Inclusive and diffractive DIS at low $x$ from HERA to the EIC

Konrad Tywoniuk
Departamento de Física de Partículas,
Universidade de Santiago de Compostela,
15706 Santiago de Compostela, Spain
E-mail: konrad.tywoniuk@gmail.com

Abstract. We describe a model for low $x$ DIS off nucleons and nuclei which provides initial conditions for QCD evolution that satisfy unitarity at low-$x$. We discuss it’s extension to the perturbative regime and it’s predictions for several DIS observables. We emphasize the well-known connection between rise of the diffractive cross section at high energies and nuclear shadowing.

1. A unitarized model for low $x$ DIS
The Regge limit of QCD ($s \to \infty$ at constant $Q^2$) is of great interest both from the perspective of high-energy collider experiments and inasmuch as it poses a challenge for the theoretical understanding of the hadronic wave-function. The rapid growth of cross sections observed at high $Q^2$ and fairly low $x$ is expected to slow down due to unitarity as $x \to 0$. Compared to the nucleon case, in $\gamma^* A$ collisions these effects are enhanced by the nuclear thickness factor $\sim A^{1/3}$ causing a depletion of the nuclear structure function observed at $x < 0.1$, compared to the incoherent superposition of $A \gamma^* p$ cross sections, called nuclear shadowing.

So far, all data from DIS experiments off both nucleons and nuclei can be well described by perturbative QCD (pQCD) with universal parton distribution functions (PDFs) incorporating scaling violations. But in spite of its success, this scheme has no predictive power on the energy dependence of PDFs at a given initial $Q_0^2$ rendering them uncertain, especially for the gluon sector, in the kinematical regime away from present day experiments, particularly at low $x$. Models that aim at predicting the low-$x$ behaviour of the structure functions have to include unitarity conserving mechanisms that tame the growth of cross sections at high energies. Recently, attempts to derive these corrections within pQCD have made significant progress.

In a frame where the target nucleus is at rest, these effects arise due to multiple scattering of the projectile. The large probability of rescattering and, thus, a large probability of diffraction dissociation, is known to arise from large, and thus principally non-perturbative, partonic fluctuations. In this sense, conservation of unitarity and growth of the probability of diffraction is intimately linked.

A suitable framework, although not rigorously established within QCD, to treat these configurations is provided by the reggeon calculus [1], where rescattering of the projectile wave function is accounted for by including multi-reggeon exchanges. In the absence of a unified QCD approach to the entirety of $\gamma^* N$ and $\gamma^* A$ processes, this framework can serve as a useful...
guidance for investigating the connection between non-perturbative and perturbative aspects of DIS valid for extrapolations to extremely small momentum fractions.

2. DIS off protons
In a particular realization within this framework one distinguishes explicitly between a large ($L$) and a small ($S$) component in the $\gamma^*$ wave-function $[2, 3]$. The former interacts strongly even at high-$Q^2$ but is quite rare, while the latter, cast in the form of a dipole model in [3], interacts according to $r \sim 1/Q$. Thus both components have a leading $1/Q^2$ dependence of the total cross section while the $L$-component gives the leading contribution to diffraction ($1/Q^2$ vs. $1/Q^4$). Large-mass diffraction is included through triple-reggeon interactions. The model gave a simultaneous description of inclusive $F_2$ and diffraction in the region of $0 < Q^2 \leq 5 - 10$ GeV$^2$, and was used to predict the structure functions at very low $x$. With the advent of high-energy colliders the need for low-$x$ structure functions for nucleons and nuclei at high-$Q^2$ have arisen, which motivates an extension of the model [3] to the perturbative regime by the inclusion of QCD scaling violations.

In [4] we describe a prescription for extracting the initial conditions at leading order for the DGLAP equations from the non-perturbative model both for inclusive $F_2$ and diffraction. In the former case, this procedure does not involve new parameters. The situation for the inclusive diffractive cross section is more complex, because it involves both more complicated reggeon exchanges and additional variables in the problem. For the proper description of data in the whole $\beta$ and $x_p$ region we identify explicitly pomeron and reggeon contributions to diffraction. One can then invoke a supplementary factorization of variables, the so-called Regge factorization, which allows for a comprehensible QCD analysis. In the reggeon case, important for small-mass diffraction, the diagrams not taken into account in the original formulation are included by a pion PDF.

Thus, equipped with properly unitarized initial conditions for the DGLAP evolution equations we obtain leading-order structure functions and PDFs for the proton down to $x \sim 10^{-8}$ at high-

![Figure 1](image-url) **Figure 1.** The proton diffractive structure function obtained from the CFSK model with QCD evolution at LO compared to a set of data from the H1 experiment (see [4] for details).
3. DIS off nuclei

In the context of DIS off nuclei, there emerges a critical length scale related to a change of the underlying space-time picture of the collision. The coherence length (or life-time) of a given fluctuation of the incoming projectile is given by

$$ l_C = \frac{1}{Q} \frac{E_{LAB}}{Q} \simeq \frac{1}{2m_N x} , $$

in the limit $2m_N E_{LAB} = W^2 \gg Q^2$, where $x$ is the Bjorken variable. At low energies, where $l_C$ is of the order of the internucleon distance, the projectile undergoes incoherent multiple scattering off the target. Remarkably, all higher-order rescatterings cancel and the total $\gamma^* p$ cross section is simply given as a superposition of $\gamma^* p$ collisions. The critical value is reached when the coherence length becomes of the order of the nuclear radius. For $l_C > R_A$, i.e. at $x < 1/2m_N R_A$, the projectile scatters coherently off all constituents of the nucleus at some given impact parameter. Despite the non-local nature of the interactions, the total cross section can be written in the form of a multiple scattering series, now including corrections from higher-order rescattering diagrams which lead to an overall depletion of the total cross section, called Gribov inelastic shadowing. This formalism relates the inclusive and diffractive $\gamma^* A$ ones by means of the AGK cutting rules [6], thus providing a neat connection between diffraction and shadowing. The multiple scattering has been truncated within fan and eikonal diagram re-summations. Thus our calculations for nuclei, based on the model presented in the previous subsection [4] can be extrapolated down to very low $x$ and thanks to the inclusion of scaling violations coming from QCD evolution it can also be used at high $Q^2$ [7]. Extension of the model to higher $x$ (and low-mass diffraction) is under way.

We show the results of our calculations for $F^2(Pb)/F^2$ in Fig. 2, where also a comparison to a recent dipole model calculation [8] (right) and a NLO pQCD fit [9] together with a
Figure 3. Nuclear diffractive-to-inclusive ratio in the Schwimmer model with CFSK PDFs.

similar calculation to ours [10] (left) is presented. At low $x$, a large deviation from the pQCD parameterization, which can be traced back to the choice of initial condition, is apparent. Needless to say, the lox-$x$ region in nuclei is of extreme importance for calculating e.g. multiplicity distributions in heavy-ion collisions

Additionally, in [7] we calculated high-mass diffraction off nuclei, noting that Regge factorization is broken in this case due to the large rescattering. We compare the ratio of total and diffractive cross section for protons and nuclei (calculated for fan diagram re-summation) in Fig. 3.

Acknowledgments

The work presented here was done in collaboration with N. Armesto, C. Salgado and A. B. Kaidalov, who I would like to thank for immense support and illuminating discussions. I would like to thank the organizers of the conference for financial support. The work is dedicated to A. B. Kaidalov, who sadly passed away in July.

References

[1] Gribov V N 1968 Sov. Phys. JETP 26 414
[2] Capella A, Ferreiro E G, Salgado C A and Kaidalov A B 2001 Nucl. Phys. B 593 336
[3] Capella A, Ferreiro E G, Salgado C A and Kaidalov A B 2001 Phys. Rev. D 63 054010
[4] Armesto N, Kaidalov A B, Salgado C A and Tywoniuk K 2010 Phys. Rev. D 81 074002
[5] Albacete J L, Armesto N, Milhano J G and Salgado C A 2009 Phys. Rev. D 80 034031
[6] Abramovsky V A, Gribov V N and Kancheli O V 1973 Yad. Fiz. 18 595
[7] Armesto N, Kaidalov A B, Salgado C A and Tywoniuk K 2010 Eur. Phys. J. C 68 447
[8] Kopeliovich B Z, Nemchik J, Potashnikova I K and Schmidt I 2008 J. Phys. G 35 115010
[9] Eskola K J, Paukkunen H and Salgado C A 2009 J. High Energy Phys. JHEP0904(2009)065
[10] Frankfurt L, Guzey V and Strikman M 2005 Phys. Rev. D 71 054001