Neutrino-nucleus cross section measurements at MINERνA

Philip Rodrigues
Bausch and Lomb Building, University of Rochester, Rochester, NY 14627 USA

Measurements of neutrino-nucleus cross sections from the MINERνA experiment at Fermilab are presented. These cross section measurements constrain major signal and background processes that are important for neutrino oscillation experiments, such as T2K. In charged-current quasielastic scattering, deviations from the prediction of a Relativistic Fermi Gas model are found, and predictions of alternative models are compared with data. In charged-current charged pion production, agreement between data and the simulated shape of the pion kinematic cross sections is shown.

1 Introduction

A precise and accurate understanding of neutrino-nucleus interactions is vital to the success of the current and future neutrino oscillation program worldwide. Neutrino oscillation experiments aim to infer the oscillation probability $P(\nu_\alpha \rightarrow \nu_\beta)$ as a function of neutrino energy by observing the number of neutrinos of flavour ν_β in a beam initially of flavour ν_α. This oscillation probability is a function of neutrino energy, but neutrino beams contain neutrinos of a range of energies. The neutrino energy must therefore be inferred on an event-by-event basis based on the final-state particles observed in the detector. Correctly modelling the relationship between neutrino energy and the particles produced in neutrino-nucleus interactions is thus of paramount importance.

Figure 1 shows an example of recent neutrino oscillation results presented at this conference[1] from the T2K experiment. They measure the oscillation probability $P(\nu_\mu \rightarrow \nu_\mu)$ by identifying a sample of ν_μ interactions in Super-Kamiokande, which acts as their far detector. The number of ν_μ events is reduced relative to the expectation based on measurements in their near detector, demonstrating that the ν_μ have oscillated into other flavours. The figure shows the breakdown of events into several interaction categories, according to the Monte Carlo. Correctly inferring the oscillation probability $P(\nu_\mu \rightarrow \nu_\mu)$ from this event sample requires understanding the overall rate, and the relation between neutrino energy and final state particles, for each of the interaction types present in the sample. The major goal of the MINERνA experiment is to measure cross sections relevant for neutrino oscillation studies, and I will show two such results in which MINERνA is contributing to our knowledge of these important processes.

2 The MINERνA experiment

The MINERνA experiment at Fermilab is dedicated to improving our understanding of these interactions in the few-GeV neutrino energy range. The MINERνA detector is located in the NuMI beamline, as used by the MINOS and NOνA experiments, which is a conventional neutrino beam: 120 GeV protons strike a graphite target, producing secondary particles which are focussed by two magnetic horns and allowed to decay in a 675 m-long helium-filled volume. A beam dump, along with 300 m of rock, absorbs the remaining charged particles, leaving a beam of neutrinos, which is more than 95% ν_μ, with a small contamination from ν_e.

By varying the relative positions of target and horns, and altering the horn current, the beamline can be configured to produce a neutrino beam of various energies, or to produce a $\bar{\nu}_\mu$-enhanced beam. For the results shown here, the beamline was configured to produce a neutrino beam of peak energy 3.5 GeV, with data taken in both neutrino and antineutrino modes. Since September 2013, the NuMI beam has been running in so-called "medium energy" mode, with a peak neutrino energy of 6 GeV. Current uncertainties on the NuMI flux are at the level of 15% or greater, which motivates the study of quantities that have minimal dependence on the flux, such as shape-only comparisons of differential cross sections.

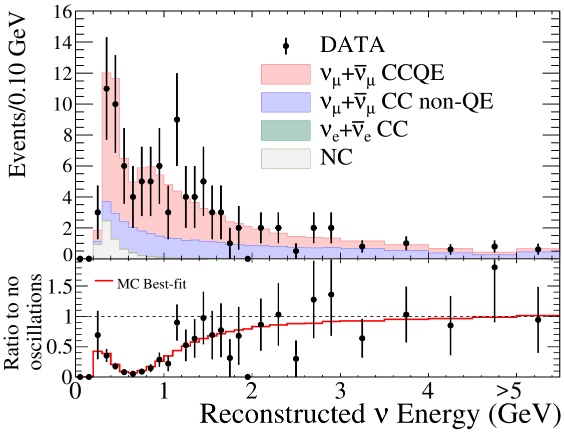

Figure 1 – The muon neutrino energy spectrum observed in the Super-Kamiokande detector by the T2K experiment. The abscissa is the neutrino energy reconstructed by assuming quasi-elastic event kinematics. The bottom panel shows the ratio of observed events to the number expected in the absence of neutrino oscillations.

The MINERνA detector consists of triangular plastic scintillator bars with base 34 mm and height 17 mm, read out by embedded wavelength shifting fibres attached to multi-anode PMTs, and arranged in planes perpendicular to the beam direction. The direction of the bars in the planes alternates between 0°, +60°, and −60° to the vertical, providing unambiguous three-dimensional event reconstruction when information from the planes is combined. In the tracker region, used as the fiducial region for the results presented here, the detector is totally active, while the downstream end of the detector has a region with lead between the scintillator planes for electromagnetic calorimetry, followed by a region with steel interspersed between the planes for hadronic calorimetry. Upstream of the tracker region are planes of passive nuclear targets, a water target, and a cryogenic helium target, which allow measurement of neutrino cross sections on a range of materials. Downstream of the MINERνA detector is the magnetized MINOS near detector, which acts as a spectrometer for muons exiting MINERνA.

3 Charged-current quasielastic analysis

The charged-current quasielastic (CCQE) process $\nu_\mu + n \rightarrow \mu^- + p$ ($\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ for antineutrinos) is the simplest charged-current interaction of a neutrino with a nucleon. The process was studied in detail by bubble chamber experiments, which characterized the process in terms of its dependence on the Lorentz invariant Q^2, the square of the four-momentum transferred to the nucleon, finding consistent results between experiments for the shape of the differential cross section $\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}$. An example is shown in Figure 2, with data from a bubble chamber at ANL [2].

In neutrino oscillation experiments, the quasielastic process is important as the the two-body kinematics allow the neutrino energy to be reconstructed from the lepton kinematics alone, when the initial neutrino direction is known. In T2K, for example, CCQE interactions are used as the main signal process (as shown in Fig 1) for exactly this reason, since final-state nucleons from neutrino interactions are typically below Čerenkov threshold. Modelling the CCQE process for oscillation experiments, based on the bubble chamber results for scattering off a single nucleon, requires the addition of a model of the nucleus. The models that have been used in Monte Carlo event generators for oscillation experiments so far model the nucleus as a Relativistic Fermi Gas (RFG), taking each nucleon to be quasi-independent in a mean field.

Comparisons of this model with CCQE data from the MiniBooNE experiment [3] show disagreements both in the overall cross section and the shape of $\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}$, as shown in Figure 2, which have been the subject of copious theoretical study, mostly concentrating on nuclear effects, which

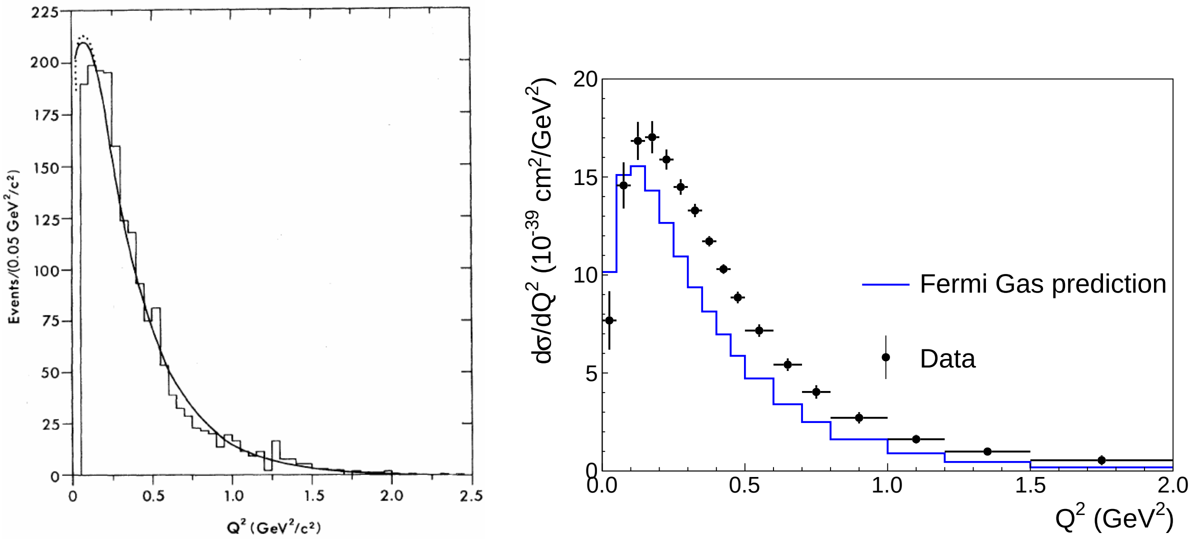

Figure 2 – Left: Distribution of Q^2 for CCQE events on deuterium in the ANL experiment, along with a theoretical fit to the data. Right: Differential cross section $\frac{d\sigma}{dQ^2}$ in CCQE measured by MiniBooNE on CH$_2$, shown with a prediction from the NEUT generator based on deuterium measurements plus a Relativistic Fermi Gas model of the nucleus. There is a clear disagreement both in shape and in normalization between the data and the prediction.

are known from electron scattering experiments to be poorly modelled by the RFG. A common feature of theoretical models of CCQE scattering in MiniBooNE is the addition of multinucleon effects, such as the formation of tightly-bound pairs of high-momentum nucleons, which the neutrino can scatter off. These models, though qualitatively similar, make quantitatively different predictions, and a key aim of the MINERνA CCQE measurement is to distinguish between available models.

The MINERνA CCQE analysis [5,6] begins by selecting samples of CCQE events in neutrino and antineutrino mode data. In both cases, the characteristic of the signal is a muon of the correct charge, and minimal extra energy from the recoiling hadronic system. We require a reconstructed neutrino interaction vertex in the fiducial volume of the tracker region, with a muon matched to a track in MINOS of the correct charge, and that there be few isolated shower-like energy deposits. We define a recoil energy region, which includes the tracker and ECal regions of the detector, and excludes the region close to the neutrino interaction vertex. The energy in this recoil region is summed calorimetrically, and we define a cut on this recoil energy as a function of reconstructed Q^2. These cuts provide event samples with purities of 47% in neutrino mode and 77% in antineutrino mode, according to the simulation. The background is constrained by a fit to a high recoil energy sideband, and subtracted. Unfolding to true quantities and dividing by efficiency, acceptance, flux and number of targets, leads to a flux-integrated differential cross section in Q^2.

Figure 3 shows comparisons between our cross section results and the predictions of some available models. Each prediction is scaled to the integral of the data, and divided by the prediction from GENIE, our default Monte Carlo. A clear discrepancy is seen between the MINERνA data and the GENIE prediction, corroborating the MiniBooNE result that the RFG model is insufficient to describe CCQE scattering on carbon. Two other models are of particular interest: the "NuWro RFG $M_A = 1.35$" (green line) is a model in which the nuclear dynamics are modelled by the simple RFG, but the axial form factor of the nucleon is modified in a way which MiniBooNE found gave good agreement with their data. It is clear that this model is disfavoured by the MINERνA data. Better agreement is seen with the "NuWro RFG $M_A = 0.99$ + TEM" (dashed red line), which is the prediction of the transverse enhancement model, an empirical model of multinucleon effects based on a fit to electron scattering data, which has

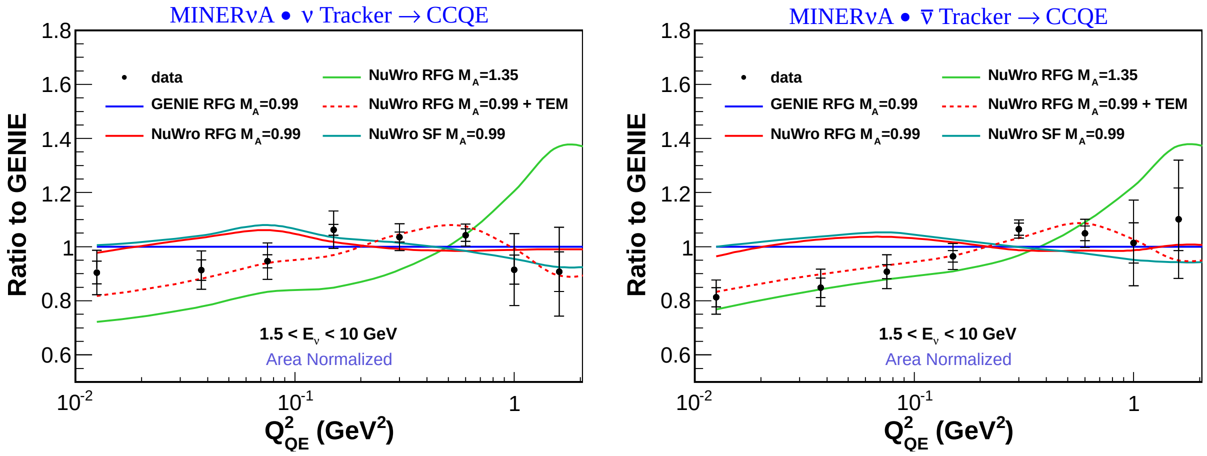

Figure 3 – Differential cross sections in MINERνA CCQE, shown as area-normalized ratios to the prediction of the GENIE generator on a logarithmic abscissa. Neutrino-mode data are shown on the left, and antineutrino-mode data are shown on the right.

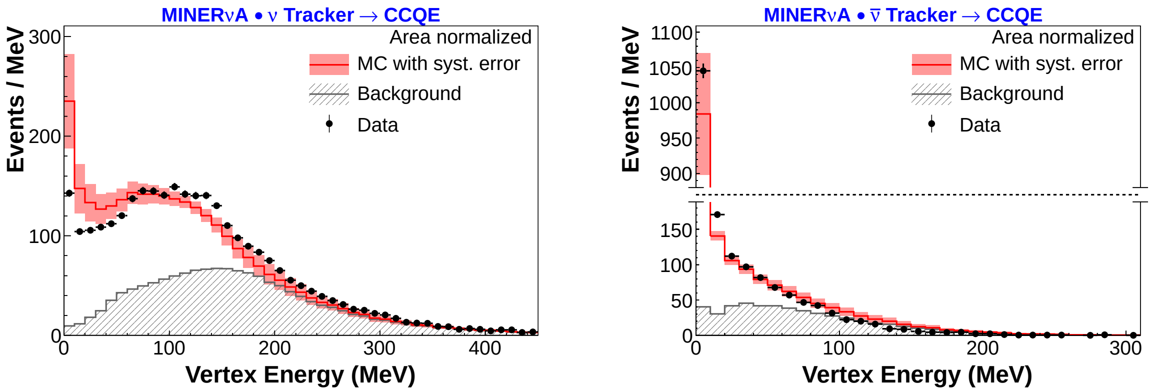

Figure 4 – Distribution of energy near the vertex in neutrino mode (left) and antineutrino mode (right). In each case, the Monte Carlo predictions have beeen scaled to the data. The extra energy relative to the prediction in neutrino mode is seen as both a deficit in the peak at zero, and an offset of the peak around 100 MeV.

been shown to also give good agreement with the MiniBooNE data.

A second measurable in the MINERνA CCQE analysis is the energy near the interaction vertex, in the region which was excluded from the calculation of recoil energy. A qualitative expectation from multinucleon models invoked to explain the MiniBooNE data is that a second nucleon involved in the scattering process may be ejected from the nucleus, and this second nucleon may be visible in the MINERνA detector. Figure 4 shows the distribution of total energy in the vertex region in neutrino and antineutrino modes, showing an excess of energy in data over the MC expectation in neutrino mode, but no such excess in antineutrino mode. This pattern would be expected in scattering from correlated np pairs, which would become pp in the final state in neutrino mode, but nn in antineutrino mode, the latter usually leaving no visible energy in the detector.

4 Charged-current charged pion production

A second important scattering process for neutrino oscillation experiments is single charged pion production, which can fake CCQE when the pion is not detected, either because the pion is below a detection threshold, or because the pion is absorbed in the nucleus after production. In the T2K ν_μ analysis shown in Figure 1, the "CC non-QE" component is largely composed of single pion production events.

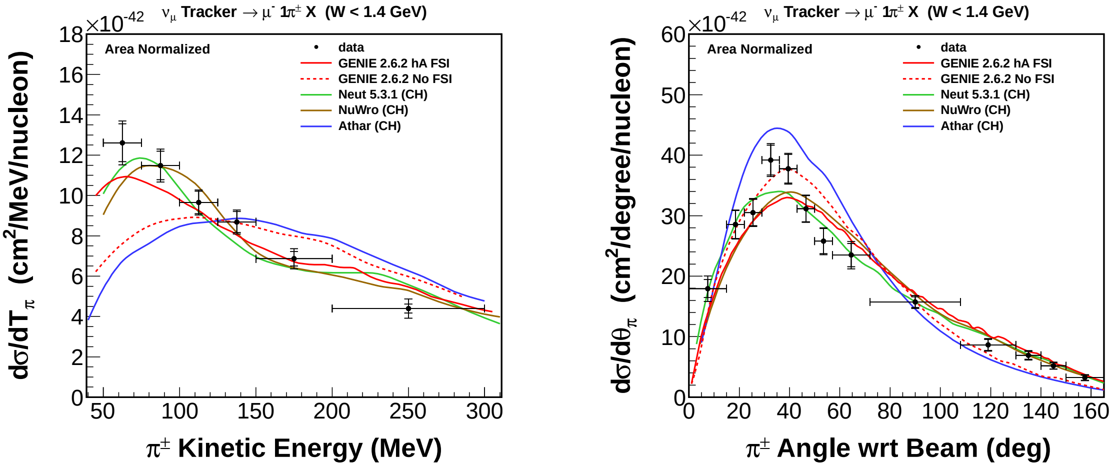

Figure 5 – MINERνA differential cross sections for charged-current single charged pion production in pion kinetic energy (left) and pion angle with respect to the beam (right). Overall, reasonable agreement between the data and predictions is seen.

Precise modelling of this process depends on precise knowledge of the cross section for the neutrino-nucleon process, and on modelling of the strong interactions of the pion as it leaves the nucleus ("final state interactions" or FSI), which can change both the kinematics and identity of the final-state particles. The understanding of both of these components has been called into question by results from the MiniBooNE experiment [4], in which measurements of the charged-current single charged pion production cross section disagree with models used in oscillation experiments both in overall normalization, and in the shape of the pion energy spectrum, which is sensitive to the presence and strength of FSI.

To select charged-current events with a single charged pion, we require a negatively-charged muon matched to MINOS and a second track with energy deposit compatible with a pion stopping in the detector. The hadronic recoil energy is reconstructed by summing the non-muon energy in the detector, and added to the muon energy to reconstruct the neutrino energy, which is required to be below 10 GeV. A cut on the reconstructed hadronic invariant mass, $W < 1.4\,\mathrm{GeV}$, produces a sample with similar kinematic coverage to the MiniBooNE measurement, and vetoes high-multiplicity events. The resulting sample contains 3474 pion candidates. The most significant background is feed-down from events with $W > 1.4\,\mathrm{GeV}$, which is constrained with data in a fit to the W distribution.

Figure 5 shows the measured differential cross sections in pion angle and kinetic energy, compared to the shapes of several available models. The models have fair agreement with the data, except for the "GENIE 2.6.2 No FSI" and "Athar" models, which have no, or limited treatment of final state interactions.

5 Conclusions

The MINERνA experiment is making important progress in understanding and constraining the neutrino-nucleus cross sections that are important to neutrino oscillation experiments. In the case of charged-current quasielastic scattering, we find, as MiniBooNE did, that the RFG model is insufficient to describe neutrino scattering on carbon, and are able to discriminate between models proposed to explain the MiniBooNE result. For charged-current charged pion production, in contrast, we find reasonable agreement between our data and the models used in oscillation experiments. These results have the potential to lead to reduced systematic uncertainties in measurements of neutrino oscillations.

References

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