Neutrino cross sections with the MINERvA Experiment

Steven Manly, University of Rochester
NOW 2010, Conca Specchiulla, Italy
September 4-11, 2010
What is MINERνA?

Main Injector ExpeRiment ν-A

- A fully active, high resolution detector designed to study neutrino reactions in detail
- Sited upstream of the MINOS near detector in the FNAL NuMI hall
- Will study neutrino reactions on a variety of nuclei
The MINERvA Collaboration
Main Injector ExpeRiment \( \nu \)-A

- University of Athens, Athens, Greece
- Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
- UC Irvine, Irvine, CA
- Fermi National Accelerator Lab, Batavia, IL
- University of Florida, Gainsville, FL
- Universidad de Guanajuato, Guanajuato, Mexico
- Hampton University, Hampton, VA
- Institute for Nuclear Research, Moscow, Russia
- James Madison University, Harrisonburg, VA
- Mass. Coll. of Liberal Arts, North Adams, MA
- University of Minnesota-Duluth, Duluth, MN
- Northwestern University, Evanston, IL
- Otterbein College, Westerville, OH
- University of Pittsburgh, Pittsburgh, PA
- Pontificia Universidad Catolica del Peru, Lima, Peru
- University of Rochester, Rochester, NY
- Rutgers University, Piscataway, NJ
- Universidad Tecnica Federico Santa Maria, Valparaiso, Chile
- University of Texas, Austin, TX
- Tufts University, Medford, MA
- Universidad Nacional de Ingenieria, Lima, Peru
- College of William & Mary, Williamsburg, VA

A collaboration of about 80 nuclear and particle physicists from 21 institutions
 ν interaction physics

• ν oscillations need to understand ν reactions on nuclear targets in the 1-10 GeV region
• Older Data Problematic
  – 20-50% uncertainties, depending on process
• The nuclear physics was not well understood
• Causes uncertainty on prediction in far detector

Plot from G. Zeller

S. Manly - Univ. of Rochester

NOW 2010, Conca Specchiulla, Italy, Sept. 4-11, 2010
CCQE – recent results

- Inconsistency between MiniBooNE/SciBooNE and NOMAD results
- Gap falls in midst of MINERνA coverage
MINERνA

- Precision measurement of cross sections in the 1-10 Gev region
  - Understand the various components of cross section both CC and NC
    - CC & NC quasi-elastic
    - Resonance production, Δ(1232)
    - Resonance ↔ deep inelastic scatter, (quark-hadron duality)
    - Deep Inelastic Scattering
- Study A dependence of ν interactions in a wide range of nuclei
- Need high intensity, well understood ν beam with fine grain, well understood detector.
NuMI Beamline

Target Hall

120 GeV protons from Main Injector

Target

Decay Pipe

Absorber

Muon Monitors

Mean $E_\nu$ increased by moving target upstream

$\pi^+$ and K$^+$ only

$\pi^+$ and K$^+$ → $\mu^+\nu_\mu$

Absorber stops hadrons not $\mu$

$\mu$ absorbed by rock, $\nu$ → detector

Before Mar 2012 LE beam, After 2012 ME beam

S. Manly - Univ. of Rochester

NOW 2010, Conca Specchiulla, Italy, Sept. 4-11, 2010
Tracking detectors

Extruded plastic scintillator + wavelength shifters.
Triangular geometry allows charge sharing for better position resolution.

64 anode PMT’s

16.7 mm
17 mm

Three views for 3D reconstruction.

Iron outer detector instrumented for EM calorimetry.

fully active tracker

U/X
V/X

NOW 2010, Conca Specchiulla, Italy, Sept. 4-11, 2010
The Detector
Nuclear Targets

- 5 nuclear targets + water target
- Helium target upstream of detector
- Near million-event samples
  \((4\times10^{20} \text{ POT LE beam} + 12\times10^{20} \text{ POT in ME beam})\)

<table>
<thead>
<tr>
<th>Target</th>
<th>Mass in tons</th>
<th>CC Events (Million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillator</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>He</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>C (graphite)</td>
<td>0.15</td>
<td>0.4</td>
</tr>
<tr>
<td>Fe</td>
<td>0.7</td>
<td>2.0</td>
</tr>
<tr>
<td>Pb</td>
<td>0.85</td>
<td>2.5</td>
</tr>
<tr>
<td>Water</td>
<td>0.3</td>
<td>0.9</td>
</tr>
</tbody>
</table>

5 Nuclear Targets
Fe  Pb  C
MINERνA μ Spectrometer installed and tested 😊

(Also known as the MINOS Near Detector)
CC Sample

- Current run plan (Aug. 2010)
  4 × 10^{20} POT LE beam
  12 × 10^{20} POT ME beam
- Yield: ~14M (CC events)
  9M in scintillator

Quasi-elastic  0.8 M
Resonance production  1.7 M
Resonance to DIS  2.1 M
transition region
DIS Low Q^2 region  4.3 M
and structure functions

Coherent Pion Production
charm / strange production  CC 89k, NC 44k

neutrino energy (GeV)
MINERνA Events

• Showing X view

S. Manly - Univ. of Rochester
NOW 2010, Conca Specchiulla, Italy, Sept. 4-11, 2010
Summary of detector capability

- Good tracking resolution (~3 mm)
- Calorimetry for both charged particles and EM showers
- Containment of events from neutrinos < 10 GeV (except muon)
- Muon energy and charge measurement from MINOS
- Particle ID from dE/dx and energy+range
  - But no charge identification except muons into MINOS
Anti-ν Inclusive CC Data

- Track in MINERνA which matches a track in MINOS, this imposes few GeV cut
  - Requires hits < 1m radius
  - X Y vertex distribution
  - Momentum from MINOS + de/dx in MINERνA
Distributions in Anti-ν Beam
Anti-ν CC, Data vs MC

- 4.04 × 10^{19} POT in anti-ν mode
- MC generator GENIE v 2.6.0
  - GEANT4 detector simulation
  - 2 × 10^{19} POT MC, LE Beam MC anti-ν flux, untuned
  - Area normalized
- Require reconstructed muon in MINOS
Distributions in Anti-$\nu$ Beam

$\nu$ CC, Data vs MC

- $\nu$ Distributions same conditions as before
- Very good agreement between Data and MC

S. Manly - Univ. of Rochester
NOW 2010, Conca Specchiulla, Italy, Sept. 4-11, 2010
Understanding the Flux

• FNAL MIPP experiment measures hadron production using 120 GeV/c P on NUMI target replica

• Measure flux with 8 different beam configurations where horn current and the target position are varied

• Goal is 7% error in flux shape and 10% on flux normalization

• Use muon monitors in alcoves downstream of the hadron absorber in the beam to measure the muon flux.

• Hope to achieve 10% error in absolute flux normalization.
Extraction of $F_A$, ME Beam

- Experiments assume dipole form for axial form factor, $(F_a)$ & determine $M_A$ by fit and/or normalization
- We can extract $F_A$ directly
  - $\sigma = aF_A^2 + bF_A + c$
- Hence, with the high statistics ME data we can extract $F_A$ in bins of $Q^2$
  - $12 \times 10^{20}$ POT
  - Expected errors with GEANT3 and NEUGEN & include detector resolution effects
  - The statistics give sensitivity for $F_A$ at the few % level at moderate $Q^2$

The range of nuclear targets will allow us to study the nuclear dependence of the extracted $F_A$
CCQE Cross Section, LE beam

- Expected statistical errors in cross section for the LE $\nu$ beam
  - $4 \times 10^{20}$ POT
- Include efficiencies and purities using NEUGEN and a GEANT 3 MC and includes detector resolution effects
- Goal of 7% flux errors on shape and 10% on absolute normalization
CCQE Cross Section, LE beam

- Expected statistical errors in cross section for the LE $\nu$ beam
  - $4 \times 10^{20}$ POT
- Include efficiencies and purities using NEUGEN and a GEANT 3 MC and includes detector resolution effects
- Goal of 7% flux errors on shape and 10% on absolute normalization
MINERνA Schedule

- 55% of MINERνA LE anti-ν
- Full MINERνA LE ν 4e20 POT
- NUMI upgrade
- Full MINERνA ME ν 12e20 POT

• MINOS request for more anti-neutrino running and some impact from potential Tevatron run extension – may change things a little (Jeff Hartnell’s talk on Tuesday)
Summary

• MINERvA is a high statistics neutrino experiment
• Greatly improved statistics on all neutrino-nucleus cross sections
• Precision measurements of A dependence of axial form factor
• Data coming in now! Results soon!
Backup slides
CCQE, Measuring $F_A$

The hadronic current for QE neutrino scattering is given by:

$$< p(p_2) | J^+_\lambda | n(p_1) > = \overline{u}(p_2) \left[ \gamma_\lambda F_V^1(q^2) + \frac{i \sigma_{\lambda\nu} q^\nu \xi F_V^2(q^2)}{2M} + \gamma_\lambda \gamma_5 F_A(q^2) \right] u(p_1) \quad (1)$$

The Dirac/Pauli form factors $F_V^1(q^2)$ and $F_V^2(q^2)$ are given in terms of the Sachs form factors by:

$$F_V^1(q^2) = \frac{G_E^V(q^2) - \frac{q^2}{4M^2} G_M^V(q^2)}{1 - \frac{q^2}{4M^2}}, \quad \xi F_V^2(q^2) = \frac{G_M^V(q^2) - G_E^V(q^2)}{1 - \frac{q^2}{4M^2}}.$$

CVC used to determine $G_E^V$ and $G_M^V$ from the electron scattering form factors $G_E^p$, $G_E^m$, $G_M^p$, and $G_M^m$:

$$G_E^V(q^2) = G_E^p(q^2) - G_E^m(q^2), \quad G_M^V(q^2) = G_M^p(q^2) - G_M^m(q^2).$$

The dipole approximation:

$$G_D(q^2) = \frac{1}{\left(1 - \frac{q^2}{M_V^2}\right)^2}, \quad M_V^2 = 0.71 \text{ (GeV/c)}^2, \quad F_A(q^2) = \frac{g_A}{\left(1 - \frac{q^2}{M_A^2}\right)^2}$$

$$G_E^p = G_D(q^2), \quad G_E^m = 0, \quad G_M^p = \mu_p G_D(q^2), \quad G_M^m = \mu_n G_D(q^2).$$

$G_E^V$ and $G_M^V$ are related in the non-relativistic limit to the charge and magnetic distribution. In the dipole approximation, $\rho(r) = \rho_0 e^{-r/r_0}$, rms of radius $\sim 0.81$ fm.
Previously, the vector factors form factors were assumed to be a dipole form.

However, there is no reason why they should be dipole.

During the last 10 years, the EM form factors have been measured with impressive accuracy.

Plot of $G_E^p / G_M^p$
- From data compilation of JJ Kelly
- Added lastest data from Puckett et al. PRL 104, 242310 (2010)
  - If $G_E^p$ and $G_M^p$ were dipole with same $M_V$, this ratio would be flat.


Hence, we can’t assume $F_A$ is dipole either.

$F_A$ is a major contribution to the cross section.
A dependence of form factor

• The form factor may be modified in the nuclear medium
  – Model predictions that form factor will be modified by a few percent, (Saito, Tsushima, Thomas, Progress in Particle and Nuclear Physics 58, 1 (2007))
  – Extraction of form factor may be influenced by conventional effects – final state interactions, for example, which effect identification of QE

• We anticipate sufficient statistics to study final states and potential changes in the form factor at low $Q^2$ at the percent level
  – Estimated total interactions, no efficiency or solid angle correction $\sim 800$ K in CH, $\sim 300$ K in Pb/Fe, $\sim 100$ K in H$_2$O in 4 year run
Coherent Pion Production

CC Coherent Pion Production Cross Section

\[ \sigma(\nu_\mu + A \rightarrow \mu^- + \pi^+ + A) \]

MINER\(\nu\)A’s nuclear targets allow the first measurement of the A-dependence of \(\sigma_{\text{coh}}\) across a wide range of nuclei.

Region where NEUGEN overestimates the cross sections.
Understanding the Flux

- Most $\nu$ experiments use a MC of beamline tuned to existing hadron production to simulate the production of the neutrinos in the beam line.
- External hadron production data:
  - Atherton 400 Gev/c $p$-Be
  - Barton 100 GeV/c $p$-C
  - SPY 450 Gev/c $p$-C
- New FNAL MIPP experiment uses 120 Gev/c $p$ on replica of NuMI target.
- Not easy to get flux precisely this way.
- Plot shows prediction of CC interactions on MINOS with different production models each consistent with experimental production data.
  - Variations 15 to 40%.
- In additional 2 to 10% error from horn angle offset & current errors and scrapping.
Measure Flux, Special Runs

- In situ method to measure flux
- Plots show \((p_z, p_T)\) of \(\pi^+\) contributing to \(\nu\) flux.
- “Special Runs” vary
  - Horn current \((p_T\) kick supplied to \(\pi^+\)s)
  - Target Position \((p_z\) of focused particles)
- Minerva will acquire data from total of 8 beam configurations
  - Measure events with QE
- Normalize flux at high energy using CCFR/CHARM total cross section
- Goal is 7% error flux shape & 10% error on flux normalization
Absolute Flux with $\mu$ Monitors

- **Alcove 1**
  - $E_{\mu,\pi}>4\text{GeV}$
  - $E_{\nu}>2\text{GeV}$

- **Alcove 2**
  - $E_{\mu,\pi}>11\text{GeV}$
  - $E_{\nu}>6\text{GeV}$

- **Alcove 3**
  - $E_{\mu,\pi}>21\text{GeV}$
  - $E_{\nu}>11\text{GeV}$

- 3 arrays of ionization chambers, 4th chamber being added;
- Signal = ionized electrons.
- Sampling $\mu$ flux = Sampling hadrons off target = Sampling $\nu$ flux.
- Sample different energy regions of the flux.
- Goal of $\mu$ monitors is to understand flux normalization to 10%

S. Manly - Univ. of Rochester

NOW 2010, Conca Specchiulla, Italy, Sept. 4-11, 2010
MINERνA Test Beam

In order to make precise measurements we need a precise calibration

- Low energy calibration

- 40 planes, XUXV, 1.07 m square

- Reconfigurable can change the absorber configuration. Plane configurations:
  - 20ECAL-20HCAL
  - 20Tracker-20ECAL

- Just finished 1st run – Jun 10-Jul 16
Test Beam $\pi$

- 20 ECAL 20 HCAL configuration
- 1.35 GeV interacting in HCAL
MINERvA Running Status

- Accumulated $0.84 \times 10^{20}$ POT of anti-$\nu$ beam with 55% of detector and Fe/Pb target
- Accumulated $>1.21 \times 10^{20}$ POT in Low Energy neutrino beam running with full detector
- Detector Live times typically above 95%
- Less than 20 dead channels out of 32k channels
PID with dE/dX

Candidate proton track from the anti-ν data set.

MC indicates this will be a successful method.