Neutrino Oscillation Experiments and Cross Section Modeling

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Abstract. In this paper I will discuss the modeling of neutrino interaction physics for neutrino oscillation experiments, focusing in particular on the cross section modeling for the MINOS experiment.

NEUTRINO OSCILLATION EXPERIMENTS

The discovery of neutrino oscillations in the solar and atmospheric fluxes has opened a new window of exploration into the standard model. Precision measurements of the lepton mixing matrix will require intense neutrino beams and large detectors at remote locations. The MINOS experiment, which began taking oscillation data in March 2005, uses a conventional neutrino beam from the Fermilab Main Injector and a 5.4 ton iron calorimeter located 730 km away in northern Minnesota [1]. A number of additional experiments are either in the construction, advanced planning, or proposal stages. Conventional "super-beams" produced by megawatt-scale proton drivers, neutrino factories, or even neutrino beams produced from radioactive ion beams have all been considered. Generally speaking the energy range of interest to future experiments is 0.5 - 10 GeV with detectors consisting primarily of carbon, oxygen, or iron.

Through the study of neutrino interactions over several decades we have learned a great deal about electroweak unification and the QCD structure of the nucleon. With the advent of high-statistics oscillation experiments the study of neutrino interactions has entered a new phase, where the ability to accurately model the cross sections and nuclear physics is important in an "engineering" sense, i.e. as the backdrop against which any oscillation signatures will play out.

NEUTRINO INTERACTION PHYSICS UNCERTAINTIES

One of the clearest challenges in modeling neutrino interactions for an experiment like MINOS is incorporating physics models over a broad range of kinematics and nuclear targets. Figure 1 shows the kinematic coverage in x and Q^2 of the NuMI (Neutrinos at the Main Injector) low energy beam, the standard configuration for the MINOS experiment. The contours indicate regions of kinematic space including 50, 75, 90, and 99% of the events. The dashed lines indicate rough boundaries for common theoretical assumptions. The line at $Q^2 = 1$ GeV^2 is the approximate minimum value for which the Plane Wave Impulse Approximation (PWIA), a key assumption in the treatment of scattering from

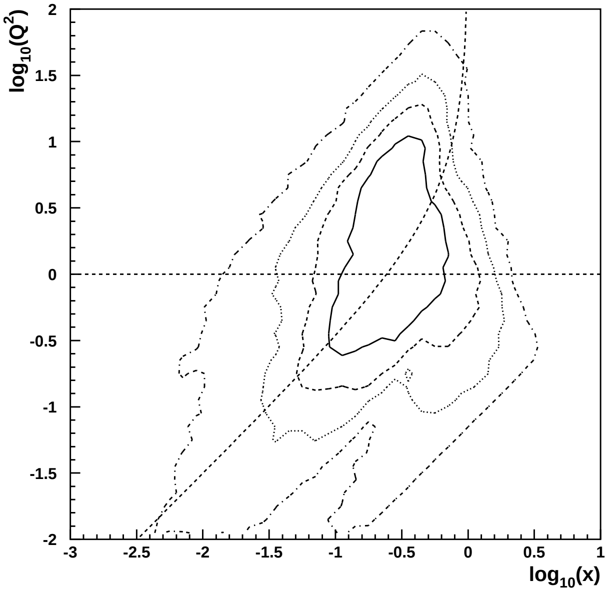

FIGURE 1. Kinematic coverage of the NuMI low energy beam.

nuclear targets, is considered valid. The other corresponds to W=2 GeV, the canonical transition into the DIS regime. Neutrino analyses historically avoided inelastic data below W=2 GeV and above the $\Delta(1232)$ because of the large higher twist corrections and difficulty in identifying a clean theoretical approach for this region which stands at the transition between perturbative and non-perturbative regimes.

In addition to uncertainties in modeling the cross section itself, uncertainties in the hadronization process and in the intranuclear rescattering of produced hadrons can have a large impact on an oscillation search. Part of the goal of a new generation of experiments, like the MINERνA [2] experiment at Fermilab, is to measure these effects with high precision so that they do not become limiting systematics for future oscillation measurements [3].

TUNING TO ELECTRON SCATTERING DATA

There is much to be gained by tuning neutrino interaction models to electron scattering data [4]. The kinematic region of primary importance to MINOS largely overlaps the kinematic range explored by electron scattering experiments at the Jefferson lab and other facilities going back many years. This data is both far more precise than neutrino data and exists over the entire resonance region.

The standard treatment for neutrino cross section modeling is now centered around the modified leading order DIS model of Bodek and Yang [5] which uses the GRV98LO parton distributions. This model describes higher twist effects through the use of new scaling variables and is able to describe electron scattering data down to the photopro-

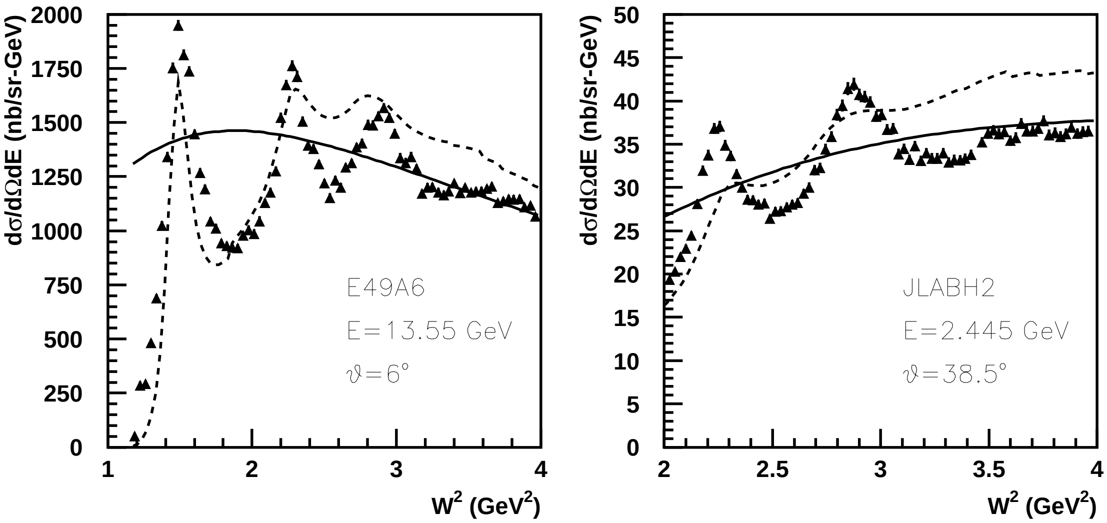

FIGURE 2. Comparison between electron scattering data and predictions from two versions of the NEUGEN3 program. The dashed curve is from the default 2004 version of the program which is dominated in this regime by the Rein-Seghal model. The solid line is the prediction of the Bodek-Yang model. Data are from [8].

duction limit. This model has been comprehensively compared against F_2 and xF_3 data from both charged lepton and neutrino scattering experiments.

Tuning cross section models in the resonance region (1.2 GeV < W < 2 GeV) has always posed a challenge because of the lack of precise neutrino data. Many neutrino programs have, in the past, relied on the Rein-Seghal model [6] which implements the Feynman-Kislinger-Ravndal model [7] of baryon resonances and attempts to describe data up to W=2 GeV in terms of 18 hadronic resonances and an incoherent background. This model has been a favorite of neutrino simulators for decades as it attempts to describe scattering over a broad range of kinematics historically avoided by perturbative QCD models. While the Bodek-Yang model gets this region right on average, some experiments may require more accurate modeling of the resonance structure, in particular the $\Delta(1232)$. Tying the Bodek-Yang model to an explicit resonance model is an area of current work.

Figure 2 shows a comparison between the 2004 NEUGEN3 [9] prediction (which was based on the Rein-Seghal model), the Bodek-Yang model and a representative sample of electron scattering data. While the Bodek-Yang model describes the data in an average sense, the Rein-Seghal model attempts to fully describe the resonance structure. For other kinematics the Rein-Seghal based predictions are not nearly as good, and can differ from the data by as much as 100%.

With the high statistics recorded in the MINOS near detector a number of additional, non-oscillation measurements will be possible. Figure 3 shows the expected statistical precision from the MINOS experiment extraction of F_2 on iron with 5 years data [10].

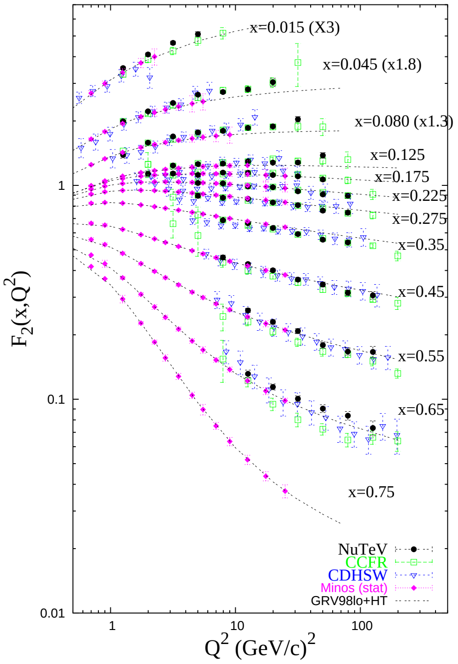

FIGURE 3. Structure function measurement capability of the MINOS experiment.

Systematic errors are not included.

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