Coherent Power Corrections to Structure Functions

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Abstract.
We calculate and resum a perturbative expansion of nuclear enhanced power corrections to the structure functions measured in deeply inelastic scattering of leptons on a nuclear target. Our results for the Bjorken $x$, $Q^2$- and $A$-dependence of nuclear shadowing in $F_A^T(x, Q^2)$ and the nuclear modifications to $F_A^L(x, Q^2)$, obtained in terms of the QCD factorization approach, are consistent with the existing data. We predict the dynamical shadowing from final state interactions in $\nu + A$ reactions for sea and valence quarks in the structure functions $F_A^T(x, Q^2)$ and $xF_A^L(x, Q^2)$, respectively. In $p + A$ collisions we calculate the centrality and rapidity dependent nuclear suppression of single and double inclusive hadron production at moderate transverse momenta.

Dynamical high twist shadowing

Under the approximation of one-photon exchange, the lepton-hadron DIS cross section $d\sigma_{lh}/dx dQ^2 \propto L_{\mu \nu} W^{\mu \nu}(x, Q^2)$, with Bjorken variable $x = Q^2 / (2p \cdot q)$ and virtual photon’s invariant mass $q^2 = -Q^2$. The hadronic tensor can be expressed in terms of structure functions based on the polarization states of the exchange virtual photon: $W^{\mu \nu}(x, Q^2) = \epsilon^{\mu \nu}_T F_T^L(x, Q^2) + \epsilon^{\mu \nu}_L F_T^L(x, Q^2)$. In DIS the exchange photon $\gamma^* = Q^2 / (2x m_N)$ probes an effective volume of transverse area $1/Q^2$ and longitudinal extent $\Delta z_N \times x_N / x$, where $\Delta z_N$ is the nucleon size, $x_N = 1/(2r_0 m_N) \sim 0.1$ and $r_0 \sim 1.2$ fm. When Bjorken $x \ll x_N$ the lepton-nucleus DIS covers several nucleons in longitudinal direction while it is localized in the transverse plane.

In the lightcone $A^+ = 0$ gauge and the Breit frame we identify the natural short and long distance separation of the multiple final state interactions from the propagator structure of the struck quark, $i(\gamma^+/2p^+) / (x_i - x \pm ie)$ (pole term) and $ixp^+ / Q^2 \gamma^-$ (contact term) [1]. The two gluon contact exchange is therefore evaluated in a single nucleon state. Resumming the $A^{1/3}$-enhanced power corrections we find [1]:

$$F_T^A(x, Q^2) \approx A F_T^{(LT)} \left( x + \frac{x_N^2 (A^{1/3} - 1)}{Q^2}, Q^2 \right), \quad (1)$$

$$F_L^A(x, Q^2) \approx A F_L^{(LT)} (x, Q^2) + \frac{4 \xi^2}{Q^2} F_A(x, Q^2). \quad (2)$$
Here, $\xi^2$ represents the characteristic scale of higher twist per nucleon to $\mathcal{O}(\alpha_s)$:

$$\xi^2 = \frac{3\pi\alpha_s(Q^2)}{8r_0^2} \langle p | \hat{F}^2(\lambda_i) | p \rangle, \quad \langle p | \hat{F}^2(\lambda_i) | p \rangle = \lim_{x \to 0} \frac{1}{2x} x G(x, Q^2).$$

The $x$- and $A$-dependence of $F_2(A)/F_2(D)$, calculated for $\xi^2 = 0.09 - 0.12$ GeV$^2$, is given in the left panel of Fig. 1. Comparison to a leading twist shadowing parameterization [2] is also shown. The right panel of Fig. 1 indicates the power law nature of the nuclear modification to the structure functions. The physical gluon exchange leads to a high twist contribution to the longitudinal structure function $F_L$ and enhances the ratio $R = \sigma_L/\sigma_T$. We emphasize that both leading twist [3] and high twist shadowing [1] have their origin in the final state coherent scattering. This provides a natural explanation of the apparent lack of gluon shadowing in the NLO global analysis [4] which is the only one directly sensitive to gluons.
**Neutrino-nucleus scattering**

Neutrino-nucleus scattering provides the unique opportunity to separately study the effect of coherent power corrections for sea and valence quarks \( F_2(x, Q^2) \) and \( xF_3(x, Q^2) \) through the structure functions:

\[
F_{1(3)}^{V_A}(x_B, Q^2) \approx A(2) \left[ \sum_{D,U} |V_{DU}|^2 \phi_D^3 \left( x_B + x_B \frac{\xi^2(A^{1/3} - 1)}{Q^2} + x_B \frac{M_D^2}{Q^2}, Q^2 \right) \right. \\
\left. + (-) \sum_{C,D} |V_{CD}|^2 \phi_C^3 \left( x_B + x_B \frac{\xi^2(A^{1/3} - 1)}{Q^2} + x_B \frac{M_D^2}{Q^2}, Q^2 \right) \right] .
\]  

(3)

Here \( V_{DU} \) are the CKM matrix elements. Eq. (3) identifies the nuclear enhanced high twist corrections with dynamical mass \( m_{dyn}^2 = \xi^2(A^{1/3} - 1) \) generated by the final state parton scattering through direct comparison to \( M_{U,D}^2 \).

The modification to the structure functions \( F_2(x, Q^2) \) and \( xF_3(x, Q^2) \) for two select values of \( x_B \) are shown in the left panel of Fig. 2. These give a good description of the observed power law deviation of the reduced cross sections measured by NuTeV \([6, 7]\) from the leading twist pQCD at small values of \( Q^2 \). Note the difference in the “shadowing” of \( F_2 \) and \( xF_3 \) due to the different steepness of sea and valence quark PDFs (in \( x \)). The right panel of Fig. 2 demonstrates the improved agreement between data and theory for the Gross-Llewellyn-Smith sum rule \( \Delta_{GLS} \) \([5]\):

\[
\Delta_{GLS} \equiv \frac{1}{3} (3 - S_{GLS}) = \frac{\alpha_s(Q^2)}{\pi} + \frac{g^2}{Q^2} + \mathcal{O}(Q^{-4}) .
\]  

(4)
Proton-nucleus collisions

The proton + nucleus analogue of the DIS coherent power corrections is the final state interactions of the small $x_b$ parton in the $|\vec{t}| \ll |\vec{s}|, |\vec{q}|$ regime. Here $\vec{t} = q^2 = (x_d P_d - P_T / z_1)^2$ and the $x_b$ rescaling in the lowest order pQCD formalism reads [8]:

$$F_{ab \rightarrow cd}(x_b) \Rightarrow F_{ab \rightarrow cd} \left( x_b \left[ 1 + C_d \frac{\xi^2}{-t} (A^{1/3} - 1) \right] \right).$$

In Eq. (5) $F_{ab \rightarrow cd}(x_b) = |M_{ab \rightarrow cd}|^2 \phi(x_b)/x_b$ and $C_d$ is a color factor, $C_{q(\bar{q})} = 1$ and $C_g = C_A/C_F = 9/4$ for quark (antiquark) and gluon, respectively.

The left panel of Fig. 3 shows the upper limit on the centrality and rapidity dependent suppression $R^{(1)}_{pA}$ of single inclusive hadron production at RHIC. Data is from BRAHMS [9]. Additional nuclear suppression arises from the energy loss in cold nuclei [10]. The right panel shows the suppression of away side dihadron correlations $R^{(2)}_{pA}$ versus transverse momentum, rapidity and centrality on the example of the area of the correlation function $C(\Delta \phi) = dN_{h_1 \rightarrow h_2} / d\Delta \phi$ The pronounced $p_T$ dependence is consistent with STAR preliminary data [11].

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REFERENCES

1. J. W. Qiu and I. Vitev, Phys. Rev. Lett. 93, 262301 (2004).
2. K. J. Eskola, V. J. Kolhinen and C. A. Salgado, Eur. Phys. J. C 9, 61 (1999); V. Kolhinen, these proceedings.
3. S. J. Brodsky, P. Hoyer, N. Marchal, S. Peigne and F. Sannino, Phys. Rev. D 65, 114025 (2002); these proceedings.
4. D. de Florian and R. Sassot, Phys. Rev. D 69, 074028 (2004).
5. J. W. Qiu and I. Vitev, Phys. Lett. B 587, 52 (2004).
6. V. A. Radescu [NuTeV Collaboration], arXiv:hep-ex/0408006.
7. M. Tzanov et al. [NuTeV Collaboration], arXiv:hep-ex/0306035; these proceedings.
8. J. W. Qiu and I. Vitev, hep-ph/0405068.
9. I. Arsene et al. [BRAHMS Collaboration], Phys. Rev. Lett. 93, 242303 (2004).
10. B. Z. Kopeliovich, J. Nemchik, I. K. Potashnikova, M. B. Johnson and I. Schmidt, hep-ph/0501260.
11. A. Ogawa [STAR collaboration], nucl-ex/0408004.