The NOvA experiment is an off-axis long-baseline neutrino oscillation experiment seeking to measure $\nu_\mu$ disappearance and $\nu_e$ appearance in a $\nu_\mu$ beam originating at Fermilab. In addition to measuring the unoscillated neutrino spectra for the purposes of predicting the oscillated neutrino spectrum in the far detector, the 293-ton near detector also enables high-statistics investigation into neutrino scattering in numerous reaction channels. We discuss the various near detector analyses currently in progress, including inclusive measurements of both electron and muon neutrino charged-current interactions and efforts to constrain the off-axis NuMI flux using the elastic scattering of neutrinos from atomic electrons.

1 Introduction

Over the course of the last three decades, neutrino oscillation experiments have sought to use the quantum-mechanical properties of the neutrino as a probe of the fundamental nature of the lepton family. Since the weak-force coupling of neutrinos to other particles is extremely small, terrestrial neutrino oscillation experiments, such as NOvA, typically construct large detectors from materials composed of heavy nuclei in an effort to maximize the neutrino interaction rate. But the intractibility of calculating the dynamics of nucleons within the nucleus in the low-energy limit of the strong force introduces significant uncertainties into the reaction predictions used in measurements made with these detectors. Even in the two-detector paradigm used by NOvA and other experiments, in which a detector close to the neutrino source (the near detector, ND) is used to constrain the product of interaction cross section models and the flux prediction (which is then extrapolated to the far detector, FD, where oscillations are observed), direct measurements of neutrino interaction cross sections on the target materials are extremely valuable for constraining and choosing between models.

The 293-ton NOvA near detector is an ideal instrument to use for this sort of cross section measurement for several reasons. First, its location 14.6 mrad off-axis in the Fermilab NuMI neutrino beam it samples yields a narrow neutrino energy spectrum centered on 2 GeV, producing an event sample rich in interaction types (including copious examples of quasielastic scattering, baryon resonance production, and deep inelastic scattering) and exhibiting multiple kinds of nuclear effects (including coherent meson production, multi-nucleon scattering, and final-state hadron rescattering). Second, the detector itself is a mostly-active, fine-grained, segmented tracking calorimeter constructed of PVC cells filled with liquid scintillator with excellent spatial and energy resolution. We present status reports on a number of measurements currently in progress using the NOvA ND.
Figure 1: Predicted distribution of muon particle identification classifier described in the text for tracks ($\nu_\mu$ CC signal, red line; other predicted reactions, blue line) compared to ND data (black points). Events with Muon ID $> 0.3$ are retained as candidate $\nu_\mu$ CC events.

2 $\nu_\mu$ charged-current inclusive scattering

During its lifetime the NOvA ND is expected to record an immense sample of charged-current (CC) interactions of muon neutrinos on the liquid scintillator ($\nu_\mu CH_2 \rightarrow \mu^- X$) ultimately numbering in the millions. The statistical power of this sample offers an unprecedented opportunity both to verify the basic nucleon-level models for CC reactions in detail and to examine the relevant nuclear effects near $E_{\nu} = 2$ GeV; this energy range has previously been explored mostly in light bubble chamber experiments in measurements reporting only total cross sections.

2.1 The lepton system

The comparatively long lifetime and clean ionization profile of muons make the lepton kinematics in CC reactions particularly amenable to precise measurement. NOvA reconstructs muons as tracks and separates them from the hadronic background using a $k$-nearest neighbors (kNN) algorithm trained with four variables: the track length, the longitudinal energy profile ($dE/dx$), the scattering along the track, and the fraction of energy in the neutrino event associated with the track. The distribution of the resulting classifier is shown in figure 1; the observed data distribution is well-described by the prediction. Events which have Muon ID $> 0.3$ and whose energy is contained inside a fiducial volume buffered from the edges of the detector by two cells are retained as candidate $\nu_\mu$ CC events. The predicted resolutions in both muon energy and angle for this sample are very good (averaged over the sample, $50$ MeV $\rightarrow 3.8\%$ and $4^\circ \rightarrow 1.6\%$, respectively), as indicated in figure 2. A doubly-differential cross section measurement in these variables is currently in progress; the influence of systematic effects (such as energy scales and the flux prediction) is currently under investigation.
Figure 2: Predicted resolutions (black dots) compared to predicted event distributions (red lines) in muon energy (left) and cosine of the muon angle (right) for selected signal candidates.

2.2 The hadronic system

Because NOvA is a tracking calorimeter, it offers detailed reconstruction of the hadronic part of $\nu_\mu$ CC interactions as well. Here the effect of the nucleus on neutrino interactions takes center stage; we observe clear evidence for an extra reaction type beyond those predicted by default GENIE 2.10.4 lying in between the quasielastic (QE) and baryon resonance (RES) channels in momentum transfer variables (where $E_\mu$ and $E_{\text{had}}$ are the reconstructed muon and non-muon energies in the system):

\[
\begin{align*}
q_0 &= E_{\text{had}} \\
E_\nu &= E_\mu + E_{\text{had}} \\
Q^2 &= 2E_\nu (E_\mu - p_\mu \cos(\theta_\mu) - M^2_\mu) \\
|\vec{q}| &= Q^2 + q_0
\end{align*}
\]

This is illustrated in figure 3. Inspired by recent work in neutrino scattering\textsuperscript{2}, we interpret this absence as the lack of a model for a two-particle, two-hole (2p2h) process, where the neutrino scatters from a nucleus and ejects two of the nucleons (which were previously in some kind of correlated state) together.

GENIE 2.10.4 does ship with an “optional” (not enabled by default), mostly empirical model for 2p2h reactions\textsuperscript{3}, “Empirical MEC\textsuperscript{a}” (previously called “Dytman MEC,” after its author). Because it is unclear whether the kinematic assumptions built in to this model that were constructed largely from observations at lower $E_\nu$ should extrapolate correctly to NOvA’s neutrino energy range, we further modify this model as follows:

1. We reverse the linear turn-off of the cross-section between 1 and 5 GeV (so that the Empirical MEC cross section becomes a constant fraction of the QE one) since there are recent indications that 2p2h exists with similar strength at energies above 5 GeV\textsuperscript{2}.

2. We reverse the fraction of scattering from neutron-neutron and neutron-proton pairs in the model to 20% and 80%, respectively, based on indications from electron scattering\textsuperscript{5} and expectations from theoretical expectations in neutrino scattering\textsuperscript{6}.\textsuperscript{b}

\textsuperscript{a}Meson Exchange Currents (MEC) are one predicted class of 2p2h which have generated intense theoretical interest in recent years. Good summaries of the various strategies can be found elsewhere.\textsuperscript{3}

\textsuperscript{b}The typo that led to the need for this correction has been corrected in GENIE 2.12.
3. We apply a momentum-transfer-dependent weight derived from our ND data as described in the next paragraph.

To construct weights that constrain the Empirical MEC to better fit our observed data, we first examine the data excess in $|\vec{q}|$ (effectively the difference of the integrals of data and simulation in each panel of figure 3). We reweight the Empirical MEC such that it agrees with the data excess in this variable. To set the fourth component of the four-momentum transfer, $q_0$, we fix it to the shape of the predicted $q_0$ distribution in each bin of $|\vec{q}|$ taken from the GENIE quasielastic channel. This somewhat underestimates the $E_{\text{had}}$ in the observed distribution, as illustrated in figure 4b, but the overall agreement relative to the untuned version (figure 4a) is substantially improved. The GENIE 2.10.4 prediction with tuned Empirical MEC is the base prediction for current oscillation analysis efforts, including those discussed elsewhere in this volume.

3 $\nu_e$ charged-current inclusive scattering

Electron neutrinos are expected to undergo the same types of reactions and their interactions are expected to experience the same types of nuclear effects as $\nu_\mu$, up to the influence of the difference in the charged lepton masses. Understanding whether this is actually the case is very important for oscillation experiments like NOvA, for which the interactions of $\nu_e$ appearing via oscillation from a $\nu_\mu$ beam comprise a critical signal channel. However, at energies around several GeV, until recently it has been challenging to accumulate enough $\nu_e$ interactions to make statistically significant measurements. The very intense NuMI beam used by NOvA, on the other hand, has about a 1% admixture of $\nu_e$, opening the door for high-statistics investigation.

For a cross section analysis, NOvA begins selecting $\nu_e$ interactions using a likelihood classifier constructed from the longitudinal energy profiles of various particle templates; the performance of this classifier (after a baseline selection requiring containment and rejecting especially minimum-ionizing tracks to reject $\nu_\mu$ CC), and the selection cut made on it, is illustrated in

\footnote{After applying the correction to non-resonant 1\pi production from neutrons suggested by Rodrigues et al.\textsuperscript{1}}
Figure 4: Visible hadronic energy distributions in ND selected $\nu_\mu$ CC events before (left) and after (right) the addition of GENIE 2.10.4 “Empirical MEC” constrained as discussed in the text.

Figure 5: Performance of variables used to select $\nu_e$ CC interactions, as described in the text: likelihood classifier preselector (left); final boosted decision tree output (right). The inset in the right plot is a zoom showing only the distribution above the cut.

4 Constraining neutrino flux with $\nu - e$ elastic scattering

The neutrino flux prediction is an essential ingredient to any cross section measurement because it represents the normalization coefficient as a function of neutrino energy; traditionally flux uncertainties comprise the largest source of error for extracted cross sections. This owes primarily to the fact that ab initio calculations of horn-focused neutrino beams like NuMI depend on predictions of the strong-force dynamics of protons colliding (and re-interacting) with complex molecular targets like graphite, which are difficult. However, it is in principle possible to constrain the flux prediction using an in situ measurement of a neutrino scattering process
with a well-understood cross section. Because of the complexities of neutrino interactions with nuclei, however, purely leptonic processes like $\nu + e \rightarrow \nu + e$ scattering (neutrinos with atomic electrons) are the the reactions most amenable to use in this fashion. Unfortunately, the cross section of $\nu + e \rightarrow \nu + e$ scattering is suppressed relative to nucleon scattering by the ratio of the electron to nucleon masses and other kinematic factors, resulting in $\sigma_{\nu-e}/\sigma_{\nu-N} \sim 10^{-4}$. Therefore statistics are typically low in this channel.

As in the $\nu_e$ CC case, NOvA uses two PID classifiers to identify candidate electron showers for this analysis: one that distinguishes between electromagnetic showers and other backgrounds, and one that specifically distinguishes between electron-induced and photon- or neutral pion-induced showers. After selections on these variables, we employ a cut at $0.005 \text{ GeV} \times \text{ rad}^2$ on the kinematic variable $E_e \theta_e^2$, which is limited to very small values by the kinematics of the interaction itself, to further enrich the signal; this is illustrated in figure 6a. The resulting electron energy spectrum, which will be used to constrain the flux, is shown in figure 6b. Currently efforts are being devoted to quantifying the size of uncertainty in the signal efficiency and background cross section and flux predictions. It is expected that this technique will constrain the flux normalization to around 10% uncertainty.

Acknowledgments

NOvA is supported by the US Department of Energy; the US National Science Foundation; the Department of Science and Technology, India; the European Research Council; the MSMT CR, Czech Republic; the RAS, RMES, and RFBR, Russia; CNPq and FAPEG, Brazil; and the State and University of Minnesota. We are grateful for the contributions of the staffs of the University of Minnesota module assembly facility and NOvA FD Laboratory, Argonne National Laboratory, and Fermilab. Fermilab is operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the US DOE.