HIGHER TWISTS AND NUCLEAR EFFECTS

S.A. KULAGIN

Institute for Nuclear Research of the Russian Academy of Sciences
Moscow 117312, Russia

We discuss the impact of nuclear effects on the higher twist terms using a particular example of the structure function $x F_3$ as extracted from a QCD fit to neutrino deep inelastic data on a heavy nucleus target.

The operator product expansion is a common theoretical framework in analyses of deep inelastic scattering (DIS) in QCD. The operators can be ordered according to their twist yielding the series in $Q^{-2}$ for physical observables. For example, for the structure function $F_3$, this reads

$$xF_3(x, Q^2) = xF_3^{LT}(x, Q^2) + \frac{H_3(x, Q^2)}{Q^2} + \ldots$$

(1)

The first term in this expansion (the leading twist, LT) dominates at sufficiently large momentum transfer $Q^2$ and invariant mass $W^2 = M^2 + Q^2(1 - x)/x$. The LT structure functions are constructed in terms of parton distribution functions (PDFs), which are universal for charged lepton and neutrino scattering and have clear probabilistic interpretation. An accurate knowledge of these plays a key role in the extraction of possible contributions of new physics at new collider energies, non-accelerator physics (cosmic neutrinos) and, as observed more recently, in the interpretation of forthcoming high precision experiments on neutrino oscillation.

PDFs are not directly observable and extracted from data in global QCD fits (see, e.g., [1]). The higher twist (HT) terms are presently poorly known and currently is a subject of both theoretical and phenomenological studies [2, 3, 4, 5]. A better understanding of HT terms, in particular their role in describing low $Q^2$ and high $x$ DIS data, is important and provides valuable information on quark–gluon correlations inside the nucleon.

Phenomenological studies of PDF and HT terms are affected by a number of uncertainties. These include the effects due to higher order perturbative terms in renormalization group analysis, threshold resummation effects, target mass corrections, the sensitivity of QCD fits to the choice of parameterization of PDFs and HT, etc. If nuclear data are involved into an analysis, nuclear effects will also have impact on the extracted PDF and HT terms.

In the present contribution we discuss the size of nuclear effects on a particular example of the HT term in the structure function $F_3$ as extracted from neutrino data of CCFR.
collaboration on iron target [3] (for more detailed discussion see [3]). In our fit, we separate the nucleon structure function $F_3^N(x, Q^2)$ into a sum of the LT and the HT terms, [11], and parametrize $xF_3^{LT}$ at some scale $Q_0^2$ in terms of a simple function,

$$xF_3^{LT}(x, Q_0^2) = a_1 x^{a_2} (1 - x)^{a_3} (1 + a_4 x).$$  \hspace{1cm}  \text{(2)}$$

Then we apply the renormalization group equation in order to calculate evolution of $xF_3^{LT}$ with $Q^2$. We solve the renormalization group equation in the leading (LO), next-to-leading (NLO) and next-to-next-to-leading (NNLO) logarithm approximations of QCD. In doing so we expand the leading twist structure function $xF_3^{LT}$ in terms of its Mellin moments within the framework of the Jacobi polynomial method and then apply the evolution equations to the moments (for more detail see [3] and references therein).

We fit 116 data points on the structure function $F_3$ from the CCFR experiment [6] in the kinematical range of $0.0075 \leq x \leq 0.75$ and $Q^2$ between 1.3 and 200 GeV$^2$. The fit parameters are $a_2$, $a_3$, and $a_4$ of Eq.(2) at the scale $Q_0^2$, the values of the function $H_3$ at the center of each $x_i$-bin of the CCFR data set, as well as the QCD scale parameter $\Lambda_{\overline{MS}}$. The parameter $a_1$ was fixed by normalizing (2) to the Gross-Llewellyn-Smith sum rule, which was calculated in QCD to the second order in $\alpha_S$ [11], $S_{GLS} = 3(1 - \alpha_S/\pi - 3.25(\alpha_S/\pi)^2)$.

It should be noticed that in general the higher twist terms can be of two kinds: those which have the kinematical nature, e.g. the terms due to finite target mass, and those which arise due to higher twist operators and reflect the quark-gluon interaction effects in the target. In order to ensure that the HT term in [11] describes effects due to quark-gluon interaction in the target we explicitly take into account target mass correction by substituting the Mellin moments by the Nachtmann moments in the Jacobi polynomial expansion of $xF_3^{LT}$.

In order to apply corrections for nuclear effects in our analysis we first calculate the “EMC ratio” for the iron target, $R_3(x, Q^2) = \frac{1}{56} F_3^{Fe}(x, Q^2)/F_3^N(x, Q^2)$, with $F_3^{Fe}$ the structure function of the $^{56}\text{Fe}_{26}$ nucleus and $F_3^N = \frac{1}{2}(F_3^p + F_3^n)$ the structure function of an isolated isoscalar nucleon. Then we extract “data” on the structure function of the isoscalar nucleon from the CCFR data as $F_3^N(x, Q^2) = F_3^{CCFR}(x, Q^2)/R_3(x, Q^2)$. In calculating the ratio $R_3$ we observe that the bulk of neutrino data with $Q^2 > 1$ GeV$^2$ is located in the region of $x > 0.1$. For this kinematical regime it is usually assumed that nuclear DIS of leptons from nuclear targets can be viewed as incoherent scattering from bound nucleons. Major nuclear effects found in this region are due to nuclear binding and Fermi motion [8]. The relation between a heavy nucleus structure function and the proton and neutron structure functions can be written as follows

$$xF_3^A = \left\langle \left(1 + \frac{p_z}{\gamma M} \right) \left( x' F_3^N + \frac{N-Z}{2A} (x' F_3^p - x' F_3^n) \right) \right\rangle,$$

where $x' = Q^2 / 2p \cdot q$ is the Bjorken variable of the bound nucleon with the four-momentum $p$, $q$ is four momentum transfer and $\gamma = |q|/q_0$ is the ‘velocity’ of the virtual boson in the target rest frame. The averaging is done with respect to the nuclear spectral function and the last term in Eq.(3) takes into account that the neutron, $N$, and the proton, $Z$, numbers are unequal in heavy nuclei. Note also that bound proton and neutron are off-mass-shell and their structure functions depend on the nucleon off-shellness $p^2$ as an additional variable that causes an additional correction [11]. The nuclear spectral function and other details of the present approach are discussed in [3].
Our results are shown in Fig.1. One can observe from Fig.1 that the scale which determines the magnitude of the HT term is $1 \text{GeV}^2$. One also sees that the magnitude of the HT term depends on the level to which the perturbation theory analysis of $F_3^{LT}$ is done. The more perturbative corrections are included into the evolution equation, the less room is left for the function $H_3(x)$. The separation of nuclear effects from data leads to a further suppression of the HT term $H_3(x)$. The effect of nuclear corrections is most pronounced at large $x$, where we observe a systematic reduction of $H_3(x)$ as compared with no-nuclear-effects analysis. Nuclear corrections result in the decrease of the values of the function $H_3(x)$ at $x > 0.6$. We also found that the separation of nuclear effects causes the $\Lambda_{\overline{MS}}$ to decrease for about 10% leading to the shift of the value of $\alpha_S(M_Z)$ for about $2 \cdot 10^{-3}$. As a final remark, we comment that a reduction of the HT terms because of nuclear effects at large $x$ has recently been observed in the analysis of charged lepton DIS data on proton and deuteron targets.

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\[\text{However, the HT term in the structure function } F_2 \text{ of } \text{[1] appears to be an order of magnitude less than the central points of } H_3 \text{ of } \text{[3, 5]. Furthermore, the effect of strong correlation between the order of pQCD analysis and the magnitude of the HT term, first observed in } \text{[4] for neutrino data, is not seen in the recent analysis of } \text{[1].}\]
Figure 1: The function $H_3(x)$ in the units of GeV$^2$, which describes the strength of the higher twist term in the $xF_3$ structure function as extracted from the fit to the CCFR neutrino data. The labels on the figure indicate the level to which the perturbation theory analysis of $xF_3^{LT}$ is done. Only statistical errors are shown.