Distinguishing scaling violations from new currents*

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Controversy exists over explanation of anomalies in antineutrino scattering. We argue that the alternatives, scaling violations or new currents, can be measured separately. Scaling violation also plays a crucial role in dilepton production, one of the best tests of b-quark production. We conclude with a discussion of the role of scaling violation in neutral-current neutrino scattering.

Since 1973 high-energy charged-current neutrino experiments have exhibited deviations from the scaling observed at low energies.[1] In particular there is an anomalous rise of $\langle y\rangle_{\bar{\nu}}$ and $R_c = \sigma^{\bar{\nu}N}/\sigma^{\nu N}$ with increasing incident neutrino energy. In addition many groups have reported dilepton (and multilepton) events[2] which appear to result from the production and semileptonic decay of new hadrons carrying new quantum numbers.[3] Among these new hadrons are the charmed particles.[4] But to explain the rise of $\langle y\rangle_{\bar{\nu}}$ and R_c, more is needed than just charm production. One possible explanation is the existence of a right-handed current $(u,b)_R$ (Refs. 5 and 6) involving a new heavy quark b with mass 5 GeV $\leq m_b \leq$ 7 GeV.[7-9] Another explanation could be the existence of large scaling violations due to quark-gluon interactions which restrict the freedom of the quark constituents [as in the asymptotically free quantum chromodynamics (QCD) theory].[8,10-12] Other causes of scaling violations have also been considered.[13] Both of these explanations give qualitatively the same kind of rise for $\langle y\rangle_{\bar{\nu}}$ and R_c. In this paper we show that it is possible to measure scaling violation and b-quark production separately.

Our calculations are done in the quark-parton-model formalism, using the scaling variable $\xi = x + m_q^2/2MEy$ ($m_q = m_c$ or m_b).[7-9,14] One effect of including asymptotic-freedom (AF) corrections is that sea-quark contributions increase while valence-quark contributions decrease with increasing Q^2. This effect is incorporated in a *first step* using the factorization approximation of Ref. 12:

$$u(x,Q^2) = u(x)U(Q^2)\,, \tag{1}$$

where $U(Q^2) \equiv \int_0^1 u(x,Q^2)x\,dx$ and similarly for d, $\bar{u}$, $\bar{d}$, s, $\bar{s}$, and gluons.[15] For this first step of AF corrections we use the procedure and parameters[16] of Ref. 12. In particular we choose the effective strong-coupling constant to be $\alpha_s(Q^2 = 1\text{ GeV}^2) = 1.1$ (corresponding to $\Lambda = 0.50$ GeV).

This factorization approximation leads to the right Q^2 dependence of the first moments of the quark distributions but not of the higher moments. So in a *second step* account is taken of the proper dependence of the higher moments. It leads to a shrinkage[17] of the valence-quark x distributions with increasing Q^2.

In deep-inelastic antineutrino scattering both asymptotic-freedom (AF) corrections and charm production are essentially sea effects.[18] On the other hand if the $(u,b)_R$ current exists, b production will be a valence effect. Most of the contribution of sea quarks is presumably concentrated at small x (e.g., at $x < 0.15$). So if we consider the y distribution for $x > 0.15$, AF corrections and charm production cannot give a large departure from $(1-y)^2$. In contrast there will be a large departure from $(1-y)^2$ for $x > 0.15$ if the $(u,b)_R$ current exists.[8] *Therefore a test of the existence of $(u,b)_R$ independent of AF corrections (or similar scaling violations) and of charm production is the measurement of the antineutrino y distribution at relatively large x.* This is illustrated in Fig. 1 which shows $\langle y\rangle_{\bar{\nu}}$ for $x > 0.15$ for both the "standard" model[4,19] and models with a $(u,b)_R$ current.[5,6] AF corrections and charm production give only a

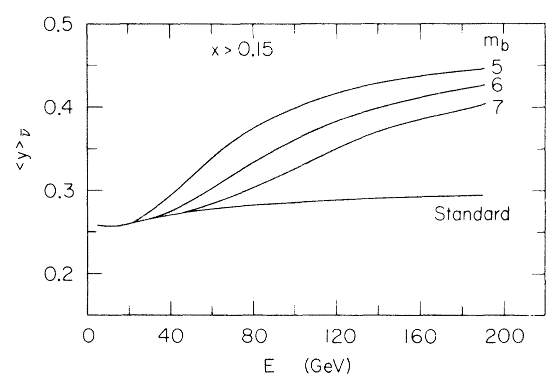

FIG. 1. Average value of y for $x > 0.15$ versus $E_{\bar{\nu}}$. "Standard" denotes the four-quark model (Refs. 4, 19). The curves labeled m_b = 5, 6, and 7 GeV correspond to models (Refs. 5, 6) which also have a $(u,b)_R$ current. In all these curves AF corrections are included and there are no experimental cuts (except $x > 0.15$).

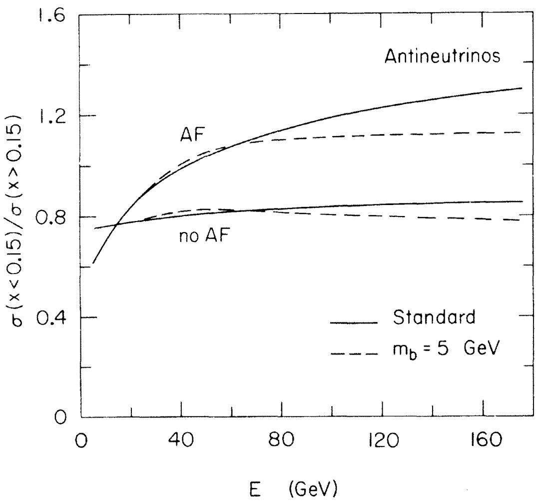

FIG. 2. Ratio R_x of small-x to large-x antineutrino cross sections versus $E_{\bar{\nu}}$. Solid curves correspond to the four-quark model (Refs. 4, 19), whereas dashed curves correspond to models (Refs. 5, 6) which have also a $(u, b)_R$ current with $m_b = 5$ GeV. AF (no AF) are curves with (without) asymptotic-freedom corrections. There are no experimental cuts.

little rise with E, while b production leads to a significant rise. Similarly, one could examine $R_c = \sigma^{\bar{\nu}N}/\sigma^{\nu N}$ at $x > 0.15$. Shrinkage of x distributions has very little effect on these results.

Let us now turn to tests of scaling violations independent of heavy-quark production. The best place to look for these scaling violations is in the x distributions.[8] Noting again that the sea-quark contribution is supposedly concentrated at small x, let us consider the ratio

$$R_x \equiv \frac{\sigma(x<0.15)}{\sigma(x>0.15)} \tag{2}$$

of small x to large x. Figure 2 shows, for antineutrino reactions, the behavior of this ratio versus E. It is shown with and without AF corrections. No AF corrections means neglecting the Q^2 dependence of the various quark distributions [e.g., $u(x,Q^2)$] and using only the x distributions of Ref. 16. In contrast to $\langle y\rangle$ for large x (Fig. 1), Fig. 2 shows that b-quark production gives only a little change of R_x with E while AF corrections lead to a significant rise. In neutrino reactions, which are until now consistent with only charm production, AF corrections give a rise which is smaller than in $\bar{\nu}$ reactions (it is a 22% rise between 15 and 100 GeV). If we include the shrinkage of the valence-quark x distributions (second step of AF corrections) the rise of R_x is even larger than shown in Fig. 2 (about 30% greater between 15 and 100 GeV for the standard model). The light-quark and target-mass effects which have been neglected in Fig. 2 might also modify the results somewhat, especially at very low energies. *In any case, the existence and size of scaling violations can be determined experimentally by measuring the ratio of small x to large x in both ν and $\bar{\nu}$ reactions below $E = 100$ GeV; this is a quantity which is independent of b-quark production.* The rise of R_x would have to be *at least* as large as shown, for scaling violations to be a plausible explanation of the observed $\langle y\rangle_{\bar{\nu}}$ and R_c anomalies.[8,12] Note that experimental cuts and efficiencies can significantly affect R_x and $\langle y\rangle$ and must not be ignored.

Let us now investigate dilepton production

$$\nu + N \to \mu + (\mu \text{ or } e) + X\,.$$

An ideal quantity[20] for consideration of these processes is the following ratio of ratios:

$$R_r \equiv \frac{\sigma(\bar{\nu}\to\mu\mu)}{\sigma(\bar{\nu}\to\mu)} \Big/ \frac{\sigma(\nu\to\mu\mu)}{\sigma(\nu\to\mu)}\,. \tag{3}$$

The semileptonic branching ratio of charm, which is not known, cancels out (assuming that mesons and baryons behave similarly). The relative $\bar{\nu}$ and ν normalizations do not enter. The efficiencies for detection of decay-product muons have been shown[2] to be the same for ν and $\bar{\nu}$ and therefore cancel out. The effects of cuts on primary muons are minimized in R_r, and can be included in theoretical calculations. The semileptonic branching ratio of b is expected[20] to be 80–100% of that of c (100% is assumed here). Other quantities such as the separate dimuon- to single-muon ratios are extremely sensitive to some of the above problems.

In Fig. 3, one sees, by comparing R_r for $m_b = 5$ GeV with and without AF corrections, that scaling violations can have an enormous effect on R_r. Since these corrections increase sea and decrease valence contributions, one finds [for the case with $(u,b)_R$] that $\sigma(\bar{\nu}\to\mu\mu)$ decreases while $\sigma(\nu\to\mu\mu)$ increases. Similarly decreasing valence causes $\sigma(\nu\to\mu)$ and to a lesser extent $\sigma(\bar{\nu}\to\mu)$ to decrease. *Therefore we conclude that while dilepton production is a good test of the current $(u,b)_R$, it is not independent and in fact can be very sensitive to AF corrections.*

Finally let us consider the influence of AF corrections and of b-quark production in the measurement of neutral currents. To the extent that experimentalists measure only the ratios of neutral to charged currents

$$R^{\nu} \equiv \frac{\sigma(\nu N\to\nu X)}{\sigma(\nu N\to\mu X)}\,, \tag{4}$$

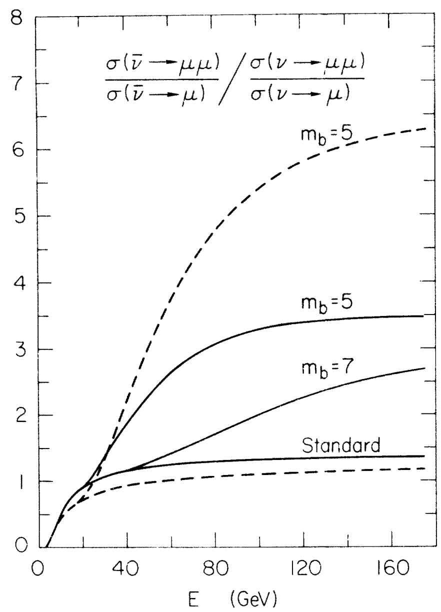

FIG. 3. Dilepton ratio of ratios R_r versus E. Solid (dashed) curves include (exclude) AF corrections. The two lower curves correspond to the four-quark model (Refs. 4, 19) whereas the three upper ones correspond to models (Refs. 5, 6) which have also a $(u, b)_R$ current with $m_b = 5$ or 7 GeV. There are no experimental cuts.

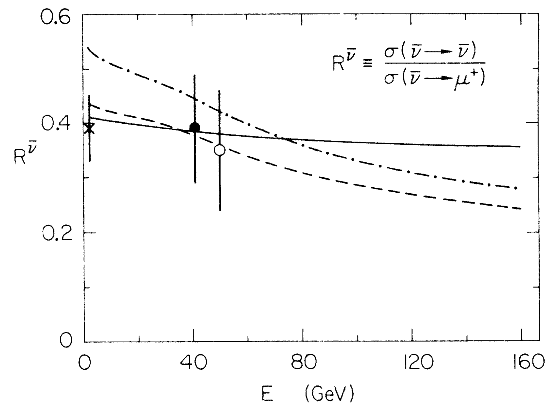

FIG. 4. Ratio $R^{\bar\nu}$ of antineutrino neutral to charged currents versus E. The solid curve corresponds to the four-quark model (Refs. 4, 19) with $\sin^2\theta_W = 0.34$, the dashed curve to models (Ref. 5) including a $(u, b)_R$ current but no $(t, d)_R$ current (with $m_b = 5$ GeV and $\sin^2\theta_W = 0.37$) and the dashed-dotted curve to models (Ref. 6) including both $(u, b)_R$ and $(t, d)_R$ currents (vector model with $m_b = 5$ GeV, $m_t = \infty$ and $\sin^2\theta_W = 0.50$). The theoretical predictions include AF corrections but no experimental cuts. The experimental points are the corrected result from Ref. 21 (cross) and the uncorrected data from Refs. 22 (black circle) and 23 (white circle). The model-dependent corrections lower the high-energy points (Ref. 22) by 20 to 30%.

the AF corrections tend to cancel (giving at most a 10% variation of $R^{\nu,\bar\nu}$). By including all energy-dependent effects (AF corrections, experimental cuts, new currents, etc.) in theoretical calculations of the numerators and denominators of R^ν and $R^{\bar\nu}$, and considering data of three experiments[21-23] which occur at different energies, we have determined the best $\sin^2\theta_W$ for various quark models.[24]

With this determination of $\sin^2\theta_W$ we can address the "problem" that rising $\sigma(\bar\nu N\to\mu X)/E$ and "constant" $R^{\bar\nu}$ (comparing the three experiments) implies $\sigma(\bar\nu N\to\bar\nu X)/E$ must be rising (suggesting, perhaps, charm-changing neutral currents). *In fact there is no problem*[25] (see Fig. 4): (a) Any rise in $\sigma(\bar\nu N\to\mu X)/E$ due to AF corrections is approximately matched in $\sigma(\bar\nu N\to\bar\nu X)/E$. (b) Accounting for experimental cuts would lower both high-energy points by 20–30% (from values shown) so $R_{\bar\nu}$ is not really constant. (c) The error bars are large.

We have seen that the separation between scaling violations and new currents is possible and experimentalists could use these tests to investigate the existence and size of each of these two effects.

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