Neutrino Interaction News: SciBooNE, MiniBooNE, & MINERνA

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Neutrino oscillation experiments need to understand neutrino-nucleus cross sections in the 1-10 GeV region. This is the transition region from quasi-elastic to inelastic scattering where cross sections are not well understood. Data is needed to guide and tune neutrino-nucleus interaction models, and current cross section data has 10-50% uncertainties depending on the process. As a result, neutrino-nucleus cross sections can be one of the largest systematic uncertainties for oscillation experiments. The MINERνA (Main INjector ExpeRiment ν-A) experiment will make precision measurements of neutrino-nucleus cross sections in the 1-10 GeV region, and study nuclear effects that modify the cross section and the kinematics of the final state. These proceedings present MINERνA's progress in determining its neutrino beam flux, muon reconstruction performance, and data taking and reconstruction stability. Recent results by the SciBooNE and MiniBooNE experiments will also be discussed.

1 Neutrino Cross Sections and Oscillation Experiments

Neutrino-nucleus cross sections are important to neutrino oscillation experiments for calculating event rates and energy distributions in both near and far detectors. Many oscillation experiments operate at a few GeV, which is the transition region from quasi-elastic to inelastic scattering where cross sections are not well understood. Cross section measurements, which are used to develop and tune neutrino-nucleus interaction models, currently have 10-50% uncertainties depending on the process. Nuclear effects that modify the final state are also not well understood.

An example of the significance of current cross section uncertainties to oscillation experiments is provided by the recent measurement of θ_{13} by the T2K experiment [1]. For $\sin^2 2\theta_{13} = 0.1$, neutrino cross sections contributed a 10.5% uncertainty to the expected far detector event rate even after normalizing to the near detector event rate. Reducing the cross section uncertainty is important to current and future oscillation experiments, particularly those with a goal of measuring CP violation in the lepton sector.

2 SciBooNE and MiniBooNE

The SciBooNE and MiniBooNE experiments are currently making precision cross section measurements near 1 GeV. Both experiments are located in Fermiab's Booster Neutrino Beam (BNB). SciBooNE is a scintillator tracker detector, while MiniBooNE is a mineral oil Cerenkov detector.

SciBooNE has published a measurement of K^+ production in the BNB line using high energy neutrino interactions [2]. High energy neutrinos are produced predominantly in the decay of kaons produced in the target. The kaon production rate can then be measured from the rate of high

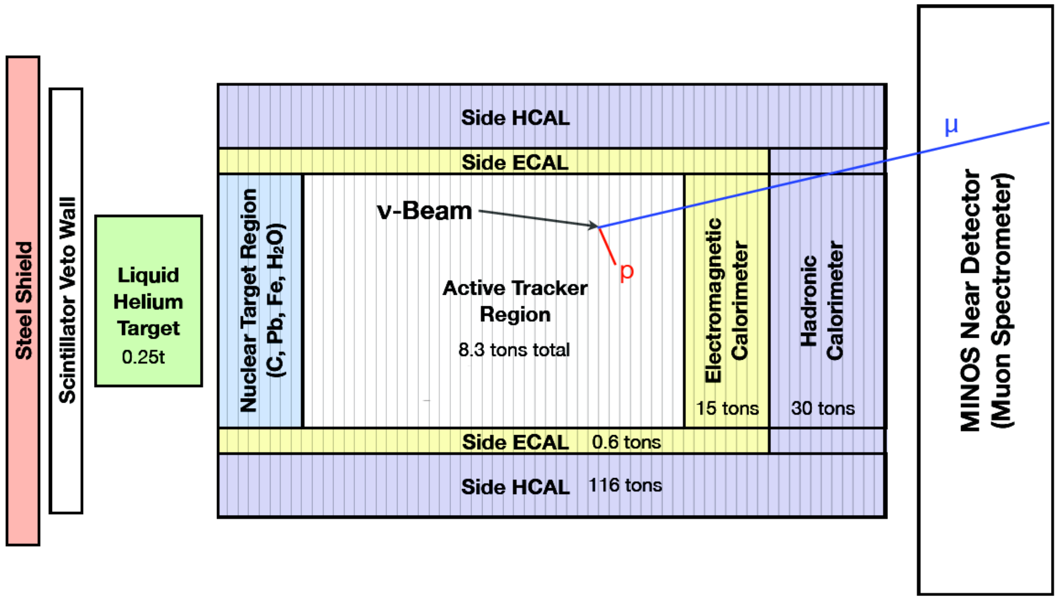

Figure 1: Schematic of the MINERνA detector.

energy interactions in their detector. SciBooNE tuned their model of kaon production in the target to this measurement, which reduced the model dependence of their electron neutrino background prediction in the BNB line.

MiniBooNE has published their measurements of inclusive CC π^+ and π^0 production cross sections [3,4]. This is the first time that full kinematics (single- and double-differential cross sections) have been reported for these interactions near 1 GeV. These results are providing important input to neutrino-nucleus interaction models.

3 The MINERνA Experment

MINERνA [5] is a neutrino-nucleus scattering experiment that utilizes Fermilab's NuMI (Neutrinos at the Main Injector) neutrino beam [6]. The goal of MINERνA is to make precise measurements of cross sections for inclusive and exclusive final states in the 1-10 GeV region. MINERνA will measure these cross sections on a variety of nuclei to study nuclear effects. The MINERνA detector (Figure 1) is similar in design to a collider detector. It consists of a fully active central tracker region surrounded by side and downstream electromagnetic and hadronic calorimeters. The active components of MINERνA consist of planes of parallel scintillator strips read out by multi-anode photo-multiplier tubes (MAPMTs). The upstream region contains a water target and passive layers of C, Pb, and Fe and constitutes the nuclear target region. A liquid He target sits in front of the detector. The MINOS near detector is situated immediately downstream of the MINERνA detector and serves as the muon spectrometer for MINERνA.

The NuMI beam is generated from a 120 GeV proton beam incident upon a graphite target. Charged hadrons produced at the target, primarily pions and kaons, are focused down a decay pipe by two focusing horns. The direction of current in the horns determines whether the beam is running in neutrino mode (forward horn current) or anti-neutrino mode (reverse horn current). The neutrino energy spectrum can be adjusted by moving either the target or the downstream horn or both. MINERνA will take data in the low and medium energy configurations, whose energy spectra are shown in Figure 2.

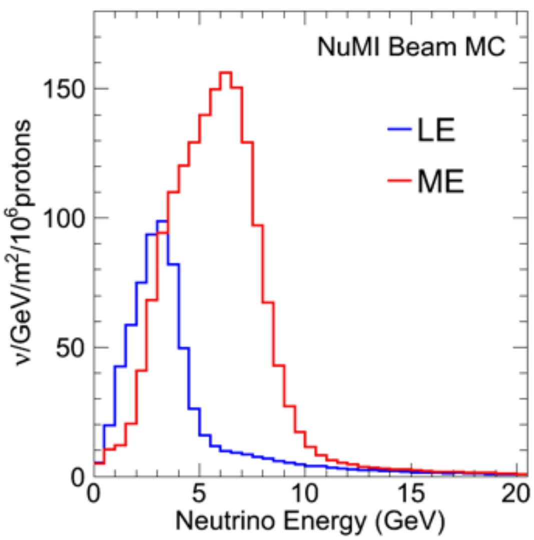

Figure 2: MC E_ν spectra prediction of the NuMI flux in the low energy (LE) and medium energy (ME) configurations.

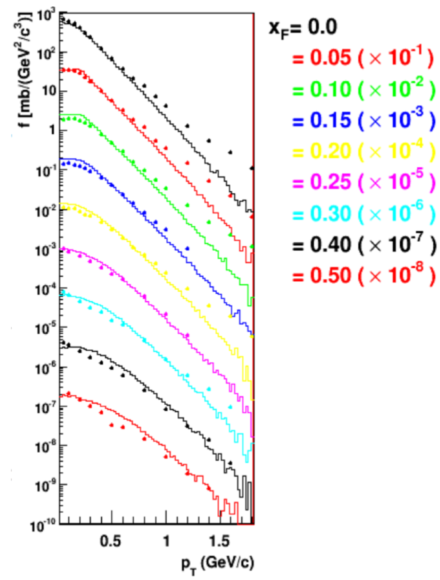

Figure 3: The p+C→π^++X production cross section as a function of pion momentum off the target in NA49 data [7] (points) and pre-tuned Geant4 QGSP (lines).

4 Flux Determination

MINERνA must understand its neutrino flux very well in order to make precision cross section measurements. Monte Carlo flux predictions have large uncertainties, primarily due to uncertainties in modeling hadron production. MINERνA's approach for determining its flux involves tuning its model of hadron production at the NuMI target to external hadron production data, and subsequently tuning its flux prediction to *in situ* MINERνA detector data.

MINERνA uses the Geant4 QGSP model to simulate hadron production at the NuMI target. MINERνA tunes this model to data of hadron production from 158 GeV protons on graphite from the NA49 experiment. The p+C→π^++X production cross section as a function of pion momentum off the target in NA49 data [7] and pre-tuned Geant4 QGSP is shown in Figure 3.

In addition to tuning to NA49 data, several effects contributing to hadron production in the NuMI beam line must be taken into account. NA49 data was taken on a thin target while the NuMI target is approximately two interaction lengths long. Re-interactions in the target are expected to be a 20-30% effect. Interactions in components downstream of the target, such as the horns and shielding, also contribute to hadron production. These effects necessitate tuning the flux prediction to *in situ* MINERνA detector data.

MINERνA is tuning its flux prediction to data taken in alternate target position and horn current configurations of the beam. The energy spectra of CC inclusive events in the alternate beam configurations data are shown in Figures 4 and 5. The flux is measured as a function of the momentum of hadrons coming off the target, and the flux measurement from each alternate beam configuration maps out a different region of the momentum space (Figure 6). The flux measurements are fit simultaneously for hadron production, which allows the systematics in measuring the flux to be deconvolved. These systematics include hadron production at the target, horn focusing, and neutrino cross sections. A set of weights are generated from the fit which are used to correct the flux prediction.

It should be noted that MINERνA will ultimately tune its flux prediction not to a CC inclusive sample, but instead to a CC quasi-elastic sample of moderate Q^2. At moderate Q^2 the CC quasi-elastic cross section is approximately independent of E_ν, which is useful for deconvolving

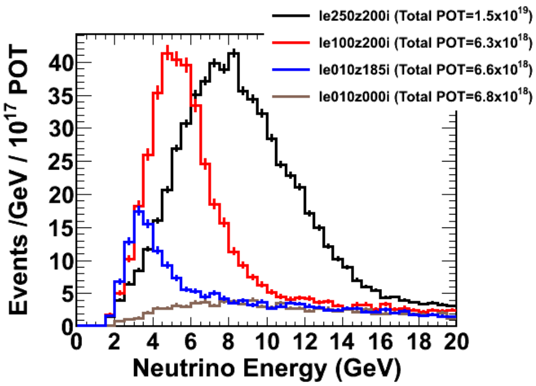

Figure 4: E_ν spectra of CC inclusive events in neutrino mode alternate beam configurations. The beam configurations are denoted by leXXXzYYYi, where XXX is the distance (cm) along the beam line between the target and the upstream horn, and YYY is the horn current (kA).

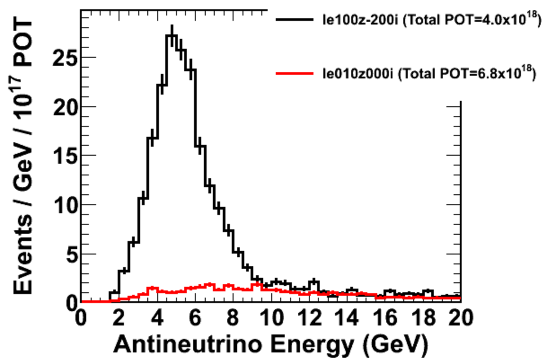

Figure 5: $E_{\bar{\nu}}$ spectra of CC inclusive events in antineutrino mode alternate beam configurations. The beam configurations are denoted by leXXXzYYYi, where XXX is the distance (cm) along the beam line between the target and the upstream horn, and YYY is the horn current (kA).

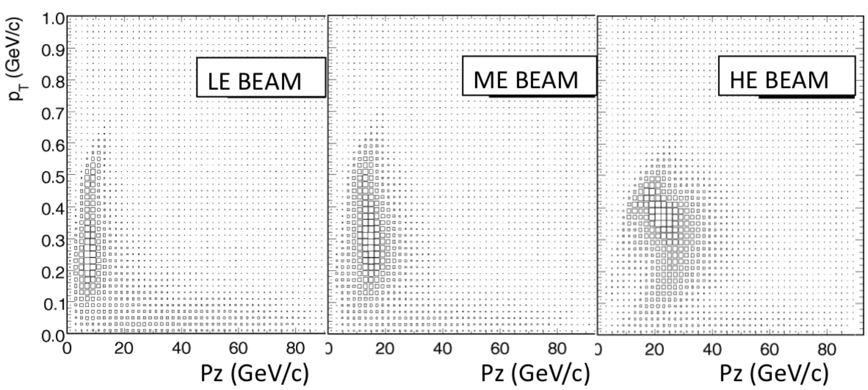

Figure 6: Predicted distribution in P_Z and P_T of hadron parents that yield a neutrino that interacts in the detector for low energy, pseudo-medium energy, and pseudo-high energy beam configurations.

the cross section and hadron production systematics.

While the alternate beam configurations data are being collected and analyzed, an estimate of the expected uncertainty on the eventual tuned flux prediction has been made. This was done using a mock data set generated from a flux simulation that employed the Fluka hadronic physics model. The mock data set was fit for hadron production as described above. The MINERνA flux prediction, which used the Geant4 QGSP hadronic physics model tuned to NA49 data, was corrected to agree with the mock data set using the weights generated from the fit. The error band on MINERνA's flux prediction before and after applying the weights is shown in Figure 7. The pre-weighted error band accounts for NA49 uncertainties, focusing uncertainties, and MC model spread. The 1σ model spread is defined as the maximum difference between relevant Geant4 hadronic physics models in describing re-interactions in the target and interactions in the downstream beam line components. Until the analysis of the alternate beam configurations data is complete, only incremental reductions to MINERνA's pre-weighted flux uncertainty estimate are expected, which will come from incorporating additional hadron production data sets in the tuning.

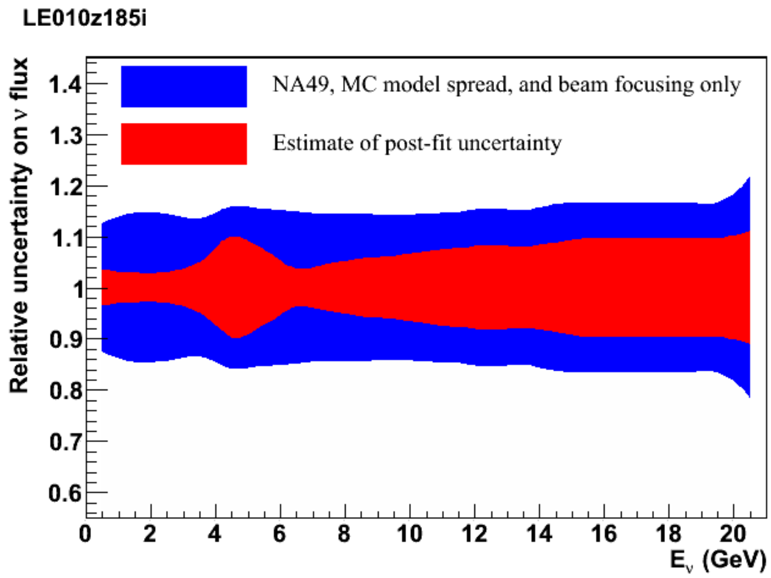

Figure 7: The estimated error band on MINERνA's flux prediction before (blue) and after (red) constraining the flux using *in situ* data.

5 Reconstruction Efficiency and Stability

As previously mentioned, the MINOS near detector serves as the muon spectrometer for MINERνA. Reconstructing a muon's path in both MINERνA and MINOS is critical to MINERνA's CC analyses. To evaluate this reconstruction, a sample of events containing a reconstructed MINOS track were selected. The MINOS track was required to pass reconstruction quality cuts, originate at the front of MINOS, and point back to MINERνA's tracker region. A cut on visible energy in MINERνA falling within the time window of the MINOS track was also imposed. Efficiency for this particular study is defined as the fraction of events having a reconstructed track in MINERνA that is matched to the MINOS track. The efficiency in data and MC as a function of the reconstructed muon momentum of the MINOS track and visible energy in MINERνA are shown in Figures 8 and 9, respectively. The difference in efficiency between data and MC is attributed to dead time and particles from neutrino interactions outside the detector that are not yet simulated in the MC.

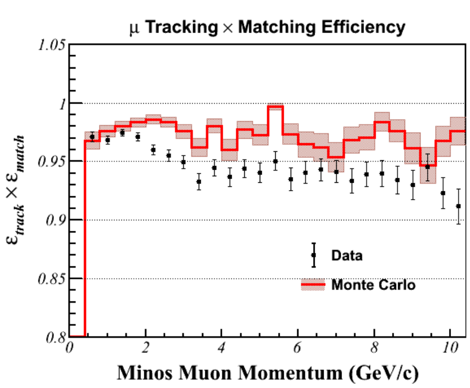

Figure 8: Efficiency of reconstructing a track in MINERνA that is matched to a track in MINOS vs. reconstructed muon momentum of the MINOS track in data and MC.

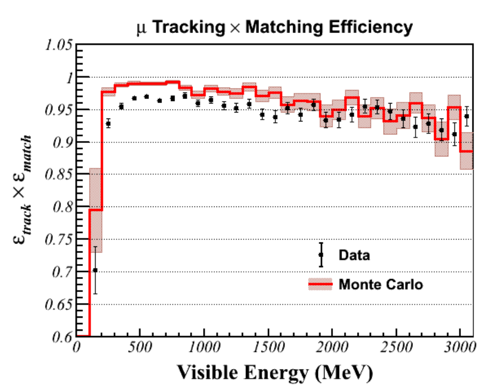

Figure 9: Efficiency of reconstructing a track in MINERνA that is matched to a track in MINOS vs. visible energy in MINERνA in data and MC.

The stability of data taking and reconstruction in MINERνA can be gauged by the rock muon rate. Rock muons are muons generated in neutrino interactions in the rock upstream of the detector hall[a]. Here, the rock muon rate is the number of rock muons normalized to protons on target (POT) for rock muons that enter at the front of MINERνA and are tracked in both MINERνA and MINOS. The rock muon rate is sensitive to performance of the NuMI beam line and the MINERνA and MINOS detectors. Figures 10 and 11 show the rock muon rate vs. integrated POT for data taken in LE neutrino mode and anti-neutrino mode runs. In both runs the rate is stable to a few percent. The rise in the rate at the end of the neutrino mode run is attributed to a reduction in dead time resulting from the beam running at ~50% intensity.

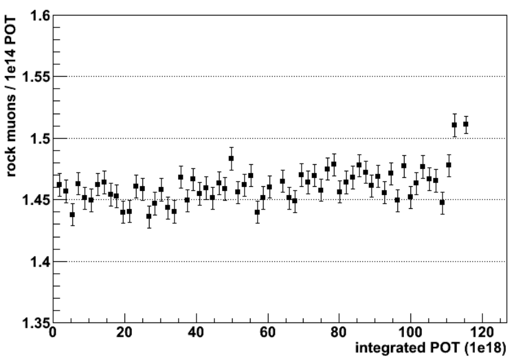

Figure 10: Rock muons per POT vs. integrated POT for one neutrino mode run comprising the first ~30% of MINERνA's total LE neutrino mode POT.

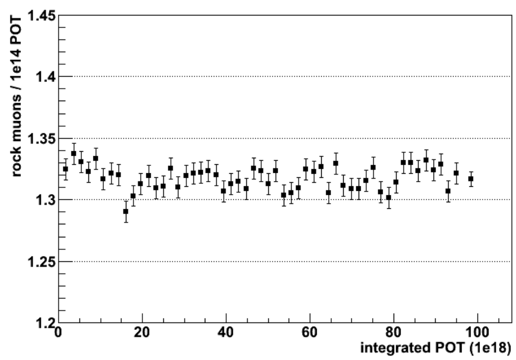

Figure 11: Rock muons per POT vs. integrated POT for one anti-neutrino mode run comprising ~50% of MINERνA's total LE anti-neutrino mode POT.

6 Conclusions

Many neutrino oscillation experiments operate at neutrino energies of a few GeV where neutrino-nucleus cross sections are not well understood. The SciBooNE and MiniBooNE experiments are currently making precision cross section measurements near 1 GeV. MINERνA is a newer experiment designed to make precision cross section measurements in the 1-10 GeV region. These proceedings have presented recent SciBooNE and MiniBooNE results, MINERνA's progress in flux determination, and MINERνA's reconstruction efficiency and stability.

References

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[a] The detector hall is located 106 m underground.