Quasi-Elastic Scattering and Pion Production at MINERvA

Minerba Betancourt
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Fermilab
Neutrino QE Scattering and Pion Production

Motivation

- Understand the weak interaction and the nucleus
- Important for neutrino oscillation experiments
- Two types of neutrino oscillation measurements: Appearance and Disappearance
- In both cases we count events induced by given type of neutrinos
- Main channel: Quasi-Elastic scattering
- Important background: Pion production


CC Quasi-Elastic
nucleon changes, but doesn’t break up

CC Resonance
nucleon excites to resonance state

CC Deep Inelastic
nucleon breaks up

Figures showing cross-sections and production of pions and leptons.
Neutrino QE Scattering and Pion Production

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Neutrino Production (NuMI beamline)

- 120 GeV protons from the Fermilab Main Injector hit a 1m graphite target, producing pions and kaons
- Target and second magnetic horn can be moved relative to the first horn to produce different energy spectrum, MINERvA used low energy beam

Figure courtesy of Ž. Pavlović

Neutrino Energy Spectrum

![Diagram showing neutrino production and energy spectrum](image)
The MINERvA Experiment

- Fine-grained scintillator tracker surrounded by calorimeters

3 different rotated plane views to resolve high multiplicity events

Design, calibration, and performance of the MINERvA detector
Nuclear Inst. and Methods in Physics Research, A, Volume 743, 11 April 2014, Pages 130-159
Quasi-Elastic Scattering

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Neutrino Cross-Sections

Sam Zeller, Low Energy Neutrino Cross Sections, NuFact 06/10/03

Past Measurements

• How well have we measured low energy $\nu$'s?
• Rely on past measurements for this knowledge
• Along the way, point out how good our current theoretical understanding is

Review the status of past measurements of $\nu$ at $E_\nu \ll 1$ GeV:

Quasi–elastic scattering
Resonance production
Deep Inelastic scattering
Coherent $\pi$ production
Multi $\pi$ production
Quasi-elastic scattering (QE)
Resonance production (RES)
Deep Inelastic scattering (DIS)

Current Knowledge

$\sigma_{\nu}$'s are not particularly well-constrained in this intermediate $E$ region (situation is embarrassingly worse for NC and for $\bar{\nu}$)

... the situation has been improving (with the availability of new higher statistics data)

NOvA
T2K
LBNE
CNGS

Charged Current Quasi-Elastic Scattering

• Event Selection:
  • Fiducial volume (5.48 tons)
Charged Current Quasi-Elastic Scattering

- Event Selection:
  - Fiducial volume (5.48 tons)
  - Vertex energy cut
  - Muon track matched to MINOS track, momentum and charge analyzed (μ⁺ for antineutrino, μ⁻ for neutrino)
  - Non vertex recoil energy vs Q² cut

Data

AntiNeutrino

μ⁺

Tracker

ECAL

HCAL

Neutrino

p

μ⁻

Tracker

ECAL

HCAL

MINOS ND Detector

Non-Vertex Recoil Energy (GeV)

Reconstructed Q² (GeV²)

MINERvA Preliminary • ν CH → CCQE

ν̄ CCQE

ν̄ non-CCQE

Signal

Sideband

Q² = −mμ² + 2E_{QE}(E_μ − p_μ cos θ_μ)
Neutrino Energy and $Q^2$ Reconstruction

- Neutrino energy is reconstructed from muon momentum and angle
  
  $E_{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos \theta_\mu)}$

  $Q^2 = -m_\mu^2 + 2E_{QE}(E_\mu - p_\mu \cos \theta_\mu)$

Antineutrino
- # of events: 16,467
- Efficiency: 54%
- Purity: 77%

Neutrino
- # of events: 29,620
- Efficiency: 47%
- Purity: 49%

Event Generator
- GENIE 2.6.2

Main background from resonance production

Background is constrained with data using a sideband sample

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Differential Cross Section

\[
\left( \frac{\partial \sigma}{\partial Q^2} \right)_i = \frac{\sum_j U_{ij} (N_{\text{data},j} - N_{\text{bg},j})}{T \phi \Delta Q^2 \epsilon_i}
\]

Differential cross section

Number of data events
Predicted background events

Unfolding matrix
Number of target
Flux
Bin width
Efficiency

Antineutrino

Neutrino

Data errors include statistical and systematic errors

MINERvA • Tracker → CCQE

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Model Comparisons

Antineutrino

Neutrino

- Different event generators: GENIE and NuWro+
- Models:
  - Relativistic Fermi Gas (RFG), $M_A=0.99\text{GeV/c}^2$ (Model used by event generators) *
  - Relativistic Fermi Gas (RFG), $M_A=1.35\text{ GeV/c}^2$ (Higher $M_A$ motivated by recent measurements)**
  - Nuclear Spectral Function (SF), $M_A=0.99\text{ GeV/c}^2$ (More realistic model of the nucleon momentum) ***
  - Transverse Enhancement Model (TEM), $M_A=0.99\text{ GeV/c}^2$ (Empirical model tuned to electron-nucleon scattering data) ****

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The data most prefer an empirical model that attempts to transfer the observed enhancement in electron-nucleus scattering to neutrino-nucleus scattering.
Neutrino Pion Production
Neutrino Charged Current Pion Production

- Event Selection:
  - Fiducial volume
  - Muon track matched to MINOS track
  - Require one or two hadron track candidates
  - Select a pion (particle ID), use energy lost dE/dx to separate pions and protons
  - Select pions that stop and decay in the detector by looking for a Michel electron at the end of the track
  - Require the hadronic invariant mass $W_{\text{exp}} < 1.4\text{GeV}$ and $E_\nu < 10\text{GeV}$

$$E_\nu = E_\mu + E_H$$

$$Q^2 = -m_\mu^2 + 2E_\nu(E_\mu - p_\mu \cos \theta_\mu)$$

$$W_{\text{exp}}^2 = Q^2 + m_n^2 + 2m_nE_H$$

Data

- $\nu_\mu$ Tracker $\rightarrow \mu^- \pi^\pm X$ ($W < 1.4 \text{ GeV}$)
- POT Normalized
- Candidates / 0.1 GeV/c^2

- Data
- Pion Mis-ID
- CC $\nu_\mu$, Multi $\pi^\pm$
- $E_\nu > 10 \text{ GeV}$
- $W_{\text{exp}} > 1.4 \text{ GeV}$
- Not CC $\nu_\mu$
- Outside F.V.
- Signal

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Reconstructed Pion Energy and Angle

- Event selection yields 3474 pion candidates
- MC simulation normalized to data

Shape comparison shows good agreement between Data and GENIE simulations.
Differential Cross Section Results

- Focus on the shape of the cross sections

Previous measurement (MiniBooNE experiment) showed the data is consistent with no final state interactions

MINERvA results prefer GENIE with final state interactions
Model Comparisons

NuWro, Neut*, and GENIE all predict the data shape well. Data insensitive to the differences in pion absorption shape between GENIE, NuWro and Neut. Athar**, the sole theoretical calculation, does not agree with data. Likely due to an insufficient FSI model.

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Conclusions

• First $\nu_\mu$, anti-$\nu_\mu$ QE scattering and neutrino pion production measurements from MINERvA experiment

• **CCQE scattering:** MINERvA measured the differential cross section $d\sigma/dQ^2$ for neutrinos and antineutrinos
  
  • The shape of both of these cross-sections disfavor a simple RFG model

• **Pion Production:** MINERvA measured the differential cross section $d\sigma/dT$, $d\sigma/d\theta$
  
  • Data prefer the GENIE model with FSI, the data is also consistent in shape with NuWro and NEUT event generator with FSI

• **New results in the near future for** $\nu_\mu$, anti-$\nu_\mu$ coherent pion production, CC $\pi^0$ production, $\nu_\mu$ CCQE proton kinematics, $\nu_e$ CCQE and Kaon production
Back Slides
Error Summary for the Quasi-elastic Scattering

- Focus on the shape of $d\sigma/dQ^2$ cross section
- Measuring the shape of the cross section reduces several normalization errors, including the knowledge of the neutrino fluxes

Shape only
Constraint on Background for Quasi-Elastic Scattering analysis

• Constraining the background with data
Pion Production Data

- MiniBooNE experiment published the pion production cross section, Phys.Rev.D83:052007,2011

- MiniBooNE data is consistent with non Final State Interactions

\begin{center}
\textbf{GiBUU}
\end{center}

\begin{center}
\textbf{GENIE}
\end{center}
Background Constraint for Pion Production

- Using the MC to create signal and background shape templates
- Fitting the data for the relative normalizations of the template
Error Summary for the Pion Production

- Fractional uncertainty for shape only
Constraining flux with Hadron Production Data

- Monte Carlo reweighted to match measured production cross sections by NA49
- Uncertainties from NA49 cross sections propagated directly to flux
QE Differential Cross Section

- Using Llewellyn-Smith formalism:

\[ \frac{d\sigma}{dQ^2} = \frac{G_F^2 M^2}{8\pi E_{\nu}^2} \left[ A \pm \frac{s-u}{M^2} B + \frac{(s-u)^2}{M^4} C \right] \]

- A, B and C are functions of the F1, F2, axial-vector FA and pseudo scalar Fp form factors of the nucleon

\[
A = \frac{m^2 + Q^2}{M^2} \left[ (1 + \eta)F_A^2 - (1 - \eta)F_1^2 + \eta(1 - \eta)F_2^2 \right. \\
+ 4\eta F_1 F_2 - \frac{m^2}{4M^2} \left( (F_1 + F_2)^2 + (F_A + 2F_P)^2 \right. \\
\left. - \left( \frac{Q^2}{M^2} + 4 \right) F_P^2 \right]. \\
B = \frac{Q^2}{M^2} F_A (F_1 + F_2), \\
C = \frac{1}{4} (F_A^2 + F_1^2 + \eta F_2^2),
\]