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Nucleon correlations and higher twist effects in nuclear structure functions

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The overlap of the nucleons in nuclei plays an important role in understanding the nuclear dependence of deep inelastic scattering data. It is shown that the nuclear modification of the higher twist scale can be essentially determined by the overlapping volume per nucleon and this effect gives a large contribution to nuclear shadowing for small x and low Q^2. In this kinematical region there is also a moderate enhancement of the longitudinal structure function in nuclei.

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The interpretation of the HERA and RHIC data and the future experiments at LHC require a deep understanding of the behavior of the parton distributions in the small x region both for the free nucleon and for nuclei.

The main ideas of the dynamical description of the small x physics are the saturation of the parton densities and the shadowing effects. Both these problems can be studied from the fundamental point of view by the nonlinear QCD evolution equations. However, since they are related with confinement, some complementary approaches, such as classical gluon field theory [1] or the pomerons exchange [2], take into account the nonperturbative dynamics.

Nuclear shadowing is a crucial ingredient of the initial state effects in hard phenomena in proton-nucleus and nucleus-nucleus collisions and some useful, model independent, phenomenological analyses of the nuclear modifications of the parton distributions have been proposed [3].

The major difficulty for a clear theoretical description of the nuclear shadowing is that the available data on deep inelastic scattering (DIS) on a nuclear target in the small x region are also for small Q^2 and then the standard QCD evolution becomes unreliable.

Recently the calculation of the nuclear parton distribution functions in the Gribov approach [4] has been updated [5], and the failure of the leading twist model to describe the DIS data indicates significant higher twist (HT) contributions in the small x region. In particular, the HT contribution to nuclear shadowing turns out about 50% of the whole suppression, and the authors argue that, in the kinematical range covered by data, it is possible to have this large corrections due to diffractive effects. On the other hand, in Ref. [6] the HT contribution turns out to be small (as will be discussed later).

In this paper we suggest that in the small x and low Q^2 region the HT contributions are relevant for the agreement with the present day data on nuclear shadowing. This conclusion, that can be obtained also by resumming QCD power corrections [7], is based on an intuitive, coarse-grain analysis of the typical nuclear HT scale by the overlap of nucleons in the nucleus.

Indeed, in the small x region, DIS is controlled by the dipole nature of the interaction of the virtual photon with the target and by the pomeron exchange. Shadowing clearly indicates that the effective coupling of the pomeron with a bounded nucleon is suppressed with respect to the free nucleon case.

On the other hand, the observed flavor dependence of the total cross sections is explained [8,9] by the suggestion that the average spatial separation of the quarks in the target determines the strength of the hadron-pomeron coupling, β_p. Moreover, the variation of total cross sections with the average quark separation, r, in the hadron involved has been quantified in Ref. [10] where it has been shown that $\beta_p \simeq r^2$.

Therefore, in a nuclear environment one expects the modifications of the structure function at small x to be related to the overlapping volume per nucleon V_A^{op} in the nucleus A.

This idea has been proposed to explain the EMC effect and also the nuclear shadowing in Refs. [11,12], where the overlapping volume has been approximately evaluated by the geometrical two-nucleon overlap. The general reasons to apply the same approximation to set also the HT nuclear scale are the following:

(a) The Glauber-Gribov theory is based on the nuclear corrections due to scattering of any pair of nucleons in the nucleus and on diffractive effects;
(b) The geometrical three-nucleon overlap is small [11].

We shall show that by a simple analysis, based on the overlapping volume per nucleon in the nucleus, one can suggest that:

(i) there is a nuclear modification of the HT scale which gives a relevant contribution to nuclear shadowing in the present day data;
(ii) the nuclear correction to the longitudinal structure function, F_{2A}^L, are small as reported in Ref. [13].

Let us first discuss the higher twist effects which are subasymptotic scaling violations, $O(\mu^2/Q^2)$, whose typical scale μ^2 is fixed by the matrix elements of the relevant operators in the light-cone expansion of the product of the currents operators. In particular, Jaffe and Soldate [14] found a complete set of nine operators, totally symmetric, traceless in Lorentz indices and depending on color, spin and flavor indices, which permits us to evaluate the twist-four, spin-two contribution to electroproduction in QCD.

The HT formalism has been largely applied [15] and it requires a specific model to evaluate the nonperturbative, target-dependent matrix elements. For example, in the MIT bag model the twist-four correction to the nucleon structure function F_{2N} turns out

$$\int dx F_{2N}^{\rm HT} = \frac{1}{2}\frac{\pi\alpha_c}{Q^2 M_N V_N}\left(-\frac{131}{27}K_1 + 8K_2\right), \qquad (1)$$

where M_N and V_N are, respectively, the nucleon mass and volume; α_C is an effective coupling constant in the bag (usually $\alpha_c = 0.5$ is assumed); and $K_1 = 1.08$ and $K_2 = 0.17$ are integrals over V_N of the bag model spinors for massless quarks in the lowest modes [14].

This result, by itself, is not useful for the comparison with DIS data because one needs to analyze the x dependence and, moreover, in the small x, low Q^2 region the valence approximation of the bag model is not reliable. A complete calculation of the matrix elements is still missing and, on the other hand, it is quite useful to have, at least, a phenomenological understanding of the HT contributions, crucial for the agreement with data at small Q^2.

Then, following the structure of Eq. (1), let us write

$$F_{2N}^{\rm HT} = \frac{1}{2}\frac{\pi\alpha_c}{Q^2 M_N V_N}C_N(x) \qquad (2)$$

and try to have some indication of the effective weight of the matrix elements for determining the HT scale of the nucleon in the small x region. The next step will be to generalize the analysis for a nuclear target.

However, before entering in the phenomenological details, let us consider some results which follow from general arguments.

Let us write the F_2 structure functions as a leading twist term (LT) plus an $O(1/Q^2)$ HT contribution. For the nucleon case we shall approximate $F_{2N} = F_{2D}/2$ since at high energy the nuclear effects in deuterium are negligible and from now on the formulas refer to structure functions per nucleon. For deuterium one has $F_{2D} = F_{2D}^{\rm LT} + F_{2D}^{\rm HT}$ and for a larger nucleus A, $F_{2A} = F_{2A}^{\rm LT} + F_{2A}^{\rm HT}$. By defining $R_A^{\rm LT} = F_{2A}^{\rm LT}/F_{2D}^{\rm LT}$ and $R_A = F_{2A}/F_{2D}$, to order $O(1/Q^2)$, one obtains

$$R_A\left[1 - \frac{F_{2A}^{\rm HT}}{F_{2A}} + \frac{F_{2D}^{\rm HT}}{F_{2D}}\right] = R_A^{\rm LT}. \qquad (3)$$

Then the HT corrections can suppress the (LT) term only if $R_A F_{2D}^{\rm HT} > F_{2A}^{\rm HT}$. Since in the small x region $R_A < 1$, if the HT correction increases the (LT) term (i.e. it is positive) then the effective HT scale must be larger in deuterium with respect to the larger nucleus A. Vice versa, if the HT terms are negative the larger nuclei have a larger effective scale at small x.

Concerning the sign of the HT correction to F_{2D} let us notice that (1) in the MIT bag model this overall correction is negative [see Eq. (1)]; (2) in the parameterization of the deuteron structure function data in Ref. [16] the $O(1/Q^2)$ leading correction in the small x region is negative.

By assuming this indication, one concludes that the nuclear HT corrections are negative and there is a larger HT effective scale at small x with respect to the nucleon case. Moreover one can use the phenomenological input given in Ref. [16] and write that

$$F_{2D}^{\rm HT} = \frac{1}{2}\frac{\pi\alpha_c}{Q^2 M_N V_N}C_D(x) \simeq -\frac{c_1 x + c_2 x^2}{Q^2}, \qquad (4)$$

where $c_1 = 1.509\ {\rm GeV}^2$ and $c_2 = -8.553\ {\rm GeV}^2$ [16]. Of course this approximation is valid only in the small x region considered in the data of Ref. [16].

Let us now consider the nuclear effects. The HT corrections come essentially from the matrix elements of quark-quark-gluon and/or four quark operators [14] in the target and then in a nucleus there are peculiar contributions, with respect to the free nucleon, due to the nuclear binding and to partons coming from different nucleons in the nucleus. A rigorous calculation is quite hard, but, according to the parameterization in Eq. (2), it is natural a description of the nuclear effects which takes into account the nuclear binding energy by an effective mass of the nucleon, $M^* = M_N + \epsilon$ (where ϵ is the removal energy; see the discussion in [17]), and the correlation among nucleons by their overlap in the nucleus as previously discussed.

More precisely, as discussed in Ref. [12], which essentially is the first simple explanation of shadowing in the dipole picture, one considers $V_N \simeq (r^2)^{3/2}$ and the HT contribution to F_{2A} per nucleon can be parameterized as [see Eq. (2)]

$$F_{2A}^{\rm HT} = \frac{1}{2}\frac{\pi\alpha_c}{Q^2 M^* V_A}C_A(x), \qquad (5)$$

where $V_A/V_N = 1 - V_A^{op}/V_N$ and $C_A(x)$, related to the matrix element of the relevant operator in the nucleus, takes also into account the HT contribution due to partons from different nucleons. It is reasonable to assume that this dynamical effect is proportional to the overlapping volume per nucleon, V_A^{op}, and then to write

$$C_A(x) = C_D(x) + C(x)\frac{V_A^{op}}{V_N}, \qquad (6)$$

where $C(x)$ is independent on A.

Then the HT nuclear correction turns out that

$$F_{2A}^{\rm HT} = F_{2D}^{\rm HT}\frac{M_N}{M^*}\frac{V_N}{V_A}\left[1 + \gamma(x)\frac{V^{op}}{V_N}\right] \equiv F_{2D}^{\rm HT}\Sigma_A, \qquad (7)$$

where $\gamma(x) = C_A(x)/C_N(x)$ will be approximated, in the small x region, with a constant parameter γ, in such a way that the HT nuclear scale is completely determined by the overlapping volume per nucleon.

By combining the previous Eqs. (3) and (7), the relation between $R_A^{\rm LT}$ and R_A in terms of the HT corrections is given by

$$R_A = \frac{R_A^{\mathrm{LT}} + \frac{F_{2D}^{\mathrm{HT}}}{F_{2D}} \Sigma_A}{1 + \frac{F_{2D}^{\mathrm{HT}}}{F_{2D}}}, \tag{8}$$

which is the starting point for the comparison with the experimental data.

In the previous formula the only free parameter is γ. Indeed the overlapping volume per nucleon has been evaluated in Ref. [11] by including a Reid-soft core potential between nucleons and considering only the two-nucleon overlap. In Ref. [18] the previous evaluation has been reanalyzed with a reduction of a factor $\simeq 0.65$ with respect to the initial values. Then the overlapping volume per nucleon for different nuclei is fixed as the 65% [19] of the values obtained in Ref. [11]. The removal energy ϵ is small (few MeV) and negative, and it has a negligible quantitative effect. F_{2D}^{HT} is given in Eq. (4) and F_{2D} is experimentally known for small value of x and accurately parameterized [16]. Finally, one has to know R_A^{LT} and different LT inputs change the fitted value of the parameter γ.

From this point of view, it should be clear that the agreement with data depends on the relative weight between the LT and the HT contributions. The power corrections are an important element of the whole analysis but their magnitude is correlated with the initial parameterization of the structure functions for the Q^2 evolution. In Ref. [5] a model of diffraction is used in order to obtain an initial condition for evolution equation at $Q_O^2 = 4\ \mathrm{GeV}^2$. On the contrary, in Ref. [6] a model, to all twist orders, is proposed for the full low Q^2 region and there is no QCD evolution. In this latter framework, where a small HT correction is reported, it is not simple to handle the $O(1/Q^2)$ and clearly separate a "LT" term. Then, in the present analysis, one considers the leading twist results in the Gribov approach obtained in Ref. [5]. In Fig. 1 we report the comparison of the leading twist theory plus higher twist contributions, according to Eq. (8) to the NMC data [20] on F_{2C}/F_{2D}. The dashed and dotted-dashed lines are, respectively, for $\gamma = 3$ and $\gamma = 4$ and the dotted line is the leading twist result in Ref. [5]. Figure 2 has the same comparison with the Ca-40 data, and in Fig. 3 the comparison is with the ratio F_{2PB}/F_{2C}. In Fig. 4 we have considered the Q^2 dependence at fixed $x = 0.0125$ of the ratio F_{2Sn}/F_{2C} [21].

The comparison with data is confined to the small x region due to the reliability of the parameterization in Eq. (4) and because the antishadowing and the energy-momentun sum rule are not implemented in the present analysis.

The phenomenological fit gives $\gamma \simeq 3$ which sets the ratio of the HT nuclear scale with respect to the free nucleon case, Σ_A. It is quite interesting to notice that, with the previous value of γ, Σ_A reproduces within 15% the nuclear scale associated with parton saturation obtained [22] by fitting the whole deep inelastic scattering nuclear data in the small x region.

Let us now comment on the longitudinal structure function F_{2A}^L. In Ref. [23] the authors initially reported a quite

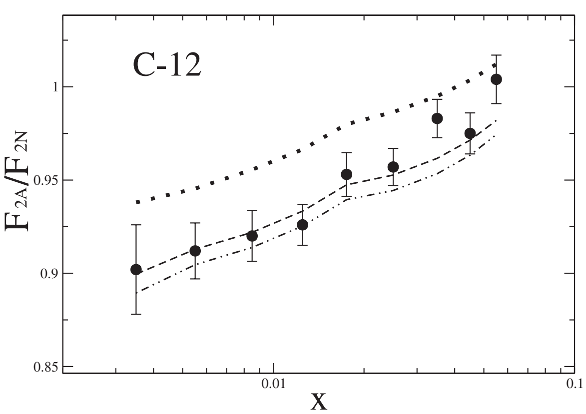

FIG. 1. Comparison of the leading twist theory plus higher twist contributions according to Eq. (8) to the NMC data [20] on F_{2C}/F_{2D} (see text). The statistical and systematic errors are quadratically added.

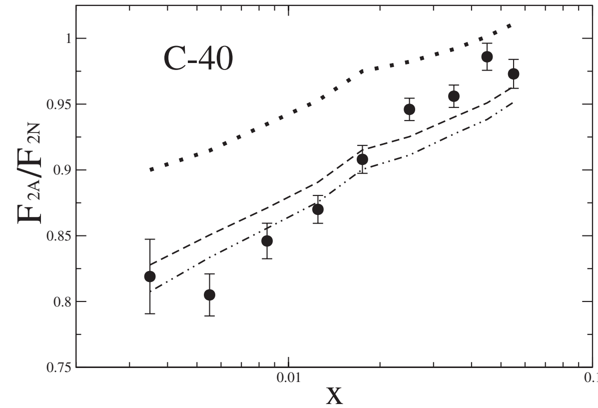

FIG. 2. Comparison of the leading twist theory plus higher twist contributions, according to Eq. (8) to the NMC data [20] on F_{2Ca}/F_{2D} (see text). The statistical and systematic errors are quadratically added.

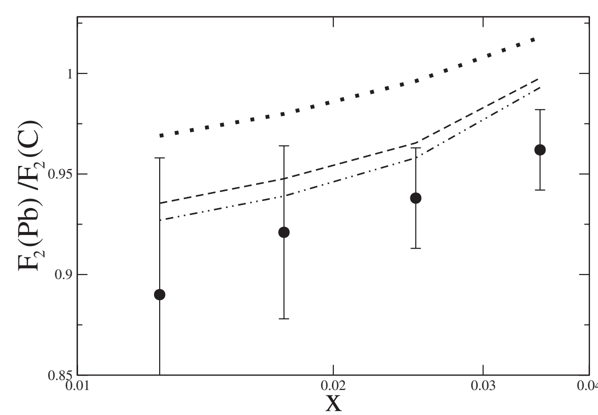

FIG. 3. Comparison of the leading twist theory plus higher twist contributions to the NMC data on F_{2Pb}/F_{2C} (see text). The statistical and systematic errors are quadratically added.

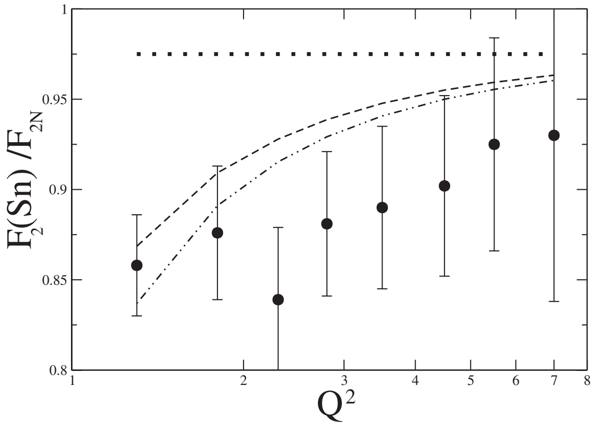

FIG. 4. Comparison of the leading twist theory plus higher twist contributions to the NMC data on F_{2Sn}/F_{2C} at $x = 0.0125$ and different Q^2 (see text). The statistical and systematic errors are quadratically added. The dotted line is the leading twist result 0.975 [5].

large value (about a factor 4) of the ratio between the longitudinal and transverse structure functions in N-14 for $x \simeq 0.0045$ and low Q^2 with respect to the deuterium case.

This enhancement has been investigated by many authors [7,24,25] with the conclusion that a large HT correction for nytrogen is required. Indeed, also in this case, the effect is due to a balance between the LT term and HT correction which depends on the absolute value of the HT scale rather than on the ratio between the nitrogen and deuterium HT scale.

In [13] the data have been reanalyzed and there is no large nuclear correction to the longitudinal structure function. By the present analysis, an enhancement should be found because the HT nuclear scale increases. However it turns out that the effective HT nytrogen scale at $x \simeq 0.0045$ is much smaller than the value of 0.056 GeV^2 required [25] to obtain the previously reported large corrections and then the final effect is small and well within the experimental error in Ref. [13]

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