdot\xi_c[\bar{u}(\xi_c) + \bar{d}(\xi_c)]\,Y_c{}^-\sin^2\psi(1 - B_{\bar{\nu}}{}^c)\} \qquad (3.8)$$

Events of Type (b). For type (b) events the cross sections are

$$\frac{d\sigma^{\nu N}}{dxdy} = \frac{G^2ME}{\pi}\{\xi_c[u(\xi_c) + d(\xi_c)]\sin^2\theta_c\cos^2\phi Y_c^+B_\nu{}^c)$$

$$+ 2\alpha\xi_c s(\xi_c)\cos^2\theta_c\cos^2\phi Y_c^+B_\nu{}^c$$
$$+ 2\alpha b(\xi_t)\xi_t\cos^2\phi Y_t{}^+B_\nu{}^t$$
$$+ \xi_t[u(\xi_t) + d(\xi_t)]\sin^2\theta_c\sin^2\phi Y_t{}^+B_\nu{}^t$$
$$+ 2\alpha\cdot s(\xi_t)\xi_t\cos^2\theta_c\sin^2\phi Y_t{}^+B_\nu{}^t$$
$$+ 2\alpha b(\xi_c)\xi_c\sin^2\phi Y_c{}^tB_\nu{}^c$$
$$+ \alpha\cdot\xi_b[\bar{u}(\xi_b) + \bar{d}(\xi_b)]\,Y_b{}^+B_\nu{}^b$$
$$+ \xi_t[u(\xi_t) + d(\xi_t)]\,Y_t{}^-\cos^2\psi B_\nu{}^t$$
$$+ \alpha\cdot 2s(\xi_t)\xi_t Y_t{}^-\sin^2\psi B_\nu{}^t$$
$$+ \alpha\cdot 2s(\xi_c)\xi_c Y_c{}^-\cos^2\psi B_\nu{}^c$$
$$+ \xi_c[u(\xi_c) + d(\xi_c)]\,Y_c{}^-\sin^2\psi B_\nu{}^c\} \qquad (3.9)$$

and

$$\frac{d\sigma^{\bar{\nu}N}}{dxdy} = \frac{G^2ME}{\pi}\{\alpha\xi_c[\bar{u}(\xi_c) + \bar{d}(\xi_c)]\sin^2\theta_c\cos^2\phi Y_c^+ B_{\bar{\nu}}^c$$
$$+ 2\alpha\xi_c\bar{s}(\xi_c)Y_c^+\cos^2\theta_c\cos^2\phi Y_c^+ B_{\bar{\nu}}^c$$
$$+ \alpha\cdot 2\bar{b}(\xi_t)\xi_t Y_t^+\cos^2\phi B_{\bar{\nu}}^t$$
$$+ \alpha\cdot\xi_t[\bar{u}(\xi_t) + \bar{d}(\xi_t)] Y_t^+\sin^2\theta_c\sin^2\phi B_{\bar{\nu}}^t$$
$$+ \alpha\cdot 2\bar{s}(\xi_t)\xi_t Y_t^+\cos^2\theta_c\sin^2\phi B_{\bar{\nu}}^t$$
$$+ \alpha\cdot 2\bar{b}(\xi_c)\xi_c Y_c^+\sin^2\phi B_{\bar{\nu}}^c$$
$$+ \xi_b[\bar{u}(\xi_b) + d(\xi_b)] Y_b^+ B_{\bar{\nu}}^b$$
$$+ \alpha\xi_t[\bar{u}(\xi_t) + \bar{d}(\xi_t)] Y_t^-\cos^2\varphi B_{\bar{\nu}}^t$$
$$+ \alpha\cdot 2\bar{s}(\xi_t)\xi_t Y_t^-\sin^2\varphi B_{\bar{\nu}}^t$$
$$+ \alpha\cdot 2\bar{s}(\xi_c)\xi_c Y_c^-\cos^2\varphi B_{\bar{\nu}}^c$$
$$+ \alpha\cdot\xi_c[\bar{u}(\xi_c) + \bar{d}(\xi_c)] Y_c^-\sin^2\varphi B_{\bar{\nu}}^c\} \qquad (3.10)$$

Single-Muon Cross Sections above New Threshold. The above neutrino single-muon cross sections above new threshold (a.n.t.) are given by

$$\left(\frac{d\sigma^{\nu N}}{dxdy}\right)_{\text{a.n.t.}} = \frac{G^2ME}{\pi}x\{(u(x) + d(x))\cos^2\theta_c$$
$$+ \alpha[(u(x) + \bar{d}(x))(1-y)^2 + 2s(x)\sin^2\theta_c]\}$$
$$+ \frac{G^2ME}{\pi}\alpha[2x(1-y)^2\bar{c}(x)\cos^2\phi$$
$$+ 2x(1-y)^2\bar{t}(x)\sin^2\phi + 2x\,c(x) + 2x^t(x)]$$
$$+ \frac{G^2ME}{\pi}\{\xi_c[u(\xi_c) + d(\xi_c)]\sin^2\theta_c\cos^2\phi Y_c^+(1-B_\nu^c)$$
$$+ \alpha\cdot 2\xi_c s(\xi_c)\cos^2\theta_c\cos^2\phi Y_c^+(1-B_\nu^c)$$
$$+ \alpha\cdot 2b(\xi_t)\xi_t\cos^2\phi Y_t^+(1-B_\nu^t)$$
$$+ \xi_t[u(\xi_t) + d(\xi_t)]\sin^2\theta_c\sin^2\phi Y_t^+(1-B_\nu^t)$$
$$+ \alpha\cdot 2s(\xi_t)\xi_t\cos^2\theta_c\sin^2\phi Y_t^+(1-B_\nu^t)$$
$$+ \alpha\cdot 2b(\xi_c)\xi_c\sin^2\phi Y_c^+(1-B_\nu^c)$$
$$+ \alpha\cdot\xi_b[\bar{u}(\xi_b) + \bar{d}(\xi_b)] Y_b^+(1-B_\nu^b)$$
$$+ \alpha\cdot 2s(\xi_c)\xi_c Y_c^-\cos^2\psi(1-B_\nu^c)$$
$$+ \xi_c[u(\xi_c) + d(\xi_c)] Y_c^-\sin^2\psi(1-B_\nu^c)$$
$$+ \xi_t[u(\xi_t) + d(\xi_t)] Y_t^-\cos^2\psi(1-B_\nu^t)$$
$$+ \alpha\cdot 2s(\xi_t)\xi_t Y_t^-\sin^2\psi(1-B_\nu^t)\} \qquad (3.11)$$

and

$$
\begin{aligned}
\left(\frac{d\sigma^{\bar{\nu}N}}{dxdy}\right)_{\text{a.n.t.}} = {} & \frac{G^2ME}{\pi} x\{[u(x)+d(x)](1-y)^2 \\
& + \alpha[\bar{u}(x)+\bar{d}(x)]\cos^2\theta_c \\
& + \alpha \cdot 2\bar{s}(x)\sin^2\theta_c\} \\
& + \frac{G^2ME}{\pi}[\alpha \cdot 2x(1-y)^2 c(x)\cos^2\phi \\
& + \alpha \cdot 2x(1-y)^2 t(x)\sin^2\phi \\
& + \alpha \cdot \bar{c}(x)2x + \alpha \cdot 2x\bar{t}(x)] \\
& + \frac{G^2ME}{\pi}\{[\alpha\xi_c(\bar{u}(\xi_c)+\bar{d}(\xi_c))\sin^2\theta_c\cos^2\phi Y_c^+ \\
& + \alpha \cdot 2\bar{s}(\xi_c)\xi_c Y_c^+\cos^2\theta_c\cos^2\phi](1-B_{\bar{\nu}}{}^c) \\
& + \alpha \cdot 2\bar{b}(\xi_t)\xi_t Y_t^+\cos^2\phi(1-B_{\bar{\nu}}{}^t) \\
& + \alpha \cdot \xi_t(\bar{u}(\xi_t)+\bar{d}(\xi_t))Y_t^+\sin^2\theta_c\sin^2\phi(1-B_{\bar{\nu}}{}^t) \\
& + \alpha \cdot 2\bar{s}(\xi_t)\xi_t Y_t^+\cos^2\theta_c\sin^2\phi(1-B_{\bar{\nu}}{}^t) \\
& + \alpha \cdot 2\bar{b}(\xi_c)\xi_c Y_c^+\sin^2\phi(1-B_{\bar{\nu}}{}^c) \\
& + \xi_b(u(\xi_b)+d(\xi_b))Y_b^+(1-B_{\bar{\nu}}{}^b) \\
& + \alpha \cdot 2\bar{s}(\xi_c)\xi_c Y_c^-\cos^2\psi(1-B_{\bar{\nu}}{}^c) \\
& + \alpha \cdot \xi_c(\bar{u}(\xi_c)+\bar{d}(\xi_c))Y_c^-\sin^2\psi(1-B_{\bar{\nu}}{}^c) \\
& + \alpha \cdot \xi_t(\bar{u}(\xi_t)+\bar{d}(\xi_t))Y_t^-\cos^2\psi(1-B_{\bar{\nu}}{}^t) \\
& + \alpha \cdot 2\bar{s}(\xi_t)\xi_t Y_t^-\sin^2\psi(1-B_{\bar{\nu}}{}^t)\}
\end{aligned} \tag{3.12}
$$

Quark Density Functions. As in Paper I, we shall use the Wilson parametrization (Wilson, 1975) for the quark distribution functions, assuming an isoscalar nucleon target, and an $SU(6)$ symmetric sea, such that $2c(\xi) = 2\bar{c}(\xi) = 2t(\xi) = 2\bar{t}(\xi) = 2b(\xi) = 2\bar{b}(\xi) = 2\bar{u}(\xi) = 2u(\xi)$.

First, we note the following bounds for our integration variables:

$$\xi_i = x + \frac{m_i{}^2}{2MEy}$$

where m_i is the mass of ith heavy quark (c, t, or b). For $\xi_i \leqslant 1$, we obtain

$$0 \leqslant x \leqslant 1 - \frac{m_i{}^2}{2MEy} \leqslant 1 - \frac{m_i{}^2}{2ME}$$

or

$$0 \leqslant x \leqslant 1 - \frac{E_{\text{th}}}{Ey}$$

where $E_{\text{th}} = m_i^2/2M$ is the threshold energy for producing heavy quark i.
Then

$$\frac{E_{\text{th}}}{E} \leqslant y \leqslant 1$$

or

$$\frac{m_i^2}{2M} \leqslant y \leqslant 1$$

so that

$$\frac{m_i^2}{2ME} \leqslant \frac{m_i^2}{2MEy} \leqslant \xi_i \leqslant 1 \tag{3.13}$$

or simply,

$$\frac{m_i^2}{2ME} \leqslant \xi_i \leqslant 1$$

For numerical calculations we shall adopt the following values:

$$\begin{aligned}
&\cos^2\theta_c \simeq 0.95, \qquad \sin^2\theta_c \simeq 0.05\\
&m_c \simeq 1.5 \text{ GeV}, \qquad m_t \simeq 5 \text{ GeV}, \qquad m_b \simeq 5 \text{ GeV}\\
&E_{\nu,\bar{\nu}} \simeq 70 \text{ GeV}, \qquad B_\nu{}^c \simeq 0.13, \qquad B_{\bar{\nu}}{}^c \simeq 0.21\\
&B_\nu{}^t \simeq 0.01, \qquad B_{\bar{\nu}}{}^t \simeq 0.01, \qquad B_\nu{}^b \simeq 0.01, \qquad B_{\bar{\nu}}{}^b \simeq 0.01\\
&Y_c^+ \simeq \left(1 - \frac{0.02}{\xi_c}\right) \text{ at } E_{\nu,\bar{\nu}} \simeq 70 \text{ GeV}, \qquad Y_b^+ \simeq \left(1 - \frac{0.18}{\xi b}\right)\\
&Y_b^+ \simeq \left(1 - \frac{0.18}{\xi b}\right)\\
&Y_t^+ \simeq \left(1 - \frac{0.18}{\xi t}\right)\\
&Y_c^- \simeq \left(0.31 + \frac{0.01}{\xi c}\right)\\
&Y_b^- \simeq \left(0.16 + \frac{0.06}{\xi b}\right)\\
&Y_t^- \simeq \left(0.16 + \frac{0.06}{\xi t}\right)\\
&\frac{m_c^2}{2ME} \simeq 0.02, \qquad \frac{m_b^2}{2ME} = \frac{m_t^2}{2ME} \simeq 0.18\\
&(1 - B_\nu{}^c) \simeq 0.87, \qquad (1 - B_\nu{}^t) \simeq 0.99\\
&(1 - B_{\bar{\nu}}{}^c) \simeq 0.80 \text{ and } (1 - B_{\bar{\nu}}{}^t) = (1 - B_{\bar{\nu}}{}^b) \simeq 0.99
\end{aligned} \tag{3.14}$$

Thus, specializing to the case of the CUNY–Harvard view (Rujula et al., 1975b): $\cos^2\psi = 1$, $\sin^2\psi = 0$, and taking $\cos^2\phi = 1$, $\sin^2\phi = 0$, we obtain the following single-muon cross sections above new thresholds:

$$
\begin{aligned}
\left(\frac{d\sigma^{\nu N}}{dxdy}\right)_{\text{a.n.t.}} = \frac{G^2ME}{\pi} x\{ & [u(x) + d(x)]\cos^2\theta_c \\
& + \alpha[\bar{u}(x) + \bar{d}(x)]\,(1-y)^2 + \alpha\cdot 2s(x)\sin^2\theta_c\} \\
& + \frac{G^2ME}{\pi}\alpha\{2\bar{c}(x)(1-y)^2 + 2c(x)x + 2t(x)x\} \\
& + \frac{G^2ME}{\pi}\{\xi_c[u(\xi_c) + d(\xi_c)]\sin^2\theta_c Y_c^{+}(1 - B_\nu{}^c) \\
& + \alpha\cdot\cos^2\theta_c(1 - B_\nu{}^c)\xi_c 2s(\xi_c)Y_c^{+} \\
& + \alpha\cdot\xi_b[\bar{u}(\xi_b) + \bar{d}(\xi_b)]\,Y_b^{+}(1 - B_\nu{}^b) \\
& + \alpha\cdot 2s(\xi_c)\xi_c Y_c^{-}(1 - B_c{}^\nu) \\
& + \xi_t[u(\xi_t) + d(\xi_t)](1 - B_\nu{}^t)Y_t^{-}\}
\end{aligned} \tag{3.15}
$$

and

$$
\begin{aligned}
\left(\frac{d\sigma^{\bar{\nu} N}}{dxdy}\right)_{\text{a.n.t.}} = \frac{G^2ME}{\pi} x\{ & [u(x) + d(x)](1-y)^2 \\
& + \alpha[\bar{u}(x) + \bar{d}(x)]\cos^2\theta_c \\
& + \alpha\cdot 2\bar{s}(x)\sin^2\theta_c + 2c(x)\alpha(1-y)^2 \\
& + \alpha\cdot 2\bar{c}(x) + \alpha\cdot 2\bar{t}(x)\} \\
& + \frac{G^2ME}{\pi}\{\alpha\cdot\sin^2\theta_c\xi_c[\bar{u}(\xi_c) + \bar{d}(\xi_c)]\,Y_c^{+} \\
& \times(1 - B_{\bar{\nu}}{}^c) \\
& + \alpha\cdot 2\bar{s}(\xi_c)\xi_c Y_c^{+}\cos^2\theta_c(1 - B_{\bar{\nu}}{}^c) \\
& + \alpha\cdot\xi_t[\bar{u}(\xi_t) + \bar{d}(\xi_t)]\,(1 - B_{\bar{\nu}}{}^t)Y_t^{-} \\
& + \alpha\cdot 2\bar{b}(\xi_t)\xi_t Y_t^{+}(1 - B_{\bar{\nu}}{}^t) \\
& + \xi_b[u(\xi_b) + d(\xi_b)]\,Y_b^{+}(1 - B_{\bar{\nu}}{}^b) \\
& + \alpha\cdot 2\bar{s}(\xi_c)\xi_c Y_c^{-}(1 - B_{\bar{\nu}}{}^c)\}
\end{aligned} \tag{3.16}
$$

The y-Distributions. Integrating equations (3.15) and (3.16), one obtains the following y distributions:

$$\frac{d\sigma^{\nu N}}{dy}(\mu^-) \simeq \frac{G^2ME}{\pi}[0.509 + 0.008(1-y)^2] \tag{3.17}$$

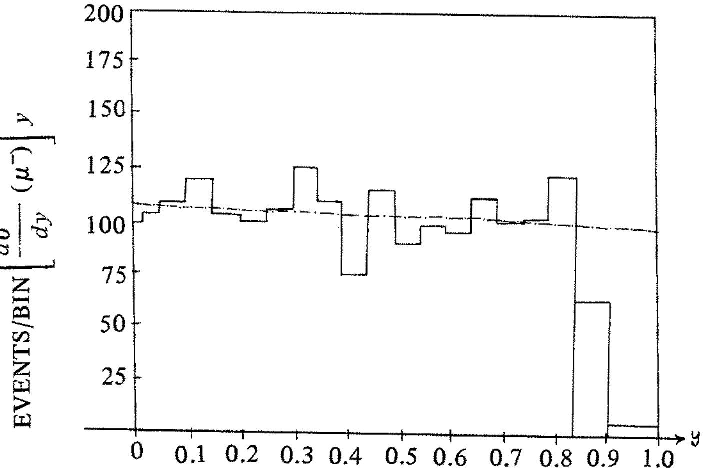

Figure 1. HPWF data on neutrino y distributions at $E_\nu \gtrsim 70$ GeV compared with the vector-model theoretical plot (in arbitrary units) above new threshold (a.n.t.) at $E_\nu \simeq 70$ GeV.

for $E_{\nu,\bar{\nu}} \simeq 70$ GeV and $\alpha = 0.1$, and

$$\frac{d\sigma^{\bar{\nu}N}}{dy}(\mu^+) \simeq \frac{G^2ME}{\pi}\,[0.129 + 0.494(1-y)^2] \tag{3.18}$$

for $E_{\nu,\bar{\nu}} \simeq 70$ GeV and $\alpha = 0.1$.

From equations (3.17) and (3.18) one obtains the total cross section as

$$\sigma^{\nu N}(\mu^-) \simeq \frac{G^2ME}{\pi}(0.51) \tag{3.19}$$

for $E_{\nu,\bar{\nu}} \simeq 70$ GeV and $\alpha = 0.1$, and

$$\sigma^{\bar{\nu}N}(\mu^+) \simeq \frac{G^2ME}{\pi}(0.2751) \tag{3.20}$$

for $E_{\nu,\bar{\nu}} \simeq 70$ GeV, $\alpha = 0.1$.

We can now estimate the ratio of the inclusive charged current antineutrino to neutrino cross sections:

$$\sigma_c^{\bar{\nu}N}(\mu^+)/\sigma_c^{\nu N}(\mu^-) \qquad \text{at } E \sim 70 \text{ GeV and } \alpha = 0.1$$

From equations (3.19) and (3.20) we obtain

$$R_c \equiv \sigma_c^{\bar{\nu}N}(\mu^+)/\sigma_c^{\nu N}(\mu^-) \simeq 0.54 \tag{3.21}$$

This result is in very good agreement with the Gargamelle-Caltech-Fermilab (CITF) data (Barish, 1975; Sciulli, 1976):

$$R_c \sim 0.50 \left\{ {}^{+0.15}_{-0.12} \right.$$

at $E \sim 50$ GeV and the Harvard–Pennsylvania–Wisconsin–Fermilab (HPWF) data: $R_c = 0.6$–0.7 in the energy region $50 \lesssim E \lesssim 100$ GeV.

Plots of $y^{\nu N}_{(\mu^-)}$ and $y^{\bar{\nu} N}_{(\mu^+)}$. Plotting equations (3.17) and (3.18), we get the graphs in Figures 1 and 2, for $E_{\nu,\bar{\nu}} \sim 70$ GeV.

Looking at Figure 2, it appears that the deviation of the experimental histogram of the single-muon antineutrino y distribution at high energies ($E_{\nu,\bar{\nu}} > 30$ GeV) from the vector-model theoretical curve of $d\sigma^{\bar{\nu}N}/dy$ at $E_{\nu,\bar{\nu}} \sim 70$ GeV is amply bridged, indicating the goodness of fit.

4. *Average Value* $\langle y \rangle^{\bar{\nu}N}$

We next calculate $\langle y \rangle^{\bar{\nu}N}$ in the vector model and compare the result with experiment. The HPWF values for $\langle y \rangle^{\bar{\nu}N}$ rise from ~0.28 at low energies to ~0.37 ±0.02 at $E \sim 60$ GeV, and to ~0.40 ± 0.03 for $80 \lesssim E \lesssim 100$ GeV.

In general, we define

$$\langle y \rangle = \frac{1}{\sigma_{\text{tot}}} \int_0^1 y \frac{d\sigma}{dy} dy \tag{4.1}$$

for the case in which the conventional Bjorken scaling applies and no heavy quark is produced. When any of the heavy quarks c, t, or b is being produced, we write

$$\langle y \rangle = \frac{1}{\sigma_{\text{tot}}} \int_{y_0}^1 y \frac{d\sigma}{dy} dy \tag{4.2}$$

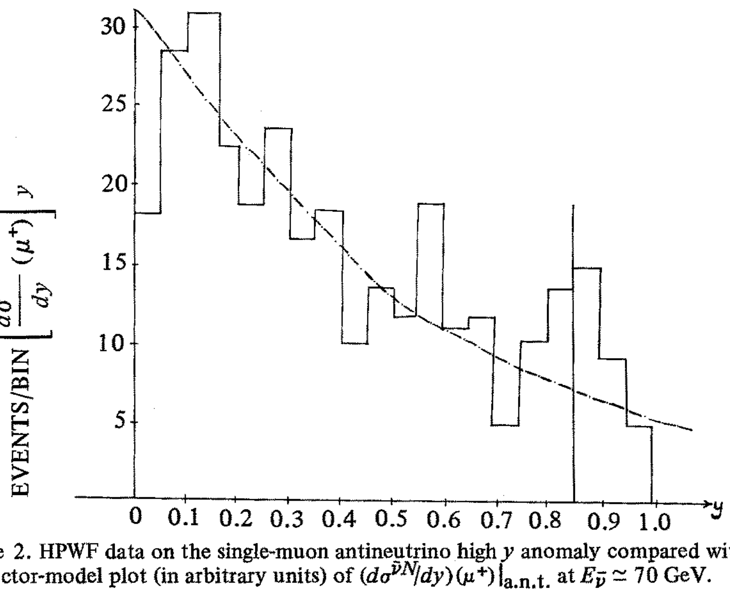

Figure 2. HPWF data on the single-muon antineutrino high y anomaly compared with the vector-model plot (in arbitrary units) of $(d\sigma^{\bar{\nu}N}/dy)(\mu^+)|_{\text{a.n.t.}}$ at $E_{\bar{\nu}} \simeq 70$ GeV.

where $y_0 = 0.02$, in the case of c production, or 0.18 in the production of either t or b, at $E \sim 70$ GeV.

Following equations (4.1) and (4.2), we have

$$\langle y\rangle^{\nu N} = \frac{1}{\sigma_{\text{tot}}^{\nu N}} \int_0^1 y \frac{d\sigma^{\nu N}}{dy} dy \tag{4.3}$$

$$\langle y\rangle^{\nu N} = \frac{1}{\sigma_{\text{tot}}^{\nu N}} \int_{y_0}^1 y \frac{d\sigma^{\nu N}}{dy} dy \tag{4.4}$$

$$\langle y\rangle^{\bar{\nu} N} = \frac{1}{\sigma_{\text{tot}}^{\bar{\nu} N}} \int_0^1 y \frac{d\sigma^{\bar{\nu} N}}{dy} dy \tag{4.5}$$

and

$$\langle y\rangle^{\bar{\nu} N} = \frac{1}{\sigma_{\text{tot}}^{\bar{\nu} N}} \int_{y_0}^1 y \frac{d\sigma^{\bar{\nu} N}}{dy} dy \tag{4.6}$$

Substituting in equation (4.3) from equation (4.5) and (4.6), we obtain

$$\langle y\rangle^{\bar{\nu} N} \simeq 0.37 \tag{4.7}$$

for $E \simeq 70$ GeV, $\alpha = 0.1$.

This value compares very favorably with the HPWF data: $\langle y\rangle^{\bar{\nu} N} \sim 0.37 \pm 0.02$ at $E \sim 60$ GeV. Thus, the vector model adequately accounts for the substantial rise in $\langle y\rangle^{\bar{\nu} N}$, at high energies, over the low-energy value of ~ 0.28.

The variation with energy of $\langle y\rangle^{\bar{\nu} N}$ for $E_{\bar{\nu}} > 30$ GeV is reasonably explained to the accuracy of experimental data, with the vectorlike model.

5. *Dimuon Events*

The unlike-sign dimuon cross sections in the vector model are given by

$$\begin{aligned}
\frac{d\sigma^{\nu N}}{dxdy}(\mu^- \mu^+) = {} & \frac{G^2 ME}{\pi}\{\xi_c[u(\xi_c) + d(\xi_c)]\sin^2\theta_c \cos^2\phi \\
& + 2\xi_c s(\xi_c)\alpha \cos^2\theta_c \cos^2\phi\} Y_c^+ B_\nu^c \\
& + \frac{G^2 ME}{\pi}\{2\alpha b(\xi_t)\xi_t \cos^2\phi\, Y_t^+ B_\nu^t \\
& + \xi_t[u(\xi_t) + d(\xi_t)]\sin^2\theta_c \sin^2\phi Y_t^+ B_\nu^t \\
& + \alpha \cdot 2s(\xi_t)\xi_t \cos^2\theta_c \sin^2\phi\, Y_t^+ B_\nu^t \\
& + \alpha 2b(\xi_c)\xi_c \sin^2\phi Y_c^+ B_\nu^c \\
& + \alpha \cdot \xi_b [\bar{u}(\xi_b) + \bar{d}(\xi_b)] Y_b^+ B_\nu^b \\
& + \alpha \cdot 2s(\xi_c)\xi_c Y_c^- \cos^2\psi B_\nu^c \\
& + \xi_c [u(\xi_c) + d(\xi_c)] Y_c^- \sin^2\psi B_\nu^c
\end{aligned}$$

$$+ \xi_t [u(\xi_t) + d(\xi_t)] Y_t^- \cos^2 \psi B_\nu^t$$
$$+ \alpha 2\bar{s}(\xi_t)\xi_t Y_t^- \sin^2 \psi B_\nu^t\} \tag{5.1}$$

and

$$\frac{d\sigma^{\bar{\nu}N}}{dxdy}(\mu^+\mu^-) = \frac{G^2ME}{\pi}\{\alpha \cdot \xi_c [\bar{u}(\xi_c) + d(\xi_c)] \sin^2\theta_c \cdot \cos^2\phi Y_c^+ B_{\bar{\nu}}^c$$
$$+ \alpha \cdot 2\xi_c \bar{s}(\xi_c) Y_c^+ \cos^2\theta_c \cos^2\phi B_{\bar{\nu}}^c$$
$$+ \alpha \cdot 2\bar{b}(\xi_t)\xi_t Y_t^+ \cos^2\phi B_{\bar{\nu}}^t$$
$$+ \alpha \cdot \xi_t [\bar{u}(\xi_t) + \bar{d}(\xi_t)] Y_t^+ \sin^2\theta_c \sin^2\phi B_{\bar{\nu}}^t$$
$$+ \alpha \cdot 2\bar{s}(\xi_t)\xi_t Y_t^+ \cos^2\theta_c \sin^2\phi B_{\bar{\nu}}^t$$
$$+ \alpha \cdot 2\bar{b}(\xi_c)\xi_c Y_c^+ \sin^2\phi B_{\bar{\nu}}^c$$
$$+ \xi_b [u(\xi_b) + d(\xi_b)] Y_b^+ B_{\bar{\nu}}^b$$
$$+ \alpha \cdot 2\bar{s}(\xi_c)\xi_c Y_c^- \cos^2\psi B_{\bar{\nu}}^c$$
$$+ \alpha \cdot \xi_c [\bar{u}(\xi_c) + \bar{d}(\xi_c)] Y_c^- \sin^2\psi B_{\bar{\nu}}^c$$
$$+ \alpha \cdot \xi_t [\bar{u}(\xi_t) + \bar{d}(\xi_t)] Y_t^- \cos^2\psi B_{\bar{\nu}}^t$$
$$+ \alpha \cdot 2\bar{s}(\xi_t)\xi_t Y_t^- \sin^2\psi B_{\bar{\nu}}^t \tag{5.2}$$

Specializing to the CUNY-Harvard view (Rujula et al., 1975b) $\cos^2\psi = 1$, $\sin^2\psi = 0$, and taking $\cos^2\phi = 1$, $\sin^2\phi = 0$, equations (5.1) and (5.2) reduce to

$$\frac{d\sigma^{\nu N}}{dxdy}(\mu^-\mu^+) = \frac{G^2ME}{\pi}\{\xi_c [u(\xi_c) + d(\xi_c)] \sin^2\theta_c$$
$$+ 2\xi_c s(\xi_c)\alpha \cos^2\theta_c\} Y_c^+ B_\nu^c$$
$$+ \frac{G^2ME}{\pi}\{2\alpha b(\xi_t)\xi_t Y_t^+ B_\nu^t$$
$$+ \alpha \cdot \xi_b [\bar{u}(\xi_b) + \bar{d}(\xi_b)] Y_b^+ B_\nu^b$$
$$+ \alpha \cdot 2s(\xi_c)\xi_c Y_c^- B_\nu^c$$
$$+ \xi_t [u(\xi_t) + d(\xi_t)] Y_t^- B_\nu^t\} \tag{5.3}$$

and

$$\frac{d\sigma^{\bar{\nu}N}}{dxdy}(\mu^+\mu^-) = \frac{G^2ME}{\pi}\{\alpha \cdot \xi_c [\bar{u}(\xi_c) + \bar{d}(\xi_c)] \sin^2\theta Y_c^+ B_{\bar{\nu}}^c$$
$$+ \alpha \cdot 2\xi_c \bar{s}(\xi_c) Y_c^+ \cos^2\theta_c B_{\bar{\nu}}^c$$
$$+ \alpha \cdot 2\bar{b}(\xi_t)\xi_t Y_t^+ B_{\bar{\nu}}^t$$
$$+ \xi_b [u(\xi_b) + d(\xi_b)] Y_b^+ B_{\bar{\nu}}^b$$
$$+ \alpha \cdot 2\bar{s}(\xi_c)\xi_c Y_c^- B_{\bar{\nu}}^c$$
$$+ \alpha \cdot \xi_t [\bar{u}(\xi_t) + d(\xi_t)] Y_t^- B_{\bar{\nu}}^t\} \tag{5.4}$$

Applying Wilson's parametrization for the quark densities as before, and using the estimated values and approximations, one obtains the following dimuon total cross sections:

$$\sigma^{\nu N}(\mu^-\mu^+) \simeq \frac{G^2ME}{\pi}(0.0033638) \tag{5.5}$$

for $\alpha = 0.1$, $E_\nu \sim 70$ GeV., and

$$\sigma^{\bar{\nu}N}(\mu^+\mu^-) \simeq \frac{G^2ME}{\pi}(0.00444882) \tag{5.6}$$

for $\alpha = 0.1$, $E_{\bar{\nu}} \sim 70$ GeV. The dimuon rates then become

$$D_\nu \equiv \frac{\sigma(\nu \to \mu^-\mu^+)}{\sigma(\nu \to \mu^-)} \simeq 10^{-2} \times 0.66 \tag{5.7}$$

for $\alpha = 0.1$, $E \sim 70$ GeV,

$$D_{\bar{\nu}} \equiv \frac{\sigma(\bar{\nu} \to \mu^+\mu^-)}{\sigma(\bar{\nu} \to \mu^+)} \simeq 10^{-2} \times 1.6 \tag{5.8}$$

The result (5.7) is in very good agreement with the data (Benvenuti et al., 1975a–c), while (5.8) is not inconsistent with the data of $(2 \pm 1) \times 10^{-2}$ at $\langle E_{\text{vis}} \rangle \sim 90$ GeV.

Thus, at the level of $\alpha = 0.1$ and for the branching ratio estimates used in the calculations, the strictly vectorlike model has faithfully reproduced the unlike-sign dimuon production rates in the deep inelastic neutrino (antineutrino) processes. The rates are further improved when we go on to higher energies: 100 and 150 GeV as shown below.

Estimates at $E_{\nu,\bar{\nu}}$ 100 GeV. At $E_{\nu,\bar{\nu}} \simeq 100$ GeV, $\alpha = 0.1$ and the heavy quark masses and the branching ratios assumed above, with $B^Q_{\bar{\nu},\nu}$ remaining as before, we have the following results

$$\sigma_c^{\bar{\nu}N}(\mu^+)/\sigma_c^{\nu N}(\mu^-) \simeq 0.8$$

$$\langle y \rangle^{\bar{\nu}N} \simeq 0.46$$

$$D_\nu \equiv \frac{\sigma(\nu \to \mu^-\mu^+)}{\sigma(\nu \to \mu^-)} \simeq 10^{-2} \times 0.76$$

$$D_{\bar{\nu}} \equiv \frac{\sigma(\nu \to \mu^+\mu^-)}{\sigma(\nu \to \mu^+)} \simeq 10^{-2} \times 0.9$$

$$y^{\nu N}(\mu^-) \simeq \frac{G^2ME}{\pi}[0.607 + 0.008(1-y)^2]$$

and

$$y^{\bar{\nu}N}(\mu^+) \simeq \frac{G^2ME}{\pi}[0.38 + 0.494(1-y)^2]$$

Estimates at $E_{\nu,\bar{\nu}} \simeq 150$ GeV. Similarly, at $E_{\nu,\nu} \simeq 150$ GeV and $\alpha = 0.1$, we have

$$\sigma_c^{\bar{\nu}N}(\mu^+)/\sigma_c^{\nu N}(\mu^-) \simeq 0.85$$

$$\langle y \rangle^{\bar{\nu}N} \simeq 0.47$$

$$D_\nu \equiv \frac{\sigma(\nu \to \mu^-\mu^+)}{\sigma(\nu \to \mu^-)} \simeq 10^{-2} \times 0.8$$

$$D_{\bar{\nu}} \equiv \frac{\sigma(\nu \to \mu^+\mu^-)}{\sigma(\nu \to \mu^+)} \simeq 10^{-2} \times 1.86$$

$$y^{\nu N}(\mu^-) \simeq \frac{G^2ME}{\pi} [0.64 + 0.008 (1 - y)^2]$$

and

$$y^{\bar{\nu}N}(\mu^+) \simeq \frac{G^2ME}{\pi} [0.4 + 0.494(1 - y)^2]$$

These trends at higher energies are summarized in Table I.

6. *Conclusions and Discussion*

From all indications, we conclude that the present new physics data on $\sigma_c^{\bar{\nu}N}(\mu^+)/\sigma_c^{\nu N}(\mu^-)$, $\langle y \rangle^{\bar{\nu}N}$, and the single-muon antineutrino y distribution, require the excitation, at high energies, of right-handed valence-strength currents involving light to heavy quark transitions. With an appropriate choice of effective quark masses, physical threshold, and appropriate muonic mean branching ratios of the heavy quarks, the vector model seems able to account adequately for the striking effects observed in present-day high-energy neutrino and antineutrino charged-current inclusive processes, as well as the appearance of dilepton ($\mu^+\mu^-$) events.

Apart from the dimuon events, none of the other striking features of the data could be explained by the standard GIM quark–parton model used previously. In particular, one was not able to reproduce the magnitude of the $d\sigma^{\bar{\nu}N}/dy$ anomaly. That these effects are due to the production of one or more quantum numbers generically called "charm," is consistent with the vector model. It seems also that with the vector model, one reaches the closest overall compromise between theory and the present data.

Other variants of the vector model, such as the Gürsey–Sikivie models B and C, as well as the model fashioned from the strictly vector model by omitting the $\binom{t}{d_\psi}_R$ coupling, appear also consistent with data. This good agreement between vectorlike models and the experimental data is found to persist to higher energies ($70 \leqslant E_{\nu,\bar{\nu}} \lesssim 150$ GeV), subject of course to a judicious choice of the heavy-quark masses, and their muonic branching ratio. Perhaps the only aspect of the vectorlike model that one should worry about is the aspect that relates to the weak neutral current sector, which is, however,

TABLE I

Quantity	Value at higher energy		
	$E = 70$ GeV	$E = 100$ GeV	$E = 150$ GeV
$\sigma_c^{\bar{\nu}N}/\sigma_c^{\nu N}$	0.54	0.80	0.85
$\langle y \rangle^{\bar{\nu}N}$	0.37	0.46	0.47
D_ν	$10^{-2} \times 0.66$	$10^{-2} \times 0.76$	$10^{-2} \times 0.80$
$D_{\bar{\nu}}$	$10^{-2} \times 1.6$	$10^{-2} \times 0.9$	$10^{-2} \times 1.86$
$\frac{d\sigma^{\nu N}}{dy}(\mu^-)$	$\frac{G^2ME}{\pi}[0.51 + 0.008(1-y)^2]$	$\frac{G^2ME}{\pi}[0.607 + 0.008(1-y)^2]$	$\frac{G^2ME}{\pi}[0.64 + 0.008(1-y)^2]$
$\frac{d\sigma^{\bar{\nu}N}}{dy}(\mu^+)$	$\frac{G^2ME}{\pi}[0.129 + P\sigma 494(1-y)^2]$	$\frac{G^2ME}{\pi}[0.380 + 0.494(1-y)^2]$	$\frac{G^2ME}{\pi}[0.40 + 0.494(1-y)^2]$

not discussed in this paper. It is known that vectorlike models predict a purely vector weak neutral hadronic current. Such a prediction is now known to be contrary to recent experimental data on the structure of the weak neutral current. There is therefore some need to modify the vectorlike model, at least insofar as neutral currents are concerned.

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