Subleading effects in QCD global fits

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Abstract. I discuss several corrections to leading twist calculations of nucleon structure functions which are needed to include experimental data at large parton fractional momentum $x$ and at low scales $Q^2$ in global fits of parton distribution functions. In particular I discuss the results of the CTEQ6X global fit, and some work in progress. Topics covered include the interplay of target mass and higher-twist corrections, the importance of nuclear corrections for deuterium target data, and applications to the study of quark-hadron duality. Implications for collider physics are highlighted.

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Precise parton distribution functions (PDFs) at large parton fractional momentum $x$ are vital for understanding the non perturbative structure of the nucleon and the effects of color confinement on its partonic constituents. For instance, the $d/u$ quark distribution ratio near $x = 1$ is very sensitive to the nature of the quark-quark forces in the nucleon; the ratios of spin-polarized to spin-averaged PDFs $\Delta u/u$, and particularly $\Delta d/d$, in the limit $x \to 1$ reflect the non perturbative quark-gluon dynamics in the nucleon, and can shed light on the origin of the nucleon’s spin. Precise PDFs at large $x$ also have impact in other areas of nuclear and high-energy physics, e.g., by allowing precise computations of QCD background processes in searches of new physics signals at hadron colliders, and systematic uncertainties in neutrino oscillation experiments.

PDFs can be extracted from experimental data through global QCD fits which combine data from many different processes and observables, and analyze them by means of perturbative QCD calculations [1, 2, 3, 4]. Currently, however, the unpolarized PDFs are well determined only for $x \lesssim 0.5$ for valence quarks, $x \lesssim 0.3$ for gluons, and $x \lesssim 0.1$ for heavy quarks. To better constrain these at large $x$ it is necessary to study hard scattering processes near kinematic thresholds, such as Deep Inelastic Scattering (DIS) at large Bjorken invariant $x_B$ and low 4-momentum transfer squared $Q^2$, Drell-Yan (DY) lepton pair production and electroweak vector boson production at large rapidity. In these kinematic regimes several corrections to leading twist perturbative QCD calculations can become important because of the rapid fall-off of the cross section near the kinematic boundary. Examples are target and jet mass corrections [5], threshold resummation [6], and higher-twists (HT) contributions [7, 8]. Moreover, data taken on nuclear targets must be corrected for nuclear effects such as shadowing, binding, Fermi motion and nucleon off-shellness, to access the partonic structure at the nucleon level. Accessing the highest values of $x$ in DIS also requires understanding quark-hadron duality [9, 10] in order to utilize data in the resonance region.

All these effects need to be incorporated in a consistent framework, simultaneously computed for a wide range observables, and utilized in a global PDF fit. The CTEQ6X
global fit published in Ref. [11] took a first step in this program by considering the combined effect of TMC and HT corrections, alongside nuclear corrections for DIS data on deuterium targets needed for flavor separation of the up and down quark. In this talk, I discuss the results of this analysis and some recent work in progress which extends it. Detailed references can be found in Ref. [11].

**TARGET MASS AND HIGHER-TWIST CORRECTIONS**

It is the usual practice in global PDF fits to place kinematic constraints on the DIS data sets, typically $Q^2 > 4 \text{ GeV}^2$ and $W^2 > 12 \text{ GeV}^2$, so that only leading twist massless QCD contributions need be considered, thereby reducing the model dependent error on the extracted PDFs. As a byproduct of this procedure the PDFs are directly constrained by data only in the region $x < 0.7$. However, plentiful DIS data exist outside this region. In order to utilize them in global fits, one needs minimally to include Target Mass Corrections (TMCs), which scale as $M_N^2/Q^2$, with $M_N$ the nucleon mass, and higher-twist corrections, which scale as $\lambda^2/Q^2$, with $\lambda$ a hadronic scale describing non perturbative parton-parton correlations inside the nucleon.

Several methods are available in the literature to perform TMCs, and have been reviewed by F. Steffens [5]. One is the well-known Georgi-Politzer formalism based on the Operator Product Expansion (OPE), whose results are also reproduced in the Covariant Parton Model. However, this formalism suffers from the problem that it leads to non-zero values of the structure function on a nucleon target in the unphysical region $x > 1$. Another prescription is a simple rescaling of the structure function, obtained by substituting $x$ with the Nachtmann variable $\xi = 2x/(1 + \sqrt{1 + 4x^2 M_N^2/Q^2})$. This also shares the above “unphysical region” problem. Lastly, working in Collinear Factorization (CF) the kinematic boundaries are naturally respected. One advantage of the CF formalism versus the OPE formalism is that the former can be also applied to semi-inclusive DIS [12], and indeed to any hard-scattering process. An application to parity-violating DIS was discussed by T. Hobbs [13].

However, TMCs do not exhaust all possible $O(1/Q^2)$ power corrections. These include dynamical higher-twist corrections (parton correlations) as well as all uncontrolled leading-twist power corrections, such as Jet Mass Corrections [14]. They also include higher-order perturbative terms, which are logarithmic in $Q^2$ but resemble a power law at low scales, and large-$x$ resummation effects [6]. Despite their disparate origin, it is customary to label these “residual” corrections as “higher-twist”, as I will do here. In the CTEQ6X fits, these HT corrections are parameterized phenomenologically using a multiplicative factor modifying the structure function of the proton and the neutron:

$$F_2^{data} = F_2^{TMC}(1 + C(x)/Q^2),$$  

where $F_2^{TMC}$ denotes the structure function after the target mass corrections have been made. The function $C(x)$ is given by $C(x) = ax^b(1 + cx)$. After inclusion of TMCs, this parameterization is sufficiently flexible to give a good description of the data. To simplify the global fits, the HT corrections for protons and neutrons where taken equal, given that their difference was found to be relatively small in other studies.
NUCLEAR CORRECTIONS

In order to separate the \(d\) and \(u\) quark at large \(x \gtrsim 0.6\) it is necessary to consider DIS data on deuteron targets, which are sensitive to a different linear combination of \(u\) and \(d\) quarks than the corresponding data on proton targets. However, at large \(x\) the deuteron deviates from a simple sum of a free proton and neutron due to significant effects of nuclear binding, Fermi motion and nucleon off-shellness [15].

Since the deuteron is weakly bound one can approximate the bound nucleon structure function by its on-shell value, and write the deuteron (\(d\)) structure function as

\[
F_2^d(x, Q^2) \approx \sum_{N=p,n} \int dy \, f_{N/d}(y, \gamma) \, F_{2N}^{TMC+HT} \left( \frac{x}{y}, Q^2 \right).
\]  

Here \(F_{2N}\) is the nucleon (proton \(p\) or neutron \(n\)) structure function including TMC and HT corrections. The “smearing function” \(f_{N/d}\) is computed from the deuteron wave function and implements nuclear binding and Fermi motion corrections; at \(Q^2 \to \infty\) it can be interpreted as the light-cone momentum distribution of nucleons in the deuteron. The variable \(y = (M_d/M_N)(p_N \cdot q/p_d \cdot q)\) is the deuteron’s momentum fraction carried by the struck nucleon, where \(q\) is the virtual photon four-momentum, \(p_{N(d)}\) the nucleon (deuteron) four-momentum, and \(M_d\) the deuteron mass; it differs from the light-cone fractional momentum by terms of \(O(M_N^2/Q^2)\). Off-shell corrections to \(F_{2N}\) can also be implemented in under a few assumptions, which are outside the scope of this talk.

The deuteron correction factor \(F_2^d/(F_2^p + F_2^n)\) computed with the Paris wave function and the CTEQ6X PDFs is plotted in Figure 1. It shows a remarkable \(Q^2\) dependence at \(Q^2 \lesssim 20\) GeV. Part of this \(Q^2\) dependence comes from the smearing function \(f_{N/d}\), which depends on the target mass through the variable \(\gamma^2 = 1 + 4x^2M_N^2/Q^2\). However, this induces only minor effects on the deuteron correction factor. Most of the \(Q^2\) dependence
shown in the figure is due to TMC and HT corrections at the nucleon level.

It is also clear that nuclear smearing corrections do not disappear at large $Q^2$: in general, they are not a subleading effect, and cannot be avoided by kinematics cuts such as those commonly used in global PDF fits.

**THE CTEQ6X PARTON DISTRIBUTIONS AT LARGE $x$**

The CTEQ6X global PDF fits [11] were performed at NLO to a wide variety of data similar to that used in the determination of the CTEQ6M1 PDFs except that no neutrino data were used since their use would involve additional nuclear corrections beyond those for deuterium. In addition, the E-866 dimuon data were added as were data for the CDF $\gamma + jet$ production, the CDF $W$ lepton asymmetry, and the DØ $W$ asymmetry.

Initially, a reference fit (“ref”) was done using the standard $W > 3.5$ GeV and $Q > 2$ GeV (labeled cut0), with TMC, HT and nuclear corrections turned off in order to compare to the CTEQ6M1 PDFs. The E866 data favor at large $x$ a slightly reduced $u$ PDF and an increased $d$ PDF; however in the latter case the $W$ asymmetry and $\gamma+jet$ data compensate the increase leaving the $d$ PDF nearly unchanged.

Subsequently, several prescriptions for TMC, HT and nuclear corrections were considered, and the DIS kinematic cuts progressively relaxed to $W > 1.73$ GeV and $Q > 1.3$ GeV, in order to avoid most of the resonance region but be able to include a good number of Jefferson Lab data. This cut is labeled cut3, with intermediate cuts labeled cut1 and cut2. As TMCs, the discussed OPE, $\xi$-scaling and CF prescriptions were considered. Nuclear smearing was performed using the Paris wave function with on-shell nucleon structure functions or off-shell corrections from the MST model [16]; the results were compared to fits obtained using either no nuclear corrections apart from isospin effects, or nuclear corrections in the Density Model, which extrapolates the nuclear effects observed in heavier nuclei to the deuteron.
The main results of the CTEQ6X analysis can be summarized as follows.

- **Standard kinematic cuts.** When using the standard DIS kinematic cuts, \( W > 3.5 \) GeV and \( Q > 2 \) GeV, the PDFs are insensitive to TMC and HT corrections; however nuclear corrections are large and start at \( x \gtrsim 0.45 \), in a region well inside what is included in the cuts (Fig. 2, left).

- **Enlarged kinematic cuts.** The PDFs are relatively stable against variations of the DIS cuts in the vicinity of the \( W > 1.73 \) GeV and \( Q > 1.3 \) cut (Fig. 2, right plot, left panel). As a consequence of the enlarged data set, there is a substantial reduction in the uncertainty of these PDFs due to the increased data, with the cut 3 errors reduced by 10–20% for \( x \lesssim 0.6 \), and by up to 40–60% at larger \( x \).

- **Stability with respect to TMCs.** The PDFs are nearly independent of the TMC prescription (Fig. 3, left); this is very important for fitting leading-twist PDFs. Changes in TMCs are absorbed by the phenomenological HT term, for which TMC modeling induces a non-negligible systematic uncertainty (Fig. 3, right).

- **Large sensitivity to nuclear corrections.** The \( d \) PDF is very sensitive to the nuclear correction model adopted (Fig. 2, right plot, right panel). This induces a large systematic uncertainty, further discussed in the next section.

**NUCLEAR UNCERTAINTIES AND COLLIDER PHYSICS**

A detailed investigation of the systematic PDF uncertainties induced by nuclear corrections modeling is underway, as reviewed by J. Owens [1]. One very important result is that, surprisingly, the large-\( x \) gluon PDF is as sensitive to nuclear corrections as the \( d \) PDF; they are anticorrelated to each other due to an interplay of DIS, DY and jet data.

This has potentially profound implications for future collider experiments, since the resulting variation of the gluon is significant even at values of \( x \) as low as 0.4. As an
FIGURE 4. Relative nuclear uncertainties on parton luminosities at $\sqrt{s} = 7$ TeV. Shown are the extremes of the variations of the $gg$, $gd$ and $d\bar{u}$ luminosities relative to an intermediate fit (“ref”).

illustration, we can consider the parton luminosities,

$$L_{ij} = \frac{1}{(1 + \delta_{ij})\hat{s}} \left[ \int_{\hat{s}/s}^{1} \frac{dx}{x} f_i(x, \hat{s}) f_j \left( \frac{\hat{s}}{xs}, \hat{s} \right) + i \leftrightarrow j \right],$$

where $s (\hat{s})$ is the hadronic (partonic) center of mass energy squared, and $f_i$ is the PDF for a parton of flavor $i$ at $Q^2 = \hat{s}$. As an example, the $gg$ luminosity controls the total main channel for Higgs production, the $gd$ luminosity controls the “standard candle” cross section for $W^-$ production, and the $d\bar{u}$ luminosity is relevant to jet production. These are plotted in Fig. 4 for $\sqrt{s} = 7$ TeV, relevant to the current LHC runs. The nuclear uncertainty grows quickly above 5-10% as $\sqrt{s}$ exceeds 1 TeV.

AN APPLICATION TO QUARK-HADRON DUALITY

Quark-hadron duality in structure functions refers to the experimental observation that inclusive structure functions in the region dominated by low-lying nucleon resonances follow deep inelastic structure functions describing high energy data, to which the resonance structure functions average [9]. The new large-$x$ CTEQ6X PDFs can be used to verify to what degree this holds true, which is important to understand the transition from the perturbative (partonic) to the non perturbative (hadronic) regime of QCD.

The handbag diagram used in the pQCD computations assumes no interaction between the scattered quark and the target remnant. This is a reasonable approximation only if their rapidity separation, $\Delta y$, is large enough. A value of $\Delta y > 2 - 4$, known as “Berger criterion” [18], should be sufficient to ensure applicability of pQCD. Since $\Delta y$ decreases as $x \to 1$ or $Q^2 \to 0$, this limits the range in $x$ and $Q^2$ where the comparison of pQCD computations and resonance region data makes sense.

In Figure 5 the ratios of Jefferson Lab data averaged over different resonance regions to computations using CTEQ6X are plotted [10, 17]. These are compared to calculations using Alekhin09 PDFs [19], which were fitted with similar TMC, HT and nuclear corrections as CTEQ6X. Only data satisfying a conservative $\Delta y > 4$ are retained. Data
FIGURE 5. Preliminary results of a comparison of averaged JLab $F_2$ data over 4 “resonance regions” and computations using CTEQ6X (red) and Alekhin09 PDFs (blue).

in the $W^2 = (3.1, 3.9)$ GeV$^2$ region were included in the CTEQ6X fit, and indeed are well described. The $W^2 = (2.5, 3.1)$ GeV$^2$ region, while not directly included in the fit, is constrained by DIS data at larger $Q^2$ because of DGLAP evolution. Data in the $W^2 = (1.9, 2.5)$ GeV$^2$ region lie in the extrapolation region of the CTEQ6X fits.

The plot shows that quark-hadron duality works within 5-10%. This opens the possibility of using resonance region data to extend the range of validity in $x$ of the fits. A study is underway [17] to further explore this issue, e.g., by determining whether duality holds for smaller values of the $\Delta y$ cut, which would enlarge the number of data points, by evaluating nuclear systematic uncertainties and by quantifying PDF uncertainties from the HT parameters, especially in the extrapolation region.

CONCLUSIONS

I have shown that a good control of global PDF fits can be achieved when including DIS data in the pre-asymptotic region of large $x$ and small $Q^2$, if one considers TMC and HT corrections. The resulting PDFs are stable against available TMC prescriptions, with the modeling uncertainty absorbed in the phenomenologically extracted HT terms. This is very good for applications to collider and neutrino physics [20], and for comparing PDF moments to lattice calculations [21, 22].

Theoretical nuclear corrections to deuteron target data are necessary for $u$ and $d$ quark separation at $x \gtrsim 0.5$. The $d$-quark and, surprisingly, the gluon PDF turn out to be very
sensitive to uncertainties in the modeling and calculation of nuclear effects. Furthermore, the induced uncertainty on parton luminosities at the LHC is non-negligible.

A careful study shows that the induced systematic $d$-quark PDF uncertainty is of the same order as the experimental uncertainty if the deuteron target data are removed from the fit [1]. Therefore, further progress in constraining the $d$ quark and the gluon PDFs at large $x$ requires a better theoretical understanding of nuclear corrections, combined with new data on free proton, but sensitive to $d$, such as from parity violating DIS or from neutrino DIS on a hydrogen target [20]. Alternatively one can use data minimizing nuclear corrections, such as from proton-tagged DIS on deuteron targets, for which the nuclear uncertainty is smaller than 2% [23]. Using quark-hadron duality to include resonance region data in the fits, thereby extending their $x$ range, seems also feasible. Finally, data sensitive to large $x$ gluons, such as from the longitudinal and charm structure functions, $F_L$ and $F_C^c$, are required to constrain the gluons independently of the jet data.

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