Reconciliation of deep-inelastic neutrino and antineutrino measurements with the four-flavor parton model*

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The high-y anomaly and the anomalous increase of the total antineutrino cross section at high energy appear consistent with the usual parton model of four flavors if the first moment of the fractional momentum distribution of the $\bar{s}$ parton is large compared with that of the $\bar{u}$, $\bar{d}$, and s partons. Various consequences and tests of this hypothesis are discussed.

Recently a number of authors[1] have proposed that there are quarks or partons having flavors other than the usual four (u, d, s, and c). Several observations have stimulated most of these proposals. These include the observed ratio $R_e = (e^-e^+ \to \text{hadrons})/\sigma(e^-e^+ \to \mu^-\mu^+)$, which appears to be about 5.5 for 4 GeV $< E_{\text{c.m.}} <$ 8 GeV. The three-color, four-flavor parton model suggests $R_e = \frac{10}{3}$, so additional elementary particles (or large corrections to asymptotic freedom) seem needed. Either heavy leptons or additional flavors would help reconcile this difference.

Observations of deep inelastic ν and $\bar{\nu}$ scattering provide very suggestive evidence for additional flavors. The pre-charm-threshold (2 GeV $\le E <$ 10 GeV) data indicate that the $\bar{u}$ and $\bar{d}$ contributions are much less than the u and d contributions; however, the post-charm-threshold data seem to require either a large contribution from the $\bar{s}$ or else a new flavor with right-handed coupling. The fractional momentum distributions are usually assumed to obey

$$n_s(x) = n_{\bar{s}}(x)\,, \tag{1a}$$

$$n_0(x) \equiv n_{\bar{u}}(x) + n_{\bar{d}}(x) = 2n_{\bar{s}}(x)\,, \tag{1b}$$

which implies that the $\bar{s}$ contribution is small, and hence a new flavor is needed.

In this paper I discuss whether the four-flavor parton model can be salvaged by abandoning Eqs. (1). I assume that excepting this, the parton model is the usual one, based on the Glashow-Iliopoulos-Maiani[2] (GIM) currents. In order to explain the high-y anomaly[3] and the rising ratio of the $\bar{\nu}$ and ν cross sections,[4] the $\bar{s}$ contribution must be larger than that allowed by Eq. (1b). If, as indicated,[5] the ν cross section does not increase more than 15% above the extrapolation of its pre-charm-threshold form, than the s contribution must be small, and Eq. (1a) must be wrong. This is indeed strange, but it does not seem to violate anything besides our intuition. The zeroth moment of n_s and $n_{\bar{s}}$ must be equal since the proton has zero strangeness, but the first moments,

$$M_j \equiv \int_0^1 dx\, x\, n_j(x)\,,$$

need not be equal for $j = s$ and $\bar{s}$, or for $j = c$ and $\bar{c}$.

The cross sections for the reactions

$$\nu p \to \mu^- X\,,$$

$$\bar{\nu} p \to \mu^+ X$$

are given by

$$\frac{d\sigma^{\nu\mu p}}{dxdy} = \left(1 - y + \tfrac{1}{2}y^2 - \frac{Mxy}{2E}\right)F_2^{\nu\mu p} - \frac{x}{2}(2-y)yF_3^{\nu\mu p}\,,$$

$$\frac{d\sigma^{\bar{\nu}\bar{\mu}p}}{dxdy} = \left(1 - y + \tfrac{1}{2}y^2 - \frac{Mxy}{2E}\right)F_2^{\bar{\nu}\bar{\mu}p} + \frac{x}{2}(2-y)y\,F_3^{\bar{\nu}\bar{\mu}p}\,, \tag{2}$$

in units of G^2ME/π, assuming Bjorken scaling and the Callan-Gross relation, $2xF_1 = F_2$. Here $x = Q^2/2M\nu$, and $Ey = \nu = E - E'$ with E the beam energy and E' the $\mu^\pm$ energy. The GIM currents imply

$$F_2^{\nu\mu p} = 2x[n_d\cos^2\theta + n_s\sin^2\theta + n_{\bar{u}} + (n_s\cos^2\theta + n_d\sin^2\theta + n_{\bar{c}})T]\,,$$

$$F_3^{\nu\mu p} = 2[-n_d\cos^2\theta - n_s\sin^2\theta + n_{\bar{u}} + (-n_s\cos^2\theta - n_d\sin^2\theta + n_{\bar{c}})T]\,, \tag{3}$$

where θ is the Cabibbo angle and $T = T(x,y,E)$ specifies the transients resulting from charm threshold. Below threshold, $T = 0$ giving the usual three-flavor parton-model results. In the threshold region, T specifies the violation of scaling. If this violation is limited to an interval of fixed width ΔW around the invariant mass W_c of the charm threshold, then $T \to 1$ as $E \to \infty$. In this limit the effects of the effective mass of the c and of corrections to asymptotic freedom vanish. The differential cross sections have the form $\sigma_{\text{post}} = \sigma_{\text{pre}} + \Delta\sigma$, where $\Delta\sigma$ results from the T terms in Eq. (3) and is the charm-production increment.

Below charm threshold, the nucleon-averaged cross sections implied by Eq. (3) are

$$\sigma^{\nu\mu}_{\text{pre}} = M_v \cos^2\theta + \tfrac{4}{3}M_0 + (2M_s - M_0)\sin^2\theta\,,$$
$$\sigma^{\bar\nu\bar\mu}_{\text{pre}} = \tfrac{1}{3}M_v + \tfrac{4}{3}M_0 + (2M_{\bar s} - M_0)\sin^2\theta\,, \tag{4}$$

with M_v the first moment of the "valence" distribution

$$n_v = n_u + n_d - n_{\bar u} - n_{\bar d}\,.$$

The usual assumptions about the "sea" distributions, Eqs (1), imply $2M_s = 2M_{\bar s} = M_0$ and thus would eliminate the last terms in Eqs. (4). Since $\sin^2\theta \simeq 0.05$, these expressions are not sensitive to $2M_s - M_0$ or $2M_{\bar s} - M_0$ unless M_v and M_0 are small. In fact they are not both small. The CERN data[6] for $1 \lesssim E \lesssim 10$ GeV suggest

$$\sigma^{\nu\mu}_{\text{pre}} = 0.48 \pm 0.01\,,$$
$$\sigma^{\bar\nu\bar\mu}_{\text{pre}} = 0.18 \pm 0.01\,, \tag{5}$$

and thus $M_v \simeq 0.49$, $M_0 \simeq 0.01$, and M_s and $M_{\bar s}$ are unspecified.

In the limit $E \to \infty$ the nucleon-averaged total cross sections implied by Eqs. (3) are

$$\sigma^{\nu\mu}_{\text{post}} = M_v + \tfrac{4}{3}M_0 + 2M_s + \tfrac{2}{3}M_{\bar c}\,,$$
$$\sigma^{\bar\nu\bar\mu}_{\text{post}} = \tfrac{1}{3}M_v + \tfrac{4}{3}M_0 + 2M_{\bar s} + \tfrac{2}{3}M_c\,. \tag{6}$$

These expressions are much more sensitive to M_s and $M_{\bar s}$ than are the precharm expressions, Eqs. (4). They also involve M_c and $M_{\bar c}$, so there are four unknowns. If $M_s = M_{\bar s}$ and $M_c = M_{\bar c}$, then the ratio of cross sections has the $E \to \infty$ limit

$$R_c = \sigma^{\bar\nu\bar\mu}/\sigma^{\nu\mu} \to \frac{\tfrac{1}{3}M_v + \epsilon}{M_v + \epsilon}\,,$$

where $\epsilon = \tfrac{4}{3}M_0 + 2M_s + \tfrac{2}{3}M_c$. The observation[4] that $R_c > 0.5$ for $E > 70$ GeV implies $\epsilon > \tfrac{1}{3}M_v$, and thus $\sigma^{\nu\mu}_{\text{post}} > 0.65$. This contradicts the indication[5] that $\sigma^{\nu\mu}_{\text{post}}$ remains within 15% of the precharm result, i.e., using Eq. (5), that $\sigma^{\nu\mu}_{\text{post}} < 0.55$. This means that one or both of the assumptions $M_s = M_{\bar s}$ and $M_c = M_{\bar c}$ must be dropped for the four-flavor parton model to work.

The four unknowns M_s, $M_{\bar s}$, M_c, and $M_{\bar c}$ could be determined by $\sigma^{\nu\mu}_{\text{post}}$, $\sigma^{\bar\nu\bar\mu}_{\text{post}}$, and the forms of their y distributions. There are two equivalent expressions for these forms which are often used:

$$\frac{d\sigma^{\nu\mu}}{dy} = \tfrac{1}{2}I_-^{\nu\mu}[1 + A^{\nu\mu}(1-y)^2]\,,$$
$$\frac{d\sigma^{\bar\nu\bar\mu}}{dy} = \tfrac{1}{2}I_-^{\bar\nu\bar\mu}[A^{\bar\nu\bar\mu} + (1-y)^2]\,, \tag{7}$$

with $A = I_+/I_-$, $I_\pm = \int dx(F_2 \pm xF_3)$, and

$$\frac{d\sigma^{\nu\mu}}{dy} = I_2^{\nu\mu}[1 - y(1 - B^{\nu\mu}) + \tfrac{1}{2}y^2(1 - B^{\nu\mu})]\,,$$
$$\frac{d\sigma^{\bar\nu\bar\mu}}{dy} = I_2^{\bar\nu\bar\mu}[1 - y(1 + B^{\bar\nu\bar\mu}) + \tfrac{1}{2}y^2(1 + B^{\bar\nu\bar\mu})]\,, \tag{8}$$

with $I_2 = \int dx F_2$ and $B = -\int dx\, xF_3/I_2$. The average values of y are given by

$$\langle y\rangle^{\nu\mu} = \frac{6 + A^{\nu\mu}}{12 + 4A^{\nu\mu}} = \frac{7 + 5B^{\nu\mu}}{16 + 8B^{\nu\mu}}\,,$$
$$\langle y\rangle^{\bar\nu\bar\mu} = \frac{6A^{\bar\nu\bar\mu} + 1}{12A^{\bar\nu\bar\mu} + 4} = \frac{7 - 5B^{\bar\nu\bar\mu}}{16 - 8B^{\bar\nu\bar\mu}}\,. \tag{9}$$

In the $E \to \infty$ limit, Eqs. (3) imply

$$A^{\nu\mu} \to \frac{M_0 + 2M_{\bar c}}{M_v + M_0 + 2M_s}\,, \quad A^{\bar\nu\bar\mu} \to \frac{M_0 + 2M_{\bar s}}{M_v + M_0 + 2M_c}\,, \tag{10a}$$

$$B^{\nu\mu} \to \frac{M_v + 2M_s - 2M_{\bar c}}{M_v + 2M_0 + 2M_s + 2M_{\bar c}}\,,$$
$$B^{\bar\nu\bar\mu} \to \frac{M_v - 2M_{\bar s} + 2M_c}{M_v + 2M_0 + 2M_{\bar s} + 2M_c}\,. \tag{10b}$$

Thus, for instance, Eqs. (6) and (10b) determine the moments,

$$M_c = \frac{3}{4}\left(\frac{1 + B^{\bar\nu\bar\mu}}{2 - B^{\bar\nu\bar\mu}}\right)\sigma^{\bar\nu\bar\mu}_{\text{post}} - \tfrac{1}{2}(M_v + M_0)\,,$$
$$M_{\bar s} = \frac{3}{4}\left(\frac{1 - B^{\bar\nu\bar\mu}}{2 - B^{\bar\nu\bar\mu}}\right)\sigma^{\bar\nu\bar\mu}_{\text{post}} - \tfrac{1}{2}M_0\,,$$
$$M_s = \frac{3}{4}\left(\frac{1 + B^{\nu\mu}}{2 + B^{\nu\mu}}\right)\sigma^{\nu\mu}_{\text{post}} - \tfrac{1}{2}(M_v + M_0)\,,$$
$$M_{\bar c} = \frac{3}{4}\left(\frac{1 - B^{\nu\mu}}{2 + B^{\nu\mu}}\right)\sigma^{\nu\mu}_{\text{post}} - \tfrac{1}{2}M_0\,. \tag{11}$$

The Harvard-Pennsylvania-Wisconsin-Fermilab observations[3] indicate

$$B^{\nu\mu} = 0.83 \pm 0.20\,, \quad B^{\bar\nu\bar\mu} = 0.41 \pm 0.13\,. \tag{12}$$

In the following I assume these represent the $E \to \infty$ limits. Assuming $M_v = 0.49$, $M_0 = 0.01$, and the observed high-E limits $\sigma^{\nu\mu}_{\text{post}} < 0.55$ and $R_c \simeq 0.6 \pm 0.1$, Eqs. (11) and (12) impose further constraints. If $B^{\bar\nu\bar\mu}$ is within one standard deviation of the measured value, then $\sigma^{\bar\nu\bar\mu}_{\text{post}}$ must be at least 0.32 to keep M_c positive. Similarly $\sigma^{\nu\mu}_{\text{post}}$ must be at least 0.51. Within the allowed ranges $0.32 < \sigma^{\bar\nu\bar\mu}_{\text{post}} < 0.38$ and $0.51 <^{\nu\mu}_{\text{post}} < 0.55$, there are further constraints on $B^{\bar\nu\bar\mu}$ and $B^{\nu\mu}$ given in Table I. These, in turn, constrain $\langle y\rangle^{\bar\nu\bar\mu}$ and $\langle y\rangle^{\nu\mu}$ as indicated. The results are compatible with the observations[3] of events with $x < 0.6$ at $E = 150$ GeV giving roughly $\langle y\rangle^{\bar\nu\bar\mu} \simeq 0.38 \pm 0.08$ and $\langle y\rangle^{\nu\mu} \simeq 0.48 \pm 0.03$.

The allowed ranges of the moments are given in Table I. Notice that $M_{\bar s}$ must be large compared to all the moments other than M_v. Since one would expect n_s and $n_{\bar s}$ to be as nearly equal as possible, the closest Table I allows is $M_s \simeq 0.02$ and $M_{\bar s} \simeq 0.07$. The additional indications that the high-y anomaly results from events[3] with $x < 0.15$, and that[7] $b^{\bar\nu\bar\mu}(x) \equiv -xF_3^{\bar\nu\bar\mu}/F_2^{\bar\nu\bar\mu}$ differs appreciably from 1 only when $x < 0.15$ imply that $n_{\bar s}$ must be confined to

TABLE I. Consistency constraints and implications for the four-flavor parton model.

Range of $\sigma_{\rm post}^{\bar\nu\mu}$	Constraints and implications
<0.32	M_c negative
0.32–0.35	$0.5 \lesssim B^{\bar\nu\mu} \Rightarrow \langle y \rangle^{\bar\nu\mu} \lesssim 0.38$;
	$0.07 \lesssim M_{\bar s} \lesssim 0.08$, $0 \lesssim M_c \lesssim 0.03$
0.35–0.38	$0.4 \lesssim B^{\bar\nu\mu} \Rightarrow \langle y \rangle^{\bar\nu\mu} \lesssim 0.39$;
	$0.08 \lesssim M_{\bar s} \lesssim 0.10$, $0 \lesssim M_c \lesssim 0.05$
>0.38	R_c larger than observed
Range of $\sigma_{\rm post}^{\nu\mu}$	Constraints and implications
<0.51	M_s negative
0.51–0.52	$0.85 \lesssim B^{\nu\mu} \lesssim 0.95 \Rightarrow 0.49 \lesssim \langle y \rangle^{\nu\mu}$;
	$0 \lesssim M_s \lesssim 0.01$, $0 \lesssim M_{\bar c} \lesssim 0.02$
0.53–0.54	$0.65 \lesssim B^{\nu\mu} \lesssim 0.95 \Rightarrow 0.48 \lesssim \langle y \rangle^{\nu\mu}$;
	$0 \lesssim M_s \lesssim 0.02$, $0 \lesssim M_{\bar c} \lesssim 0.05$
>0.55	more than 15% above $\sigma_{\rm pre}^{\nu\mu}$

$x \lesssim 0.2$. This suggests that n_s and $n_{\bar s}$ have the forms schematized in Fig. 1. Several authors have given fits for n_v and n_0 derived from precharm electroproduction and neutrino data. (See, for instance, Ref. 8.) An example of n_v is sketched in Fig. 1. Presumably n_0 lies under n_s and/or $n_{\bar s}$.

Before proceeding to constraints on the c and $\bar c$ contribution, and to consequences, one should ask if this skewing of n_s and $n_{\bar s}$ is plausible. The proton does not carry strangeness, so the areas under n_s and $n_{\bar s}$ must be equal. Moreover, since the sum of the moments, $\sum M_j$, indicates how much of the proton's momentum is carried by partons (instead of gluons) it must be, at most, one. These conditions are easily satisfied. Charge-conjugation invariance implies that, in an antiproton, the s distribution is given by $n_{\bar s}$ and the $\bar s$ distribution by n_s, but does not imply $n_s = n_{\bar s}$. An underlying cause of skewing could be the following: The quark model implies that the virtual states of nucleons corresponding to two strange hadrons involve a light hadron containing $\bar s$ and a heavier hadron containing s (for example $p \to \Lambda K^+$). Thus the radial distribution of the $\bar s$ should be broader than that of the s. Perhaps this asymmetry causes $n_s \neq n_{\bar s}$.

The contribution from c and $\bar c$ are not constrained very well, as indicated in Table I. An additional constraint is given by deep-inelastic leptoproduction ($l^\pm p \to l^\pm X$). At high Q^2 and ν, the nucleon-averaged structure function is predicted to be

$$F_2^l \to \tfrac{1}{18} x[5n_v + 10 n_0 + 2(n_s + n_{\bar s}) + 8(n_c + n_{\bar c})] . \quad (13)$$

Recent data on μ scattering,[9] combined with SLAC measurements, give

$$\int_{0.004}^{1} dx\, F_2^l = 0.153 \pm 0.005 .$$

With the estimates for M_v, M_0, M_s, and $M_{\bar s}$, this implies that $0 \lesssim M_c + M_{\bar c} \lesssim 0.02$.

In summary the above considerations suggest

$$\begin{aligned} &M_v \simeq 0.49 , \quad M_0 \simeq 0.01 , \\ &M_s \simeq 0.02 , \quad M_{\bar s} \simeq 0.07 , \\ &M_c + M_{\bar c} \lesssim 0.02 . \end{aligned} \quad (14)$$

With this fit, $M_{\bar s}$ plays the role attributed to new-flavor production. To see if this is correct, we must examine final states. In the following, various consequences are discussed.

Leptoproduction. The large $\bar s$ and s distributions imply a large amount of strange-particle production with $x < 0.2$. It is not obvious whether experiments at SLAC would observe this since Q^2 is not large enough to see scaling in x at small x.[10] The effect should show up in μ scattering experiments at Fermilab, and may be correlated with the increase[11] of νW_2 by about 20% above the SLAC values when $x \lesssim 0.2$ and $Q^2 = 3$ GeV^2. This increase could be caused by $n_c + n_{\bar c}$ contribution as well. Since charmed hadrons are expected to decay mostly with $\Delta C = \Delta S$, this would also lead to a large amount of strange-particle production.

Strangeness changing below charm threshold. The cross sections for strangeness ±1 final state are predicted to be

$$\begin{aligned} &\sigma_{\rm pre}^{\nu\mu}(s=1) = (\tfrac{1}{3}M_0 + 2M_s)\sin^2\theta , \\ &\sigma_{\rm pre}^{\bar\nu\bar\mu}(s=-1) = (\tfrac{1}{3}M_v + \tfrac{1}{3}M_0 + 2M_{\bar s})\sin^2\theta . \end{aligned} \quad (15)$$

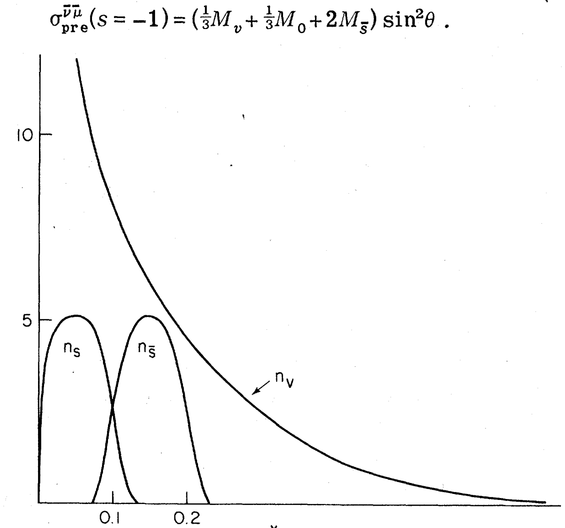

FIG. 1. A plot of n_v (from Ref. 8) and a sketch of n_s and $n_{\bar s}$.

These might be useful for measuring M_s and $M_{\bar{s}}$ although θ is small and kinematics might prevent scaling from occuring at x small enough to feel the effects of n_s and $n_{\bar{s}}$ and still be below charm threshold. If scaling at small x requires $Q^2 > 3$ GeV^2 (as μ scattering suggests[11]) and if threshold is at $W_c = 2.5$ GeV, then x must be greater than 0.37 for prethreshold scaling.

Strangeness changing above charm threshold. The difference $\Delta\sigma = \sigma_{\text{post}} - \sigma_{\text{pre}}$ gives the charm-production part of the cross sections. With the estimates in Eq. (14), these are $\Delta\sigma^{\nu\mu} \simeq 0.07$ and $\Delta\sigma^{\bar{\nu}\bar{\mu}} \simeq 0.14$. If the charm states decay via $\Delta C = \Delta S$, then the effective strangeness-producing cross sections at high E are the sums of $\Delta\sigma$ and Eqs. (15), i.e.,

$$\begin{aligned}\sigma^{\nu\mu}_{\text{post}}(s) &= (M_v + \tfrac{4}{3}M_0 + 2M_s + \tfrac{2}{3}M_{\bar{c}})\sin^2\theta \\ &\quad + (2M_s + \tfrac{2}{3}M_{\bar{c}})\cos^2\theta \\ &\simeq 0.07\,, \\ \sigma^{\bar{\nu}\bar{\mu}}_{\text{post}}(s) &= (\tfrac{1}{3}M_v + \tfrac{4}{3}M_0 + 2M_{\bar{s}} + \tfrac{2}{3}M_c)\sin^2\theta \\ &\quad + (2M_{\bar{s}} + \tfrac{2}{3}M_c)\cos^2\theta \\ &\simeq 0.15\,.\end{aligned} \tag{16}$$

The $\sin^2\theta$ terms leave one strange particle in the final state and the $\cos^2\theta$ terms leave two, so the average numbers of strange particles per event are predicted to be at least

$$\begin{aligned}N^{\nu\mu}(s) &= (1+\cos^2\theta) - \frac{2(M_v + \frac{4}{3}M_0)\cos^2\theta}{\sigma^{\nu\mu}_{\text{post}}} \simeq 0.19\,, \\ N^{\bar{\nu}\bar{\mu}}(s) &= (1+\cos^2\theta) - \frac{2}{3}\,\frac{(M_v + 4M_0)\cos^2\theta}{\sigma^{\bar{\nu}\bar{\mu}}_{\text{post}}} \simeq 0.89\,.\end{aligned} \tag{17}$$

These estimates do not include the effects of associated production in the final states. There are bubble-chamber data[12] from Fermilab on strange-particle production $\nu p \to \mu X$. The result is $\sigma^{\nu\mu p}_{\text{post}}(V^0)/\sigma^{\nu\mu p}_{\text{post}} = 0.16 \pm 0.03$.

Dileptons. The semileptonic decays of charmed hadrons leads to final states with an extra $l = \mu$ or e. With four flavors, the cross sections for these reactions are

$$\begin{aligned}\sigma^{\nu\mu\bar{l}} &= \Delta\sigma^{\nu\mu}B(c=+1)\,, \\ \sigma^{\bar{\nu}\bar{\mu}l} &= \Delta\sigma^{\bar{\nu}\bar{\mu}}B(c=-1)\,,\end{aligned} \tag{18}$$

where $B(c=\pm 1)$ are the effective branching ratios for charm ± 1 states. The average numbers of strange particles per dilepton event are at least

$$\begin{aligned}N^{\nu\mu\bar{l}}(s) &= 1 + \frac{2(M_s + \frac{1}{3}M_{\bar{c}})\cos^2\theta}{\Delta\sigma^{\nu\mu}} \simeq 1.6\,, \\ N^{\bar{\nu}\bar{\mu}l}(s) &= 1 + \frac{2(M_{\bar{s}} + \frac{1}{3}M_c)\cos^2\theta}{\Delta\sigma^{\bar{\nu}\bar{\mu}}} \simeq 2.0\,.\end{aligned} \tag{19}$$

These are being measured.

Neutral currents. If the parton model with GIM currents is joined with the Weinberg-Salam model it predicts the cross sections for

$$\binom{\bar{\nu}}{\nu}p \to \binom{\bar{\nu}}{\nu}X\,.$$

The results for the nucleon averages are[13]

$$\begin{aligned}\frac{d\sigma^{\nu\nu}}{dy} &= \sigma_1 + (1-y)^2\sigma_2\,, \\ \frac{d\sigma^{\bar{\nu}\bar{\nu}}}{dy} &= (1-y)^2\sigma_1 + \sigma_2\,,\end{aligned} \tag{20}$$

where

$$\begin{aligned}\sigma_1 &= (\tfrac{1}{2} - \sin^2\theta_W + \tfrac{5}{9}\sin^4\theta_W)M_v \\ &\quad + (\tfrac{1}{2} - \sin^2\theta_W + \tfrac{10}{9}\sin^4\theta_W)M_0 \\ &\quad + (\tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W + \tfrac{2}{9}\sin^4\theta_W)M_s + \tfrac{2}{9}\sin^4\theta_W M_{\bar{s}} \\ &\quad + (\tfrac{1}{2} - \tfrac{4}{3}\sin^2\theta_W + \tfrac{8}{9}\sin^4\theta_W)M_c + \tfrac{8}{9}\sin^4\theta_W M_{\bar{c}}\,, \\ \sigma_2 &= \tfrac{5}{9}\sin^4\theta_W M_v + (\tfrac{1}{2} - \sin^2\theta_W + \tfrac{10}{9}\sin^4\theta_W)M_0 \\ &\quad + \tfrac{2}{9}\sin^4\theta_W M_s + (\tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W + \tfrac{2}{9}\sin^4\theta_W)M_{\bar{s}} \\ &\quad + \tfrac{8}{9}\sin^4\theta_W M_c + (\tfrac{1}{2} - \tfrac{4}{3}\sin^2\theta_W + \tfrac{8}{9}\sin^4\theta_W)M_{\bar{c}}\,.\end{aligned}$$

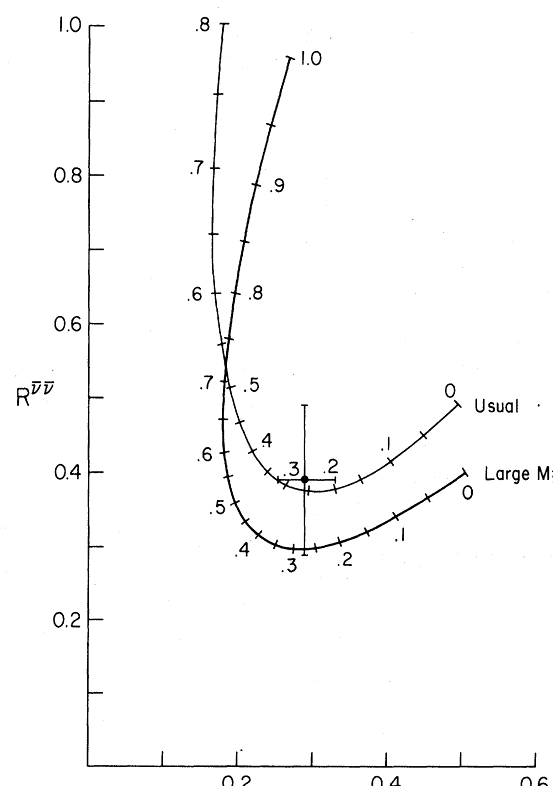

FIG. 2. The $\sin^2\theta_W$ dependence of $R^{\nu\nu}$ and $R^{\bar{\nu}\bar{\nu}}$. The data values are from Ref. 14.

The ratios $R^{\nu\nu}=\sigma^{\nu\nu}/\sigma^{\nu\mu}$ and $R^{\bar\nu\bar\nu}=\sigma^{\bar\nu\bar\nu}/\sigma^{\bar\nu\bar\mu}$ are plotted in Fig. 2 as functions of $\sin^2\theta_W$ for both the "usual" case $M_v=0.49$, $M_0=2M_{\bar s}=2M_s=0.01$, $M_c=M_{\bar c}=0$, and the "large-$M_{\bar s}$" case where, instead, $M_s=0.02$ and $M_{\bar s}=0.07$. The ratio $R^{\bar\nu\bar\nu}$ is relatively sensitive to $M_{\bar s}$ and is shifted lower as $M_{\bar s}$ increases. There is recent data for these ratios indicating[14]

$$R^{\nu\nu}=0.29\pm0.04\,,\quad \langle E\rangle=85\text{ GeV}$$

$$R^{\bar\nu\bar\nu}=0.39\pm0.10\,,\quad \langle E\rangle=41\text{ GeV}\,.$$

These values are indicated in Fig. 2. The $R^{\nu\nu}$ value suggests $\sin^2\theta_W\simeq0.25$, whereas the $R^{\bar\nu\bar\nu}$ value suggests $\sin^2\theta_W\simeq0$ or 0.55 if $M_{\bar s}$ is large; however, the errors are large. For a better fit, the experimental result for $R^{\bar\nu\bar\nu}$ should drop about 20% at high energy, or else $R^{\nu\nu}$ should shift up about 20% (above and below charm threshold). In the latter case, the fit to $\sin^2\theta_W$ would decrease, which in turn would help the Weinberg-Salam model if the atomic neutral-current experiments establish that parity violation is small.[15] In the above, M_c and $M_{\bar c}$ were assumed to be zero. If they contribute, the prediction for $R^{\nu\nu}$ would be shifted down and that for $R^{\bar\nu\bar\nu}$ would not be altered appreciably.

There are many less testable consequences or implications of the large-$M_{\bar s}$ hypothesis. For instance, the fraction of the proton's momentum carried by partons is estimated to be in the range $0.60\lesssim\sum M_j\lesssim0.62$. Another consequence concerns the x distributions of the strangeness-changing and dimuon events. It will be difficult to prove that n_s and $n_{\bar s}$ are different using the observed x distribution since n_v, n_0, and possibly n_c and $n_{\bar c}$ contribute. A more tenuous implication is the following: There is some, as yet, unknown connection between n_s, $n_{\bar s}$ and the configuration of virtual strange quarks in (static) nucleons. The existence of large $n_{\bar s}$ and $n_{\bar s}$ could be related to the observation[16] that the measured value of the πN σ term agrees with chiral-symmetry breaking if the static matrix elements of the proton obey

$$|\langle p|\bar s s|p\rangle|\simeq\tfrac14|\langle p|\bar u u+\bar d d|p\rangle|\,.$$

The hypothesis of large $M_{\bar s}$ is contrary to the usual assumption about the sea, but it is consistent with observations of $\sigma^{\bar\nu\bar\mu}$, $\sigma^{\nu\mu}$, $B^{\bar\nu\bar\mu}$, and $B^{\nu\mu}$. Since these are rather tightly constrained, more precise measurements of these could disprove the four-flavor parton model. Also if $\sigma^{\bar\nu\bar\mu}/\sigma^{\nu\mu}$ or $\langle y\rangle^{\bar\nu\bar\mu}$ continues to rise as E increases or if high-energy μ scattering does not produce strange particles at small x, a fifth flavor would seem necessary. Even in this case, it appears plausible that n_s and $n_{\bar s}$ are skewed and contribute, along with the new flavor(s).

If the hypothesis of large $M_{\bar s}$ is correct it implies that strange partons are more significant than expected.

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