Pion and Kaon Production at MINERvA*

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Abstract

The MINERvA (Main INjector ExpeRiment for v-A) detector is situated in Fermilabs NuMI beam, which provides neutrinos and antineutrinos in the 1-20 GeV range. It is designed to make precision cross-section measurements for scattering processes on various nuclei which are important for neutrino oscillation experiments and the probing of the nuclear medium. Presented are recent results from MINERvA on neutral kaon production and various pion production processes.

INTRODUCTION

The MINERvA experiment is a fully active, high resolution detector designed to study neutrino-nucleus scattering in the few-GeV region and provide inputs for neutrino oscillation experiments. The experiment also examines nuclear effects and parton distribution functions (PDFs) using a variety of targets materials. Precision neutrino measurements aiming to determine mass hierarchy, probe CP violation, or look for new physics, require precise knowledge of cross sections, final states, and nuclear effects in neutrino scattering. These experiments need models that will correctly predict the rate and spectrum of events for neutrino interactions, especially using medium-heavy materials such as steel, argon, carbon and oxygen. The relation between true neutrino energy and the final state particles is also a key information for neutrino oscillation physics, since the flavor oscillation probability depends on neutrino energy.

The detector is situated in Fermilab's NuMI beamline [1] along with the MINOS and NOvA experiments. During the period of 2010 through the Spring of 2012 the MINERvA detector took data in the "low energy" mode, in which the peak for the neutrino energy was around 3 GeV. Since then, the NuMI beamline has been working in "medium energy" mode with the neutrino energy peak at 6 GeV.

MINERvA [2] is comprised of 120 hexagonal modules stacked along the beamline. The detector is segmented transversely into: the inner detector, with planes of solid scintillator and passive nuclear target regions of carbon, iron, lead and water; a region of pure scintillator strips; downstream electromagnetic and hadronic calorimeters; and an outer detector composed of a frame of steel with embedded scintillator, which also serves as the supporting structure. The scintillator strips have a triangular shape that permits 3 mm of position resolution and are placed in adjacent planes offset by 60 degrees from each other, enabling a

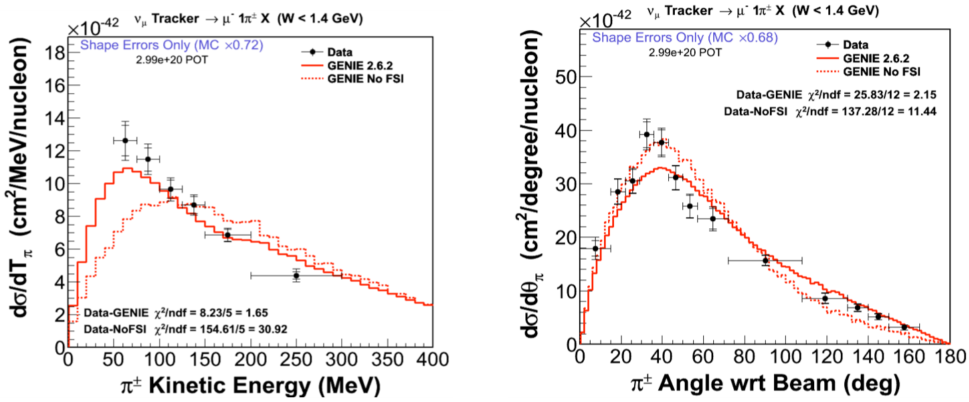

FIG. 1: Differential cross section vs. charged pion kinetic energy (left) and angle (right), in comparison with GENIE with and without FSI.

three-dimensional track reconstruction. The MINOS near detector [3] is situated two meters downstream of the MINERvA detector and serves as a magnetized muon spectrometer.

PION PRODUCTION ANALYSIS

The delta resonance, which decay to a pion and a nucleon, is the main method of pion production. Final state interactions (FSI) can absorb the pion in interactions with nuclear targets, mimicking the quasi-elastic signal and making pion production a major background for detectors that use CCQE as their signal. On the other hand, FSI can produce pions that can contaminate the quasi-elastic signal presenting a indistinguishable topology.

MINERvA has measured the cross section for pion production in two different channels, charged current single charged pion production by neutrino scattering and charged current single pion production by antineutrino scattering. For each channel we present two different analysis: using the hadronic kinematics, which provide information on FSI within the nucleus; and using the leptonic kinematics, which is more sensitive to the initial interaction within the nucleus.

Neutrino Single charged pion production

The main contribution for pion production comes from charged-current processes in which a neutrino scatters from scintillator to produce a muon and a single charged pion ($\nu_\mu A \rightarrow$

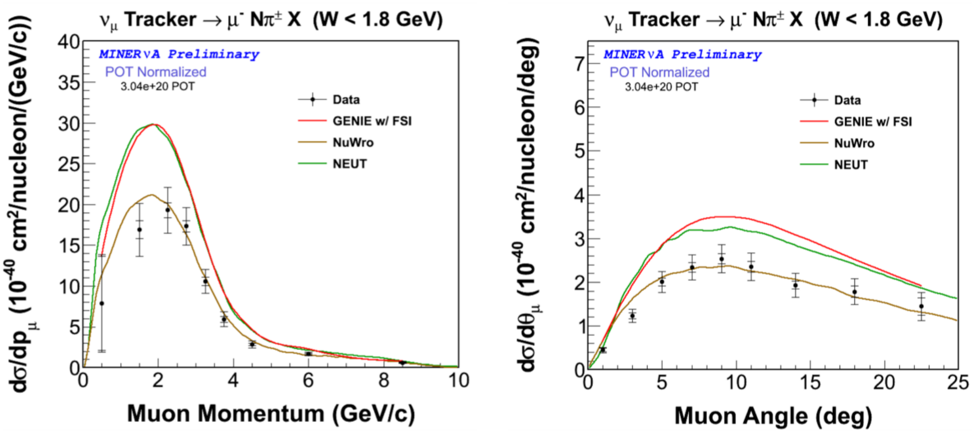

FIG. 2: Differential cross section vs. muon momentum (left) and angle (right), in data and different generators.

$\mu^-\pi^+A$ or $\nu_\mu A \to \mu^-\pi^\pm X$ where A is the initial nucleus and X refers to the recoil nucleus which may not be the same as A, plus any other particles that are not pions).

The event selection required a muon that reached the MINOS near detector, and a candidate pion reconstructed inside the MINERvA detector without creating a hadron shower. Pions can be identified in MINERvA by their dE/dx and the presence of a Michel electron from the pion to muon to electron decay chain.

Differential cross sections are measured with respect to the outgoing pion's kinetic energy [4] and the angle between the pion and the neutrino beam. We unfold our signal using GENIE [5], which models pion production using the Rein-Sehgal model [6].

The pion energy plot in Figure 1, in particular, shows the data's clear preference for models including FSI effects, highlighting the importance of these processes to pion energy distributions. The results of this study can be used by generators to constrain both the primary interaction rate for these processes and the FSI parameters.

Figure 2 shows the measurement in term of muon energy and the comparison to GENIE with final-state interactions enabled; to the models used in NuWro [7] and Neut [8]. It's clear that both GENIE and NEUT overestimate the cross section while NuWro provides better prediction.

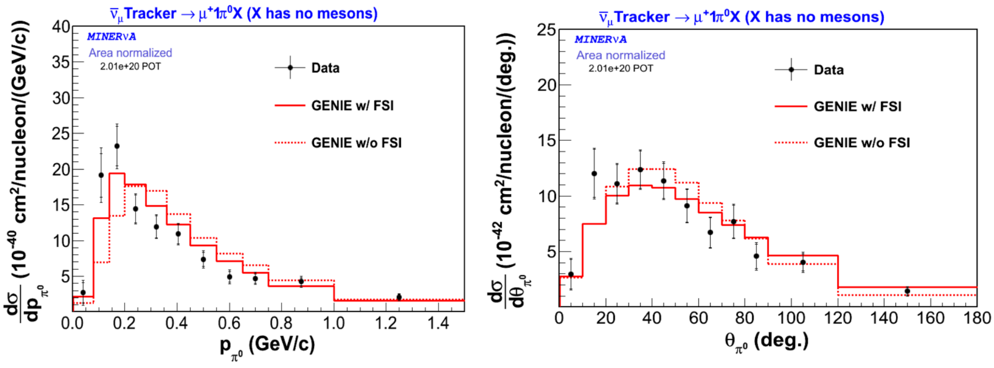

FIG. 3: Differential cross section vs. neutral pion kinetic energy (left) and angle (right), in data and GENIE with and without FSI.

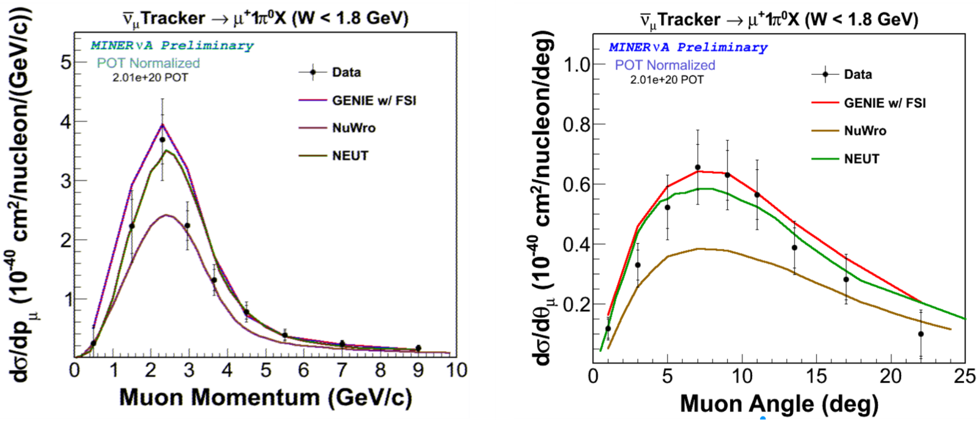

FIG. 4: Differential cross section vs. neutral pion kinetic energy (left) and angle (right), in data and various generators.

Antineutrino Single neutral pion production

The cross section for charged-current neutral pion production from antineutrinos on scintillator ($\bar{\nu}_\mu A \rightarrow \mu^+\pi^0 X$, where A is the initial nucleus and X refers to the recoil nucleus) is not well-studied, and generators' models vary significantly. It is, however, important to oscillation experiments, as its neutral-current analog ($\bar{\nu}_\mu A \rightarrow \bar{\nu}_\mu \pi^0 X$) can mimic a $\bar{\nu}_e$ appearance signature, due to the electromagnetic shower of the $\pi^0 \rightarrow \gamma\gamma$ decay.

The pion is identified by looking for the two photon showers from its decay. Its energy, and angle are reconstructed from the calorimetrically measured energy and the positions of these photons with respect to the muon vertex [9].

Figure 3 presents the hadronic analysis results and shows differential cross sections with

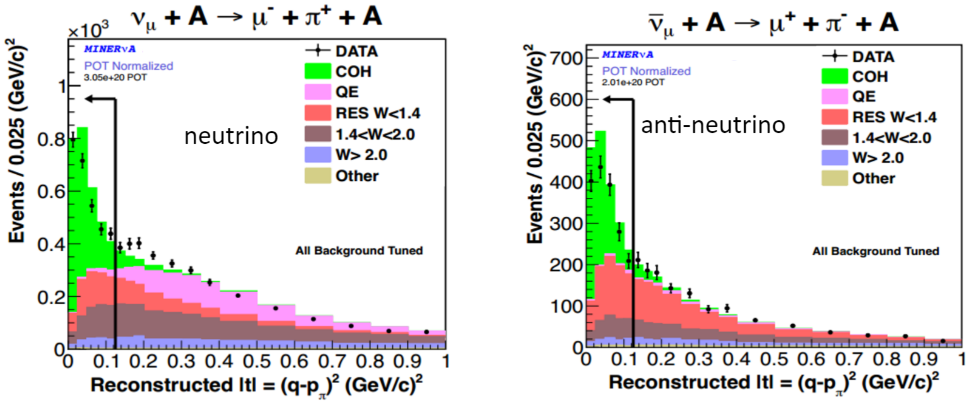

FIG. 5: Reconstructed momentum exchange between the nucleus and the system of the leptons and produced pion ($|t|$) for neutrino and antineutrino.

respect to the kinetic energy and angle of the neutral pion. The plots compare the measured cross section distributions to those predicted by GENIE [5] with and without FSI. Final State Interactions for pions is typically studied in pion beams, and as only charged pion beams are available, π^0 interaction rates must be inferred through isospin relations, leading to significant uncertainties. This measurement will be of use in evaluating the approximations made in generators' models.

Figure 4 shows the result of the new analysis that uses muon variables. The measured cross section distribution are compared with GENIE [5] with FSI, NuWro [7] and Neut [8]. The generators differ in their FSI modeling methods; GENIE and NEUT predictions are similar and higher than NuWro.

Coherent Pion Production

Coherent pion production is the production of a pion after the neutrino scatters off the entire nucleus leaving the nucleus in its ground state. It is characterized by a small momentum exchange between the nucleus and the system formed by leptons and produced pion ($|t|$) defined from the masured muon (p_μ) an pion (p_π) energies and directions as

$$|t| = |(p_\nu - p_\mu - p_\pi)^2| \approx (\sum_{i=\mu,\pi} E_i - p_{i,L}\ )^2 + |\sum_{i=\mu,\pi} \overrightarrow{p}_{i,T}\ |^2 \qquad (1)$$

where the approximation made is that zero energy is transferred to the recoil nucleus and where $\overrightarrow{p}_T$ and p_L are the transverse and longitudinal momenta with respect to the known

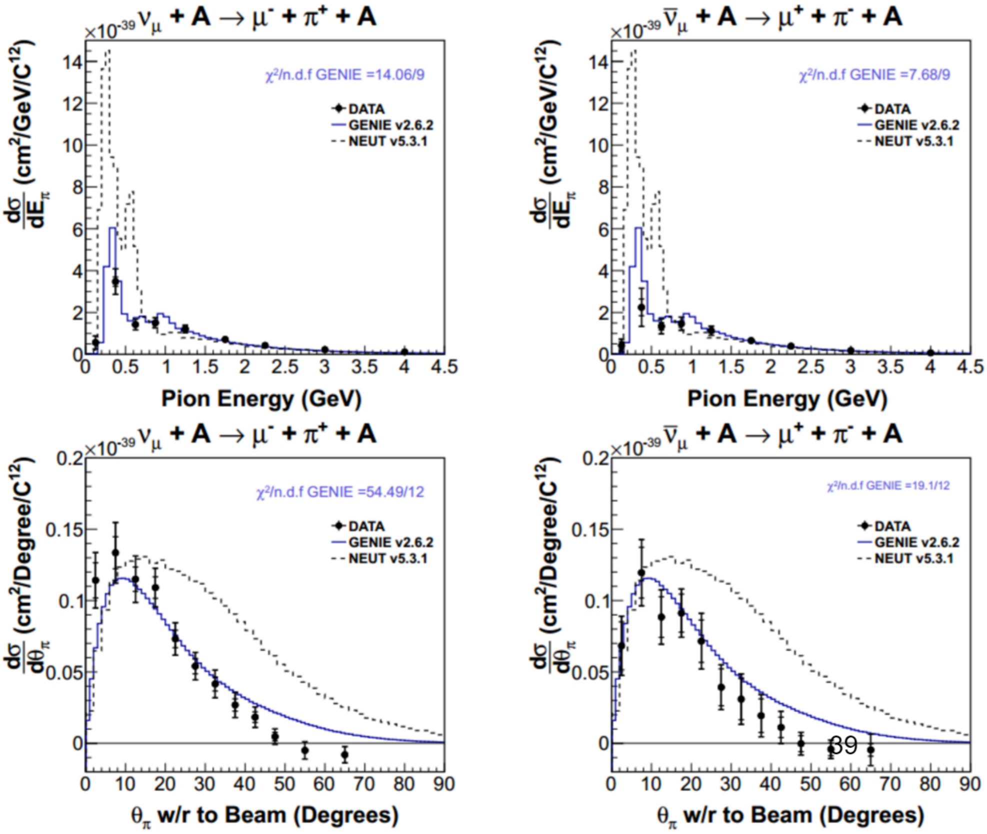

FIG. 6: Cross section distributions in respect of pion energy (top) and pion angle (bottom) for neutrino (left) and antineutrino (right) data.

neutrino beam direction.

The theory in this regime is not well understood, and many different approaches are included in neutrino event generators. Previous experiments have found evidence of this process at neutrino energies of several GeV, but the K2K and SciBooNE experiments made measurements consistent with no coherent pion production around 1 GeV [10, 11]. This process is important in the analysis of accelerator neutrino experiments where this process is a background to the desired quasielastic signal.

Figure 5 shows the distribution of reconstructed $|t|$ for neutrino and antineutrino data, in which the population of coherent events at low $|t|$ is clearly visible [12].

The default simulation overpredicts the backgrounds in the high $|t|$ region, and so we tune the prediction with a fit to pion energy distributions in the $0.2 < |t|/GeV^2 < 0.6$ region. The differential cross sections in pion energy and angle are shown in Figure 6. In

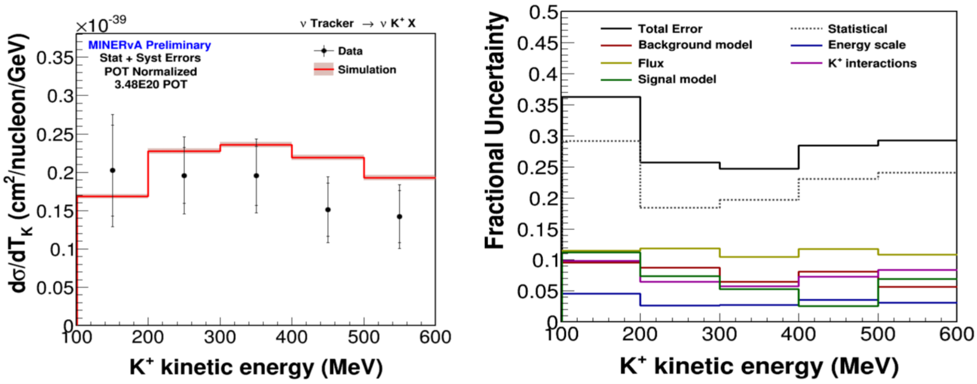

FIG. 7: Preliminary neutral current kaon production cross section with respect to K^+ kinetic energy (left) and the respective fractional uncertanties (right).

both neutrino and antineutrino data, the data favor lower pion angles with respect to the beam, and a lower peak at low pion energies than the prediction of the Rein-Sehgal model, which is used in current neutrino event generators.

KAON PRODUCTION

Neutral Current Kaon

Supersymmetry grand unification models predict proton decay into a K^+ with lifetimes of a few 10^{34} years. For water Cherenkov detector, K^+ is below detection threshold, so the signal consists of the μ^+ from the K^+ decay. The kaon cross section though, is still not well understood.

Strangeness conservation prevents K^+ absorption, and processes like $\pi + n \to K^+\Lambda$ inside the nucleus enhance the cross section. For proton decay searches neutral-current reactions like $\nu + p^+ \to \nu K^+\Lambda$ and $\nu + n^0 \to \nu K^+\Sigma$ are backgrounds. Charged-current reactions are generally not backgrounds because they produce a detectable charged lepton. Neutral current is very important to understand and predict events in future detectors like HyperK. It's also relevant for future Liquid Argon detectors modeling K^+ FSI to understand the signal and any FSI processes that can fake the kaon signal.

Figure 7 shows the preliminary cross section measurement. Neutral current K^+ rate below water Cherenkov threshold is well modeled by GENIE. This analysis is a work in progress and will be presented soon.

SUMMARY

The MINERvA collaboration is looking into a large range of important neutrino-nucleus cross section measurements which aim to understand, test and improve the model of these processes, and thus reduce systematics in oscillation experiments. The experiment is currently taking a new dataset in the Medium Energy beam configuration that will not only provide higher statistics for these analyses, but will also provide the ability to measure these processes on different nuclei.

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