PHYSICAL REVIEW D VOLUME 14, NUMBER 5 1 SEPTEMBER 1976

Problem with parton-model descriptions of neutrino data?*

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(Received 3 May 1976)

The present results from νN and $\bar{\nu} N$ scattering experiments appear to place conflicting requirements on conventional quark-parton models. The strong rise with energy of $\langle y \rangle^{\bar{\nu} N}$ and $\sigma_T^{\bar{\nu} N}/\sigma_T^{\nu N}$ seems to require new-particle (charm) production from valence quarks in $\bar{\nu} N$ interactions, whereas the x dependence of dimuon events and the $d\sigma/dy$ anomaly suggest that $\bar{\nu} N$ charm production comes from sea quarks. No single model gives a fully satisfactory explanation of all the present data. We draw attention to this problem, illustrate the conflicting requirements of data with particular models, and discuss possible resolutions. The closest overall compromise with the present data is obtained with the six-quark model, using charm-quark masses $m_c = 1.5$ GeV, $m_b = 5$ GeV, and a higher t-quark mass.

I. INTRODUCTION

High-energy $\nu N \to \mu^- X$ and $\bar{\nu} N \to \mu^+ X$ charged-current measurements have revealed a number of striking effects that include a change in the $\bar{\nu} N$ y dependence at small x,[1-3] a rise[2,3] in the average value $\langle y \rangle^{\bar{\nu} N}$, the appearance of dilepton $\mu\mu$ and μe events,[4-7] and a rise[8] in the ratio $\sigma_T^{\bar{\nu} N}/\sigma_T^{\nu N}$. These effects are generally attributed to the production of one or more new quantum numbers (generically called "charm"), and can each separately be fitted by various charm-production mechanisms in the quark-parton framework.[9-13] However, different features of these data appear to place conflicting requirements on the charm-production mechanisms, in the conventional quark-parton-model (QPM) framework, so that no single model gives a fully satisfactory explanation of all the present data. In the present paper we draw attention to this problem; we discuss the various data and illustrate their conflicting requirements with particular models; finally we discuss how the problem may be resolved.

The problem is this: Two effects (the $d\sigma/dy$ anomaly and dileptons) are sensitive to x; both suggest that $\bar{\nu} N$ charm production occurs at small x, and is hence a sea-dominated process. The other two effects above (the rises in $\langle y \rangle^{\bar{\nu} N}$ and $\sigma_T^{\bar{\nu} N}/\sigma_T^{\nu N}$) are averaged over x; however, their magnitudes are simply too large to be explained by the sea in conventional parton models. This inconsistency hinges on the smallness of the sea components, as measured in low-energy neutrino experiments. It does not depend on technical details, such as fast or slow rescaling, or the precise choice of charm thresholds.

II. MODELS

In the quark-parton model (QPM), cross sections for an average nucleon target can be simply expressed in terms of valence and sea distributions:

$$N_{\text{val}}(x) = \mathcal{P}(x) + \mathcal{N}(x) - \bar{\mathcal{P}}(x) - \bar{\mathcal{N}}(x), \tag{1}$$

$$N_{\text{sea}}(x) = \bar{\mathcal{P}}(x) + \mathcal{N}(x) = 2\lambda(x) = 2\bar{\lambda}(x). \tag{2}$$

Here $\mathcal{P}(x)$, $\mathcal{N}(x)$, $\lambda(x)$, etc. are the probability distributions of $\mathcal{P}$-, $\mathcal{N}$-, and λ-type quarks in the proton; $x = Q^2/(2M\nu)$, $y = \nu/E$ in standard notation. An SU(3)-symmetric sea has been assumed for simplicity; this is not crucial for our subsequent discussion. Possible charm-anticharm sea components can be introduced, e.g. by defining

$$N'_{\text{sea}}(x) = 2c(x) = 2\bar{c}(x) \tag{3}$$

for charmed c-type quarks; such components are usually supposed to be small.

The conventional uncharmed charged-current cross sections $\sigma(x,y) = d^2\sigma/dxdy$ therefore have the forms

$$\sigma^{\nu N}(x,y)/x = [1 + (1-y)^2] N_{\text{sea}}(x) + \cos^2\theta_C N_{\text{val}}(x), \tag{4}$$

$$\sigma^{\bar{\nu} N}(x,y)/x = [1 + (1-y)^2] N_{\text{sea}}(x) + N_{\text{val}}(x)(1-y)^2 \tag{5}$$

in units G^2ME/π, where θ_C is the Cabibbo angle ($\cos^2\theta_C \simeq 0.95$).

Charm production can occur when the hadronic recoil energy W exceeds charm threshold: $W^2 = 2MEy(1-x) + M^2 > W_{\text{th}}^2$. Some way above threshold the charm cross section is expected to obey

Bjorken scaling and to agree with QPM calculations. Two approaches to this rescaling have been used in the literature.

(i) Fast rescaling.[9–11] Scaling is imposed immediately above threshold, using QPM formulas with the x, y scaling variables. However, an *effective threshold* value is chosen for W_{th}, considerably higher than the lowest charmed invariant mass, to allow for expected suppression effects near the true charm threshold.

(ii) Slow rescaling.[12–15] A slow turning-on of charm production can be achieved by using QPM formulas with modified scaling variables such as[12–15]

$$x' = x + m_c^2/(2MEy), \tag{6}$$

where m_c is the produced charm-quark mass: Asymptotically $x' \to x$. In this case the true charm threshold is used for W_{th}.

We have found by many explicit calculations that these two approaches are practically indistinguishable when computing spectrum-averaged quantities (averaged over incident neutrino energies) for appropriately chosen thresholds W_{th}. This is illustrated in Fig. 1 for x and y distributions of the fast muon in dimuon production, calculated in a six-quark model. In the rest of this paper we shall use slow rescaling, with Eq. (6).

We shall illustrate the problem facing parton-model descriptions of neutrino data by reference to the following four specific examples.

Model A: four quarks (GIM charm, $m_c = 1.5$). In the four-quark model of Glashow *et al.*[16] (GIM) there is one charmed quark c. The c-excitation cross sections using the slow-rescaling variable x' are[13]

$$\sigma_c^{\nu N}/x'' = N_{sea}(x') + \sin^2\theta_C N_{val}(x'), \tag{7}$$

$$\sigma_c^{\bar{\nu} N}/x'' = N_{sea}(x'), \tag{8}$$

where $x'' = x' - m_c^2/(2ME)$. A factor $\theta(W - W_c)$ is understood to multiply each cross section. We take $m_c = 1.5$ GeV and threshold $W_c = m_c + M = 2.4$ GeV.

Model B: six quarks ($m_c = 1.5$, $m_t = 3$, $m_b = 5$). In the six-quark model of Fritzsch *et al.* (FGM) and Wilczek *et al.*[17,18] (WZKT), there are three charmed quarks c, t, b with excitation cross sections

$$\sigma_c^{\nu N}/x'' = [1 + (1-y)^2 r]\, N_{sea}(x') + \sin^2\theta_C N_{val}(x'), \tag{9}$$

$$\sigma_c^{\bar{\nu} N}/x'' = [1 + (1-y)^2 r]\, N_{sea}(x'), \tag{10}$$

$$\sigma_t^{\nu N}/x'' = (1-y)^2 r[N_{sea}(x') + N_{val}(x')], \tag{11}$$

$$\sigma_t^{\bar{\nu} N}/x'' = (1-y)^2 r N_{sea}(x'), \tag{12}$$

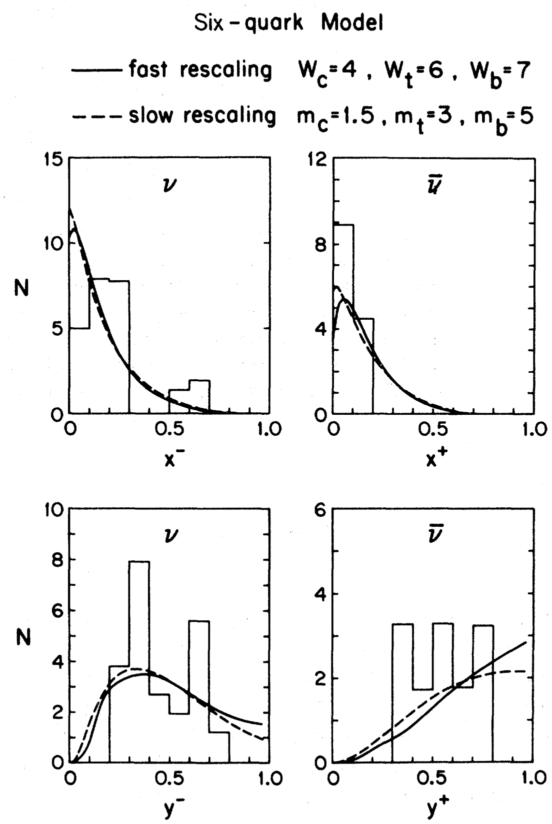

FIG. 1. Fast-muon x and y distributions from dimuon production. The curves illustrate that fast- and slow-rescaling calculations of spectrum-averaged quantities are practically indistinguishable for appropriately chosen thresholds. Data are from Ref. 4.

$$\sigma_b^{\nu N}/x'' = N_{sea}(x'), \tag{13}$$

$$\sigma_b^{\bar{\nu} N}/x'' = N_{sea}(x') + N_{val}(x'), \tag{14}$$

where

$$r = [x' + m_c^2/(2ME(1-y))]/[x' - m_c^2/(2ME)].$$

In each case the quantities x', x'', and r are defined with the appropriate charmed-quark mass. We take $m_c = 1.5$, $m_t = 3$, $m_b = 5$ GeV with corresponding thresholds $W_i = m_i + M$ ($i = c, t, b$). This is essentially the model used by Barnett.[13]

Model C: six quarks ($m_c = 1.5, m_t = 10$, $m_b = 5$). To illustrate the effects of suppressing the t-quark contribution, we take a high t-quark threshold, $m_t = 10$ GeV.

Model D: six quarks ($m_c = 1.5$, $m_t = 5$, $m_b = 4$). To illustrate the effects of enhanced b excitation we take $m_b = 4$ GeV and include a modest t contribution by the choice $m_t = 5$ GeV.

To compare these models with experiment, we calculate cross sections averaged over the appropriate incident spectra, with due regard to W

thresholds. For the valence and sea quark distributions we take solution 3 of Ref. 19, which was determined from fitting νN and $\bar{\nu} N$ x distributions below 30 GeV.

III. EXPERIMENTAL EFFECTS

A. y dependence

At low energies $E=1-11$ GeV the y dependences of νN and $\bar{\nu} N$ cross sections[20] are approximately isotropic and $(1-y)^2$, respectively, consistent with dominant valence and small-sea components in Eqs. (4) and (5). At energies above 30 GeV a substantial isotropic term appears[1-3] in $d\sigma/dy(\bar{\nu}N)$ at small x, as seen in Fig. 2; it shows up clearly at large y. This "$\bar{\nu}N$ high-y anomaly" is commonly attributed to charm production. The fact that it is much stronger at small x suggests that $\bar{\nu}N$ charm production comes largely from the sea; the large-x data place some upper bound[10] on valence contributions isotropic in y. Less can be said about νN charm production, since the shape of $d\sigma/dy$ is not as sensitive to charm contributions. Most of the data are from the Harvard-Pennsylvania-Wisconsin-Fermilab (HPWF) experiments,[1-3] but there is a low-statistics supporting evidence from Caltech-Fermilab[5] and Fermilab-Michigan[21] results.

For quark-parton models, the high-y anomaly requires substantial $\bar{\nu}N$ charm production with flat y dependence, but not too much at large x associated with the valence term of b-type quarks. In model A the charm production is at small x as required, though the net effect is too small compared to the latest data; see Fig. 2. Models B and C are indistinguishable for $\bar{\nu}N$ (t excitation in $\bar{\nu}N$ is small); they fit the $x<0.15$ data well, with the help of substantial $\mathcal{P}\to b$ excitation, but this implies a substantial $x>0.15$ effect also, going somewhat above the large-y data. Model D has a lower b threshold, more b production, and worse disagreement.

Figure 3 shows νN and $\bar{\nu}N$ model predictions for small and large x combined ($0\leq x\leq 0.6$). Valence $\mathfrak{N}\to t$ excitation gives a $(1-y)^2$ contribution to νN for which there is no experimental evidence. Model B with a low t threshold is clearly unsatisfactory in this respect.

B. Average value $\langle y\rangle^{\bar{\nu}N}$

The HPWF group reports[2,3] that the average value $\langle y\rangle^{\bar{\nu}N}$ of observed charged-current events rises sharply above 50 GeV. Part of this effect is instrumental, as explained in Refs. 2 and 3, but a strong $\bar{\nu}N$ effect remains, suggesting a threshold effect such as charm production. See Fig. 4.

QPM charm production from the usual small sea components proves quite inadequate to produce the reported effect; model A is typical of this class of model. The only way to achieve the dramatic effect required is to have charm production from *valence* quarks with *isotropic* y dependence.[10]

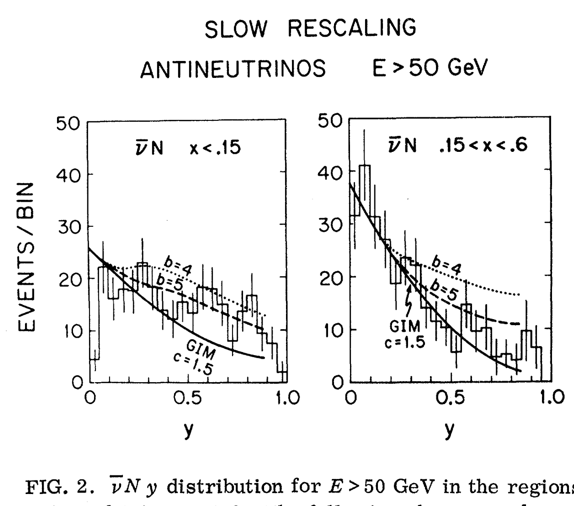

FIG. 2. $\bar{\nu}N$ y distribution for $E>50$ GeV in the regions $x<0.15$ and $0.15<x<0.6$. The following charm-production models are illustrated: A ($m_c=1.5$ GeV) solid curve, B or C ($m_c=1.5$, $m_b=5$ GeV) dashed curve, D ($m_c=1.5$, $m_b=4$ GeV) dotted curve. Data are from Ref. 3. The normalization between small-x and large-x regions is experimentally fixed. No experimental constraint on the overall $\bar{\nu}N$ cross-section normalization is used here.

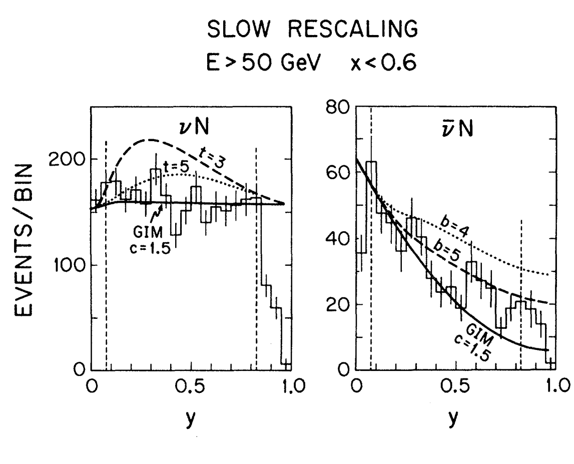

FIG. 3. νN and $\bar{\nu}N$ y distributions for $E>50$ GeV and $x<0.6$. The charm-production models illustrated are A ($m_c=1.5$ GeV) solid curve, B ($m_c=1.5$, $m_b=5$, $m_t=3$ GeV) dashed curve, D ($m_c=1.5$, m_b 4, $m_t=5$ GeV) dotted curve. The predictions of model C are essentially the same as model A for νN and model B for $\bar{\nu}N$. Data are from Ref. 3. Dashed vertical lines indicate regions of poor experimental detection efficiency at small and large y. The normalization of the $\bar{\nu}N$ curves relative to the data is the same as in Fig. 2.

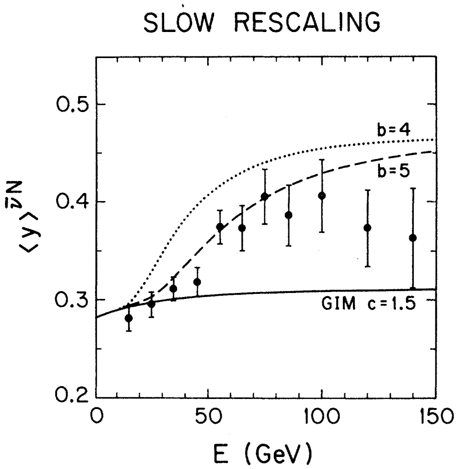

FIG. 4. Average y versus energy for single-μ^+ production by $\bar{\nu}N$. The charm-production models illustrated are A ($m_c = 1.5$ GeV) solid curve, B or C ($m_c = 1.5$, $m_b = 5$ GeV) dashed curve, D ($m_c = 1.5$, $m_b = 4$ GeV) dotted curve. Data are from Ref. 3. Cuts are based on the mean experimental angular acceptance result in a 5% reduction in these curves at high energies.

Models B, C, and D are typical of this approach; both give large threshold effects associated with b production.

Introducing charmed sea components (hitherto neglected) is not a viable alternative explanation. In model A the $c\bar{c}$ sea would add the term $N'_{\text{sea}}(1-y)^2 r$ on the right-hand side of Eqs. (7) and (8); this would actually depress $\langle y \rangle^{\bar{\nu}N}$ a little, except just above threshold. In models B and D, if we suppressed b excitation by taking a higher b threshold, the $\bar{c}c$ and $\bar{t}t$ sea would give an additional $N'_{\text{sea}}[1+(1-y)^2 r]$ term in Eqs. (9) and (10) and a N'_{sea} term in Eqs. (11) and (12). This could double to triple the sea effect (compared to model A) if we assumed $N'_{\text{sea}} = N_{\text{sea}}$, but would be still too small to agree well with the data. Furthermore, the magnitude of the sea would then be difficult to reconcile with $\mu N \to \mu X$ measurements[22] at small x.

Here we see a dilemma developing for quark-parton-model descriptions of the data. If the $\bar{\nu}N$ high-y anomaly is indeed a small-x effect, it calls for charm production from the sea. But the sea effects in current models are too small to explain the $\langle y \rangle^{\bar{\nu}N}$ rise. The further effects below sharpen this dilemma.

C. Dilepton events

The generally accepted interpretation of dilepton $\mu^-\mu^+$ and μ^-e^+ events in electronic[4,5] and bubble-chamber[6,7] experiments is that the second (slow) lepton comes from the decay of a new charmed particle. The x and y distributions of the fast muon, associated with the incident neutrino vertex, are then sensitive indicators of the charm-production mechanism and can be compared directly with QPM calculations.

In practice the observables are x_{vis} and y_{vis}, but these reduce to x and y if we neglect the final decay neutrino energy (which is not unreasonable since its energy distribution should be similar to the slow decay charged lepton). The HPWF results[4] for y_{vis} distributions are inconclusive because of systematic biases; small-y events are suppressed by W thresholds; large-y events have poor experimental acceptance. However, the x_{vis} distributions[4] are relatively unbiased, for νN they give $\langle x_{\text{vis}} \rangle = 0.23 \pm 0.04$, indicating substantial valence contributions, but for $\bar{\nu}N$ they give $\langle x_{\text{vis}} \rangle = 0.06 \pm 0.02$ suggesting a sea-dominated process, within the limited statistics available. The corresponding spectrum-averaged values for the models are

Model	$\langle x \rangle_{\mu\mu}^{\bar{\nu}N}$	$\langle x \rangle_{\mu\mu}^{\nu N}$
A	0.10	0.18
B	0.16	0.17
C	0.16	0.16
D	0.18	0.16

Models B, C, and D with b-quark production give $\langle x \rangle_{\mu\mu}^{\bar{\nu}N} \simeq \langle x \rangle_{\mu\mu}^{\nu N}$, whereas the data give $\langle x \rangle_{\mu\mu}^{\bar{\nu}N} \simeq 0.3 \times \langle x \rangle_{\mu\mu}^{\nu N}$.

Figure 5 shows dimuon x_{vis} and v distributions[4] compared with models A and B ($v = xy$ has the advantage of being directly measured; the v dependence strongly reflects the x dependence). For $\bar{\nu}N$ model A is typical of sea-dominated models and fits well; for νN the fit is reasonable and can be improved by enhancing the νN valence contribution[9] (but this is not relevant to our present discussion). Models B, C, and D have substantial $\bar{\nu}N$ valence terms and give poor agreement with the $\bar{\nu}N$ x and v dependences.

D. Total-cross-section ratio

The HPWF group recently reported a dramatic rise in the $\bar{\nu}N/\nu N$ total-charged-current-cross-section ratio, reaching about 0.6 at 80 GeV, compared to a ratio 0.38 ± 0.02 for the 1–11-GeV range.[20] See Fig. 6.

If we write S and V for the integrated sea and valence contributions, the conventional uncharmed cross sections are

$$\sigma_T^{\bar{\nu}N} = \tfrac{4}{3} S + \tfrac{1}{3} V \,, \qquad (15)$$

$$\sigma_T^{\nu N} = \tfrac{4}{3} S + V \cos^2\theta_C, \qquad (16)$$

and the low-energy σ_T data indicate $S/V \lesssim 0.6$.

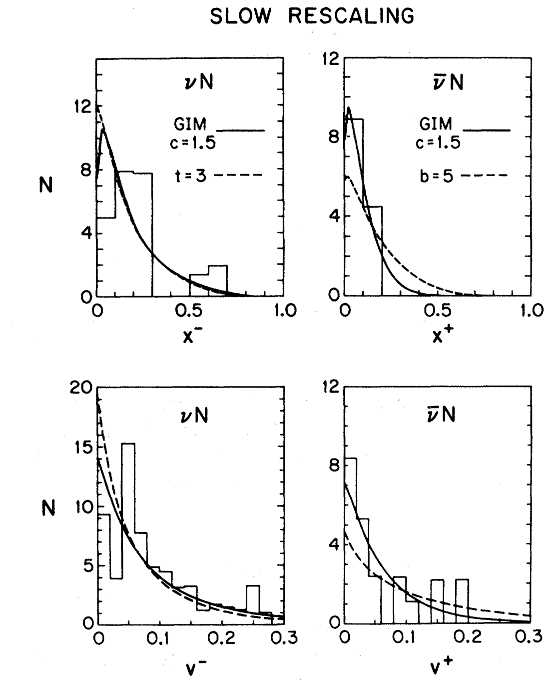

FIG. 5. Fast-muon x and v $(=xy)$ distributions in dimuon production. The predictions of model A (solid curve) and model B (dashed curve) are illustrated. Model C give the same result as model B. Data are from Ref. 4.

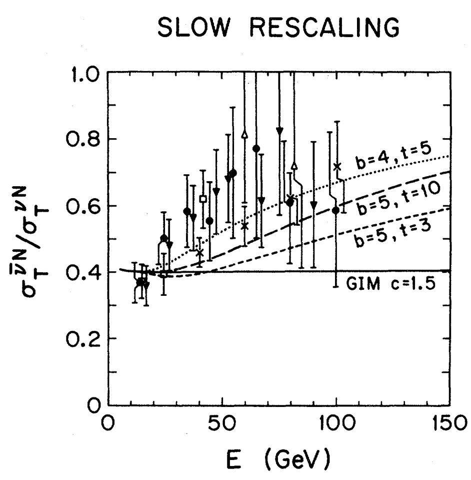

FIG. 6. Ratio of total cross sections $\sigma_T^{\bar{\nu}N}/\sigma_T^{\nu N}$ for single-muon production as a function of energy. The curves illustrate model A (solid), model B (short dashes), model C (long dashes), and model D (dotted). Data are from Ref. 8. The sets of data points represent different experimental analyses: × (flux-dependent normalization); □ (quasielastic normalization); Δ, ●, ▼ (normalization to events in low-W^2 intervals).

Note that sea contributions to $\bar{\nu}N$ and νN are always equal, including charm production too. Hence to achieve a high-energy ratio 0.6 with sea charm production along would require $S/V \simeq 0.44$, an order-of-magnitude enhancement of the sea not foreseen in any present parton model. If we admit valence charm production for νN but not $\bar{\nu}N$, as indicated by dimuon data, the required sea enhancement is much larger still.

In terms of quark-parton models, this σ_T ratio increase demands substantial $\bar{\nu}N$ valence charm production, preferably with isotropic y dependence, supporting the evidence from $\langle y\rangle^{\bar{\nu}N}$ and sharpening the dilemma for parton models. Figure 6 shows a comparison of data with models. Model D with strong $\bar{\nu}N$ valence b production fits the data quite well. Model C with a higher b threshold is less satisfactory. Model B shows the effects of substantial t excitation; the ratio is pulled down even further. Model A with no valence b excitation fails completely.

IV. DISCUSSION

Within the QPM framework, some of the new high-energy phenomena apparently call for $\bar{\nu}N$ charm production to come from sea quarks, but others require it to come from valence quarks. That is the dilemma facing parton models.

This difficulty has been present for some time, but not in an acute form. Uncertainty has attached to the $\langle y\rangle^{\bar{\nu}N}$ data because of questions about the y dependence at small x, small y (the "low-y anomaly", a source of controversy[1,5,23] that has still not been publicly resolved). However, the HPWF group have recently repeated[2,3] their claim about $\langle y\rangle^{\bar{\nu}N}$, with increased statistics, and the completely new results on the $\bar{\nu}N/\nu N$ σ_T ratio[8] have appeared. A problem for quark-parton-model interpretations of the data now clearly exists and must be recognized.

In seeking a resolution of this problem, we may question the quark-parton models, the assumptions made in interpreting data, or the data themselves.

(i) Models. Crucial properties of the parton models are the smallness and energy independence of the sea. Could the sea components have been grossly underestimated in the low-energy parton-model fitting? The low-energy total cross-section ratio[20] is $\bar{\nu}N/\nu N = 0.38 \pm 0.02$ (our parameterization gives 0.40); this severely bounds the integrated sea contribution, which is all that matters for the high-energy ratio. There is no way out here. Should there really be some energy dependence? Altarelli *et al.*[24] have argued on the basis of asymptotically free field theory that there

should be an enhancement of the sea and a suppression of valence effects as Q^2 increases; this might provide an explanation—but would imply abandoning the conventional parton model.

Within the conventional model, the only way to get large sea enhancements is to increase greatly either the basic coupling constant or the number of degrees of freedom.

(ii) Interpretations. It has been tacitly assumed that the same charmed quarks cause all the effects. When several different charmed quarks are excited, this need not be so.

For example, the dimuon part of the puzzle can be sidestepped, if we postulate that b-type quarks (valence-produced in $\bar{\nu}N$) have relatively small decay branching ratio to leptons. Then b production can occur copiously without affecting the dimuon distributions.

However, the $d\sigma/dy$ effect remains: It refers to the same charged-current cross section that generates $\langle y\rangle$ and σ_T. These three observables are simply different projections of the same set of events, so they cannot be completely decoupled.

(iii) Data. The dimuon data have the flimsiest statistics, and might be set aside on these grounds. The other data have better statistics but are not immune to suspicion of systematic error. For example, the y distributions have been controversial, and the high-energy total cross sections depend in part upon a theoretical normalization prescription.

It is profitless to try to guess if some measurement might be wrong. We simply stress that it will be very important to check these results with really good statistics that will enable a separation of x and y dependences to be made simultaneously. In the meantime, while we remain restricted to distributions in a single variable, it may also be instructive to examine W distributions and average Q^2 for single-muon events. Model predictions for $d\sigma/dW$ averaged over the HPWF spectra for $50 \leq E \leq 100$ GeV are shown in Fig. 7. The b quark produces a hump on the high-energy tail of the $\bar{\nu}N$ W distribution. The t quark causes an enhancement near the maximum of $d\sigma/dW$ for νN. Predictions for $\langle Q^2\rangle^{\bar{\nu}N}$ versus energy are shown in Fig. 8. The b-quark valence contribution produces a dramatic change in slope of $\langle Q^2\rangle^{\bar{\nu}N}$ near 50 GeV: This does not occur if the charm contribution is from the sea since $Q^2 = 2MExy$.

On the basis of our parton-model comparisons with the present data, we reach the following conclusions:

(a) All conventional quark-parton models seem to be in some degree of difficulty with the data. The different experimental measurements seem to place conflicting requirements on the $\bar{\nu}N$ charm-production mechanism.

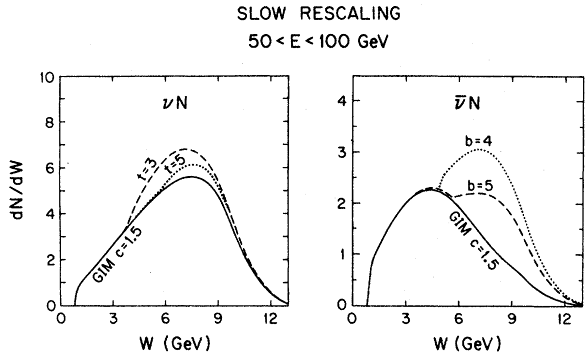

FIG. 7. Model predictions of W distributions for νN and $\bar{\nu}N$ for $50 < E < 100$ GeV: Model A (solid curve), model B (dashed curve), model D (dotted curve). Model C gives results similar to model A for νN and to model B for $\bar{\nu}N$.

(b) In particular the four-quark GIM model, previously thought to be satisfactory,[9] cannot explain the rise with energy of $\sigma_T^{\bar{\nu}N}/\sigma_T^{\nu N}$ and $\langle y\rangle^{\bar{\nu}N}$, and also does not succeed in quantitatively reproducing the magnitude of the $d\sigma/dy$ anomaly in $\bar{\nu}N$ at small x.

(c) With the six-quark model, the closest overall compromise with the present data is obtained with model C, which has charm-quark masses $m_c = 1.5$ GeV, $m_b = 5$ GeV, and a higher t-quark mass. This adequately reproduces the behavior of $\sigma_T^{\bar{\nu}N}/\sigma_T^{\nu N}$ and $\langle y\rangle^{\bar{\nu}N}$ and is not badly inconsistent with $d\sigma/dy$ for $\bar{\nu}N$. To reconcile it with the dimuon data we can postulate that the produced b-charm particles have small muonic branching ratios.

Note added. After completion of this paper, we learned that similar investigations are in progress by C. Albright, R. Shrock, and S. Nandi.

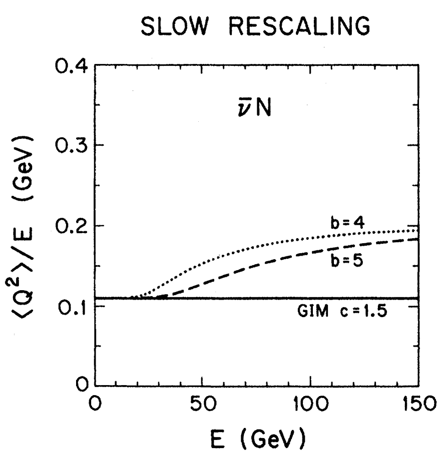

FIG. 8. Average Q^2 versus energy for $\bar{\nu}N$. The curves represent predictions of models A (solid), B and C (dashed), and D (dotted).

*Work supported in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation, and in part by the Energy Research and Development Administration under Contract No. E(11-1)-881, C00-527.

[1]B. Aubert *et al.*, Phys. Rev. Lett. 33, 984 (1974).

[2]A. Benvenuti *et al.*, Phys. Rev. Lett. 36, 1478 (1976); report at the Vanderbilt Conference, 1976 (unpublished).

[3]D. Cline, reports at Palermo Conference, 1975 (unpublished) and Irvine Conference, 1975 (unpublished); A. Mann, report at Orbis Scientiae, 1976 (unpublished).

[4]A. Benvenuti *et al.*, Phys. Rev. Lett. 34, 419 (1975); 35, 1199 (1975); 35, 1203 (1975); 35, 1249 (1975).

[5]B. Barish *et al.*, Phys. Rev. Lett. 36, 939 (1976); B. Barish, Cal Tech Report No. 68-510, 1975 (unpublished); A. Bodek, Cal Tech report No. 68-511, 1975 (unpublished).

[6]J. Van Krogh *et al.*, Phys. Rev. Lett. 36, 710 (1976).

[7]J. Blietschau *et al.*, Phys. Lett. 60B, 207 (1976).

[8]A. Benvenuti *et al.*, Phys. Rev. Lett. 37, 189 (1976).

[9]V. Barger *et al.*, Phys. Rev. Lett. 35, 692 (1975); Phys. Lett. 62B, 227 (1976); Phys. Rev. D 13, 2511 (1976).

[10]V. Barger *et al.*, Phys. Lett. 59B, 56 (1975).

[11]W. Wilson, Berkeley Report No. LBL-3862, 1975 (unpublished).

[12]S. Pakvasa *et al.*, Hawaii Report No. UH-511-207-75 (unpublished).

[13]R. M. Barnett, Phys. Rev. D 14, 70 (1976).

[14]A. De Rújula *et al.*, Rev. Mod. Phys. 46, 391 (1974).

[15]H. Georgi and D. Politzer, Harvard report, 1975 (unpublished).

[16]S. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

[17]H. Fritzsch, M. Gell-Mann, and P. Minkowski, Phys. Lett. 59B, 256 (1975); F. Wilczek, A. Zee, R. Kingsley, and S. Treiman, Phys. Rev. D 12, 2768 (1975).

[18]Six-quark vectorlike models have also been proposed by A. De Rújula *et al.*, Phys. Rev. D 12, 3589 (1975) and S. Pakvasa *et al.*, Phys. Rev. Lett. 35, 703 (1975).

[19]V. Barger *et al.*, Nucl. Phys. B102, 439 (1976).

[20]H. Deden *et al.*, Nucl. Phys. B85, 269 (1975); T. Eichten *et al.*, Phys. Lett. 46B, 274 (1973).

[21]W. G. Scott, Vanderbilt conference report, 1976 (unpublished).

[22]L. Mo, in *Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California*, edited by W. T. Kirk (SLAC, Stanford, 1976), p. 651.

[23]D. Perkins, in *Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California*, edited by W. T. Kirk (SLAC, Stanford, 1976), p. 571.

[24]G. Altarelli *et al.*, Rome report, 1976 (unpublished).