Recent Results from MINERνA

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Abstract. The MINERνA collaboration is currently engaged in a broad program of neutrino-nucleus interaction measurements. Several recent measurements of interest to the accelerator-based oscillation community are presented. These include measurements of quasi-elastic scattering, diffractive pion production, kaon production and comparisons of interaction cross sections across nuclei. A new measurement of the NuMI neutrino beam flux that incorporates both external hadro-production data and MINERνA detector data is also presented.

1. Introduction

Reduction of systematic uncertainties is becoming increasingly critical to accelerator-based oscillation measurements. Figure 1 shows the CP sensitivity of the DUNE experiment as a function of exposure for several systematics goals, and illustrates that the difference between a 1% and 3% systematic uncertainty on the ν_e signal relative to other neutrino species is equivalent to nearly doubling the exposure required to reach 5σ coverage of 50% of δ_{CP} phase space [2]. Reaching such low systematics goals will require control of all systematics, including those from neutrino interaction cross sections, flux and detector response.

Reduction of systematics arising from neutrino cross-section parameters is complicated by the fact that a single cross section measurement simultaneously measures dozens of parameters, describing both the underlying nucleon cross section and initial and final state nuclear effects. Untangling these many parameters can only be achieved through many independent measurements, of many different interaction channels, at various energies, on different nuclei and with varying reconstruction techniques.

The MINERνA experiment [3] was designed to make such measurements. Composed of plastic scintillator strips interspersed with other materials, MINERνA sits in the NuMI beam at Fermilab and has accumulated large datasets in both the low energy and medium energy configurations of the NuMI beam. As of this writing, the MINERνA collaboration has produced fifteen neutrino cross-section publications, and is hard at work on many more. A selection of these results are described in detail here.

2. The NuMI Flux

A key ingredient in all of MINERνA's cross section measurements is a prediction of the number, flavor and energy spectrum of neutrinos in the NuMI beamline. An estimate of the neutrino fluxes at MINERνA using external hadro-production data was recently made [4], and achieved flux uncertainties of approximately 8% in the focusing peak. MINERνA has

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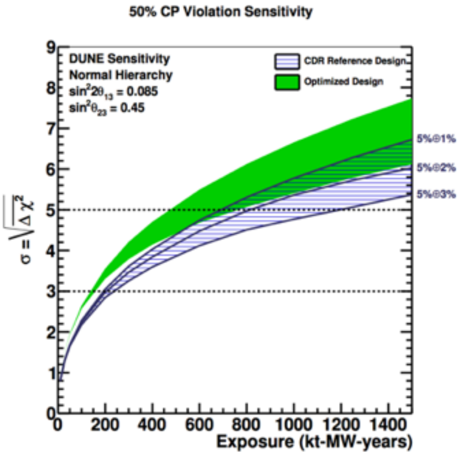

Figure 1. Estimated sensitivity of the DUNE experiment to 50% of the possible values δ_{CP}, versus exposure for two different beam options and assuming systematic uncertainties on the ν_e signal relative to other species of 1% (top), 2% (middle) and 3% (bottom) [2].

further demonstrated the use of neutrino-electron scattering as a standard candle for flux measurement [5]. Because neutrino-electron scattering has an extremely small cross section, only 135 events (after background subtraction and acceptance correction) were identified in MINERνA's complete low energy neutrino run. Combining the measured electron energy spectrum of these events with the *a priori* flux uncertainty based on external measurements reduces the total flux uncertainty in the focusing peak form 8% to 7%, as illustrated in Figure 2

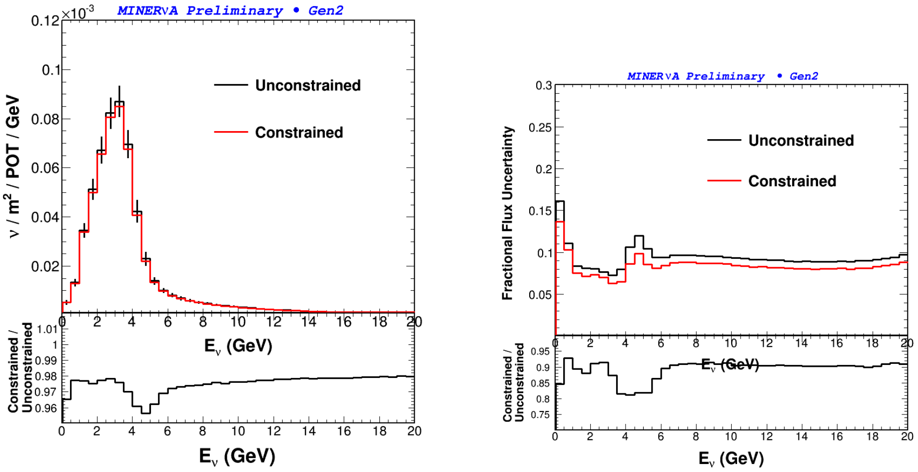

Figure 2. Predicted NuMI low energy, muon neutrino flux (left) and flux uncertainties (right) at MINERνA before and after constaint with neutrino-electron scattering data. [4].

3. Quasi-elastic Scattering

Among MINERνA's most important measurements are those of quasi-elastic scattering. Dominating the charged-current cross section near 1 GeV and having a relatively simple final state, these processes are considered a golden channel for oscillation experiments. In recent

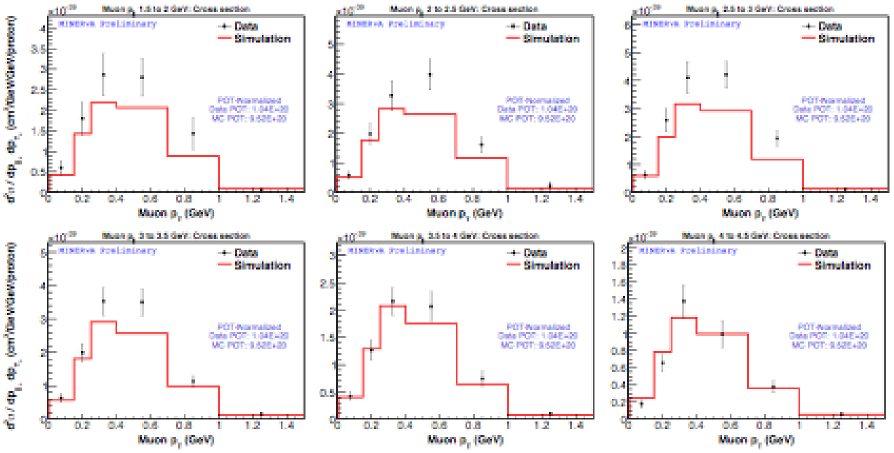

Figure 3. Double differential muon neutrino charged current quasi-elastic scattering cross sections versus muon longitudinal and transverse momentum.

years, it has become clear that measurements of this process are complicated by "quasielastic-like" final states that can arise both from pion production processes wherein a pion is absorbed before exiting the nucleus, and by neutrino interactions with multi-nucleon bound states.

MINERνA's program of quasi-elastic measurements demonstrates the experiment's ability to study a process from multiple perspectives. MINERνA's first measurements were of single differential muon neutrino and antineutrino cross section versus Q^2 (the momentum transferred from the initial state neutrino to the final state nucleon). Those studies are currently being expanded to measurements double-different cross sections with respect to muon transverse and longitudinal momentum. A preliminary version of the antineutrino measurement is shown in Figure 3, with MINERνA data indicating significant additional strength at moderate transverse momentum when compared to the GENIE [6] event generator.

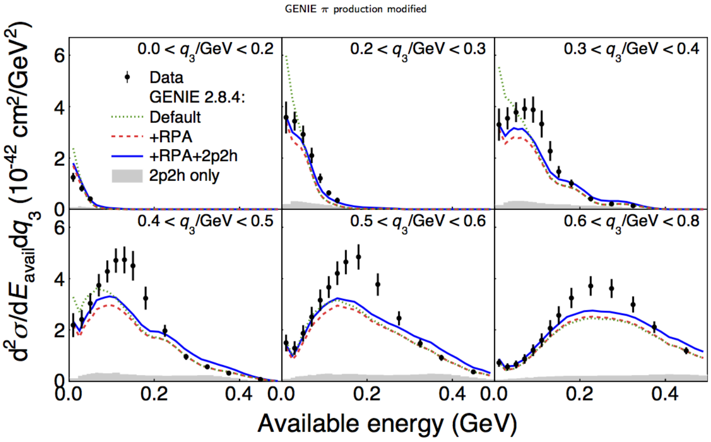

Figure 4. Double differential cross sections of charged current inclusive scattering as a function of q^3 and available energy [7]. Available energy is the sum of proton and charged pion kinetic energy and neutral pion, electron, and photon total energy.

Quasi-elastic and quasi-elastic final states have also been studied through a measurement of inclusive charged-current scattering with low recoil energy. Results of this analysis are reported in [7] and shown in figure 4. Significant discrepancies with GENIE models with and without two-particle, two-hole additions are found in regions of moderate energy. The excess in this inclusive neutrino analysis appears in a similar kinematic region to the exclusive antineutrino quasi-elastic analysis discussed above.

Although muon neutrinos and antineutrinos make up the majority of the NuMI beam, there is a small ($\sim 1\%$) component of electron neutrinos. MINERνA has used this portion of the flux to study electron neutrino quasi-elastic scattering. Of particular interest is the ratio of electron neutrino to muon neutrino scattering. Uncertainties on electron neutrino scattering that are uncorrelated with the corresponding muon neutrino processes (which can arise from unknown nuclear effects coupling to known differences in the cross sections due to differences between the electron and muon mass) are amongst the most critical to constrain for future oscillation measurements. The ratio of the electron neutrino CCQE cross section versus Q^2 is shown in Figure 5. Within uncertainties, the GENIE neutrino event generator models differences between these two processes well.

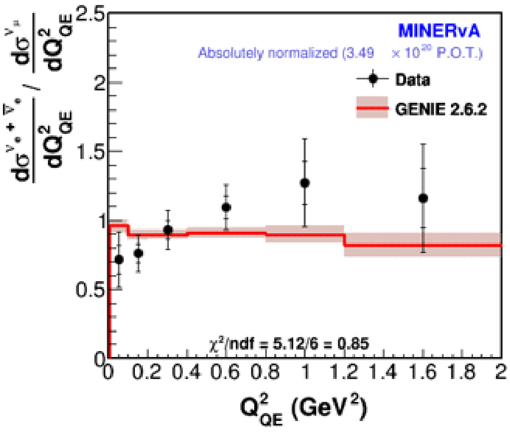

Figure 5. Ratio of electron neutrino and muon neutrino charged-current quasi-elastic cross sections as a function of Q^2 [8].

4. Diffractive Neutral Current Pion Production

The dE/dx distribution at the upstream end of the electron candidate in the electron neutrino CCQE analysis described in the previous section is shown in Figure 6. The signal region peaked near 1.5 MeV/cm corresponds to the energy deposition expected for a minimum ionizing particle. In the sideband between 2.2 and 3.5 GeV, an excess beyond the Monte Carlo prediction is observed consistent with two overlapping minimum ionizing particles. This excess of events has been studied and found to have a signature that is similar to coherent pion production, in that the electromagnetic showers are very forward, and there is little other energy present in the event. However, when considering energy in a cone extending upstream from the shower vertex, these excess events contain significantly more energy than that simulated coherent events. This energy is consistent with diffractive pion production from Hydrogen, a process that is not simulated in GENIE.

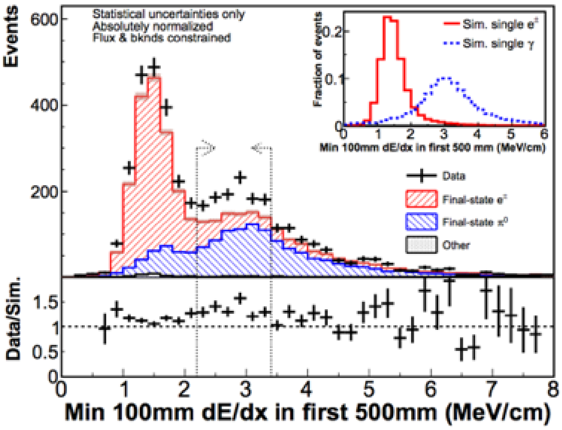

Figure 6. Energy deposition per unit length at the upstream end of candidate electron showers in the electron neutrino CCQE analysis. The region between the arrows defines the “excess region” containing unmodeled events consistent with neutral current diffractive scattering. The region to the left of the arrows is the signal region in the CCQE analysis [9].

5. Kaon Production

Neutrino induced pion production is of interest because it is a background to the SUSY-preferred proton decay channel $p \to K^+\nu$. This is a particularly problematic background for water Cherenkov detectors, where the kaon is typically below the Cherenkov threshold. Kaon production by neutrinos is also a sensitive test of kaon FSI models, which will be necessary for discovering proton decay in any detector, including liquid Argon detectors such as DUNE.

MINERνA’s nanosecond-level timing resolution enables identification of kaon production via observation of the time delay between a kaon track and its decay products. This technique has been used to measure cross sections for both neutral current and charged current kaon production, shown in Figure 7. In both cases, good agreement is found with the GENIE event generator, in spite of known deficiencies in that model, including the omission of single pion production. These data indicate that, as those deficiencies are addressed, the overall rate of kaon production should not be substantially changed [10].

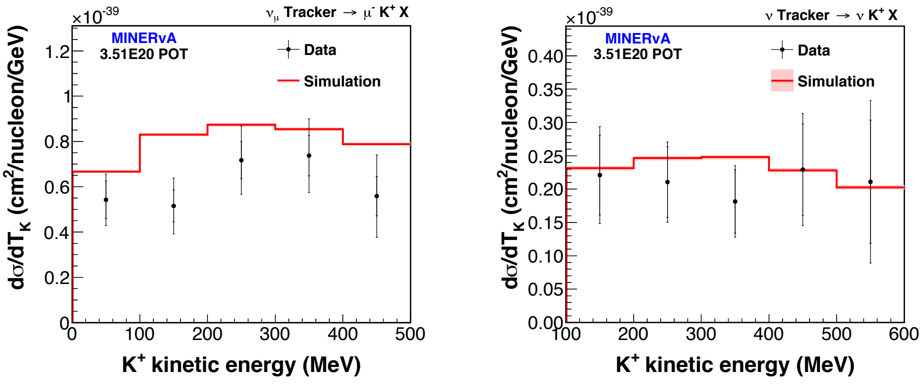

Figure 7. Differential cross sections of charged current (left) and neutral current (right) kaon production as a function of kaon kinetic energy [10].

6. Comparison of Cross Sections across Different Nuclei

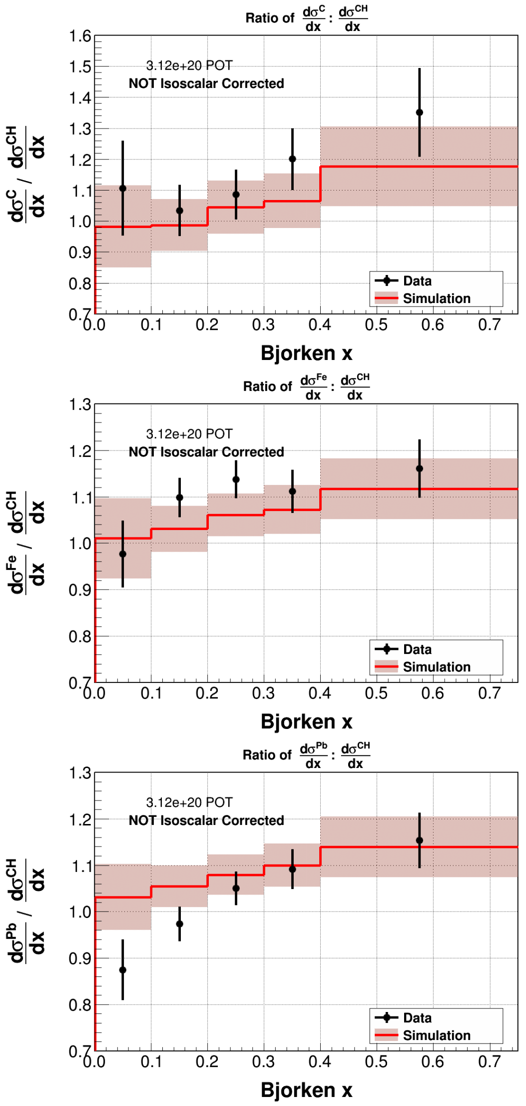

Figure 8. Ratios to scintillator of carbon (left), iron (middle) and lead (right) differential cross sections of charged current deep inelastic scattering as a function of function of Bjorken x. [12].

An important feature of the MINERνA detector is the ability to measure cross sections as a function of different nuclei. Recently, MINERνA has studied deep inelastic scattering as a function of Bjorken x on Carbon, Iron, Lead and scintillator. Ratios of these cross sections are shown in Figure 8. A small unmodeled deficit in heavy nuclei at low x, the so called "shadowing region" is observed here and mirrors an earlier measurement of charged current inclusive cross section ratios [11].

7. Prospects for the Future

With fifteen publications so far, MINERνA is nearing the completion of analysis of its low energy datasets. Attention is now turning to a large dataset currently being accumulated in the medium energy tune of the NuMI beamline. This beam provides a higher flux beam with

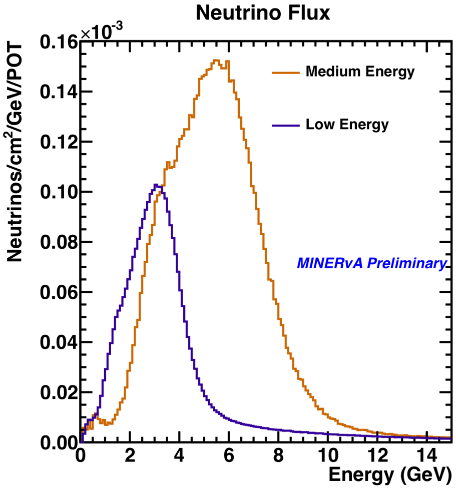

Figure 9. Comparison of simulated neutrino-mode muon neutrino fluxes at MINERνA in the low and medium energy NuMI beam tunes.

spectrum shown in Figure 9. A factor of three more protons-on-target than were used in the analyses discussed above have already been accumulated, and an antineutrino dataset is also expected. These will provide a much stronger flux constraint from neutrino-electron scattering and will facilitate high statistics comparisons of exclusive channels across nuclei.

Acknowledgements

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References

[1] R. Acciarri *et al.* [DUNE Collaboration], arXiv:1601.05471 [physics.ins-det].
[2] R. Acciarri *et al.* [DUNE Collaboration], arXiv:1601.05471 [physics.ins-det].
[3] L. Aliaga *et al.* [MINERvA Collaboration], Nucl. Instrum. Meth. A **743** (2014) 130 doi:10.1016/j.nima.2013.12.053 [arXiv:1305.5199 [physics.ins-det]].
[4] L. Aliaga *et al.* [MINERvA Collaboration], [arXiv:1607.00704 [hep-ex]].
[5] J. Park *et al.* [MINERvA Collaboration], Phys. Rev. D **93** (2016) no.11, 112007 doi:10.1103/PhysRevD.93.112007 [arXiv:1512.07699 [physics.ins-det]].
[6] C. Andreopoulos *et al.*, Nucl. Instrum. Meth. A **614** (2010) 87 doi:10.1016/j.nima.2009.12.009 [arXiv:0905.2517 [hep-ph]].
[7] P. A. Rodrigues *et al.* [MINERvA Collaboration], Phys. Rev. Lett. **116** (2016) 071802 doi:10.1103/PhysRevLett.116.071802 [arXiv:1511.05944 [hep-ex]].
[8] J. Wolcott *et al.* [MINERvA Collaboration], Phys. Rev. Lett. **116** (2016) no.8, 081802 doi:10.1103/PhysRevLett.116.081802 [arXiv:1509.05729 [hep-ex]].

[9] J. Wolcott *et al.* [MINERvA Collaboration], Phys. Rev. Lett. [Phys. Rev. Lett. **117** (2016) 111801] doi:10.1103/PhysRevLett.117.111801 [arXiv:1604.01728 [hep-ex]].

[10] C. M. Marshall *et al.* [MINERvA Collaboration], Phys. Rev. D **94** (2016) no.1, 012002 doi:10.1103/PhysRevD.94.012002 [arXiv:1604.03920 [hep-ex]].

[11] C. M. Marshall *et al.* [MINERvA Collaboration], Phys. Rev. D **94** (2016) no.1, 012002 doi:10.1103/PhysRevD.94.012002 [arXiv:1604.03920 [hep-ex]].

[12] J. Mousseau *et al.* [MINERvA Collaboration], Phys. Rev. D **93** (2016) no.7, 071101 doi:10.1103/PhysRevD.93.071101 [arXiv:1601.06313 [hep-ex]].