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ENERGY DEPENDENCE OF NEUTRAL AND CHARGED CURRENT
CROSS-SECTIONS FROM ASYMPTOTIC FREEDOM

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ABSTRACT

We compare asymptotic freedom predictions for charged current processes with recent ν and $\bar{\nu}$ experiments. The agreement is good. We estimate asymptotic freedom effects in neutral current processes and point out that these effects may have some influence on the determination of the Weinberg angle θ_W .

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Asymptotically free gauge theories (AFGT) ¹⁾ play a vital role in attempting to understand scaling violations observed in deep inelastic ep ²⁾ and up ³⁾ collisions. In fact, many analyses ⁴⁾ show that these theories account, with good accuracy, for the measured Q^2 dependence of the electromagnetic structure functions. On the other hand, until recently the role of asymptotic freedom in explaining new phenomena, so-called high y anomalies, in $\bar{\nu}$ processes seemed to be less prominent. The strong energy dependence of $\sigma^{\bar{\nu}}/\sigma^{\nu}$ and $\langle y \rangle_{\bar{\nu}}$ observed by the HPWF collaboration ⁵⁾ was, as estimated by many theorists ⁶⁾⁻⁸⁾, far too strong to be explained by asymptotic freedom in the context of the standard WSGIM ⁹⁾ model. A new quark (b quark) with a right-handed coupling to ordinary quarks was needed. In addition, since the effect of this new quark in $\sigma^{\bar{\nu}}/\sigma^{\nu}$ or $\langle y \rangle_{\bar{\nu}}$ is in the range of presently available energies roughly four times bigger (for $m_b \approx 5$ GeV) than that given by asymptotic freedom, in most - but not all ^{6)-8), 10)-12)} - of the studies, asymptotic freedom effects have been neglected.

Now, since the strong high y anomalies and consequently the existence of the b quark with a sizeable right-handed coupling have not been confirmed ¹³⁾⁻¹⁵⁾, it is very probable that also in ν and $\bar{\nu}$ processes asymptotic freedom will play an important role as it already did in electromagnetic processes. In fact the recent experiments ¹³⁾⁻¹⁵⁾ seem to indicate a very weak energy dependence of various cross-sections in qualitative agreement with the asymptotic freedom predictions. The question is now whether this agreement is also quantitative. In particular, it is of great importance to check whether this theory is able to explain simultaneously scaling violations in electroproduction and weak current processes with the same Q^2 dependent coupling constant.

There have been already several estimates of asymptotic freedom effects in charged current processes ^{6)-8), 10)-12)}. Less is known about corresponding effects in neutral current processes, although some discussions have already appeared in the literature ^{8), 16)}.

Here we present a comparison of asymptotic freedom predictions with the results of the recent ν and $\bar{\nu}$ neutral and charged current experiments. We concentrate on global quantities such as the ratios

$$R_{cc} = \frac{\sigma_{cc}^{\bar{\nu}}}{\sigma_{cc}^{\nu}}, \quad R^{\nu} = \frac{\sigma_{NC}^{\nu}}{\sigma_{cc}^{\nu}}, \quad R^{\bar{\nu}} = \frac{\sigma_{NC}^{\bar{\nu}}}{\sigma_{cc}^{\bar{\nu}}},$$

absolute cross-sections and average quantities $\langle x \rangle$, $\langle y \rangle$ and $\langle xy \rangle$. Local quantities $d\sigma/dx$ and $d\sigma/dy$ as well as the details of the calculations will be presented elsewhere ¹⁷⁾.

In our calculations we restrict ourselves to the leading order in the effective quark-gluon coupling which implies the use of the standard parton formulae with Q^2 dependent parton distributions. We take the latter from our asymptotic freedom analysis ¹⁸⁾ of ep and μp scattering. As a gauge model for the weak interactions we adopt the WSGIM model ⁹⁾.

This model cannot account for the parity non-violation in atomic physics. This problem may be circumvented by choosing a larger gauge group. There exists at least one such extension which has effectively the same neutral current structure for the (u,d,s, and c) quarks as the standard model. [for a discussion see Ref. 19)]. Another problem is that the model does not give CP violation ^{*)}.

Adding a new left-handed doublet $\begin{pmatrix} t \\ b \end{pmatrix}_L$ ²¹⁾ allows for the inclusion of CP violation without affecting visibly the ν and $\bar{\nu}$ predictions of the standard model at presently available energies. This fact is due to the large mass of the new quarks ($m_b, m_t \geq 5$ GeV) and the small mixing with ordinary quarks as required by Cabibbo universality ²²⁾. In spite of the problems mentioned above we take the WSGIM model as a starting point for our discussion.

Before presenting our results we recall our assumptions about the quark distributions at a particular value of $Q^2 = Q_0^2$, which we have taken to be $Q_0^2 = 1.8 \text{ GeV}^2$

$$\begin{aligned}
 x V(x) &= x u_v(x) + x d_v(x) = 5.5 x^{0.7} (1-x)^{2.6} \\
 x (\bar{u}(x) + \bar{d}(x)) &= x (u_s(x) + d_s(x)) = 0.275 (1-x)^{10} \\
 x (\lambda(x) + \bar{\lambda}(x)) &= 0.22 (1-x)^{10} \\
 x (c(x) + \bar{c}(x)) &= 0 \\
 x G(x) &= 4.86 (1-x)^{10}
 \end{aligned}
 \tag{1}$$

*) See, however, Weinberg ²⁰⁾.

Here u_V and d_V are valence quarks, whereas u_S and d_S stand for the corresponding quarks in the sea. G denotes the gluon distribution.

For $Q^2 > Q_0^2$ the distributions above are given by asymptotic freedom. Analytic expressions for these distributions for any $Q^2 > Q_0^2$ can be found in Ref. 18). For $Q^2 < Q_0^2$, where ASF calculations are doubtful due to the larger quark-gluon coupling, we assume no Q^2 dependence, i.e., Eq. (1). Since we consider global quantities, we expect that although at $Q^2 < Q_0^2$ direct channel resonances are important, on the average these resonances may reproduce the $Q^2 = Q_0^2$ distributions²³⁾.

We emphasize that the cleanest way to test asymptotic freedom effects in ν and $\bar{\nu}$ collisions would be to make experimental cuts in Q^2 at some Q_0^2 above which asymptotic freedom calculations make sense⁷⁾. Since the present experiments do not have such cuts, we have to make some assumptions (outside the field theoretical framework) about the low Q^2 region. This implies that our predictions for low energies, let us say below 20 GeV, are less certain.

The distributions of Eqs. (1) differ from those used in Ref. 18) in that the total amount of the non-charmed sea is smaller (7%) and some SU(3) breaking in the sea has been introduced^{*)}. Both changes are dictated by the GGM experiments²⁴⁾ as well as by the recent ν and $\bar{\nu}$ data^{13),15)}. We have checked that the distributions above fit well both Fermilab μp data as well as SLAC $e p$ data, except at very small values of x ($x \leq 0.05$) where we are slightly below the data. Notice the high powers of both sea and gluon distributions. Had we used a smaller power of the sea, let us say $(1-x)^7$, as indicated by Drell-Yan calculations, the disagreement at small values of x would be much larger. On the other hand, the power in $G(x, Q^2)$ could be even decreased to 5 without sizeably affecting our results of both this and our previous paper¹⁸⁾. We shall discuss the sensitivity of our results to the assumed parton distributions in Ref. 17).

In calculating the contributions from charm production, we have used the scaling variable²⁵⁾

$$\xi = \frac{Q^2 + m_c^2}{2\nu} \quad (2)$$

*) With increasing Q^2 the sea will be more and more SU(3) symmetric. At very high Q^2 it will be also SU(4) symmetric.

m_c being the charmed quark mass. On the other hand, we have neglected target mass corrections ^{25),26)}. The latter, although visible when compared with the very accurate SLAC ep data, are not of such importance that they could not be neglected in the comparison with the less accurate ν and $\bar{\nu}$ experiments. In addition, the latter experiments explore higher Q^2 values than the present ep or μp collisions which implies smaller m_p^2/Q^2 corrections. From the low Q^2 ($2 \leq Q^2 \leq 16 \text{ GeV}^2$) analysis ²⁷⁾ of ep data, we learn, however, that the target mass corrections effectively increase the value of the parameter Λ , which determines the Q^2 dependence of the strong interaction coupling constant

$$\bar{g}^2(Q^2) = \frac{48 \pi^2}{25 \ln \frac{Q^2}{\Lambda^2}} \quad (3)$$

This increase is from $\Lambda=0.3$ ¹⁷⁾ to $\Lambda=0.45$ ²⁷⁾. Therefore in what follows we shall present our results for $\Lambda=0.3$ and $\Lambda=0.5$. We shall also show our calculations without asymptotic freedom included.

In Fig. 1 we present our predictions ^{*)} for R_{cc} together with the data of Refs. 13)-15). The agreement of ASF with the very accurate data of Ref. 13) is very good. The value $\Lambda=0.5$ is slightly preferred if one wants to reproduce Gargamelle value at the same time. The agreement with the data of Refs. 14) and 15) is within one standard deviation.

It is to be noted that the effects of asymptotic freedom manifest themselves through a change in R_{cc} with respect to the free parton model value, but that there is no strong energy dependence of R_{cc} for energies above 30 GeV.

In Fig. 2 we compare our predictions with the absolute cross-sections for ν and $\bar{\nu}$ charged current processes as measured by 14) and 15). Again agreement is good with the preferred $\Lambda=0.5$. Notice that the WSGIM model without asymptotic freedom effects (denoted by FPM) fails completely in explaining the energy behaviour of the cross-sections in question. In fact, in this model both σ_{cc}^ν/E and $\sigma_{cc}^{\bar{\nu}}/E$ increase due to production of charm. The strong decrease with energy E of σ^ν/E in ASF theory is due to the decrease with Q^2 of the dominant valence contribution. This effect is also seen on a smaller scale [$\bar{\nu}$ is here replaced by $\nu(1-y)^2$] at low energies in $\bar{\nu}$ scattering. At higher energies the increase of charm production as well as of non-charm sea contribution due to asymptotic freedom is strong enough so that $\sigma^{\bar{\nu}}/E$ increases slowly. Both latter effects are smaller in ν cross-sections.

*) All calculations in this paper are for isoscalar targets. Cuts in the hadronic energy present in Ref. 13) are not taken into account. These cuts will be discussed in Ref. 17).

In Fig. 3 we plot $R^{\bar{\nu}}$ vs. R^{ν} for various values of $\sin^2\theta_W$ and few values of E , together with the data (averaged over E) of Refs. 13), 15) and 24). The dashed lines show how R^{ν} and $R^{\bar{\nu}}$, as given by asymptotic freedom, vary with energy for a fixed value of $\sin^2\theta_W$. The curves correspond to $\Lambda=0.5$. For a smaller Λ they are closer to each other. We observe a very weak and a slightly stronger energy dependence of R^{ν} and $R^{\bar{\nu}}$ respectively. This energy dependence is within errors of Ref. 13). We would like to emphasize that asymptotic freedom effects in neutral currents, as shown in Fig. 3, may slightly affect the experimental determination of $\sin^2\theta_W$. This determination is usually done in the free parton model corresponding to a single curve in Fig. 3. To this end an average value of R^{ν} and $R^{\bar{\nu}}$ over some energy range is taken. More correctly one should plot in Fig. 3 the experimentally determined pair $(R^{\nu}, R^{\bar{\nu}})$ for various values of E resulting in an experimental line. The intersection points of this line with the theoretical curves of Fig. 3 would then give the best value of $\sin^2\theta_W$.

We are, however, aware of the fact that such a procedure would require very accurate measurements of R^{ν} and $R^{\bar{\nu}}$, even more accurate than those given in Ref. 13).

We again emphasize that the change with energy of the curves in Fig. 3 is related to the fact that the effective amount of valence and sea quarks is, according to asymptotic freedom, different for different energies. This also means that the curves in question are also slightly sensitive to the input distributions [our Eq. (1)]. But since we reproduce at the same time R_{cc} , absolute cross-sections and R^{ν} , $R^{\bar{\nu}}$ of Refs. 13)-15), our input assumptions seem to be properly chosen. We shall elaborate on this in Ref. 17).

Finally we observe that the energy dependence of R^{ν} and $R^{\bar{\nu}}$ is different for different values of $\sin^2\theta_W$. With increasing $\sin^2\theta_W$ it is stronger and weaker for $R^{\bar{\nu}}$ and R^{ν} , respectively. This is easy to understand if one recalls that according to the WSGIM model in the range of interest ($0.2 \leq \sin^2\theta_W \leq 0.4$) increasing $\sin^2\theta_W$ means to increase (decrease) the importance of valence quark contribution in $R^{\bar{\nu}}$ (R^{ν}). The decrease of V with increasing Q^2 and consequently with energy underlines the behaviour seen in the graph.

In the Table we show our predictions for $\langle x \rangle$, $\langle y \rangle$ and $\langle xy \rangle$ for various values of E for both neutral and charged currents. The values in the Table correspond to $\Lambda=0.5$ and $\sin^2\theta_W=0.26$, a value consistent with both Refs. 13) and 15). We observe a very weak energy dependence of $\langle y \rangle$ and a stronger energy dependence of $\langle xy \rangle$ and $\langle x \rangle$. Notice in particular

that $\langle y \rangle_\nu$ in both neutral and charged current processes is constant up to 1%. This is due to the fact that $\langle y \rangle_\nu$ in both processes is already close to its limiting value at $Q^2 = \infty$, which is 0.44. We will present a detailed comparison of these quantities with the existing data in Ref. 17).

In summary, the energy dependence of various integrated cross-sections or their ratios as given by ASF is weak for $E > 30$ GeV and sufficiently strong for $E < 30$ GeV so that the Gargamelle data and the recent high energy data ¹³⁾⁻¹⁵⁾ for charged currents can be understood at the same time. [Remember, however, that the treatment of very low Q^2 and consequently low E region is not very certain.] From this it is clear that a better experimental study of the energy range below 30 GeV is very desirable.

Also $\langle y \rangle$ and y distributions ^{7),17),28)} show very weak energy dependence. On the other hand, $\langle x \rangle$ and x distributions ¹⁷⁾, not surprisingly show much stronger energy dependence and should be a good place to study asymptotic freedom effects.

Similar conclusions ^{*)} for charged currents have been reached by the authors of Ref. 18) whose preprint we received while writing this paper.

TABLE Energy dependence of $\langle x \rangle$, $\langle y \rangle$ and $\langle xy \rangle$ for various processes as given by asymptotic freedom.

	E (GeV)	$\langle x \rangle$		$\langle y \rangle$		$\langle xy \rangle$	
		c.c.	n.c.	c.c.	n.c.	c.c.	n.c.
ν	10	0.28	0.27	0.48	0.46	0.13	0.12
	50	0.25	0.25	0.48	0.46	0.12	0.11
	300	0.22	0.22	0.48	0.46	0.10	0.10
$\bar{\nu}$	10	0.27	0.26	0.28	0.33	0.065	0.079
	50	0.23	0.23	0.29	0.34	0.056	0.069
	300	0.19	0.20	0.33	0.35	0.048	0.059

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*) We disagree only with the claim of the authors of Ref. 18) that according to asymptotic freedom $\langle y \rangle_\nu$ decreases with E. We find an increase.

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FIGURE CAPTIONS

- Figure 1 : The ratio $\sigma^{\bar{\nu}}/\sigma^{\nu}$ as a function of energy. The calculated curves are for the free parton model (FPM) and the parton model with asymptotic freedom effects (ASF) for two values of Λ . The data are from Refs. 13)-15).
- Figure 2 : The absolute cross-sections σ^{ν}/E as a function of energy. The theoretical curves are calculated with the same assumptions as in Fig. 1. The data are from Ref. 14) : ($\bullet$), and 15) : ($\square$).
- Figure 3 : The neutral current ratios R^{ν} and $R^{\bar{\nu}}$ as a function of the Weinberg angle for $0.10 \leq \sin^2 \theta_W \leq 0.40$, for three different energies. The data are from Refs. 13), 15) and 24).

FIG. 1

FIG.2

FIG. 3