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 $F_2^A(x,Q^2)$ and the nuclear modifications to $F_L^A(x,Q^2)$, obtained in terms of the QCD factorization approach, are consistent with the existing data. We predict the dynamical final state shadowing in $\nu+A$ reactions for sea and valence quarks in the structure functions $F_2^A(x,Q^2)$ and $F_3^A(x,Q^2)$, 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.

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Dynamical high twist shadowing

Under the approximation of one-photon exchange, the lepton-hadron DIS cross section $d\sigma_{\ell h}/dx dQ^2 \propto L_{\mu\nu} W^{\mu\nu}(x,Q^2)$, 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: $W^{\mu\nu}(x,Q^2) = \varepsilon_T^{\mu\nu} F_T(x,Q^2) + \varepsilon_L^{\mu\nu} F_L(x,Q^2)$. In DIS the exchange photon γ^* of virtuality Q^2 and energy $\nu = Q^2/(2xm_N)$ probes an effective volume of transverse area $1/Q^2$ and longitudinal extent $\Delta z_N \times x_N/x$, where Δz_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, $i(\gamma^+/2p^+)/(x_i - x \pm i\varepsilon)$ (pole term) and $i(xp^+/Q^2)\gamma^-$ (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]:

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

$$F_L^A(x,Q^2) \approx A F_L^{(\mathrm{LT})}(x,Q^2) + \frac{4\xi^2}{Q^2} F_T^A(x,Q^2) \, . \quad (2)$$

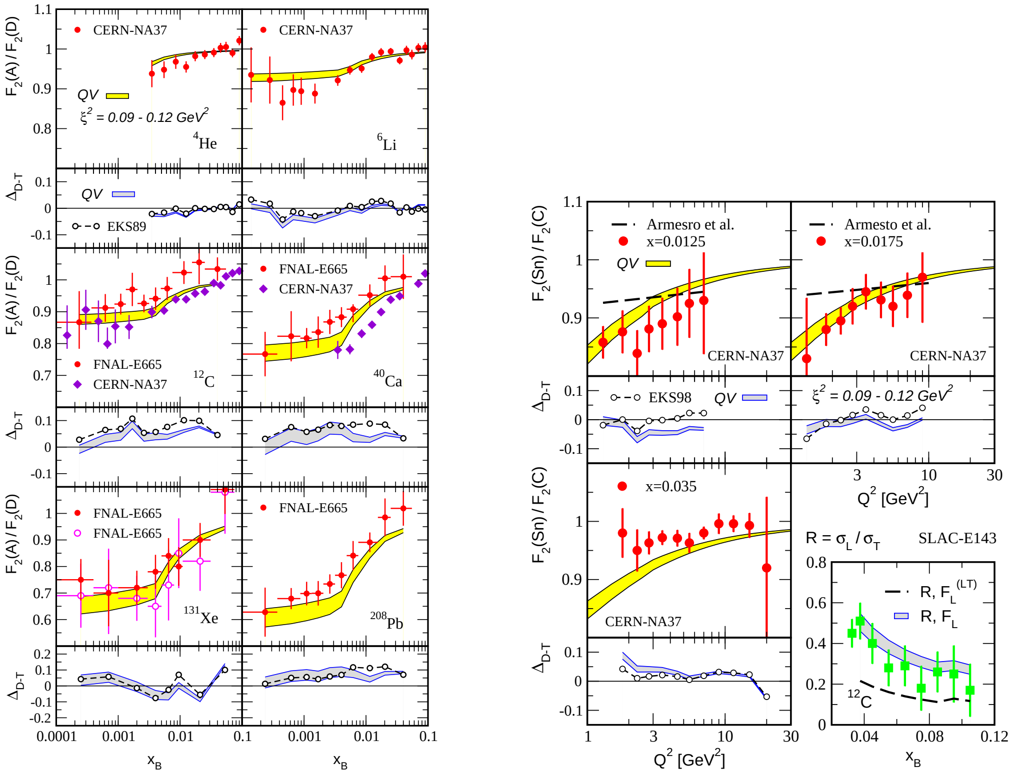

FIGURE 1. Left panel: $F_2(A)/F_2(D)$ calculation of resummed power corrections versus nuclear A and Bjorken-x [1]. Right panel: $F_2(Sn)/F_2(C)$ show evidence for a power-law in $1/Q^2$ behavior consistent with the all-twist resummed calculation [1]. The bottom right panel illustrates the role of higher twist contribution to F_L on the example of $R = \sigma_L/\sigma_T$.

Here ξ^2 represents the characteristic scale of higer twist per nucleon to $\mathscr{O}(\alpha_s)$:

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

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.

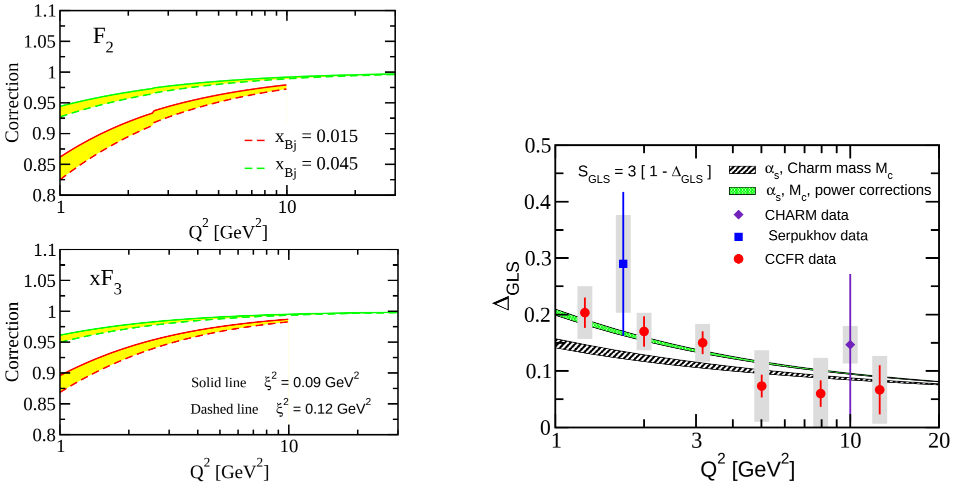

FIGURE 2. Left panel: power corrections to the structure functions $F_2(x,Q^2)$ and $xF_3(x,Q^2)$ [5] for two values of x_B corresponding to NuTeV measurements [7]. Right panel: high twist modification to the Gross-Llewellyn-Smith sum rule Δ_{GLS} [5].

Neutrino-nucleus scattering

Neutrino-nucleus scattering provides the unique opportunity to separately study the effect of coherent power corrections for sea and valance quarks [5] through the structure functions:

$$\begin{aligned} F_{1(3)}^{\nu A}(x_B,Q^2) \;\; &\approx \;\; A(2)\left[\sum_{D,U} |V_{DU}|^2 \phi_D^A \left(x_B + x_B \frac{\xi^2(A^{1/3}-1)}{Q^2} + x_B \frac{M_U^2}{Q^2}, Q^2 \right)\right. \\ &\left. +(-) \sum_{\bar{U},\bar{D}} |V_{\bar{U}\bar{D}}|^2 \phi_{\bar{U}}^A \left(x_B + x_B \frac{\xi^2(A^{1/3}-1)}{Q^2} + x_B \frac{M_D^2}{Q^2}, Q^2 \right)\right] . \qquad (3) \end{aligned}$$

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 [5]:

$$\Delta_{\rm GLS} \equiv \frac{1}{3}(3 - S_{\rm GLS}) = \frac{\alpha_s(Q^2)}{\pi} + \frac{\mathscr{G}}{Q^2} + \mathscr{O}(Q^{-4}) \, . \qquad (4)$$

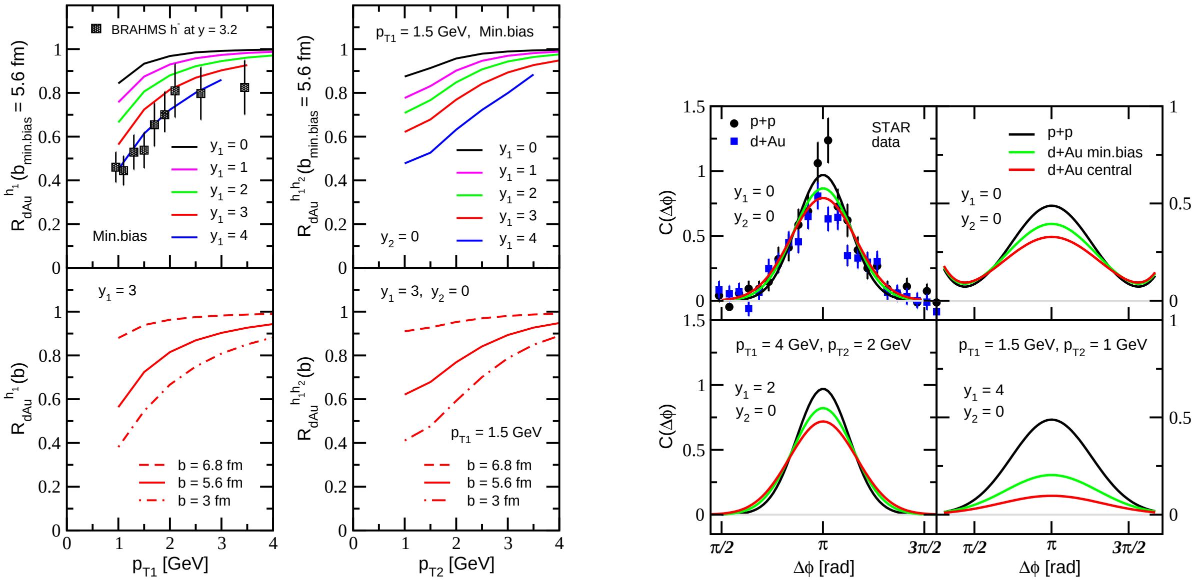

FIGURE 3. Left panel: upper limit on the suppression of the single inclusive particle production $R^{(1)}_{pA}(p_{T_1})$ from coherent power corrections versus rapidity and centrality [8]. Data is from BRAHMS [9]. Right panel: suppression of the double inclusive cross section $R^{(2)}_{pA}(p_{T_1}, p_{T_2})$ for different rapidity gaps, p_{T_1}, p_{T_2} ranges and centrality.

Proton-nucleus collisions

The $p+A$ analogue of the DIS coherent power corrections is the final state interactions of the small x_b parton in the $|\hat{t}| \ll |\hat{s}|, |\hat{u}|$ regime. Here $\hat{t} = q^2 = (x_a P_a - P_c/z_1)^2$ and the x_b rescaling in the lowest order pQCD formalism reads [8]:

$$F_{ab\to cd}(x_b) \quad \Rightarrow \quad F_{ab\to cd}\left(x_b \left[1 + C_d \frac{\xi^2}{-t}(A^{1/3} - 1) \right] \right) \,. \qquad (5)$$

In Eq.(5) $F_{ab\to cd}(x_b) = |M_{ab\to cd}|^2 \phi(x_b)/x_b$ 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 form 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 $C(\Delta\phi) = dN^{h_1,h_2}/d\Delta\phi$ The pronounced p_{T_2} dependence is consistent with STAR preliminary data [11].

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