Recent Results from MINERvA

Jonathan Miller[1] for the MINERvA Collaboration

[1]Departamento de Física Universidad Técnica Federico Santa María
Casilla 110-V, Valparaíso, Chile

DOI: http://dx.doi.org/10.3204/DESY-PROC-2014-04/158

MINERvA (Main INjector ExpeRiment for v-A) is a few-GeV neutrino nucleus scattering experiment at Fermilab using various nuclei as targets. The experiment provides measurements of neutrino and anti-neutrino cross sections off of nuclear targets which are important for neutrino oscillation experiments and the probing of the nuclear medium. Presented are recent results from MINERvA on quasi-elastic, inclusive charged-current neutrino scattering, and pion production processes.

The MINERvA physics program is a broad based particle and nuclear physics program to measure important cross sections and channels for other particle physics experiments like IceCube and NOvA, and to use the neutrino to probe the weak component of nucleon and nuclear structure. For both, measurements in the range of 1-20 GeV are necessary, as this is where the complementary electromagnetic and hadronic data exists from nuclear physics and is the energy range that many neutrino experiments are sensitive. The results presented in these proceedings are available [1, 2, 3], where more detail on the analysis and the results may be obtained.

These first results from MINERvA include coherent pion production [1], charged pion production [2], and inclusive charged current cross section ratios [3]. These results are relevant for the analyses of neutrino experiments such as T2K and provide important input into understanding the effects of nuclear structure.

MINERvA is an experiment situated at Fermilab, near Chicago in the United States. It utilises the NuMI beam line in order to measure neutrino-nuclear cross sections at neutrino energies of between 1.5 and 20 GeV. The results presented here include data from the Low Energy (LE) run with median energy of 3.5 GeV, future results will include data from the Medium Energy (ME) run with median energy of 5.7 GeV.

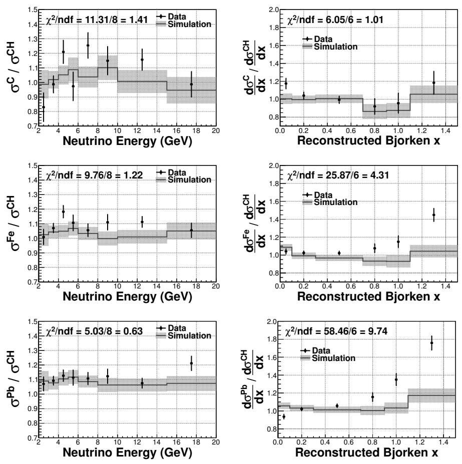

Figure 1: The ratios of the differential cross section per nucleon with respect to reconstructed bjorken x and of the cross section per nucleon depending on reconstructed energy (E_ν) for Pb, Fe, and C relative to CH. The error bars in data are statistical and in simulation are systematic. The calculation for χ^2 includes correlations. Events not shown with $x >$ 1.5.

The MINERvA detector[4] consists of a target region with 5 nuclear targets. Each target consists of a module with passive targets consisting of lead (Pb), iron (Fe), and graphite (C) and is separated by 4 active tracker modules. Downstream is an active tracker region. Active modules are made up of strips of plastic scintillator (CH) aligned in three orientations. Down stream of this region are the electromagnetic and hadronic calorimeters, with scintillator surrounded by iron and lead to induce energy loss. Downstream (2m) of the MINERvA detector is the MINOS near detector, a magnetised iron spectrometer.

The recent results from MINERvA have utilised charged current interactions in the neutrino and anti-neutrino datasets. The selection of charged current events are those where the muon travels from the interaction vertex through the MINERvA detector (leaving a minimum ionising track) and into the MINOS detector. MINOS serves as a muon spectrometer, and is used for a precise measurement of the muon momentum and charge. Two of the results presented here have charged pions in the final state. Charged pions may be identified using the deposited energy along the track, and by the observation of a Michel electron ($\pi \to \mu \to e$) at the end of the track in the tracker or electromagnetic calorimeter region. Details about basic tracking and vertex determination may be found in [4].

The charged current cross section, where a lepton (in MINERvA's case, a muon) is in the final state, are the most important cross sections to the neutrino physics program. Measuring the inclusive ratio of the cross sections of the main nuclear targets in MINERvA (0.628 tons of Fe, 0.711 tons of Pb, 0.159 tons of C, and 5.48 tons of CH), provides a flux independent probe of the structure of the nucleus. To have a well understood acceptance at all nuclear targets, the reconstructed neutrino energies are restricted to being above 2 GeV and the reconstructed muon angles to being less than 17°. The hadronic energy of the event E_h is calculated by the calorimetric sum not associated with the muon track. This allows the reconstruction of the kinematic variables $E_\nu = E_\mu + E_h$, $Q^2 = 4E_\nu E_\mu \sin^2(\theta_\mu/2)$, and $x = Q^2/(2M_N E_h)$. In this inclusive event selection, the GENIE sample is not dominated by any one process or classification (such as deep inelastic scattering (DIS)). The data used for this analysis consisted of $2.94e20$ protons on target (pot) in the neutrino configuration.

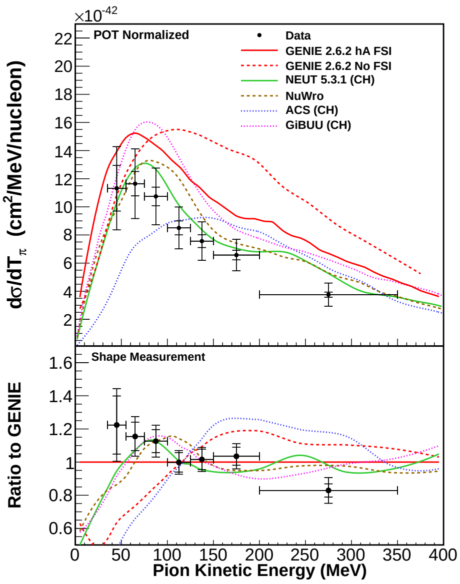

Figure 2: The charged pion differential cross section with respect to pion kinetic energy (top) and the ratio of this cross section to that predicted by GENIE with FSI normalised to the measured integral (bottom). Included are predictions from GENIE, ACS[7], NEUT[8], GiBUU[9] and NuWro[10]. Shown are the statistical uncertainty (inner error bars) and total uncertainty (outer error bars).

The results of this inclusive charged current ratios are shown in Fig. 1. The ratios of the cross section depending on reconstructed neutrino energy show broad agreement with the GENIE simulation, however, the differential cross section with respect to reconstructed bjorken x shows disagreement. This disagreement is a suppression at low x and enhancement at high

x, and the overall level changes as a function of the number of nucleons in the nucleus with the high x point showing agreement for the C over CH ratio and the low x point showing agreement for the Pb over CH ratio. The difference between data and simulation at low x may be due to poorly modelled nuclear shadowing effects. At high x most of the events are quasielastic, and so improvements in nuclear scaling models from the quasielastic to the deeply inelastic regime may be required.

A common case of charged current scattering is where a pion is produced. This is important to current and future long baseline experiments. Charged current pion production becomes convoluted with quasielastic scattering due to final state interactions (FSI) possibly causing the absorption of the pion in the nucleus causing the signature to appear quasielastic like. Models for the nuclear interactions which the produced pion may undergo are included in various generators/models including GENIE, ACS, NEUT, GiBUU and NuWro and the pion may undergo absorption, scattering, and charge exchange. The MiniBooNE measurement of this cross section shows agreement with the generators when they do not include FSI for pions with kinetic energy of 20 to 400 MeV (pions likely produced by delta decays)[5]. The charged current pion production differential cross section with respect to pion kinetic energy was measured by selecting events with a charged muon and at least one pion. The reconstructed pion provides the pion kinetic energy and the angle the pion travels with respect to the beam. To select events with only a single produced pion, a cut on the invariant mass (W) is used. The muon energy (E_μ), angle (θ_μ), and hadron energy (E_h) were used to reconstruct the invariant mass using the equations: $E_\nu = E_\mu + E_h$,$Q^2 = 2E_\nu(E_\mu - |\vec{p}_\mu| \cos\theta_\mu) - m_\pi^2$, and $W^2 = M_p^2 - Q^2 + 2M_pE_h$.

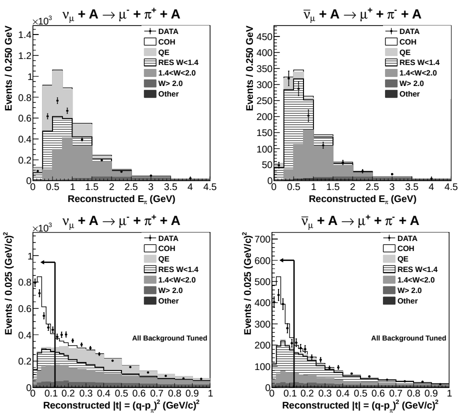

Figure 3: The top two plots show reconstructed energy in the $0.2 < t < 0.6$ (GeV/c)^2 sideband for the ν and $\bar{\nu}$ datasets. On the bottom is reconstructed t after background tuning. The shape in t near 0 is determined by the resolution.

The results of the measurement of charged pion production are shown in Fig. 2. Models of interactions within the nucleus cause pions to *migrate* to lower energies through scattering or be suppressed due to absorption or charge exchange. The shape is particular sensitive to such effects, and demonstrates that the models included in the favoured generators give broad agreement with the data when the generators include FSI for pions for pions with kinetic energy between 20 and 400 MeV. These results come from $3.04e20$ pot in the neutrino configuration.

Coherent pion production is the production of a pion after the neutrino scatters off the entire nucleus leaving the nucleus unchanged. It is characterised by a small momentum exchange between the nucleus and the system of the leptons and produced pion. The theory in this regime is not well understood, and many different approaches are included in neutrino event generators. This process is important in the analysis of accelerator neutrino experiments where this process is a background to the desired quasielastic signal, in these experiments the analyses use neutrino event generators to interpret their data and understand their background. A measurement of coherent charged pion production constrains the neutrino event generators for these processes and so improves the aforementioned analyses.

The coherent pion events were selected by requiring a charged pion and muon in the final state and little activity in the vertex region. The measured transferred four momentum (t) is required to be small. Other backgrounds are constained by use of a high t sideband. This provides a selection of model independent coherent pion production events and allows the study of the differential cross section with respect to pion angle and energy. As shown in Fig. 3, the background in the sideband region was tuned to the data correcting the incoherent background which was subtracted from the low t sample providing a sample of coherent pion events.

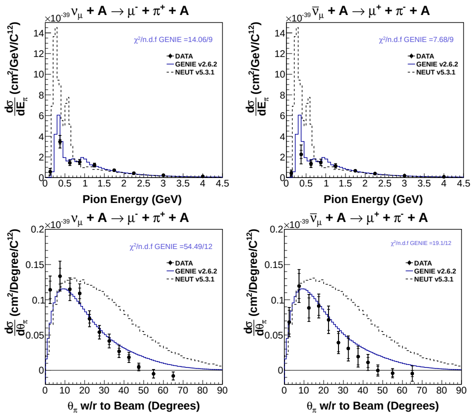

Figure 4: Shown is $\frac{d\sigma}{dE_\pi}$ on top and $\frac{d\sigma}{d\theta_\pi}$ on bottom with inner error bars showing the statistical uncertainty and outer error bars showing the total uncertainty. The χ^2 compares the data versus bin averaged cross sections from GENIE[6].

The coherent pion differential cross section is shown in Fig. 4 versus both pion angle and pion energy. Here the pion angle with respect to the beam is more forward than that of the commonly used Rein-Sehgal model in GENIE[6].

In conclusion, MINERvA has made important contributions to understanding the neutrino-nucleon interactions in the moderate energies (1-10 GeV) which are crucial to accelerator and atmospheric based neutrino experiments. Measurements of the pion production cross section and the ratio of the inclusive scattering cross section show broad agreement with the generators. The behaviour of the ratio of the cross section with respect to Bjorken x is not well modelled in the generator and requires theoretical input. Also, the pions produced in coherent pion production are more forward scattering than what exists within the generators. The start of the ME run has provided much larger statistics for future measurements studying nuclear structure and neutrino cross sections.

J.M. was supported by the National Science Foundation under Grant No. NSF PHY11-25915 and by PROYECTO BASAL FB 0821 CCT-Val and by Fondecyt (Grant No. 11130133) during the completion of this report.

References

[1] A. Higuera, A. Mislivec, L. Aliaga, O. Altinok, A. Bodek, A. Bravar, A. Butkevich and M. F. Carneiro *et al.*, arXiv:1409.3835.

[2] B. Eberly *et al.* [MINERvA Collaboration], arXiv:1406.6415.

[3] B. G. Tice *et al.* [MINERvA Collaboration], Phys. Rev. Lett. **112**, 231801 (2014) [arXiv:1403.2103].

[4] L. Aliaga *et al.* [MINERvA Collaboration], Nucl. Instrum. Meth. A **743**, 130 (2014) [arXiv:1305.5199].

[5] A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Phys. Rev. D **83**, 052007 (2011) [arXiv:1011.3572].

[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].

[7] M. Sajjad Athar, S. Chauhan and S. K. Singh, Eur. Phys. J. A **43**, 209 (2010) [arXiv:0908.1443 [nucl-th]].

[8] Y. Hayato, Acta Phys. Polon. B **40**, 2477 (2009).

[9] U. Mosel, O. Lalakulich and K. Gallmeister, Phys. Rev. D **89**, 093003 (2014) [arXiv:1402.0297 [nucl-th]].

[10] T. Golan, C. Juszczak and J. T. Sobczyk, Phys. Rev. C **86**, 015505 (2012) [arXiv:1202.4197 [nucl-th]].