Results from MINERvA

Deborah Harris, Fermilab
Rencontres de Vietnam
ICISE Quy Nhon, Viet Nam
July 18, 2017
Neutrino Oscillations In One Slide

- Flavor eigenstates are not the same as mass eigenstates
- The existence of 3 generations of neutrinos means that there’s a possibility of observing CP-violation in neutrino oscillations
- We also can use oscillations to tell us if the mass ordering of the neutrinos is like that of other fermions
- It’s all done by measuring oscillation probabilities vs. Energy

\[ P_1 = \sin^2 \theta_{23} \sin^2 2\theta_{13} \left( \frac{\Delta_{13}}{B_{\pm}} \right)^2 \sin^2 \frac{B_{\pm} L}{2} \]

\[ P_2 = \cos^2 \theta_{23} \sin^2 2\theta_{12} \left( \frac{\Delta_{12}}{A} \right)^2 \sin^2 \frac{A L}{2} \]

\[ P_3 = J \cos \delta \left( \frac{\Delta_{12}}{A} \right) \left( \frac{\Delta_{13}}{B_{\pm}} \right) \cos \frac{\Delta_{13} L}{2} \sin \frac{A L}{2} \sin \frac{B_{\pm} L}{2} \]

\[ P_4 = \mp J \sin \delta \left( \frac{\Delta_{12}}{A} \right) \left( \frac{\Delta_{13}}{B_{\pm}} \right) \sin \frac{\Delta_{13} L}{2} \sin \frac{A L}{2} \sin \frac{B_{\pm} L}{2} \]

\[ \Delta_{ij} \text{ proportional to } 1/E \]

Minakata & Nunokawa JHEP 2001
Next Steps in Neutrino Oscillation Measurements

- Ambitious plans for new oscillation experiments: expect 1000’s of events
  - Because of “large” mixing angles, will be looking for small differences in oscillation probabilities between neutrino and antineutrino mode
  - Neutrino Energy is a big part of extracting oscillation parameters

DUNE: arXiv:1512.06148
Hyper-K: arXiv:1412.4673
We are entering a world where systematics are important

- \( \theta_{13} \) is large: need to understand signal process AND background process
- How a neutrino’s energy shows up in a detector is an important effect: both for water-Cerenkov and “fully active” detectors
Why is reconstructing Neutrino Energy complicated?

- The nucleus is a complicated place...
- First you have to get the quarks inside the proton right
- Then you have to get the nucleons inside the nucleus right
- Then you have to get the effects on the nucleus on the outgoing particles right

\[
\begin{align*}
\nu_e &: \text{e} \\
\nu_e &: \text{e} \\
d &: \text{u} \\
n &: \text{n} \\
p &: \text{p} \\
W^+ &: \text{W}^+ \\
W &: \text{W} \\
\end{align*}
\]
MINERvA’s vital statistics

• Broad Range of Neutrino Energies
  – This gives a broad range of interaction channels
  – Able to measure $\nu_\mu$ and $\nu_e$ both

• Capable detector
  – Low thresholds, good particle identification

• High intensity Neutrino Beam
  – Provides high statistics, but…
  – Need good flux constraints too

• Broad Range of Target Nuclei
  – To constrain both the nucleon-level processes and the role of the nucleus in what actually enters the detector
MINERvA Collaboration

~ 65 Particle, nuclear and theoretical physicists from 21 Institutions:

- Aligarh Muslim University
- Centro Brasileiro de Pesquisas Fisicas
- Fermilab
- University of Florida
- Universite de Geneva
- Universidad de Guanajuato
- Hampton University
- Massachusetts College of Liberal Arts
- University of Minnesota at Duluth
- University of Mississippi
- Otterbein University
- Universidad Nacional de Ingenieria
- Pontifcia Universidad Catolica del Peru
- University of Pennsylvania
- University of Pittsburgh
- University of Rochester
- Rutgers, the State University of New Jersey
- Universidad Tecnica Federico Santa Maria
- Tufts University
- College of William and Mary
- University of Wroclaw
Interactions Studied by MINERvA

• Can go from low to high momentum transfer to the nucleus
  – Quasi-elastic: this is most of the events at T2K and MicroBooNE
  – Resonance: backgrounds in T2K, signal in NOvA and DUNE
  – DIS: part of the signal in the DUNE experiment, + ICECUBE
MINERvA’s Flux in Oscillation Landscape

- NuMI Beamline
  - 120GeV protons
  - 2 focusing horns
  - 675m long decay region
  - MINERvA on axis at 1km

- MINERvA can see processes relevant for oscillation experiments from T2K to ICECUBE

Plot courtesy P. Rodrigues
MINERvA: Low Energy Flux Uncertainties

- Use world’s collection of hadron production data
- Compare with in situ flux shape measurement
- Constrain with neutrino-electron scattering events (standard candle)
- Low Energy Flux Uncertainty: ~8% at focusing peak, 10% integrated

MINERvA Detector

- Core of solid scintillator (CH) tracker
  - Tracking, particle ID, good energy reconstruction
  - Cell size: 1.7cm (transverse) x 1.7cm (longitudinal)
- Surrounding electromagnetic and hadronic calorimetry
- MINOS Near Detector for $\mu$ charge and momentum
MINERvA’s Nuclear Target Region

- Simultaneous targets in beam for robust test of models
Recipie for Cross Section Measurements

\[ \left( \frac{d\sigma}{dx} \right)_\alpha = \sum_j U_j \alpha \left( N_{data,j} - N_{bkgd, data,j} \right) \frac{A_{\alpha}(\Phi T)}{\Delta x} \]

- Count events \((N_{data,j})\)
- Subtract backgrounds, predict using data \((N_{bkgd, data,j})\)
- Unsmear the data \((U_{j\alpha})\) to take out detector resolution
- Divide by acceptance x efficiency \((A_{\alpha})\)
- Divide by flux and # of targets \((\Phi T)\)
- \(\Delta x\): normalize by bin width
- \(j\) and \(\alpha\): reconstructed and true bin number
Events in MINERvA

One out of three views shown, color = energy

$v_\mu n \rightarrow \mu^- p$ Candidate

$\mu$ candidate

Tracker

$\pi$ candidate

$\nu_\mu \rightarrow \mu^- \Delta^{++}, \Delta^{++} \rightarrow p\pi^+$ Candidate

$\nu_\mu p \rightarrow \mu^- \Delta^{++}, \Delta^{++} \rightarrow p\pi^+$ Candidate

$\nu_\mu e^- \rightarrow \nu_\mu e^-$ Candidate

$\nu_\mu e^- \rightarrow \nu_\mu e^-$ Candidate

$e^-$ candidate

Deep Inelastic Scattering candidate

Module number

Module Number

Fermilab

D. Harris | Results from MINERvA
Quasi-Elastic Cross Section Ratios on Fe, Pb, C

- Study of momentum transfer from the proton arm

\[ Q^2 = (M')^2 - M_p^2 + 2M'(T_p + M_p - M') \]

\[ M' = M_n - E_b \]
\[ E_b : \text{binding energy} \]
\[ T_p : \text{proton kinetic energy} \]
\[ M_n : \text{neutron mass} \]
\[ M_p : \text{proton mass} \]

Ref: arXiv:1705:03791
Quasi-Elastic Event Coplanarity on C, Fe, Pb

φ: Coplanarity

180° for proton at rest and 2-body interaction and no final state interactions

Ref: arXiv:1705:03791
Quasi-Elastic Cross Sections on C, Fe, Pb

- Just because a model gets C right does not mean it gets higher Z right
- Need to get nuclear effects of primary interaction AND Final state Interactions correct

Ref: arXiv:1705.03791
Looking at more than just the proton...

- Electron Scattering measurements have seen surprises when looking near the Quasi-elastic peak.
Try to get to the same kinematics in neutrino scattering

- Variables of interest: momentum transfer $q$
  - Total three-momentum transferred ($q_0$)
  - Total momentum along the beam direction ($q_3$)
Now go to variables we can reconstruct well

- Problem with “$q_0$” is that it also depends on energy that goes into neutrons, which we don’t see well
- Define new variable: “available energy” which is the energy that does go into our detector (KE of charged pions, photons, KE of protons, etc.)

Energy Transfer:
$$q_0 = \text{Calorimetric Hadronic Energy}$$

Neutrino Energy:
$$E_\nu = E_\mu + q_0$$

Momentum Transfer Squared:
$$Q^2 = 2E_\nu (E_\mu - p_\mu \cos \theta_m) - M^2_\mu$$
What do the data look like?

- Slice the 2-d space into two 1-d distributions

Missing ingredients

- Weak charge screening
- “2p2h” events to fill in the “dip” region between QE and resonance
What happens when we add those two ingredients?

• The 2p2h contribution predicted by Nieves is not quite enough, but close!

Fit to neutrino data, add extra strength to “dip” region

Fine, but does this new model have any predictive power?
Double Differential Neutrino CCQE Cross Sections

- Isolate only CCQE events: cut on extra energy outside the vertex, subtract backgrounds, extract cross sections
What about Antineutrinos?

- Look in the same two kinematic regions: first with “out of the box” prediction  
  Ref: R. Gran, NuINT’07
Antineutrino Inclusive Events at low recoil

- Add the fit from neutrino data to the antineutrino prediction...

Ref: R. Gran, NuINT’17
Double Differential Antineutrino CCQE Cross Sections

- Isolate only CCQE events: cut on extra energy outside the vertex, subtract backgrounds, extract cross sections

Extra strength coming at the right place in muon angle and momentum too
Electron Neutrino CCQE Cross Section

\( \nu_e \) CCQE is oscillation signal, but almost no data.

We all assume fundamental coupling is universal, but know nuclear effects are not!

Measured cross sections and \( \nu_e/\nu_\mu \) ratio consistent with GENIE model @ 1\( \sigma \)

\((\sim 10-20\% \) uncertainties) Absolute level is high

Also found an unsimulated background of photon like events, which we believe are due to diffractive production of \( \pi^0 \) from protons in scintillator.

What about Pion Production?

- After CCQE, pion production is the next most common channel for oscillation experiments.
- Energy seen in detector depends on $\pi^\pm$ vs $\pi^0$ and how much energy pion loses leaving the nucleus.
- MINERvA measuring all 4 modes, both $\pi$ and $\mu$ kinematics.

**Phys.Rev. D94 (2016) no.5, 052005**
New precision on anti-$\nu$/\nu cross section ratio

- Take advantage of standard candle to determine the shape on anti-$\nu$/\nu shape as a function of energy
- Important for atmospheric $\nu$ experiment
- Mass Hierarchy measurements
- Systematics include known model deficiencies in multi-nucleon effects
- In anti-$\nu$/\nu ratio many systematics cancel

[Graphs and data plots are shown to illustrate the precision in the cross section ratio as a function of energy.]
Summary

• MINERvA looking at many processes in new ways

• Getting better understanding of role of nucleus
  – Beware of your simulation: “out of the box” event generator is not nature!
  – Putting together a new model, tuned on neutrino events that has predictive power on antineutrino events!
  – By looking at 4 modes of pion production we can probe final state interactions
  – Both affect the visible energy prediction for incoming $\nu$ energy
  – Better energy prediction means better oscillation measurements

• MINERvA taking $\sim 6$GeV antineutrino data now, working on our 6GeV neutrino statistics to extend these results
Summary of MINERvA’s 21 publications

NuMI Flux Determination
\((a\ priori, \ and \ from \ e^- \ scattering)\)

Using Lepton variables only:
\(\nu_\mu \) and anti-\(\nu_\mu\) quasi-elastic
\(\nu_e \) CCQE

Inclusive “low recoil”
\(\pi^\pm\) production by \(\nu_\mu\)
\(\pi^0\) production by anti-\(\nu_\mu\)
\(K^\pm\) production by \(\nu_\mu\) (NC, CC)
Coherent \(\pi^\pm, K^\pm\) production
Inclusive anti-\(\nu_\mu/\nu_\mu\) ratios

Ratios comparing Pb,Fe,C to CH:
Total CC cross sections
Deep Inelastic Scattering
CCQE

See http://minerva.fnal.gov
Backup
MINERvA’s Current Physics Program

- Medium Energy results will feature 10x statistics
  - Higher flux and cross section, 3x more protons on target collected
  - Chance to look at nuclear effects in DIS at few % level!
- Statistics above assume $12 \times 10^{20}$ POT (2+ years) in antineutrino exposure
- Exclusive channel ratio results for Fe, Pb, C, CH
- Better Precision on $\nu_e$ scattering measurements

![Graph showing cross-section ratio for different elements and neutrino types](image-url)
MINERvA: Neutrino-Electron Scattering to constrain Flux

- Neutrinos scattering off electrons: $\nu_\mu$, pure electroweak process
- MINERvA used this channel in lower energy exposure to put 11% constraint on flux
- Medium Energy statistics expected to give 5% constraint on flux in neutrino mode

Ref: Phys. Rev. D 93, 112007
MINERvA: Ratios of Inclusive CC Reactions on Nuclei

1. At low $x$, deficit that increases with $A$
2. At high $x$, excess that increases with $A$

These effects are not reproduced by current neutrino interaction models.


D. Harris | Results from MINERvA

Targets are passive and there is contamination from nearby scintillator.

Use events in the tracker modules to estimate and subtract contamination from scintillator events.
MINERvA is the first experiment to look for the “EMC Effect” in neutrino scattering. No evidence of discrepancy with model (which does not include EMC effect). Low Energy measurement statistically limited.
What about Antineutrinos?

- Look in the same two kinematic regions: jump to where we have added in two new effects: screening and 2p2h
NuMI Beamline

- 120GeV protons strike a C target
- 2 focusing horns
- 675m decay volume
- Near detector hall at 1km from target, home of MINERvA
- Off Axis trick used for NOvA in same beamline