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# NuTeV Cross Section and Structure Function Measurements

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*NuTeV Collaboration*

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The NuTeV experiment has obtained a unique high statistics sample of neutrino and antineutrino interactions using its high-energy sign-selected beam. Charged-current $\nu$ and $\overline{\nu}$ differential cross sections are extracted. Neutrino-Iron structure functions, $F_2(x, Q^2)$ and $xF_3(x, Q^2)$, are determined by fitting the $y$-dependence of the differential cross sections. NuTeV has precise understanding of its hadron and muon energy scales, which improves the systematic precision of this measurement.

## 1 Introduction

Neutrino deep-inelastic scattering offers a precise and complimentary probe of nucleon structure and QCD. Neutrinos only experience the weak force and are uniquely sensitive to the parity violating structure function, $xF_3(x, Q^2)$.

NuTeV is a second generation neutrino deep inelastic scattering experiment which used the refurbished CCFR detector and Fermilab's Sign-Selected Quadrapole Train (SSQT) beamline to produce seperate high purity neutrino and antineutrino beams. QCD results benefit from the precise determination of muon and hadron energy scales, and measured detector response functions obtained using NuTeV's precision calibration beam. Muon energy scale was determined to 0.7% and hadron scale to 0.43%. A more detailed description of the experiment and the precision calibration can be found in [1].

## 2 Cross Section Measurement

The differential cross section in $x$, the Bjorken scaling variable, and $y$, the inelasticity, is determined from,

$$\frac{d^2\sigma^{\nu(\overline{\nu})}(E)}{dxdy} = \frac{1}{\Phi(E)}\frac{d^2N^{\nu(\overline{\nu})}(E)}{dxdy}. \tag{1}$$

where $\Phi(E)$ is the relative flux at neutrino energy $E$. Beam energy ranges from 30-350 GeV. Data selection for this sample requires event containment, a momentum analyzed muon in the toroid spectrometer, and minimum energy requirements; hadronic energy, $E_{HAD} > 10$ GeV, muon energy, $E_\mu > 15$ GeV, and reconstructed neutrino energy $E_\mu > 30$ GeV. $Q^2 > 1$ is required to minimize the non-perturbative contributions in the cross section. A total of $8.6\times10^5$ neutrino and $2.3\times10^5$ anti-neutrino events passed selection requirements.

Neutrino flux is determined from a sample of events at low $E_{HAD} < 20$ GeV using the "fixed $\nu_o$" method [2]. The integrated number of events with $E_{HAD} < 20\ GeV$ as $y = \frac{E_{HAD}}{E_\nu} \rightarrow 0$ is proportional to the flux. Corrections, determined from the data, up to order $y^2$ are applied to determine the relative flux to about the 1% level. Flux is normalized using the world average $\nu - Fe$ cross section $\frac{\sigma^\nu}{E} = 0.677\times10^{-38}$ cm$^2$/GeV from reference [3].

The Monte Carlo simulation , used to account for acceptance and resolution effects, requires an input cross section model which is iteratively tuned to fit the data. Cross section data are fit to empirically determine a set of parton distribution functions and the procedure is iterated until convergence.

Figure 1 shows the preliminary extracted cross sections compared with the CCFR [4] for $E_\nu = 85\ GeV$. NuTeV's $\overline{\nu}$ cross section is in good agreement at all $x$ with CCFR. The neutrino cross section agrees for $x < 0.45$ but is systematically above CCFR for high-$x$ at high $y$. In the high-$x$, high-$y$ region, smearing effects are larger and detector modeling is more important.

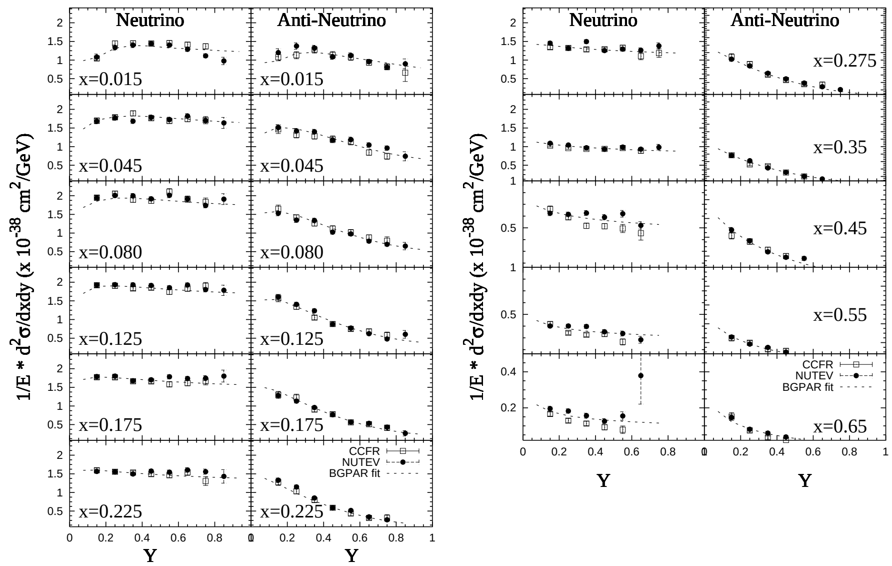


Figure 1: Preliminary differential cross sections for neutrinos (left each side) and anti-neutrinos (right each side) at $E = 85$ GeV. Points are NuTeV (filled circles) and CCFR (open squares). Curve shows fit to NuTeV data.

## 3 Structure Functions

The sum of the differential cross sections can be expressed as:

$$\left[\frac{d^2\sigma^{\nu}}{dxdy} + \frac{d^2\sigma^{\overline{\nu}}}{dxdy}\right] = \frac{y^2 G_F^2 M E}{\pi(1-\epsilon)} \left[(1+\epsilon R_L)\, 2xF_1 + \frac{y(1-y/2)}{1+(1-y)^2}\Delta x F_3\right] \qquad (2)$$

where $G_F$ is the Fermi weak coupling constant and M is the proton mass. The $y$-dependence of the first term is implicit in $\epsilon = \frac{2(1-y)-Mxy/E}{1+(1-y)^2+Mxy/E}$, the polarization of the virtual $W$-boson. $R_L(x,Q^2)$ relates the structure functions $F_2(x,Q^2)$ and $2xF_1(x,Q^2)$ by, $F_2(x,Q^2) \approx 2xF_1(1+R_L(x,Q^2))$ In the last term, $\Delta xF_3 = xF_3^{\nu} - xF_3^{\overline{\nu}}$, is sensitive to the heavy-quark seas, $\Delta xF_3 \approx 4x\,(s-c)$.

To extract $F_2(x, Q^2)$ we use $\Delta x F_3$ from a NLO QCD model as input (TRVFS [6]) and $R_L(x, Q^2)$ from $R_L^{world}$ [7]. Cross sections are corrected for small excess of neutrons in the target (5.67%) and for radiative effects [5] before fits are performed. NuTeV's $F_2(x, Q^2)$ is shown in Figure 2 compared with CCFR[4]. $F_2(x, Q^2)$ is in good agreement with CCFR for $x < 0.45$ and systematically above at higher $x$ consistent with the higher measured $\nu$ cross section in this region. The curve shown is a NLO QCD model from [6].

The difference of differential cross sections is proportional to $xF_3(x, Q^2)$,

$$\left[\frac{d^2\sigma^{\nu}}{dxdy} - \frac{d^2\sigma^{\overline{\nu}}}{dxdy}\right] = \frac{2G_F^2 ME}{\pi}\left(y - \frac{y^2}{2}\right) xF_3^{AVG}(x, Q^2) \tag{3}$$

where $xF_3^{AVG} = \frac{1}{2}(xF_3^{\nu} + xF_3^{\overline{\nu}})$. Figure 2 shows the NuTeV measurement of $xF_3(x, Q^2)$ which is in agreement with CCFR [8] for $x < 0.45$ and again systematically above for higher $x$.

NuTeV plans to extend the differential cross section sample to a previously inaccessible high-$y$ range. The sign-selected beam allows NuTeV to use a low energy muon sample, (with $E_\mu$ down to 4 GeV), with momentum determined from range in the calorimeter and muon sign assumed by the running mode (*i.e.* $\nu$ or $\overline{\nu}$). The addition of this sample will provide a lever arm to better constrain $R_L$ in two-parameter fits.

## 4 Conclusions

NuTeV has extracted preliminary differential cross sections for $\nu$-Fe and $\overline{\nu}$-Fe deep-inelastic scattering. Differential cross sections provide the most model-independent observable which can be reported for this process. NuTeV has precise understanding of muon and hadron energy scales, and a detector response determined over the entire energy range allowing improved systematic precision for this measurement.

Preliminary $\nu$-Fe structure functions have been extracted from fits to the differential cross section. QCD fits to the non-singlet structure function will provide stringent constraints on $\Lambda_{QCD}$.

## References

[1] D. A. Harris *et. al*, Nucl. Instrum. Methods **A447** (2000) 377.

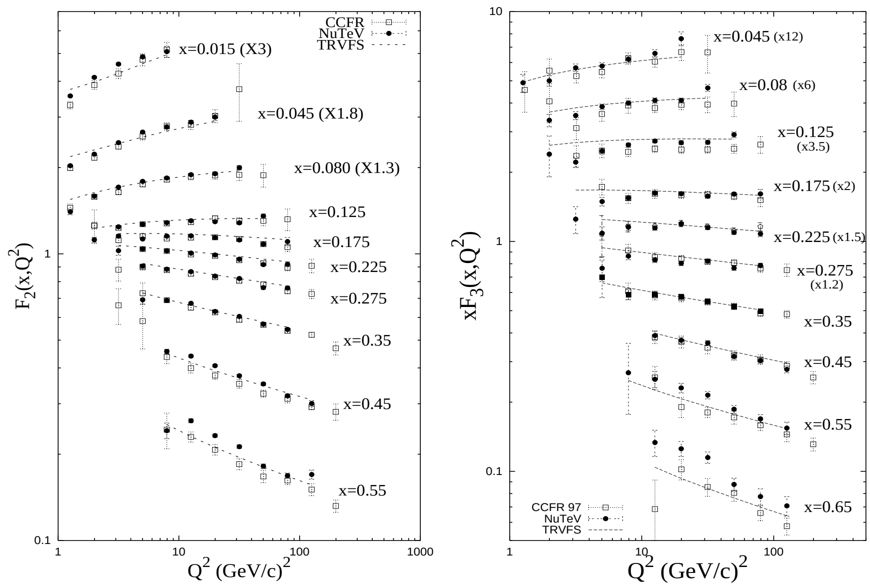


Figure 2: (Left) NuTeV's Preliminary Measurement of $F_2(x, Q^2)$ compared with previous $\nu$-Fe results from CCFR [4]. (Right) $xF_3(x, Q^2)$ extracted from the cross section difference and a comparison with the measurement from CCFR [8]. Curves show Thorne-Roberts NLO model [6].

[2] J. Conrad, M. H. Shaevitz, and T. Bolton, Rev. Mod. Phys. **70** (1998) 4.

[3] W. Seligman, Ph. D. Thesis, Columbia University, Nevis 292 (1997).

[4] U. K. Yang , Ph. D. Thesis, University of Rochester, (2001), U. K. Yang *et. al*, Phys. Rev. Lett. **87** (2001) 251802.

[5] Bardin, D. Y. and Dokuchaeva, JINR-E2-86-260 (1986).

[6] R. S. Thorne and R. G. Roberts, Phys. Lett. **B 421** (1998) 303. A. D. Martin *et. al.* Eur. Phys. J. **C 18** (2000) 117.

[7] L. W. Whitlow *et. al*, Phys. Lett. **B 250** (1990) 193.

[8] W. G. Seligman *et. al*, Phys. Rev. Lett. **79** (1997) 1213.