FULL OF CHARM NEUTRINO DIS

R. Fiore and V.R. Zoller

1 Dipartimento di Fisica, Università della Calabria
and
INFN, Gruppo collegato di Cosenza, Italy
2 ITEP, Moscow 117218, Russia

The color dipole analysis of small-\((x, Q^2)\) neutrino DIS induced by the charmed-strange \((cs)\) current reveals ordering of dipole sizes \(m_c^{-2} < r^2 < m_s^{-2}\) typical of the Double Leading Log Approximation (DLLA). The DLLA resummation leads to the \(cs\) component of the longitudinal structure function \(F_L\) rising to small \(x\) much faster than its light quark component. Based on the color dipole BFKL approach we report quantitative predictions for this effect in the kinematical range of the CCFR/NuTeV experiment.

We report our analysis of the charged current (CC) non-conservation effects in small-\(x\) neutrino DIS. We use the color dipole (CD) basis of high-energy QCD and quantify the phenomenon of weak current non-conservation in terms of the light cone wave functions (LCWF) \(\Psi^cs_\lambda\) in the Fock expansion of the \(W^+\)-boson state with helicity \(\lambda\),

\[
|W^+_\lambda\rangle = \Psi^cs_\lambda|cs\rangle + \Psi^{ud}_\lambda|ud\rangle + ...
\]

At small \(Q^2 \lesssim m_c^2\) the strong un-equality of masses of the charmed and strange quarks manifests its effects and the CD analysis reveals the ordering of dipole sizes

\[
(m_c^2 + Q^2)^{-1} \lesssim r^2 \ll m_s^{-2}
\]

typical of the Double Leading Log Approximation (DLLA). The multiplication of log’s like

\[
\alpha_s \log\left(\frac{m_c^2 + Q^2}{\mu_G^2}\right)\log(1/x)
\]

to higher orders of perturbative QCD ensures the dominance of the charmed-strange component, \(F_L^{cs}\), of the longitudinal structure function (LSF)

\[
F_L = F_L^{ud} + F_L^{cs}
\]
in the kinematical domain covered by the CCFR/NuTeV experiment.4

In the vacuum exchange dominated region of $x \lesssim 0.01$ the contribution of excitation of open charm/strangeness to the longitudinal ($\lambda = L$) and transverse ($\lambda = T$) structure functions is given by

$$F_L(x, Q^2) = \frac{Q^2}{4\pi^2\alpha_W} \int dzd^2r |\Psi_L(z, r)|^2 \sigma(x, r),$$

(5)

where $\alpha_W = g^2/4\pi$ and the weak charge $g$ is related to the Fermi coupling constant $G_F$, $G_F/\sqrt{2} = g^2/m_W^2$. $|\Psi_L(z, r)|^2$ is the light cone density of $c\bar{s}$ dipoles of the size $r$ with the $c$ quark carrying fraction $z$ of the $W^+$ light-cone momentum. In particular, $|\Psi_L|^2$ is the incoherent sum of the vector ($V_L$) and the axial-vector ($A_L$) terms: $|\Psi_L|^2 = |V_L|^2 + |A_L|^2$. At $Q^2 \gg m_c^2$ the $S$-wave component of $|\psi\rangle$ dominates,5,6

$$|V_L|^2 \sim |A_L|^2 \propto Q^2 z^2 (1 - z)^2 K_0^2(\varepsilon r).$$

(6)

At $Q^2 \lesssim m_c^2$ the $P$-wave, that arises due to the current non-conservation, takes over,

$$|V_L|^2 \sim |A_L|^2 \propto \frac{m_c^2}{Q^2} z^2 K_1^2(\varepsilon r).$$

(7)

Here $\varepsilon^2 = z(1 - z)Q^2 + (1 - z)m_c^2 + zm_s^2$ controls the size of $c\bar{s}$ dipole, $r^2 \sim \varepsilon^{-2}$.

At small $Q^2 \lesssim m_c^2$ integrating over $z$ for $r^2$ from the region defined by the inequality2 yields11

$$\int dz |\Psi_L(z, r)|^2 \approx \frac{\alpha_W N_c}{\pi^2} \frac{m_c^2}{m_c^2 + Q^2 Q^2 r^4}$$

(8)

so that Eqs.5,8 give rise to nested logarithmic integrals over dipole sizes.

In the CD approach the BFKL-log$(1/x)$ evolution7 of $\sigma(x, r)$ is described by the CD BFKL equation of Ref.8. For qualitative estimates it suffices to use the DLLA. In the Born approximation (2g-exchange)1

$$\sigma(r) \approx C_F \pi^2 r^2 \alpha_S(r^{-2}) L(r^{-2}).$$

(9)

where

$$L(k^2) = \frac{4}{\beta_0} \log \frac{\alpha_S(\mu_G^2)}{\alpha_S(k^2)}.$$  

(10)

and $\alpha_S(k^2) = 4\pi/\beta_0 \log(k^2/\Lambda^2)$ with $\beta_0 = 11 - 2N_f/3$.

Perturbative gluons do not propagate to large distances and $\mu_G$ stands for the inverse Debye screening radius, $\mu_G = 1/R_c$. The lattice QCD data suggest $R_c \approx 0.3$ fm.12 Because $R_c$ is small compared to the typical range of strong interactions, the dipole cross section evaluated with the decoupling of soft gluons, $k^2 \lesssim \mu_G^2$, would underestimate the interaction strength for large color dipoles. In Ref.13,14,15 this missing strength was modeled by a non-perturbative, soft correction $\sigma_{\text{soft}}(r)$ to the dipole cross section $\sigma(r) = \sigma_{\text{pt}}(r) + \sigma_{\text{soft}}(r)$. Here we concentrate on the perturbative component, $\sigma_{\text{pt}}(r)$, represented by Eq. (9).

Then, at $Q^2 \lesssim m_c^2$

$$F_L^{cs} \sim \frac{N_c C_F}{4} \frac{m_c^2}{m_c^2 + Q^2} \frac{1}{2! L^2(m_c^2 + Q^2)}$$

(11)

There is also a contribution to $F_L^{cs}$ from the region $0 < r^2 < (m_c^2 + Q^2)^{-1}$

$$F_L^{cs} \sim \frac{N_c C_F}{4} \frac{m_c^2}{m_c^2 + Q^2} \alpha_S(m_c^2 + Q^2) L(m_c^2 + Q^2)$$

(12)
which is short of one power of $L$, though. The rise of $F_{cs}^{cs}(x,Q^2)$ towards small $x$ is generated by interactions of the higher Fock states, $c\bar{s} +$ gluons. One can estimate the leading contribution to $F_{cs}^{cs}$ associated with the Fock state $c\bar{s} +$ one gluon,

$$\delta F_{cs}^{cs} \sim \frac{N_c C_F}{4} \frac{m_c^2}{m_c^2 + Q^2} \delta^3(m_c^2 + Q^2) \eta,$$

where $\eta = C_A \log(x_0/x)$.

The DLLA resummation at $Q^2 \lesssim m_c^2$ puts the P-wave component of $F_{L}^{cs}$ in the form

$$F_{L}^{cs} \sim \frac{N_c C_F}{4} \frac{m_c^2}{m_c^2 + Q^2} L^3(m_c^2 + Q^2) \eta^{-1} I_2(2\sqrt{\xi}),$$

where $\xi = \eta L(m_c^2 + Q^2)$ is the DLLA expansion parameter and $I_2(z) \simeq \exp(z)/\sqrt{2\pi z}$ is the Bessel function. Therefore, $F_{L}^{cs}$ rises rapidly to small $x$.

Evidently, the perturbative mechanism of enhancement described above does not work in the light quark ($ud$) channel. Besides, Adler’s theorem allows only a slow rise of $F_{L}^{ud}(x,0)$ to small $x$:

$$F_{L}^{ud}(x,0) \propto (1/x)^{\Delta_{soft}},$$

where $\Delta_{soft} \simeq 0.08$.

At $Q^2 \gg m_c^2$ for $\sigma(x,r) \approx \alpha_S(r^{-2}) G(x,Q^2)$ from [23] and [24] it follows that $F_{L}^{cs} \sim \alpha_S(Q^2) G(x,Q^2)$, what corresponds to the dominance of “non-partonic” configurations with $z \sim 1/2$. Here $G(x,k^2) = xg(x,k^2)$ is the gluon structure function.

We evaluate $F_L$, $F_T$ and $F_2 = F_L + F_T$, for the $\nu Fe$ and $\nu Pb$ interactions making use of the approach to nuclear shadowing developed in [14]. The log$(1/x)$-evolution is described by the
CD BFKL equation with boundary condition at $x_0 = 0.03$. In Fig. our results (valence-quark contributions are neglected) are compared with experimental data. We conclude that the excitation of charm contributes significantly to $F_2$ at $x \lesssim 0.01$ and dominates $F_2$ at $x \lesssim 0.001$ and $Q^2 \lesssim m_c^2$. The agreement with data is quite reasonable but it should be taken with some caution. The point is that the perturbative light-cone density of $u \bar{d}$ states, $|\Psi_{ud}|^2 \sim r^{-2}$, apparently overestimates the role of short distances at small $Q^2$ and gives the value of $F_{L}^{ud}(x,0)$ smaller than that required by Adler’s theorem. This may lead to underestimation of $F_2$ in the region of moderately small $x \gtrsim 0.01$ dominated by the $ud$-current.

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