# How can we use neutrino nucleus interactions as a probe of the strong interaction?

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**Abstract.** Neutrino scattering experiments have been studying QCD for around 40 years. An example of the more recent studies of QCD with neutrinos is the NuTeV $\nu$-Fe experiment at Fermilab. The problem the community faces in trying to study QCD with neutrino data is that there is no experimentally verified way to convert neutrino-nucleus (for example, Fe) results to the equivalent neutrino-nucleon values making it difficult to combine neutrino nucleus scattering data in QCD global fits to extract parton distribution functions. This is particularly significant since there are now indications that nuclear effects in neutrino nucleus interactions might be different than those measured in charged-lepton nucleus scattering. To better understand this situation, the MINER$\nu$A neutrino-nucleus scattering experiment at Fermilab, a collaboration of elementary-particle and nuclear physicists, is systematically studying neutrino nuclear effects off of He, C, O, Fe and Pb for a more thorough A-dependent study of nuclear PDFs and these correction factors.

## 1. Introduction

Neutrino scattering plays a crucial role in extraction of fundamental parton distribution functions (PDFs). These PDFs describe parton constituents of protons and other hadrons, and (in the $\overline{MS}$ convention) are precisely defined in terms of operator matrix elements. The necessity of neutrino measurements is obvious, because only neutrinos can resolve the flavor of the nucleon's constituents: the $\nu$ interacts with d, s, $\overline{u}$ and $\overline{c}$ while the $\overline{\nu}$ interacts with u, c, $\overline{d}$ and $\overline{s}$. The weak current's unique ability to "taste" only particular quark flavors significantly enhances the study of parton distribution functions.

Large samples, and dedicated effort to minimizing beam-related systematics will allow neutrino experiments to independently isolate all the structure functions $F_1^{\nu N}(x,Q^2)$, $F_1^{\overline{\nu} N}(x,Q^2)$, $F_2^{\nu N}(x,Q^2)$, $F_2^{\overline{\nu} N}(x,Q^2)$,$xF_3^{\nu N}(x,Q^2)$ and $F_3^{\overline{\nu} N}(x,Q^2)$ for the first time. By taking differences and sums of these structure functions, specific parton distribution functions in a given $(x,Q^2)$ bin can in turn be determined. With the manageable systematic uncertainties expected, neutrino experiments can dramatically improve the isolation of individual PDFs by measuring the full set of $\nu$ and $\overline{\nu}$ structure functions. Extracting this full set of structure functions will rely on the y-variation of the structure function coefficients in the expression for the cross-section.

In the helicity representation, for example:

$$\frac{d^2\sigma^\nu}{dxdQ^2} = \frac{G_F^2}{2\pi x}[\frac{1}{2}(F_2^\nu(x,Q^2) + xF_3^\nu(x,Q^2)) + \frac{(1-y^2)}{2}(F_2^\nu(x,Q^2) - xF_3^\nu(x,Q^2)) - 2y^2F_L^\nu(x,Q^2)] \quad (1)$$

By analyzing the data as a function of (1-$y^2$) in a given (x,$Q^2$) bin, all six structure functions can be extracted[1].

## 2. Neutrino iron scattering results

To acquire significant statistics, the use of heavy nuclear targets is unavoidable due to the weak nature of the neutrino interactions. This complicates the extraction of free nucleon PDFs because corrections must be applied to the data to convert from the nucleus A to a nucleon. The results of the latest study of QCD using neutrino scattering comes from the NuTeV experiment [1]. The NuTeV experiment accumulated over 3 million $\nu$ and $\overline{\nu}$ events in the energy range of 20 to 400 GeV off a manly Fe target. The main points are that the NuTeV cross section agrees with the CCFR values (obtained using the same detector) for values of $x_{Bj} \leq 0.4$ but is systematically higher for larger values of $x_{Bj}$ . NuTeV agrees with charged lepton data for $x_{Bj} \leq 0.5$ but there is increasing disagreement for higher values. Although NuTeV $F_2$ and $xF_3$ agree with theory for medium x, they find a different $Q^2$ behavior at small x and are systematically higher than theory at high x. These results can be summarized in four main questions to ask subsequent neutrino experiments:

- At high x, what is the behavior of the valence quarks as $x \rightarrow 1.0$?
- At low W, what is happening in the transition region between resonance production and the DIS regions?
- At all x and $Q^2$, what is yet to be learned if we can measure all six $\nu$ and $\overline{\nu}$ structure functions to yield maximal information on the parton distribution functions?
- At all x, how do nuclear effects with incoming neutrinos differ from nuclear effects with incoming charged leptons?

This last item highlights an overriding question when trying to get a global view of structure functions from both neutrino and charged-lepton scattering data. How do we compare data off nuclear targets with data off nucleons and, the associated question, how do we scale nuclear target data to the comparable nucleon data.
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 then 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 $\chi^2$ values. These results suggested on a purely phenomenological level that the appropriate nuclear corrections for $\nu$-DIS may well be smaller than the assumed $l^{\pm}$-nucleus corrections.
To investigate this question further, the data from the high-statistics $\nu$-DIS experiment, NuTeV, was used to perform a dedicated PDF fit to neutrino-iron data [2]. The methodology for this fit is parallel to that of the previous global analysis [1], but with the difference that only Fe data has been used and no nuclear corrections have been applied to the analyzed data; hence, the resulting PDFs are for a bound proton in an iron nucleus. Specifically, the iron PDFs were determined using the recent NuTeV differential neutrino (1371 data points) and anti-neutrino (1146 data points) DIS cross section data [3], as well as the NuTeV/CCFR dimuon data (174 points) which are sensitive to the strange quark content of the nucleon. Kinematic cuts of $Q^2 \geq 2$ GeV$^2$ and W$\geq$ 3.5 GeV were imposed, and a good fit with a $\chi^2$ of 1.35 per data point was obtained [2].

[1] Note that for this type of parton distribution function study, anti-neutrino running will be essential.

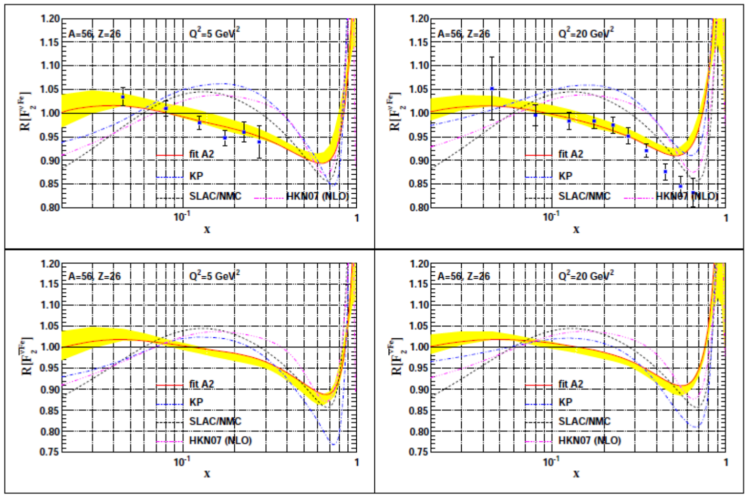


**Figure 1.** Nuclear correction factor R for the structure function $F_2$ in neutrino and anti-neutrino scattering from Fe for $Q^2 = \{5,20\}$ GeV$^2$. The solid curve shows the result of the analysis of NuTeV data; the uncertainty from the fit is represented by the shaded (yellow) band. For comparison, the correction factor from the Kulagin-Petti model (— · —) KP, HKN07 (— · · —) Kumano, and the SLAC/NMC parametrization (– – –) are shown.

## 3. Nuclear correction factor

By comparing these iron PDFs with the free-proton PDFs (appropriately scaled) a neutrino-specific heavy target nuclear correction factor R can be obtained which should be applied to relate these two quantities. In addition to kinematic variables, R can depend on the observable under consideration simply because different observables may be sensitive to different combinations of PDFs. For example, the nuclear correction factor R for $F_2^A$ and $F_3^A$ will, in general, be different. The nuclear correction factors for $F_2^{\nu Fe}$ and $F_2^{\overline{\nu} Fe}$ at $Q^2 = 5$ GeV$^2$ and 20 GeV$^2$ derived in this analysis and labeled A2 are shown in Fig 1.

The SLAC/NMC curve in the figures has been obtained from an A and $Q^2$-independent parametrization of calcium and iron charged-lepton DIS data [1]. The curves labeled "KP" are from the Kulagin-Petti model [4] constructed specifically to compute the nuclear effects in neutrino-nucleus interactions. Due to the neutron excess in iron, both the A2 and the KP curves differ when comparing scattering for neutrinos and anti-neutrinos.

Although the results of this analysis have general features in common with the KP model and the SLAC/NMC parametrization, the magnitude of the effects and the x-region where they apply are quite different. The present 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. More specifically, there is no indication of "shadowing" in the NuTeV neutrino results. 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.

## 4. Continuing the study of neutrino nucleus interactions

While the nuclear corrections extracted from charged current $\nu$-Fe scattering have similar characteristics as the $l^{\pm}$-Fe charged-lepton results, the detailed x and $Q^2$ behavior is quite different. This observation raises the deeper question as to whether the neutrino and charged-

lepton nuclear correction factors may be substantially different. The CTEQ study of the iron PDFs provides a foundation for a general investigation (involving a variable A parameter) that can definitively address this topic. Resolving these questions is essential if we are to reliably use nuclear data to obtaining free-proton PDFs which form the basis of the LHC analyses.
Experimentally, the MINER$\nu$A experiment, a collaboration of elementary-particle and nuclear physicists, is performing a hight-statistics, systematic study of neutrino nucleus interactions. The overall goals of the experiment are to measure absolute exclusive cross-sections and study nuclear effects in $\nu$-A interactions with He, C, O, Fe and Pb nuclear targets. For QCD oriented studies, they are planning systematic studies of the resonance-DIS transition region and the low $Q^2$ DIS region including the extraction of high-$x_{Bj}$ parton distribution functions.

## 5. Conclusions

Using the results from the NuTeV neutrino Fe experiment, nuclear effects of charged current deep inelastic neutrino-iron scattering have been studied in the frame-work of a $\chi^2$ analysis of parton distribution functions (PDFs). A set of iron PDFs has been extracted which is then 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. Upon comparing our results with nuclear correction factors from neutrino-nucleus scattering models and correction factors for $l^\pm$-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. There is no a priori reason to expect them to be the same. On the contrary, with the introduction of the axial-vector current in neutrino scattering, it would be difficult to understand if they were exactly the same. What was unexpected was the degree to which the R factors differ between $\nu$-Fe scattering compared to $l^\pm$-Fe charged-lepton results. In particular the lack of evidence for shadowing in neutrino scattering, confirmed by [5] for NuTeV data, is quite surprising.
The nuclear correction factors R are being measured over a wider range of A and with reduced errors by the MINER$\nu$A experiment in the NuMI beam in the near future.

## References

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