Scaling deviations in charged-current neutrino reactions

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A set of quark-parton distributions functions incorporating violations of Bjorken scaling which fit ep data and hadroproduction at large transverse momenta are tested in neutrino and antineutrino charged-current reactions. A satisfactory description of the behavior of quantities such as $\sigma^{\bar{\nu}}/\sigma^{\nu}$, $\langle x\rangle^{\bar{\nu}}$, $\langle y\rangle^{\bar{\nu}}$, and $\langle xy\rangle^{\bar{\nu}}$ as a function of energy is obtained.

The scaling breakdown observed in deep-inelastic μN and eN scattering[1] has led to a reinterpretation of the parton model. Different parametrizations of the parton distributions within a hadron have appeared, either phenomenological or theoretically motivated. Some of these distributions[2,3,4] have been used within the Berman-Bjorken-Kogut mechanism[5] to examine if the P_T^{-8} behavior of hadronic collisions at large P_T can be recovered. In Ref. 3 the set of parton distributions has a logarithmic pattern of scale violation; it is in reasonable agreement with μN data and fits the single and double inclusive cross section (correlations) for hadron production at large P_T.

Another ground where we can test the violation of Bjorken scaling is neutrino interactions. Various experiments in neutrino physics have been performed[6,7,8] covering the energy range 20–200 GeV; these suggest departures from Bjorken scaling similar to those observed in muon and electron experiments. In this paper we proceed to a quantitative comparison of these data with the predictions of the scale-violating parton model of Ref. 3. We calculate quantities such as

$$\sigma^{\bar{\nu}}/\sigma^{\nu},\ \ \langle x\rangle^{\bar{\nu}},\ \ \langle y\rangle^{\bar{\nu}},\ \ \langle xy\rangle^{\bar{\nu}},\ \ \int x(q+\bar{q})\,dx\,dy\,;$$

which are most sensitive to scale violations, and we find a satisfactory agreement.

In the standard quark-parton model the inclusive cross sections for ν and $\bar{\nu}$ on an isoscalar target are

$$\begin{aligned}\frac{d\sigma^{\nu N}}{dxdy}&=\frac{G^2ME}{\pi}\,x\,[q(x,Q^2)+\bar{q}(x,Q^2)(1-y)^2]\,,\\ \frac{d\sigma^{\bar{\nu} N}}{dxdy}&=\frac{G^2ME}{\pi}\,x\,[q(x,Q^2)(1-y)^2+\bar{q}(x,Q^2)]\,,\end{aligned}\tag{1}$$

where $Q^2=2MExy$, $q=u+d$, $\bar{q}=\bar{u}+\bar{d}$. We have neglected charm production and assumed $\theta_c=0$. According to asymptotic freedom[9] and scale-invariant parton models,[10] as Q^2 increases an effective redistribution of momentum among valence, sea quarks, and gluons takes place. If we write

$$u=2v_u+t\,,\quad d=v_d+t\,,\quad s=\bar{s}=\bar{u}=\bar{d}=t\,,\tag{2}$$

then as $Q^2\to\infty$, the quark distribution functions decrease at large x and increase at small x, $\langle xv\rangle\to 0$ and $\langle xt\rangle\to$ const. Conservation of quantum number requires also

$$\int_0^1 v_i\,dx=1\,,\quad i=u,d\,.\tag{3}$$

In Ref. 3 the following parametrization for the quark distributions was given:

$$\begin{aligned}v_i(x,Q^2)&=B_{v_i}(Q^2)\left(\frac{Q^2}{Q_0^2}\right)^{-bx}v_i(x,Q_0^2),\quad i=u,d\\ t(x,Q^2)&=B_t(Q^2)\left(\frac{Q^2}{Q_0^2}\right)^{-bx}t(x,Q_0^2)\,.\end{aligned}\tag{4}$$

$v_i(x,Q_0^2)$, $t(x,Q_0^2)$ are the distribution functions at a reference momentum $Q_0^2=1.5$ GeV^2 and we have used the forms of a version of the modified Kuti-Weisskopf model.[11] $B_{v_i}(Q^2)$ is determined from (3); it follows that at large Q^2 $B_{v_i}\sim(\ln Q^2)^{1/2}$ while when $Q^2\to 0$, $B_{v_i}\to 0$. $B_t(Q^2)$ is determined from the following requirements:

(i) Momentum conservation implies that for large Q^2, $B_t(Q^2)\sim c_1 b\ln(Q^2/Q_0^2)$ where $c_1=\frac{5}{56}$ for four flavors and three colors.[9,3]

(ii) At $Q^2=Q_0^2$ we should recover $t(x,Q_0^2)$, i.e., $B_t(Q_0^2)=0.2$.

(iii) As $Q^2\to 0$, $B_t(Q^2)\to 0$.

A form satisfying the above requirements is

$$B_t(Q^2)=(1-e^{-c_3Q^2/Q_0^2})c_1 b\ln\left(\frac{Q^2}{Q_0^2}+c_2\right).\tag{5}$$

We have chosen the minimum value $c_2=6$ and requirement (ii) fixes $c_3=3.19$.

The only unknown parameter is b, which fixes the strength of the scaling violations. In Ref. 3 it was determined to be 1.2 and we use this value in our calculations. It should be pointed out that the moments of the structure functions at large Q^2 behave as

$$M_n(Q^2)=\int_0^1 \nu W_2(x,Q^2)x^n dx\sim(\ln Q^2)^{-n}\,,\tag{6}$$

i.e., quite similar to the moment behavior pre-

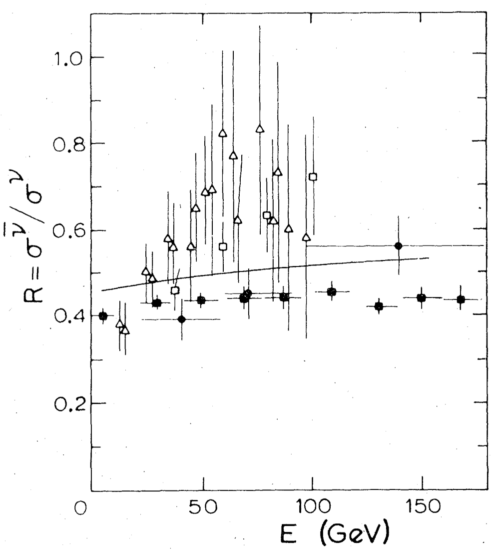

FIG. 1. The antineutrino/neutrino cross-section ratio R versus energy. Theoretical calculation does not take into account charm production. Data are from Ref. 7.

dicted in asymptotically free field theories.[9]

Since $\langle xv\rangle$ ($\langle x\bar{t}\rangle$) decreases (increases) as Q^2 increases, we expect $\sigma_t^{\nu N}/E$ which mostly depends on valence quarks to decrease as a function of energy. On the other hand, for the antineutrino $\sigma_t^{\bar{\nu}N}/E$ it is not clear if the rise of $\langle x\bar{t}\rangle$ will offset the decrease of $\langle xv\rangle$. Our calculations gave the following results:

E (GeV)	50	150	200
$\sigma_t^{\nu N}/E$ (10^{-38} cm^2/GeV)	0.53	0.474	0.462
$\sigma_t^{\bar{\nu}N}/E$ (10^{-38} cm^2/GeV)	0.262	0.251	0.250.

In our scheme, violations of Bjorken scaling make $\sigma_t^{\bar{\nu}N}/E$ fall with E. Any constant value or rising trend has to be attributed to charm production (see below).

Figure 1 presents the ratio $R=\sigma_t^{\bar{\nu}N}/\sigma_t^{\nu N}$. The rise with energy is due to the faster decrease of $\sigma_t^{\nu N}/E$, compared with that of $\sigma_t^{\bar{\nu}N}/E$.

Since all the parton distributions are shifted to smaller x, as Q^2 increases [see Eq. (4)], we expect $\langle x\rangle = \int x(d\sigma/dxdy)dx\,dy/\sigma_t$ to decrease as E is increasing. Figure 2 shows such a trend in antineutrino data[6] and the predictions resulting from our model. The corresponding $\langle y\rangle^{\bar{\nu}}$ is found to have a very gentle rise (due to the rise of $\bar{q}$). $\langle xy\rangle^{\bar{\nu}}$ decreases with E (see Fig. 2) indicating that any calculation based on a linear relationship between $\langle Q^2\rangle$ and E is not justified.

Figure 3 presents B as a function of energy. B determines the relative importance of sea quarks within the nucleon. We estimated B using the relation

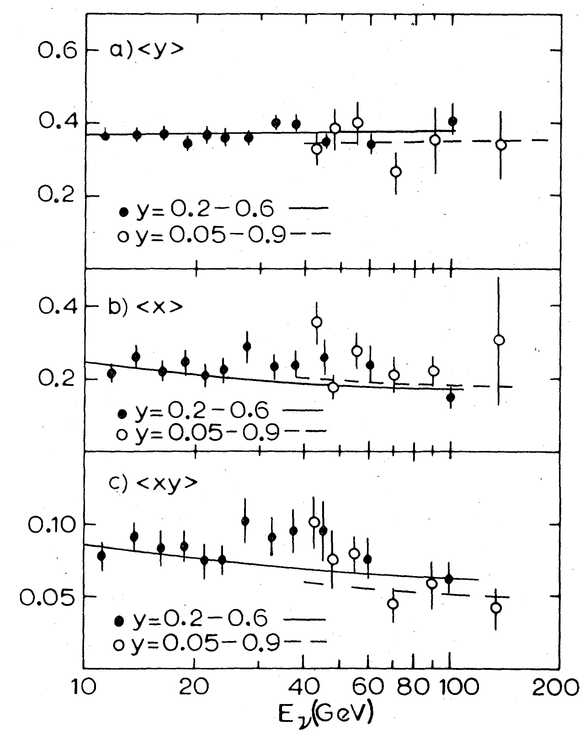

FIG. 2. Average values of y, x, xy as measured in antineutrino reactions versus energy. Data are from Ref. 6.

$$B=\int \frac{q-\bar{q}}{q+\bar{q}}\,dx\,dy\,. \tag{7}$$

Since the experimental B values are extracted from the y distributions, the comparison with our curve is only indicative. The decrease of B reflects the decrease (increase) of the momentum shared by valence (sea) quarks.

For very small values of y we may write

$$\frac{d\sigma}{dxdy} \simeq \frac{G^2ME}{\pi}\,x(q+\bar{q})\,. \tag{8}$$

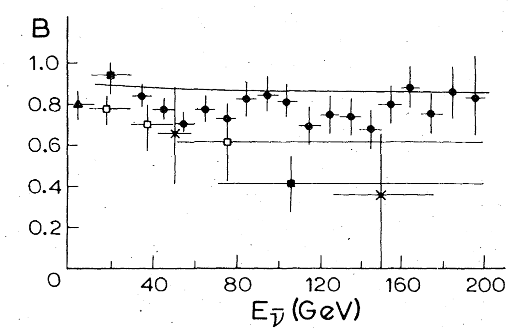

FIG. 3. The B values as a function of antineutrino energy, where the theoretical curve corresponds to Eq. (7) in text. Data are from second paper in Ref. 7.

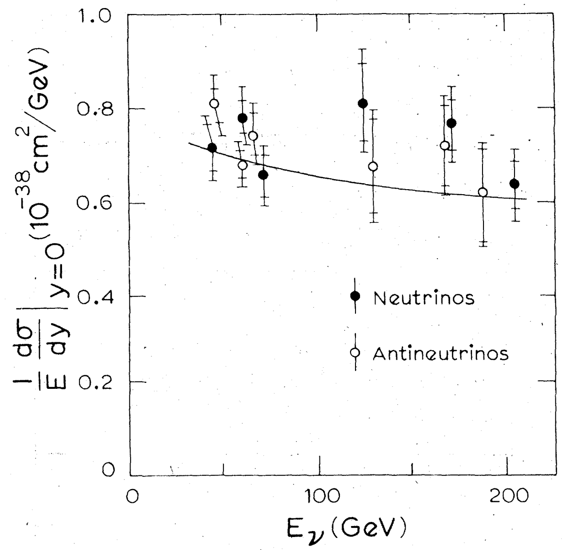

FIG. 4. $\Delta\sigma/E\Delta y$ versus energy. The curve corresponds to neutrino and we have used $\Delta y = 0.1$. For small Δy, $\Delta\sigma/E\Delta y \approx$ (momentum fraction carried by valence and sea quarks) multiplied by 1.53. Data are from Ref. 8.

Then, if

$$\Delta\sigma \equiv \int_0^{\Delta y}\int_0^1 (d\sigma/dxdy)\,dx\,dy$$

where Δy is small, $\Delta\sigma/E\Delta y$ is directly proportional to the momentum carried by valence and sea quarks. Since the momentum fraction carried by gluons increases as Q^2 increases, conservation of momentum implies that the momentum fraction carried by valence and sea quarks decreases and therefore $\Delta\sigma/E\Delta y$ should decrease with energy. Recent data[8] are not inconsistent with such a trend. In Fig. 4 we compare these data with our prediction.

So far, we did not deal with charm production in order to isolate the effects of scaling violations. It is interesting to note that our results are in fair agreement with calculations based on asymptotic freedom.[12] Rough arguments[13] indicate that charm production will raise the total neutrino (antineutrino) cross section by 10% (15%). A calculation, using an SU(3)-symmetric sea, no charm sea quarks, and no energy thresholds gives at $E = 150$ GeV,

$$\sigma_t^{\nu N}/E = 0.55\times10^{-38}\ \mathrm{cm}^2/\mathrm{GeV}\,,$$

$$\sigma_t^{\bar\nu N}/E = 0.34\times10^{-38}\ \mathrm{cm}^2/\mathrm{GeV}\,,$$

$$R = 0.61$$

in agreement with the recent BEBC data.[7] $\sigma_t^{\bar\nu N}/E$ remains almost constant at that value over the entire energy region. Charm production will also produce a decrease in the B values as measured in the antineutrino experiments, since the strange sea quarks are also operative. At $E = 150$ GeV, we find that B falls from 0.86 to 0.83.

Finally, we would like to stress that in describing the neutrino data we did not attempt to find the optimal parameters. It is clear, for example, that a steeper sea term [ours falls like $\sim(1-x)^5$] will improve the ratio R at moderate energies. We have preferred instead to use the same parameters that were deduced and employed in electroproduction and hadroproduction, trying to see if a consistent picture emerges. And it is encouraging that the present parton model can successfully confront the data in such diverse areas as charged-current neutrino reactions, electroproduction, and hadron production at large P_T.

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