

## Axial and Vector Structure Functions for Lepton-Nucleon Scattering, NuFact 2021 Update

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We report on an update (2021) of a phenomenological model for inelastic neutrino- and electron-nucleon scattering cross sections using effective leading order parton distribution functions with a new scaling variable  $\xi_w$ . Non-perturbative effects are well described using the  $\xi_w$  scaling variable in combination with multiplicative  $K$  factors at low  $Q^2$ . The model describes all inelastic charged-lepton-nucleon scattering data (HERA/NMC/BCDMS/SLAC/JLab) ranging from very high  $Q^2$  to very low  $Q^2$  and down to the  $Q^2 = 0$  photo-production region. The model has been developed to be used in analyses of neutrino oscillation experiments in the few GeV region. The 2021 update accounts for the difference between axial and vector structure functions which brings it into much better agreement with neutrino-nucleon total cross section measurements. The model has been developed primarily for hadronic final state masses  $W$  above 1.8 GeV. However with additional parameters the model also describes the *average* neutrino cross sections in the resonance region down to  $W=1.4$  GeV.

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## 1. Introduction

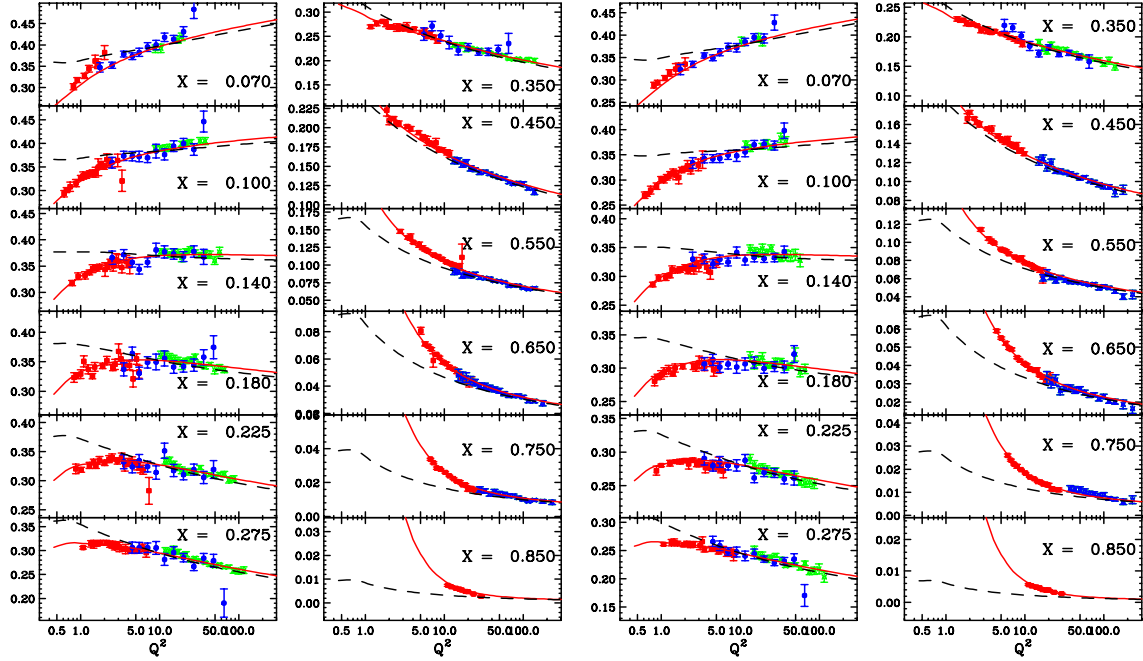
In the few GeV region there are contributions from several kinds of lepton-nucleon interaction processes as defined by the final state invariant mass  $W$  and square of the momentum transfer  $Q^2$ . These include quasi-elastic reactions ( $W < 1.07 \text{ GeV}/c^2$ ), the  $\Delta(1232)$  region ( $1.1 < W < 1.4 \text{ GeV}/c^2$ ), higher mass resonances ( $1.4 < W < 2.0 \text{ GeV}/c^2$ ), and the inelastic continuum region ( $W > 2.0 \text{ GeV}/c^2$ ). At low momentum transfer the inelastic continuum is sometimes referred to as "shallow inelastic", and at high momentum transfer it is referred to as "deep inelastic". It is quite challenging to disentangle each of those contributions separately, and in particular the contribution of resonance production and the inelastic scattering continuum. At low  $Q^2$  there are large non-perturbative contributions to the inelastic cross section. These include kinematic target mass corrections, dynamic higher twist effects, higher order Quantum Chromodynamic (QCD) terms, and nuclear effects in nuclear targets.

In the Bodek-Yang model we focus on the inelastic part of the cross sections above the region of the  $\Delta(1232)$  resonance (i.e. the higher mass resonances, and the inelastic continuum). The model is duality based model of neutrino interactions using effective leading order parton distribution functions (PDFs). Earlier versions of the model[1, 2] have been incorporated into several Monte Carlo generators of neutrino interactions including NEUT, NEUGEN, NUANCE and GENIE. The current version of GENIE is using the NUINT04[2] version of the model. These early versions assume that the axial structure functions are the same as the vector structure functions. The model is based on parameters extracted from electron scattering data. The leading order GRV98 PDFs are used with modifications that include a new scaling variable ( $\xi_w$ ) to account for deviations from Bjorken scaling at lower values of  $Q^2$  and low  $Q^2$  K factors that extend the validity of the model down the  $Q^2=0$  photo-production limit. Figure 1 shows a comparison of electron scattering structure functions to predictions of the GRV98 PDFs, with and without our modifications.

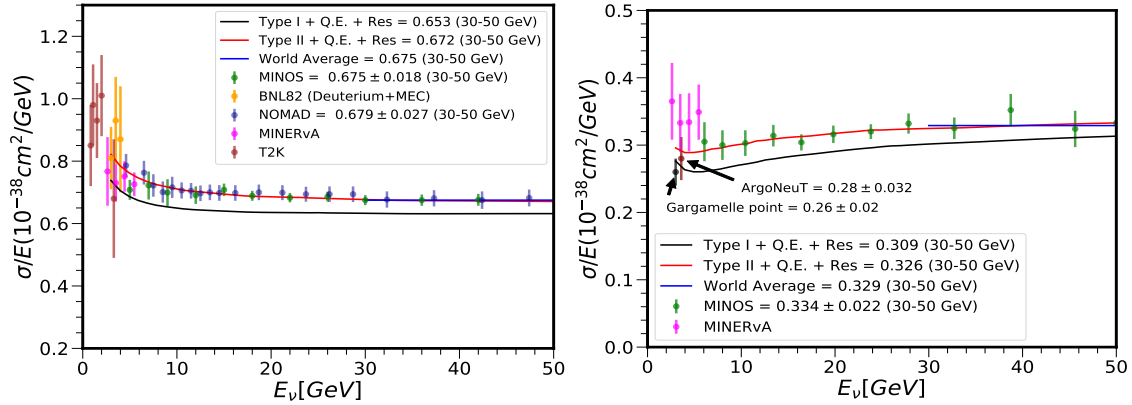
In this conference report we present a short a summary of the results of a 2021 update (details in ref.[3] in which we further refine the model and *also* account for the difference between axial and vector structure functions at low values of  $Q^2$ . We refer to the version of the model which assumes that vector and axial structure functions are the same as "Type I". The "Type I" version should be used to model electron and muon scattering. We refer to the updated version of the model that accounts for the difference in vector and axial structure functions as "Type II". "Type II" model should be used to model neutrino scattering.

Figure 1 shows the Bodek-Yang model with effective LO PDF model compared to charged-lepton  $\mathcal{F}_2$  experimental data (SLAC, BCDMS, NMC). Left:  $\mathcal{F}_2$  proton. Right  $\mathcal{F}_2$  deuteron (per nucleon). The solid lines are the model, and the dashed lines are predictions of the GRV98 PDFs without our low  $Q^2$  modifications

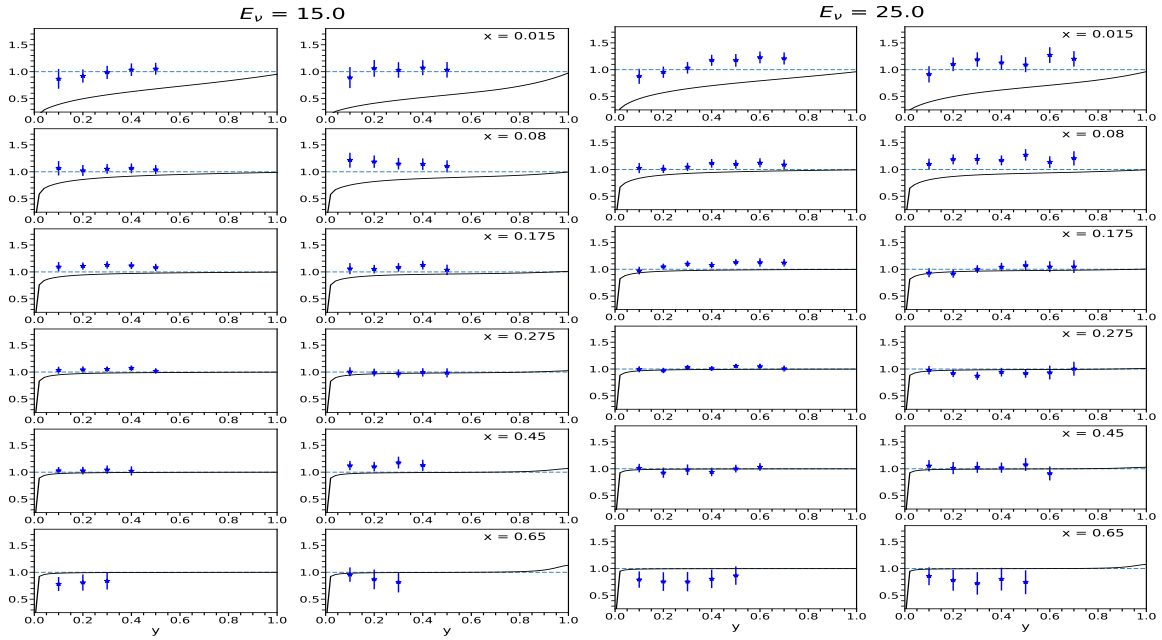
Figure 2 shows the model predictions (per nucleon) for neutrino total cross sections on an isoscalar target compared to measurements.  $\sigma_\nu/E$  data as a function of energy are shown on the left and  $\sigma_{\bar{\nu}}/E$  are shown on the right. The green points are MINOS  $\sigma_\nu/E$  data, the blue points are NOMAD, and the yellow crosses are BNL82. The MINERvA and T2K data are shown in purple and brown, respectively. The Gargamelle and ArgoNeut measurements of  $\sigma_{\bar{\nu}}/E$  per nucleon are identified on the figure. There is good agreement of the the Type II (A>V) model predictions with neutrino and antineutrino total cross section measurements.



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**Figure 3:** The ratio of charged-current neutrino and antineutrino differential cross sections  $d^2\sigma/dxdy$  on lead from CHORUS (blue points) to the Type II ( $A>V$ ) default model predictions. The ratios are shown for energies of 15 and 25 GeV. On the left side of each panel we show the comparison for neutrino cross sections and on the right side we show the comparisons for antineutrinos. The black line is the ratio of the predictions of the Type I ( $A=V$ ) model for which the axial structure functions are set equal to the vector structure functions, to the predictions of the Type II ( $A>V$ ) default model. The differential cross section data favor the Type II ( $A>V$ ) model.

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## References

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- [3] Arie Bodek, Un Ki Yang, Yang Xu, "Inelastic Axial and Vector Structure Functions for Lepton-Nucleon Scattering, 2021 Update", arXiv:2108.09240v2 [hep-ph] (2021).