PARTON DISTRIBUTION FUNCTION UNCERTAINTIES & NUCLEAR CORRECTIONS FOR LHC[†]

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We study nuclear effects of charged current deep inelastic neutrino-iron scattering in the frame-work of a χ^2 analysis of parton distribution functions (PDFs). We extract a set of iron PDFs which are used to compute x_{Bj}-dependent and Q^2-dependent nuclear correction factors for iron structure functions which are required in global analyses of free nucleon PDFs. We compare our results with nuclear correction factors from neutrino-nucleus scattering models and correction factors for $\ell^{\pm}$-iron scattering. We find that, except for very high x_{Bj}, our correction factors differ in both shape and magnitude from the correction factors of the models and charged-lepton scattering.

1 Impact of Nuclear Corrections on PDFs

The high statistics measurements of neutrino deeply inelastic scattering (DIS) on heavy nuclear targets has generated significant interest in the literature since these measurements provide valuable information for global fits of parton distribution functions (PDFs). The use of nuclear targets is unavoidable due to the weak nature of the neutrino interactions, and this complicates the extraction of free nucleon PDFs because model-dependent corrections must be applied to the data. In early PDF analyses, the nuclear corrections were static correction factors without any (significant) dependence on the energy scale Q, the atomic number A, or the specific observable. The increasing precision of both the experimental data and the extracted PDFs demand that the
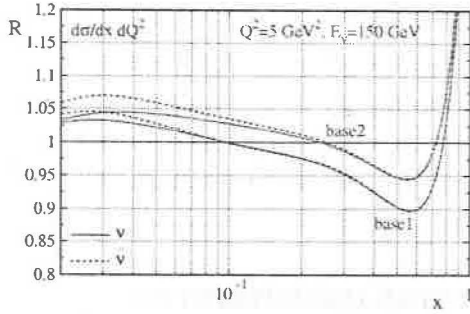

[†]Presented by Fred Olness.

Figure 1: Nuclear correction factor R according to Eq. 1 for the differential cross section $d^2\sigma/dx\,dQ^2$ in charged current neutrino-Fe scattering at $Q^2 = 5$ GeV^2. Results are shown for the charged current neutrino (solid lines) and anti-neutrino (dashed lines) scattering from iron. The upper (lower) pair of curves shows the result of our analysis with the Base-2 (Base-1) free-proton PDFs.
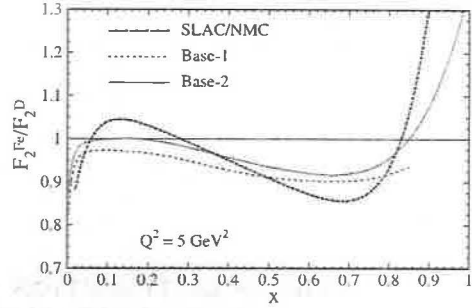
Figure 2: Predictions (solid and dashed line) for the structure function ratio F_2^{Fe}/F_2^D using the iron PDFs extracted from fits to NuTeV neutrino and anti-neutrino data. The SLAC/NMC parameterization is shown with the dot-dashed line. The structure function F_2^D in the denominator has been computed using either the Base-2 (solid line) or the Base-1 (dashed line) PDFs.

applied nuclear correction factors be equally precise as these contributions play a crucial role in determining the PDFs. In this study we reexamine the source and size of the nuclear corrections that enter the PDF global analysis, and quantify the associated uncertainty. Additionally, we provide the foundation for including the nuclear correction factors as a dynamic component of the global analysis so that the full correlations between the heavy and light target data can be exploited.

A recent study [1] analyzed the impact of new data sets from the NuTeV [3], Chorus, and E-866 Collaborations on the PDFs. This study found that the NuTeV data set (together with the model used for the nuclear corrections) pulled against several of the other data sets, notably the E-866, BCDMS and NMC sets. Reducing the nuclear corrections at large values of x reduced the severity of this pull and resulted in improved χ^2 values. These results suggest on a purely phenomenological level that the appropriate nuclear corrections for ν-DIS may well be smaller than assumed.

To investigate this question further, we use the high-statistics ν-DIS experiments to perform a dedicated PDF fit to neutrino–iron data [2]. Our methodology for this fit is parallel to that of the previous global analysis,[1] *but* with the difference we use only Fe data and that no nuclear corrections are applied to the analyzed data; hence, the resulting PDFs are for a bound proton in an iron nucleus. Specifically, we determine iron PDFs using the recent NuTeV differential neutrino (1371 data points) and anti-neutrino (1146 data points) DIS cross section data,[3] and we include NuTeV/CCFR dimuon data (174 points) which are sensitive to the strange quark content of the nucleon. We impose kinematic cuts of $Q^2 > 2$ GeV and $W > 3.5$ GeV, and obtain a good fit with a χ^2 of 1.35 per data point.[2]

2 Nuclear Correction Factors

We now compare our iron PDFs with the free-proton PDFs (appropriately scaled) to infer the proper heavy target correction which should be applied to relate these quantities. Within the parton model, a nuclear correction factor $R[\mathcal{O}]$ for an observable $\mathcal{O}$ can be defined as follows:

$$R[\mathcal{O}] = \frac{\mathcal{O}[\text{NPDF}]}{\mathcal{O}[\text{free}]} \tag{1}$$
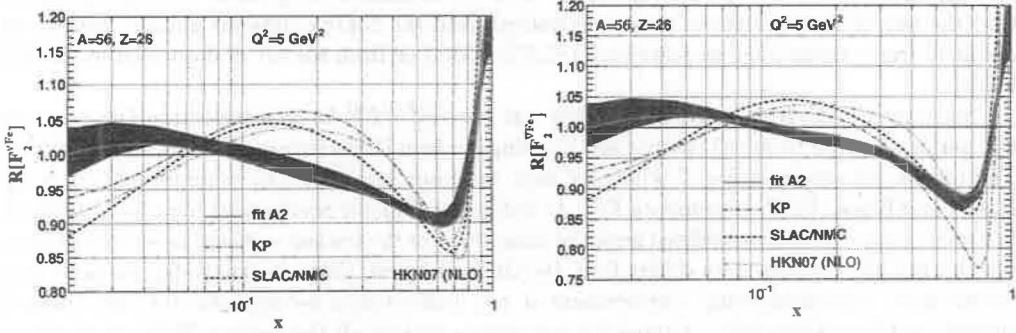
Figure 3: Nuclear correction factor R for the structure function F_2 in a) neutrino and b) anti-neutrino scattering from Fe. The solid curve shows the result of our analysis of NuTeV data; the uncertainty from the fit is represented by the shaded (yellow) band. For comparison we show the correction factor from the Kulagin–Petti model (dashed-dot line),[4] HKN07 (dashed-dotted line),[5] and the SLAC/NMC parametrization (dashed line).[2]

where $\mathcal{O}[\text{NPDF}]$ represents the observable computed with nuclear PDFs, and $\mathcal{O}[\text{free}]$ is the same observable constructed out of the free nucleon PDFs. In addition to the kinematic variables and the factorization scale, R can depend on the observable under consideration simply because different observables may be sensitive to different combinations of PDFs. This means that the nuclear correction factor R for F_2^A and F_3^A will, in general, be different. Additionally, the nuclear correction factor for F_2^A will yield different results for the charged current ν–Fe process ($W^\pm$ exchange) as compared with the neutral current $\ell^\pm$–Fe process (γ exchange). Because we have extracted the iron PDFs from only iron data, we do not assume any particular form for the nuclear A-dependence; hence the extracted $R[\mathcal{O}]$ ratio is essentially model independent.

We begin by computing the nuclear correction factor R for the neutrino differential cross section $d^2\sigma/dx\,dQ^2$, as this represents the bulk of the NuTeV data included in our fit, cf., Fig. 1. We have computed R using two separate proton PDFs denoted as Base-1 and Base-2; the difference of these curves, in part, reflects the uncertainty introduced by the proton PDF.[2] We also observe that the neutrino and anti-neutrino results coincide in the region of large x where the valence PDFs are dominant, but differ by a few percent at small x due to the differing strange and charm distributions.

We next display the nuclear correction factors for $F_2^{\nu Fe}$ and $F_2^{\bar{\nu}Fe}$ in Fig. 3. The SLAC/NMC curve has been obtained from an A and Q^2-independent parameterization of calcium and iron charged–lepton DIS data.[1] Due to the neutron excess in iron, both our curves and the KP curves differ when comparing scattering for neutrinos and anti-neutrinos. For our results (solid lines), the difference between the neutrino and anti-neutrino results is relatively small, of order 3% at $x = 0.6$. Conversely, for the KP model (dashed-dotted lines) the ν–$\bar{\nu}$ difference reaches 10% at $x \sim 0.7$, and remains sizable at lower values of x.

Comparing the nuclear correction factors for the F_2 structure function (Fig. 3) with those obtained for the differential cross section (Fig. 1), we see these are quite different, particularly at small x. This is because the cross section $d^2\sigma$ is comprised of a different combination of PDFs than the F_2 structure function. Again, we emphasize that it is important to use an appropriate nuclear correction factor which is matched to the particular observable.

Our results have general features in common with the KP model and the SLAC/NMC parameterization, but the magnitude of the effects and the x-region where they apply are quite different. Our results are noticeably flatter than the KP and SLAC/NMC curves, especially at moderate-x where the differences are significant. The general trend we see when examining these nuclear correction factors is that the anti-shadowing region is shifted to smaller x values, and

any turn-over at low x is minimal given the PDF uncertainties. In general, these plots suggest that the size of the nuclear corrections extracted from the NuTeV data are smaller than those obtained from charged lepton scattering (SLAC/NMC) or from the set of data used in the KP model.

Since the SLAC/NMC parameterization was fit to F_2^{Fe}/F_2^D for charged-lepton DIS data, we can perform a more balanced comparison by using our iron PDFs to compute this same quantity. The results are shown in Fig. 2 where we have used our iron PDFs to compute F_2^{Fe}, and the Base-1 and Base-2 PDFs to compute F_2^D. As before, we find our results have some gross features in common while on a more refined level the magnitude of the nuclear corrections extracted from the charged current iron data differs from the charged lepton data. In particular, we note that the so-called "anti-shadowing" enhancement at $x \sim [0.06 - 0.3]$ is *not* reproduced by the charged current (anti-)neutrino data. Examining our results among all the various $R[\mathcal{O}]$ calculations, we generally find that any nuclear enhancement in the small x region is reduced and shifted to a lower x range as compared with the SLAC/NMC parameterization. Furthermore, in the limit of large x ($x \gtrsim 0.6$) our results are slightly higher than the data, including the very precise SLAC-E139 points; however, the large theoretical uncertainties on F_2^D in this x-region make it difficult to extract firm conclusions.

3 Conclusions

While the nuclear corrections extracted from charged current $\nu-Fe$ scattering have similar general characteristics as the neutral current $l^\pm-Fe$ charged-lepton results, the detailed x and Q^2 behavior is quite different. There is *a priori* no requirement that these be equal; in fact, given that the $\nu-Fe$ process involves the exchange of a W and the $\ell^\pm-Fe$ process involves the exchange of a γ we necessarily expect this will lead to differences at some level.

These results raise the deeper question as to whether the charged current and neutral current correction factors may be substantially different. A combined analysis of neutrino and charged-lepton data sets, for which the present study provides a foundation, will shed more light on these issues. Resolving these questions is essential if we are to reliably use the plethora of nuclear data to obtaining free-proton PDFs which form the basis of the LHC analyses.

References

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