The Impact of e+A Collisions on Nuclear PDFs

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Abstract. In this text we comment on the importance of measurements of electron-nucleus collisions and how that data would allow us to check the validity of the collinear factorization framework and constrain the existing set of nuclear parton distribution functions. We exemplify this using the EPS09 nPDF set and $F_2$ pseudodata generated from a saturation model.

1. Why e+A collisions?
One fundamental consequence of QCD dynamics is the emergence of parton saturation, a regime in which the evolution of the theory is non-linear due to how the parton densities grow at asymptotically small $x$. This parton saturation is characterized by the momentum $Q_s(x)$, the so-called saturation scale, and separates the dilute and dense regimes. The smaller $x$ is, the higher $Q_s(x)$ gets. Data from e+A collisions can prove that the non-linearity of QCD evolution is truly essential or render it insignificant.

e+A collisions can also bring measurements with strong evidence of saturation, as well as some knowledge about the properties of this dense regime.

From a theoretical point of view, QCD is best approximated in the saturation regime by the Color Glass Condensate (CGC) effective theory. One of CGC weak points is that its results need, among other non-perturbative inputs, the impact parameter dependence of the gluon density. e+A measurements can give information about this and so help reduce the uncertainties of the CGC.

But one of the main reasons to study e+A collisions resides in the fact that they will provide precise measures of the longitudinal structure function $F_L$, that is related to the distribution of gluons. A linear combination of $F_L$ and the structure function $F_2$ (related to the distribution of quarks) gives the total cross section of the process $\gamma^* + A$, measured in inclusive deep inelastic scattering (DIS). Having precise data of $F_2$ and $F_L$ is of utmost importance to be able to answer a hugely interesting question: if linear DGLAP evolution models (such as EPS09 [1]) can simultaneously describe $F_2$ and $F_L$ data coming from e+A collisions, taking into account that saturation behaves as the saturation models that are now in the market (such as the running-coupling Balitsky-Kovchegov (rcBK) equation [2]) predict.

More information about what e+A measurements can bring us is provided in [3].

2. What do we want to do?
The objective of this work is to constrain the nuclear parton distribution functions (nPDFs) given some e+A pseudodata of the structure function $F_2$. There is work in progress to do the...
same with $F_L$ pseudodata.

3. How do we do it?

Our work consists of two different parts: how to generate and how to deal with the pseudodata. We consider an $e+\Lambda$ DIS process in which an electron interacts with a nucleus via a virtual photon. This process can be looked at from two different frames: the Bjorken and the dipole frames. In the Bjorken one, we can express $F_2$ through the usual relation

$$F_2(x, Q^2) = \sum_q e_q^2 \left[ xq(x, Q^2) + x\bar{q}(x, Q^2) \right]$$

(1)

via the nPDFs $xq(x, Q^2)$, while, in the dipole frame, $F_2$ takes the following form

$$F_2(x, Q^2) = \frac{Q^2}{4\pi^2\alpha_{em}}(\sigma_T + \sigma_L)$$

(2)

where $\sigma_T$ and $\sigma_L$ are the transverse (T) and longitudinal (L) cross section of the process, respectively [4]. We generate our pseudodata with expression (2), and given the equivalence between the two frames, we can use it to impose some constrains on the nPDFs via a reweighting process.

3.1. How do we generate the pseudodata?

In the dipole frame (valid in the regime $x \ll 1$), the cross section of the process $\gamma^* + p$ is given by

$$\sigma_{\gamma^*h}^{T,L}(x, Q^2) = \sum_q \int_0^1 dz \int d^2r |\Psi_{T,L}^q(e_q, m_q, z, Q^2, r)|^2 \sigma_{\text{dip}}^{ep}(r, x)$$

(3)

the convolution of $|\Psi_{T,L}^q|^2$, the wavefunction squared of a virtual photon splitting into a quark-antiquark dipole (the expressions to lowest order in $\alpha_{em}$ can be found in [5]) and $\sigma_{\text{dip}}^{ep}(r, x)$, the cross section of the quark-antiquark dipole scattering off the hadronic target [6]. The extension to $\gamma^* + A$ is realized by the substitution $\sigma_{\text{dip}}^{ep}(r, x) \rightarrow \sigma_{\text{dip}}^{eA}(r, x)$. The optical theorem tell us that this new cross section can be calculated as the integral over impact parameter $b$ of the (imaginary part of the) dipole-nucleus scattering amplitude:

$$\sigma_{\text{dip}}^{eA}(r, x) = \int d^2b \sigma_{\text{dip}}^{eA}(r, x, b)$$

(4)

All the information about the strong interactions and the $x$-dependence of the scattering process is encoded in this dipole amplitude.

The model of the nucleus we are using [7][8] has a Woods-Saxon density distribution $T_A(b)$ without fluctuations. The dipole-nucleus amplitude takes the following form:

$$\sigma_{\text{dip}}^{eA}(r, x, b) = 2 \left[ 1 - \exp \left( -\frac{1}{2} AT_A(b) \sigma_{\text{dip}}^{ep}(r, x) \right) \right]$$

(5)

which is an average of the dipole cross section over the fluctuating positions of the nucleons in the nucleus, i.e., a mean field approach.
3.2. How do we deal with the pseudodata?

Once the pseudodata is generated according to the model described above, we have to see how it affects the nPDFs. To do so, we perform a reweighting of the existing nPDFs that takes into account the new pseudodata. A reweighting is a process developed to save time, since it can give us a quantitative estimation of the degree of incompatibility between the data and the theory [9][10][11]. In case the new data and the theory are compatible, the nPDFs get reweighted and the resulting nPDFs are linear combinations of the original ones and include the new data. If data and theory are incompatible, a new global fit for the nPDFs is mandatory.

The performed reweighting is a Hessian method [12] that follows the steps indicated in [13]. The consistency of the new data with the original nPDFs is given by the relation between the so-called penalty term $P$ and the tolerance $\Delta \chi^2$ of the original fit. If $P \ll \Delta \chi^2$, the existing nPDFs accepts the new data without causing trouble with the other data. However, if $P \gtrsim \Delta \chi^2$ the new data may be in conflict with the nPDFs considered, so it is not guaranteed that the result of the reweighting process would be reliable.

4. What do we get?

The set of nPDFs we have used is EPS09. The preliminary results of the reweighting process with the generated pseudodata for $F_2$ can be seen in Figure 1. For the valence quark, we can see that there is a suppression on the shadowing part with respect to the original fit, as well as an important constrain on the uncertainties. The reweighted nPDF follows the behaviour of the original fit. As for the gluon distribution, there is an enhancement in the small-$x$ region, but the new uncertainties, far from being constrained, exceed the old ones, so we can’t make any claim. Results for the sea quark distribution follow the same pattern as those for the gluon distribution. The trouble with the gluon and sea results can be understood if we pay attention to the penalty of the reweighting.

The values for the tolerance $\Delta \chi^2$ of the EPS09 nPDF set and the penalty term for the performed reweighting process are listed in Table 1. As we can observe, $P \gg \Delta \chi^2$, so the reweighted EPS09 with the $F_2$ pseudodata might not be reliable.

One possibility for the discrepancy we see between the pseudodata and theory is that the
Table 1. Reweighting results

| nPDF   | $\Delta\chi^2$ | Penalty    |
|--------|----------------|------------|
| EPS09  | 50             | 817.48     |

collinear factorization framework is not right as it is for $e+A$ and it should be improved adding more QCD dynamics in the formalism. But we cannot claim this hypothesis is true until we have pseudodata from a more realistic saturation model.

5. Are there any conclusions?
We have seen that $e+A$ measurements can give a lot of useful information as well as shed some light on important topics such as saturation. We have commented on how to use $F_2$ data from $e+A$ collisions to enforce some contrains, if possible, into the existing nPDFs. We have done it for the EPS09 set and see that the pseudodata might not be compatible with the rest of the data in the nPDF. We wonder if this incompatibility comes from the collinear factorization framework, but given that the results are not final we cannot venture to take any further conclusion yet.

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