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DIFFRACTION AND NUCLEAR SHADOWING*

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I present results from our recent leading twist QCD analysis of nuclear shadowing and contrast them with predictions using the eikonal model. By exploiting QCD factorisation theorems, the leading twist approach employs diffractive parton distributions, extracted from diffractive DIS measurements at HERA, to calculate the nuclear shadowing correction on the parton level. Large nuclear shadowing effects are found for the gluon channel which are reflected in the predictions for $F_{\rm L}^A$.

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The most naive assumption about Deep Inelastic Scattering (DIS) on a nucleus one can make is that the photon scatters independently of each nucleon, which gives for the nuclear structure function: $F_2^A = AF_2^N$. For small $x \lesssim 0.05$ the main negative nuclear correction is nuclear shadowing, *i.e.* the coherent interaction of the photon with several nucleons at once, which leads to $F_2^A/AF_2^N < 1$. For a low density nucleus, nuclear shadowing is closely related to diffraction off a nucleon. The leading twist QCD analysis of Frankfurt and Strikman [1] relates nuclear PDFs to Diffractive Parton Distribution Functions (DPDFs), by exploiting the QCD factorisation theorem for inclusive diffraction [2]. In this talk I present some results from the detailed analysis of [3] which exploited the latest available DPDFs to make predictions for nuclear shadowing and hence nuclear PDFs. The leading twist approach has a sharply contrasting space-time picture and predictions to the popular eikonal approach to nuclear shadowing (which is closely related to the $q\bar{q}$-dipole model of diffraction).

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Why should one be interested in DIS on a nucleus? Firstly, nuclear PDFs provide boundary conditions for novel process (*e.g.* the search for beyond the standard model effects, or for new matter states in QCD such as the quark gluon plasma) as well as for "standard" QCD processes in nuclear collisions. Secondly, a particularly interesting feature of eA is the access to a high parton density regime at much lower energies than in DIS on nucleons. Thirdly, because of the intimate connection between nuclear shadowing and diffraction on a nucleon, high statistics data on nuclear PDFs could be used to discriminate between competing models of diffraction. Lastly, the study of DIS on nuclei is timely since high energy electron nucleus collisions are currently being considered seriously for HERA after 2006 and there is an Electron–Ion Collider (EIC) planned for the USA circa 2012.

The starting point of the leading twist approach to nuclear shadowing is the application of the logic of Gribov [4] to DIS on the deuteron. The optical theorem relates the total cross section, $\sigma_{\rm tot}(\gamma^* D)$ to the imaginary part of the forward scattering amplitude. On the forward amplitude level the photon may interact elastically with either the proton or the neutron or diffractively with both. The latter case corresponds to the nuclear shadowing correction (see Fig. 1). Hence the nuclear shadowing correction $\delta F_2^D = F_2^p + F_2^n - F_2^D$, can be expressed in terms of the structure function for the diffractive scattering of the photon off a nucleon:

$$\delta F_2^D(x,Q^2) = 2\frac{1-\eta^2}{1+\eta^2}\int dt\, dx_{\mathbb{P}} F_2^{D(4)}\left(\beta,Q^2,x_{\mathbb{P}},t\right) F_D\left(4t+4x_{\mathbb{P}}^2 m_{\rm N}^2\right)\,, \qquad (1)$$

where the pre-factor, involving $\eta = {\rm Re}A^D/{\rm Im}A^D = \pi/2(\alpha_{\mathbb{P}}(0)-1)$ comes from the AGK cutting rules and F_D is the deuteron form factor.

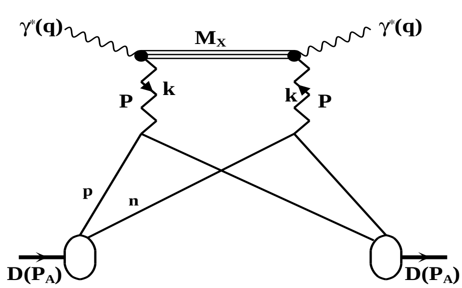

Fig. 1. Nuclear shadowing diagram in virtual photon deuteron scattering.

The result for deuteron generalises easily to any pair of nucleons in a nucleus with A nucleons:

$$\delta F_2^{A(2)} = \frac{A(A-1)}{2} 16\pi \mathrm{Re}\Bigg[\frac{(1-i\eta)^2}{1+\eta^2} \int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \int_{x}^{x_{\mathbb{P},0}} dx_{\mathbb{P}} \times F_2^{D(4)}(\beta, Q^2, x_{\mathbb{P}}, k_t^2)\Big|_{k_t^2=0} \rho_A(b,z_1)\rho_A(b,z_2)\, \mathrm{e}^{ix_{\mathbb{P}} m_N (z_1-z_2)} \Bigg], \quad (2)$$

where ρ is the nucleon density, z, b are longitudinal position and impact parameter of the nucleon concerned. The interaction with more than two nucleons requires some modelling, and we invoke σ_{eff} for the re-scattering cross section (calculated in the quasi-eikonal approximation).

Since inclusive and diffractive structure functions both factorise, and have the same coefficient functions, one can factor off the hard pieces to relate the PDFs themselves. Hence, on the parton level

$$\delta f_{j/A}(x, Q^2) = \frac{A(A-1)}{2} 16\pi \mathrm{Re}\Bigg[\frac{(1-i\eta)^2}{1+\eta^2} \int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \int_{x}^{x_{\mathbb{P},0}} dx_{\mathbb{P}} \times f_{j/N}^{D}(\beta, Q^2, x_{\mathbb{P}}, 0)\, \rho_A(b,z_1)\, \rho_A(b,z_2) \times \mathrm{e}^{ix_{\mathbb{P}} m_N (z_1-z_2)}\, \mathrm{e}^{-\left(\frac{A}{2}\right)(1-i\eta)\sigma_{\mathrm{eff}}^{j} \int_{z_1}^{z_2} dz \rho_A(z)} \Bigg], \quad (3)$$

where $f_{j/N}^{D}$ is the DPDF for a parton of flavour j. The exponential factor in the last line calculates the re-scattering. We used several models of DPDFs, tuned to the HERA data [5]. For the effective cross section for re-scattering of octet configurations we found that it was necessary to introduce corrections to prevent unitarity being violated (so called saturation effects). Since gluon DPDFS are large we find a corresponding large nuclear shadowing for gluons (see Fig. 2).

For a discussion of enhanced nuclear shadowing correction for central collisions, of the uncertainties associated with the unmeasured diffractive slope, and of the implementation of charm, we refer the reader to our paper [3].

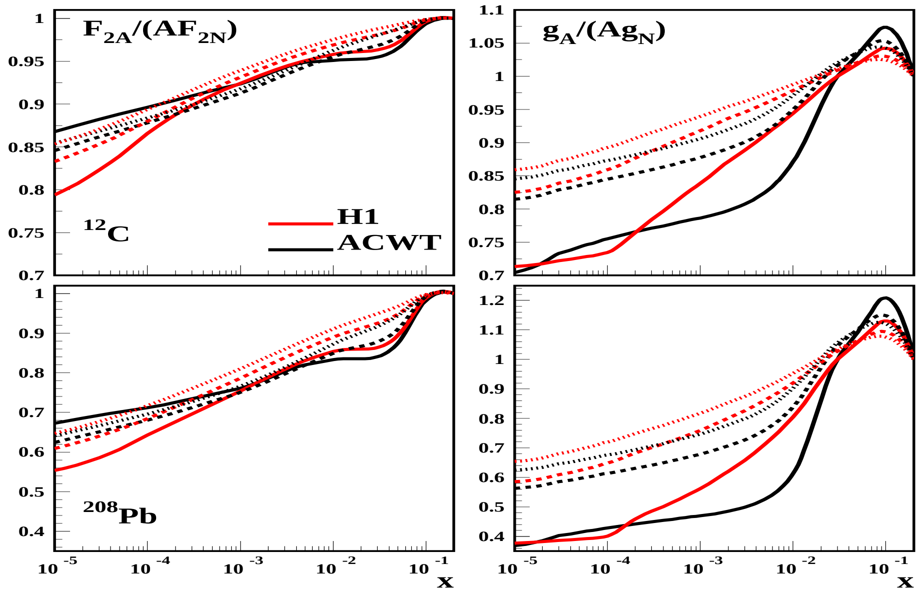

Fig. 2. Predictions for F_2^A and nuclear gluon PDFs for $Q = 2,\ 5,\ 10\,\mathrm{GeV}$ (solid, dashed, dotted curves). In each case two curves are shown to indicate the spread associated with extreme choice of DPDFs models.

In the eikonal model for nuclear shadowing [6] the $q\bar{q}$ pair scatters elastically off many nucleons in the target (see Fig. 3). The fundamental interaction of the dipole with a nucleon is eikonalised and the formula is given by:

$$
\begin{aligned}
\delta F_2^A(x,Q^2) = \frac{Q^2}{4\pi^2\alpha_{em}}\frac{A(A-1)}{2}\mathrm{Re}\Bigg[(1-i\eta)^2\int d\alpha\ d^2d_t \sum_i\ \left|\psi\left(\alpha,Q^2,d_t^2\right)\right|^2 \\
\times \int d^2b \int\limits_{-\infty}^{\infty} dz_1 \int\limits_{z_1}^{\infty} dz_2 \left[\sigma_{q\bar{q}N}^{\mathrm{tot}}\left(x,d_\perp^2,m_i\right)\right]^2 \rho_A(b,z_1)\rho_A(b,z_2) \\
\times\, \mathrm{e}^{i2xm_N(z_1-z_2)}\mathrm{e}^{-\left(\frac{A}{2}\right)(1-i\eta)\sigma_{q\bar{q}N}^{\mathrm{tot}}\left(x,d_\perp^2,m_i\right)\int_{z_1}^{z_2} dz\rho_A(z)}\Bigg], \qquad (4)
\end{aligned}
$$

where ψ is the light-cone wavefunction for $\gamma^* \to q\bar{q}$, taken from QED (α is the momentum fraction carried by the quark). Generally, the mixing with higher Fock states in the virtual photon is neglected (this implies that Q^2-dependence is not consistent with DGLAP!). Hence a parton level description of nuclear shadowing in the eikonal model is impossible. To implement the eikonal model we employed the MFGS-dipole [7] for $\sigma_{q\bar{q}N}^{\mathrm{tot}}$, but we could also have used other dipole models. In the eikonal model nuclear shadowing is suppressed by colour transparency (since $\sigma \propto d_t^2$, at small

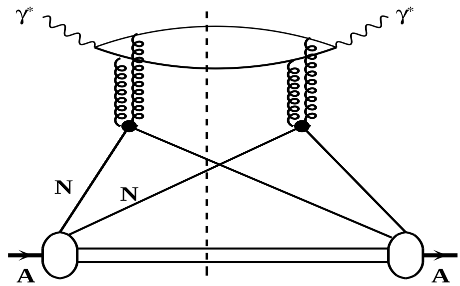

Fig. 3. The eikonal model for nuclear shadowing.

transverse size d_t). This implies that nuclear shadowing of F_2^A decreases rapidly with increasing Q (see Fig. 4). This higher-twist nature of nuclear shadowing in the eikonal model is clearest for hard processes, which are most sensitive to small size configurations (*e.g.* F_L^A at large Q^2, see Fig. 5).

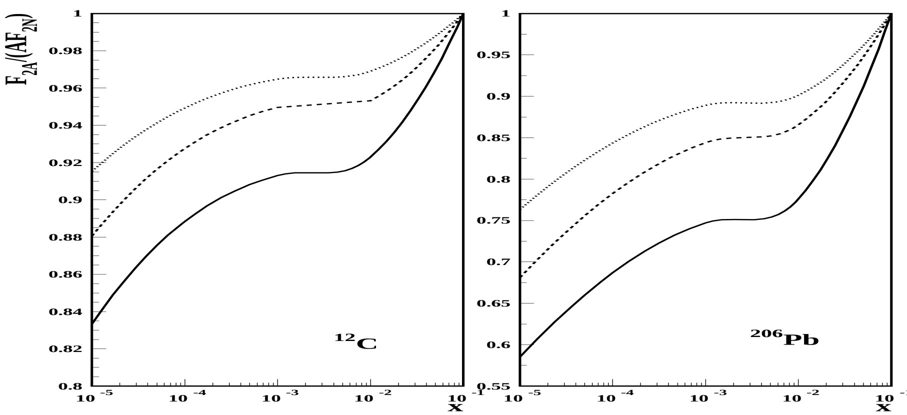

Fig. 4. Eikonal model predictions for F_2^A for $Q = 2,\ 5,\ 10\,\mathrm{GeV}$ (solid, dashed, dotted curves).

To conclude, the leading twist QCD analysis of [3] suggests that nuclear shadowing is a leading twist phenomena. It produces radically different predictions to the eikonal approach popular in the literature, (*cf.* the dipole model for diffraction) for which nuclear shadowing is a higher twist effect. A systematic measurement of nuclear PDFs (via $F_{2,L}^A$, nuclear DVCS and Drell–Yan, which should be possible at HERA III and EIC), and hence of nuclear shadowing, can help establish the correct model for diffraction. It may well be possible to investigate non-linear QCD in DIS on a large nucleus, but one needs to understand nuclear shadowing first.

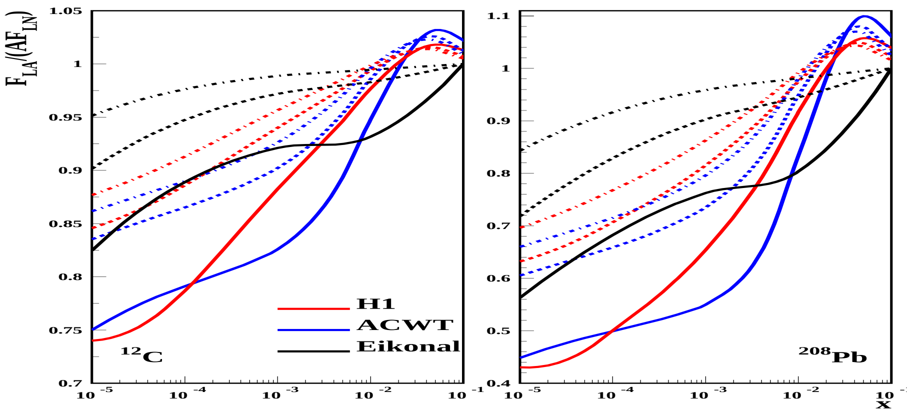

Fig. 5. Contrasting predictions from the eikonal model (curves as in Fig. 4) and the leading twist model for F_L^A (the lower curves at moderate x are ACWT and the upper curves are H1) for $Q = 2, 5, 10$ GeV (solid, dashed and dotted curves, respectively).

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