CCQE Results from MINERνA

Laura Fields, for the MINERνA Collaboration

Northwestern University

Abstract.
   A precision understanding of neutrino and anti-neutrino quasi-elastic interactions is crucial to current and future neutrino oscillation measurements. However, recent experimental results indicate that the nuclear environment of modern neutrino detectors modifies free nucleon cross sections in a variety of ways, many of which are not currently well understood. The MINERνA collaboration aims to make precision measurements of neutrino-nucleon quasi-elastic cross sections, as well as to understand the impact of nuclear effects on these cross sections. We present three preliminary quasi-elastic analyses that are the first steps towards these goals.

Keywords: neutrino interactions, quasi-elastic, nuclear effects

INTRODUCTION.

While neutrino quasi-elastic interactions on free nucleons are relatively well understood processes, it is becoming increasing clear that this is not the case for similar cross sections on bound nucleons. For instance, results from experiments such as MiniBooNE [5, 4] suggest the presence of quasi-elastic-like interactions on multi-nucleon bound states. Two major goals of the MINERνA experiment are to make high precision quasi-elastic cross section measurements, as well as to identify and quantify the effect of the nuclear environment on these cross sections. The latter goal will be accomplished in part through comparison and combination of quasi-elastic measurements made using different reconstruction techniques and on different nuclei. Below, we present preliminary results from three early MINERνA quasi-elastic analyses, including two simple neutrino and anti-neutrino companion analyses that attempt reconstruction of the muon track only and consider only interactions on the plastic scintillator region of the detector, as well as a third analysis that demonstrates some of the more advanced capabilities of MINERνA by fully reconstructing a second track and considering quasi-elastic interactions on the lead, iron and carbon passive targets.

DETECTOR AND SIMULATION

The MINERνA detector [1] consists of an inner core of active plastic scintillator bars surrounded by scintillator interspersed with passive material to form electromagnetic and hadron calorimeters. High energy charged particles are identified as tracks, while untracked particles are measured calorimetrically. The MINOS near detector, which sits immediately downstream from MINERνA, functions as a spectrometer for muons that exit the back of MINERνA. Upstream passive targets composed of carbon, iron, lead, water and helium enable measurements of neutrino cross sections in each of these materials in addition to high statistics measurements of cross sections on plastic scintillator. The detector resides in the NuMI beamline and has been exposed to both neutrino and anti-neutrino enriched beams with peak energies of around 3.5 GeV. This low energy dataset was completed in 2012; data taking with a higher energy beam will resume in 2013.

   Because the emphasis of all of the preliminary results described here is on comparisons of MINERνA data with Monte Carlo, it is useful to briefly review the details of our simulation. We use a GEANT4 based simulation of the NuMI beamline [3] tuned with data from the NA49 collaboration [9] and combined with neutrino interactions produced by the GENIE Neutrino Monte Carlo Generator, version 2.6.6 [6]. Quasi-elastic interactions are simulated using the Lewellyn-Smith formulation [7], including a dipole axial form factor with $M_A = 0.99$ GeV and BBBA2005 vector form factors [8]. The nuclear model is based on the Bodek-Ritchie parametrization of the Fermi Gas Model [11]; intranuclear rescattering is modeled by INTRANUKE [6]. This simulation is the basis for all acceptance corrections and background subtractions of our data. In the case of the one track anti-neutrino analysis only, we compare differential cross sections that have been fully corrected with this GENIE simulation with predictions of the NuWro
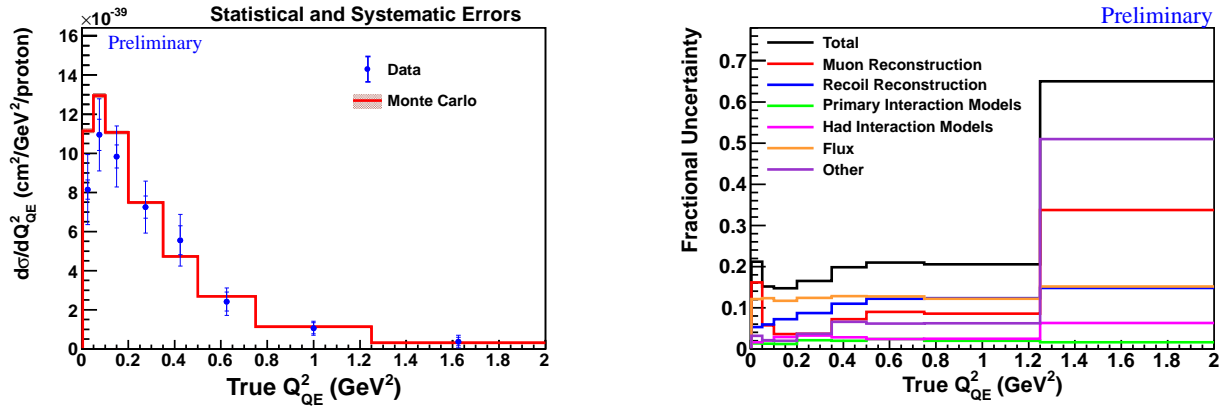
FIGURE 1. Fully corrected differential anti-neutrino quasi-elastic cross sections on the tracker volume, compared with the GENIE simulation (left), and a summary of fractional systematic uncertainties on the differential cross sections (right). The cross sections are flux-integrated over the NuMI flux up to 12 GeV.

generator, details of which can be found in [10].

## ONE TRACK ANTI-NEUTRINO CCQE ON SCINTILLATOR

MINERνA's first fully unfolded cross section measurements use an early sample of anti-neutrino data corresponding to 8.96e19 protons on target that exposed a partially constructed detector. This sample includes roughly 1/3 of the anti-neutrino interactions on the tracker volume that were collected during the full MINERνA low energy run. The analysis begins by looking for muon tracks that originate in the MINERνA scintillator volume that are matched to positively charged tracks in the MINOS near detector. Since the only non-muon daughter of most $\bar{\nu}$ quasi-elastic interactions is a neutron, we further require that there are no additional tracks found within MINERνA and that there is no more than one large energy deposition. We also estimate all non-track energy, excluding a 10 cm radius region around the reconstructed muon vertex, and require this to be less than $Q^2/4$, where Q is the 4-momentum transferred from the neutrino to the neutron, derived from the muon energy and angle. This cut is equivalent to requiring that MINERνA observes less than half of the neutron's kinetic energy. The 10 cm black-out region around the interaction vertex is made to minimize dependence on simulations of vertex activity.

To produce cross sections from this anti-neutrino quasi-elastic enriched sample, we subtract backgrounds estimated using our GENIE simulation constrained by fits to the recoil energy distributions in data. Background subtracted distributions are then unfolded and acceptance corrected. The fully corrected differential cross sections versus Q^2 are shown in Figure 1. The data, with error bars that include a first estimate of systematic uncertainties are compared with the GENIE prediction, which is higher than the data, particularly at low Q^2. A summary of systematic uncertainties is also shown in Figure 1; these uncertainties are currently dominated by large flux uncertainties which are expected to be significantly reduced in the future.

We have also compared these differential cross sections with predictions of another event generator, NuWro, which includes a standard $M_A = 0.99$ model similar to our nominal GENIE simulation, as well as a model, known as the transverse enhancement model [12], that parameterizes an observed enhancement of the transverse part of the electron-nucleus scattering cross section and applies it to neutrino-nucleus cross sections. The enhancement at intermediate Q^2 values may be due to nucleon-nucleon correlation effects such as meson exchange currents. Because MINERνA's currently large flux uncertainties are nearly fully correlated across Q^2, it is most interesting to compare the shape of the differential cross section, which has significantly lower uncertainties; this comparison is shown in Figure 2. While we cannot currently rule out any of the models, the data agree quite favorably with the TEM model. This agreement becomes more interesting upon examination of the energy within the 10 cm vertex region in our sample. A comparison of the visible energy in this region with the standard GENIE simulation is shown in Figure 3. Here, we see excellent Monte Carlo agreement with data at very low Q^2, but an excess of vertex energy in data at high Q^2. The MINERνA collaboration is currently working to further understand these vertex energy distributions, in the hopes that this will
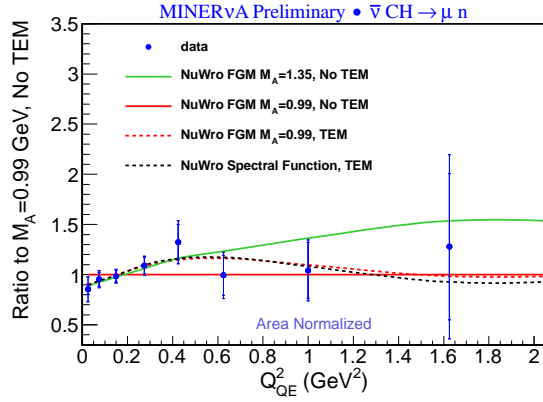
FIGURE 2. Shape comparison of fully corrected anti-neutrino quasi-elastic differential cross sections with several NuWro models, including a model very similar to the GENIE simulation (solid red) and two models that include the Transverse Enhancement Model (TEM) [12]. The plotted quantity is the ratio of a given model or data to the nominal $M_A = 0.99$ GeV model with no TEM.
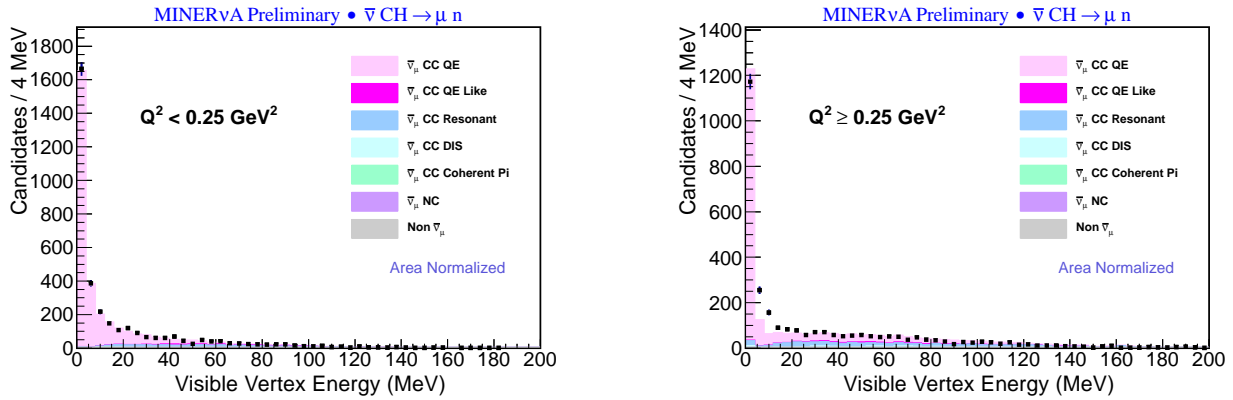

FIGURE 3. Visible vertex energy distributions in the anti-neutrino quasi-elastic sample at very low Q^2 (left) and at higher Q^2 (right). We observe a harder vertex energy distribution in data at high Q^2.

shed further light on the presence (or lack thereof) of multi-nucleon contributions to the cross section.
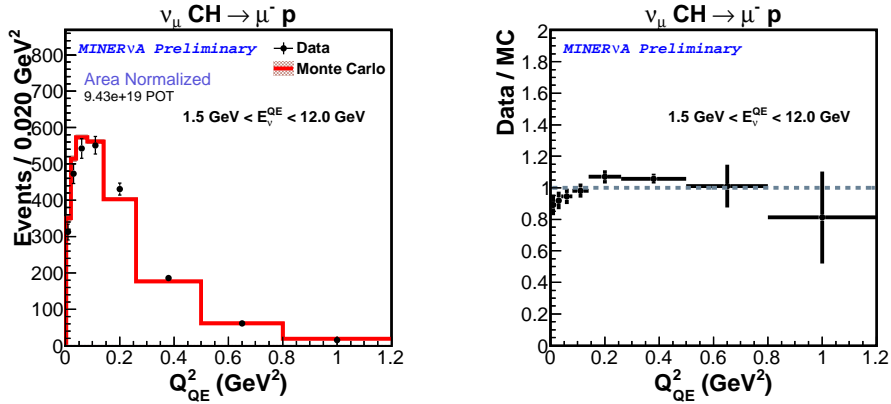
ONE TRACK NEUTRINO CCQE ON SCINTILLATOR

MINERvA has also begun an analysis of neutrino data that follows the same path as the anti-neutrino analysis described above. This analysis uses a data sample corresponding to approximately 9.54e19 protons on target, and approximately one quarter of MINERvA's total low energy neutrino exposure. Like the anti-neutrino analysis, this analysis requires a MINOS matched muon. To account for different recoil topologies caused by a recoiling proton rather than neutron, here we require less than three large energy depositions and again make a Q^2 dependent total recoil cut (excluding activity in the vertex region). Shape comparisons of the Q^2 spectrum of this sample and the anti-neutrino sample are shown in Figure 4. We observe similar discrepancies between the data and the GENIE simulation in the two samples – namely a deficit in data at low Q^2.

Backgrounds are again estimated and subtracted from the data, and the background subtracted data are unfolded. A shape comparison of the data with the GENIE simulation is shown in Figure 5. The collaboration is currently working on full efficiency corrected cross sections and a complete systematic uncertainty evaluation for this analysis, further details of which can be found in [2].
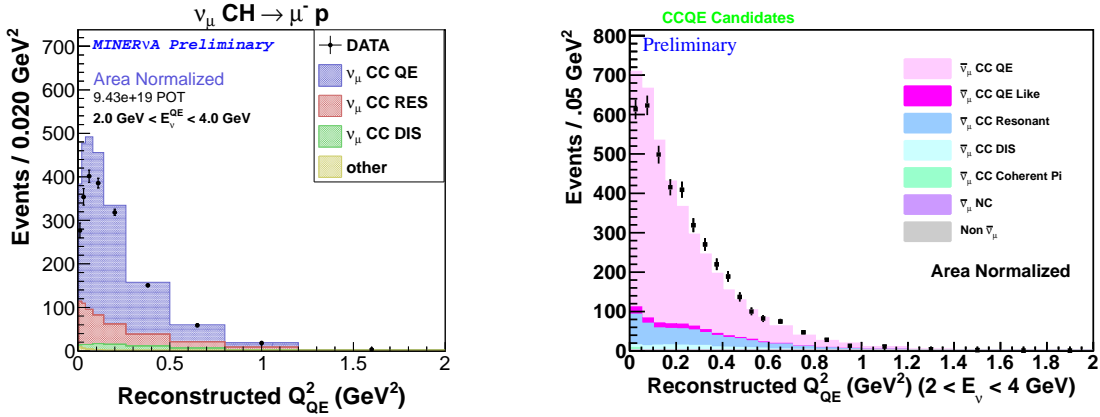
FIGURE 4. Q^2 distributions for the $2.0 < E_\nu < 4.0$ portion of the neutrino and anti-neutrino one track quasi-elastic samples. Similar discrepancies in shape between the data and the GENIE simulation are observed in the two samples.

FIGURE 5. The background subtracted and unfolded Q^2 distribution in the neutrino one track quasi-elastic sample, compared with the GENIE simulation

2-TRACK NEUTRINO CCQE ON NUCLEAR TARGETS

In addition to the analyses above which examine quasi-elastic interactions on scintillator, MINERνA has also begun analysis of quasi-elastic interactions in the upstream iron, lead and carbon passive targets. This analysis uses neutrino mode data, the same sample used above for the one track neutrino mode scintillator analysis. Because acceptance into the MINOS detector is poor for interactions originating in the upstream targets, this analysis considers not just MINOS matched muons but adds all muons that exit the MINERνA tracker region, including those matched to the outer hadronic calorimeters and those that stop in the ECAL/HCAL border region. In some of these reconstruction scenarios, the kinematics of the event cannot be reconstructed from muon information alone, since the muon's momentum is not known. The analysis therefore requires a second track be reconstructed in addition to the muon, and that the dE/dx profile of that second track be consistent with a proton. Similar to the two one track analyses, this analysis also requires that only small amounts of non-track recoil energy be present in the event. Finally, we require that the angle between the neutrino-muon and neutrino-proton plane normals be within 30 degrees of the back to back expectation for quasi-elastic interactions. Proton momentum distributions for the quasi-elastic enriched samples reconstructed in iron and lead are shown in Figure 6. The data is consistent with the nominal GENIE prediction. The MINERνA collaboration is currently working to produce background subtracted, acceptance corrected distributions, as well as ratios of cross sections on different targets.
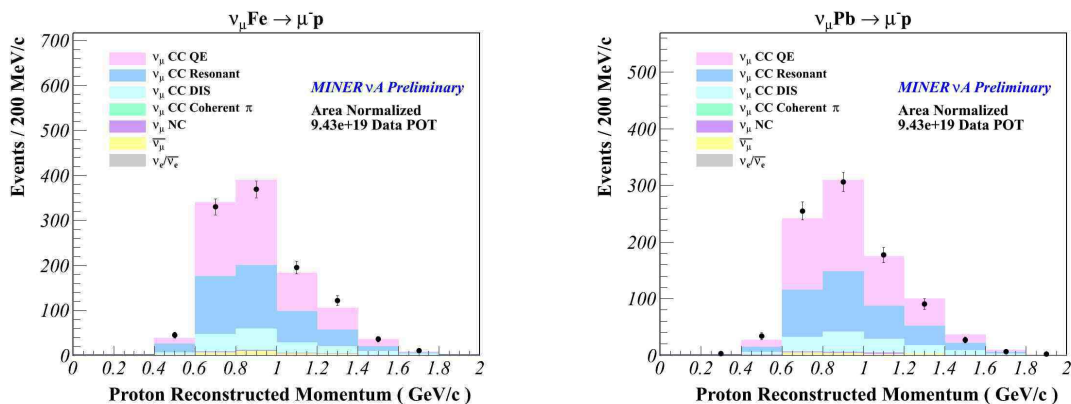
FIGURE 6. Proton momentum distributions in iron and lead, compared with the GENIE simulation. Error bars show statistical uncertainties only.

CONCLUSIONS

The three analyses shown here illustrate significant progress towards MINERvA's goals of high precision quasi-elastic cross section measurements. We have presented our first fully corrected differential cross sections, our first side by side comparisons of neutrino and anti-neutrino mode data, as well as a first look at quasi-elastic candidates in the passive nuclear targets. Much more progress can be expected in the next year, with the publications of the one track analysis expected by summer 2013, with the first papers examining quasi-elastics in the nuclear targets to follow soon thereafter. In the longer term, we plan to add a Michel veto to improve background rejection, and to compare and combine the one and two track analyses. The collaboration is also actively working to produce an improved flux simulation with significantly lower flux uncertainties. This will enable completion of the full MINERvA quasi-elastic program, which includes measurements of absolute quasi-elastic cross sections as a function of energy as well as double differential cross sections.

ACKNOWLEDGMENTS

REFERENCES

1. A. Fiorentini, "The MINERvA detector", these proceedings (2012).
2. A. Fiorentini, "Charged Current Quasi-Elastic Neutrino Analysis at MINERvA", these proceedings (2012).
3. D. Harris, "Understanding the NuMI Flux for MINERvA", these proceedings (2012).
4. A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], arXiv:1301.7067 [hep-ex].
5. A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Phys. Rev. D **81**, 092005 (2010) [arXiv:1002.2680 [hep-ex]].
6. C. Andreopoulos, A. Bell, D. Bhattacharya, F. Cavanna, J. Dobson, S. Dytman, H. Gallagher and P. Guzowski *et al.*, Nucl. Instrum. Meth. A **614**, 87 (2010) [arXiv:0905.2517 [hep-ph]].
7. C. H. Llewellyn Smith, Phys. Rept. **3** 261 (1972).
8. A. Bodek, R. Bradford, H. Budd and J. Arrington,Nucl. Phys. Proc. Suppl. **159** 127 (2006).
9. C. Alt *et al.* [NA49 Collaboration], Eur. Phys. J. C **45**, 343 (2006) [hep-ex/0510009].
10. T. Golan, C. Juszczak and J. T. Sobczyk, Phys. Rev. C **86**, 015505 (2012) [arXiv:1202.4197 [nucl-th]].
11. A. Bodek and J. Ritchie, Phys. Rev. **D23** 1070 (1981)
12. A. Bodek, H. S. Budd and M. E. Christy, Eur. Phys. J. C **71**, 1726 (2011) [arXiv:1106.0340 [hep-ph]].