Neutrino Nucleus Deep Inelastic Scattering at MINERvA

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(on behalf of the MINERvA Experiment)
(anti-)neutrino DIS cross section data are valuable for the separation of individual quark parton flavors.

- Inclusion of NuTeV and CCFR data in global analyses of parton distribution functions (PDFs) inside protons.

Common theme: neutrino experiments need heavy targets (Fe, Pb, Ar, C, etc) to get high enough statistics yield.

Challenges:
- Fermi motion
- Correlations between nucleons,
- Partonic nuclear effects

Nuclear effects affect kinematic and distorts neutrino energy reconstruction to determine proton PDFs, the data have to be corrected for nuclear effects.
Partonic Nuclear Effect

- Nuclear effects still not well understood in neutrino physics. Difficult to combine data sets with different neutrino fluxes, acceptances, thresholds, and resolutions.
- Maybe the same for neutrino DIS... maybe not. All precise neutrino data is on Pb or Fe targets!
- We adapt partonic nuclear effects from electron scattering into neutrino simulation model (GENIE)

- Need more neutrino-nucleus DIS data to tell us:
  - if neutrino nuclear effects are different to charged lepton.
  - if we have modeled the nuclear effects correctly.
We know neutrino oscillates, but does it violate CP symmetry?

- Recent interest in neutrino interactions in the few GeV energy region comes from the need of accelerator based neutrino oscillation experiments to reduce systematic errors.
- Oscillation experiments (DUNE, NOvA, T2K, etc.) measure neutrino energy $E_\nu$ in the 1-10 GeV region, where many interactions channels are active.
Enter MINERvA

• MINERvA: a dedicated on-axis neutrino-nucleus scattering experiment running at Fermilab in the NuMI (Neutrinos at the Main Injector) beamline.

• Our goal:
  • Make high precision measurement of neutrino interaction cross sections in the energy region of interests (1-50 GeV).
  • Study nuclear effects
NuMI Beamline and Neutrino Flux

- Both the target and the second magnetic horn can be moved to change the energy of the beam.
  - Completed low-energy (LE) run which peaks at 3 GeV. Currently accumulating data in medium-energy (ME) run which peaks at 6 GeV.
MINERvA Detector

Spatial resolution: ~3 mm
Timing resolution: ~3 ns
MINERvA Takes Data on Many Different Targets, *Simultaneously*!
CC DIS Event Reconstruction

vertex x, y determines the material!

vertex z determines if it's a target event!

Hadronic system

Summed calorimetrically!

Only one muon reconstructed Muon angle ($\Theta_{\mu} < 17^\circ$).
Isolating DIS sample (LE)

\[ Q^2 = 4E_\nu E_\mu \sin^2 \left( \frac{\theta_\mu}{2} \right) \]

\[ W = \sqrt{m_n^2 + (2m_n^2 (E_\nu - E_\mu)) - Q^2} \]

- We consider \( Q^2 > 1.0 \text{ (GeV/c)}^2 \) to be enough momentum transfer to resolve the quark structure of the nucleons.

- \( W > 2.0 \text{ (GeV/c)} \) safely avoids the majority of resonances, and gives us confidence the hadronic shower is from deep inelastic scattering off of a parton.

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J. Mousseau, NuInt. November 2015
• GENIE 2.6.2 is the neutrino generator. DIS simulation is based on 2003 Bodek-Yang model (partonic $\nu_\mu^+$ quark cross sections computation at the level using GRV98LO PDFs).

• We measured ratios of cross sections to reduce systematic errors from the neutrino flux calculation.

• Ratios of the C, Fe, Pb to CH gives the evidence for nuclear effect.

• x-dependent ratios translate to x dependent nuclear effects.

• The shape of the data in low x, especially with Pb/CH is consistent with additional nuclear shadowing.
What Medium Energy Brings

- NuMI beamline currently running with increased beam energy mode which peaks at ~6 GeV (ME mode).
- We have taken ~12E20 POT in neutrino mode and currently taking data in anti-neutrino mode.
- About factor of 4 increase from LE data at 3E20 POT!
- Higher statistics yields improve comparisons across nuclei
- The peak of energy now moves to the DIS-rich kinematic region. Access to expanded kinematics and nuclear structure functions.
DIS in LE and ME

- More events shift up to higher Hadronic Invariant Mass ($W$) range and $Q^2$
  - GENIE simulation, v2.6.2

Higher statistics with increased beam energy gives us better sensitivity to probe high and low $x$
Challenge in Medium Energy

- With the **increase** of our **beam energy**, we see an **increase** in the **hadronic showers** near the event of interactions.
- Cause **more difficulty** in **vertexing** with increase rates of failure in getting the correct vertex position:
  - Events with **high invariant hadronic mass** tend to have tracks that are created by **secondary interactions or decays**.
  - **Shower activity** **occludes** the **vertex** region.
Enter Deep Convolutional Neural Net

Machine learning:
(1) take some data,
(2) train a model on that data,
(3) use the trained model to make predictions on new data.

Feature learning algorithms find important common patterns used to distinguish classes, then automatically extract them to be used in a classification or regression process -> time consuming.

Deep Learning is automatically extracting important features of a dataset without a great deal of "by-hand" feature engineering.
Goal: Find the location of the event vertex

Treat localization as a classification problem: DNN gives prediction which segment out of the 11 segments an interaction is from.

Events in MINERvA are easily represented as images.

Challenges: Different type of interaction → different characteristics
Comparisons to Track Based Vertexing

- Pick a row
- For a given reconstructed target, what is the distribution of the true source target

- Number of segments correctly defined as a fraction of true vertices originating in the segment.

Odd segment: passive target
Even segment: active scintillators
## Comparisons to Track Based Vertexing

<table>
<thead>
<tr>
<th>Target</th>
<th>Track-Based Row Normalized Event Counts (%)</th>
<th>DNN Row Normalized Event Counts (%)</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream of Target 1</td>
<td>41.11</td>
<td>68.1</td>
<td>27.0</td>
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<tr>
<td>1</td>
<td>82.6</td>
<td>94.4</td>
<td>11.8</td>
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<td>Between target 1 and 2</td>
<td>80.8</td>
<td>82.1</td>
<td>1.3</td>
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<tr>
<td>2</td>
<td>77.9</td>
<td>94.0</td>
<td>16.1</td>
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<tr>
<td>Between target 2 and 3</td>
<td>80.1</td>
<td>84.8</td>
<td>4.7</td>
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<tr>
<td>3</td>
<td>78.0</td>
<td>92.4</td>
<td>14.4</td>
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<tr>
<td>Between target 3 and 4</td>
<td>90.5</td>
<td>93.0</td>
<td>2.5</td>
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<tr>
<td>4</td>
<td>78.3</td>
<td>89.6</td>
<td>11.3</td>
</tr>
<tr>
<td>Between target 4 and 5</td>
<td>54.3</td>
<td>51.6</td>
<td>-2.7</td>
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<tr>
<td>5</td>
<td>81.6</td>
<td>91.2</td>
<td>9.6</td>
</tr>
<tr>
<td>Downstream of target 5</td>
<td>99.6</td>
<td>99.3</td>
<td>-0.3</td>
</tr>
</tbody>
</table>
Systematics Errors and Outlook

- Currently working on improving the analysis in medium energy by addressing other challenges:
  - Reassessing the effect of larger event pileup to dead time in detector.
  - Improving resolution of the muon angle which directly improve the $Q^2$ resolution:
    \[ Q^2 = 4E_\nu E_\mu \sin^2 \left( \frac{\theta_\mu}{2} \right) \]
  - Further study to understand the fraction of backward energy in deep inelastic scattering.
  - Optimizing analysis cuts for medium energy.
  - Study to understand the non-DIS background fraction in ME and improve technique of non-DIS background fitting.
  - Study of efficiency.
  - Have started taking anti-neutrino data (21 Feb this year!), which will allow x-dependent ratios measurement at \(~5\%\) precision for Fe and Pb and better measurement of structure function.
From MINERvA Collaboration: Thank You!!
Backup
Why care about cross section?

- In a period of precision neutrino oscillation measurements
  - Reducing systematics uncertainties is critical
- Reaching low systematics goals requires control of all systematics, including neutrino interaction cross sections.
- Oscillation experiments rely on neutrino-nucleus interaction models in neutrino event generators.
- Need better model and high precision data -> goals of MINERvA

DUNE CDR, arXiv:1512.06148

50% CP Violation Sensitivity

![Graph showing DUNE sensitivity with CDR Reference Design and Optimized Design]

- 1% ~650 kt-MW-yr
- 3% ~1200 kt-MW-yr

~2x exposure!
DIS and Transition Region Simulation in GENIE

- Genie uses the Whitlow parameterization for RL.
- Bodek-Yang accounts for target-mass modification and higher-twist effects by calculating the nucleon structure functions as a function of a modified scaling variable.
- Coefficients of this scaling variable are tuned to data from a variety of charged-lepton scattering experiments, and the uncertainties on these fits are propagated to the analysis.
- The nuclear modification made to the structure functions is applied identically to all elements heavier than helium. genie's predicted total DIS and differential cross sections of carbon, polystyrene scintillator (CH), iron, and lead are identical once the differing neutron fractions are taken into account.
- This treatment does not take account of the A-dependence of shadowing and the EMC effect established in charged-lepton scattering.
- For a given x and Q2, the coherence length of hadronic fluctuations may be longer for the axial-vector current than the vector current. This would allow shadowing to occur for neutrino scattering in the lowest x bin.
Expected Statistics in Same x bins: Neutrino Mode

- Hit-level simulation on Medium Energy event sample, using cuts and reconstruction techniques from Low Energy analysis:

<table>
<thead>
<tr>
<th>Bjorken x</th>
<th>0-0.1</th>
<th>0.1-0.3</th>
<th>0.3-0.7</th>
<th>0.7-0.9</th>
<th>0.9-1.1</th>
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</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>7.2</td>
<td>14.3</td>
<td>10.7</td>
<td>2.5</td>
<td>7.2</td>
</tr>
<tr>
<td>Iron</td>
<td>36.1</td>
<td>70.9</td>
<td>55.5</td>
<td>10.9</td>
<td>36.1</td>
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<tr>
<td>Lead</td>
<td>39.3</td>
<td>83.8</td>
<td>66.9</td>
<td>55.5</td>
<td>83.8</td>
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<td>Scintillator</td>
<td>307.1</td>
<td>663.0</td>
<td>490.4</td>
<td>95.1</td>
<td>307.1</td>
</tr>
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</table>

Event rate for 6E20 POT for all events vs x (reconstructed x)

<table>
<thead>
<tr>
<th>Bjorken x</th>
<th>0-0.1</th>
<th>0.1-0.3</th>
<th>0.3-0.7</th>
<th>0.7-0.9</th>
<th>0.9-1.1</th>
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<td>3.6</td>
<td>3.6</td>
<td>3.2</td>
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<tr>
<td>Iron</td>
<td>3.0</td>
<td>3.6</td>
<td>3.6</td>
<td>3.5</td>
<td>3.5</td>
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<tr>
<td>Lead</td>
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<td>4.0</td>
<td>4.1</td>
<td>4.1</td>
<td>4.4</td>
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<tr>
<td>Scintillator</td>
<td>4.1</td>
<td>4.7</td>
<td>4.9</td>
<td>4.7</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Ratio of events/POT ME / LE:
At increased energy beam, we have higher fraction of DIS events. DIS sample has low background after applying the reconstruction cut.
Current Estimated Data Sets

Inclusive Events

DIS Selected Only

Higher statistics with increased beam energy gives us better sensitivity to probe high and low x

Reconstructed $Q^2 > 1 \text{ GeV}^2$
Reconstructed $W > 2 \text{ GeV}$
Projected Statistical Error on Ratio

Integrated over $Q^2$, we can see that the fractional statistical error is less than 10% over a large range of Bjorken $x$, including the Anti-Shadowing and EMC Effect Region.
Non DIS Background

- **DIS Signal**: true $Q^2 > 1$ and true $W > 2$.
- **DIS Background**: true $Q^2 < 1.0 \text{(GeV/c)}^2$ and $W < 2.0 \text{(GeV/c)}$.
- Use background as sideband to predict how many events with low $Q^2$ and low $W$ are in the data.
- Scale factor are summed per material: C, Fe, Pb, CH.
Plastic Background

**Signal:**
True vertex is in iron, AND reconstructed in iron

**Background:**
True vertex is in scintillator, BUT reconstructed in iron

Event selection allows some contamination from plastic surrounding passive targets.

Correct the weight of plastic background based on their geometrical acceptance to MINOS ($E_\mu$, $\theta_\mu$)

Events from this region used to predict the plastic background...

Up here...
• Results are shown for the deeply inelastic events in C, Fe, Pb and CH.
• We measured ratios of cross sections to reduce systematic errors from the neutrino flux calculation.
• Ratios of the C, Fe, Pb to CH gives the evidence for nuclear effect.
Convolution: mathematical operation describing the rule of mixing two functions or pieces of information: (1) The feature map (or input data) and (2) the convolution kernel mix together to form (3) a transformed feature map.

- A convolutional neural network (CNN) uses convolutional layers that filter inputs for useful information.
- These convolutional layers have parameters that are learned so that these filters are adjusted automatically to find the best feature for the task at hand.
Uncertainties as percentage of ratio if DIS differential cross sections

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
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<tr>
<td>0.00–0.10</td>
<td>13.6</td>
<td>2.6</td>
<td>6.8</td>
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<td>10.3</td>
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<tr>
<td>0.20–0.30</td>
<td>6.9</td>
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<td>3.5</td>
<td>2.8</td>
<td>1.4</td>
<td>10.2</td>
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<td>0.6</td>
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<td>1.4</td>
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</tr>
</tbody>
</table>
• Minerva is the first experiment that is able to do precision measurements to study neutrino deep inelastic scattering simultaneously on multiple nuclear targets under identical beam.

• We have just finished taking neutrino scattering data using the Medium Energy beam and currently calibrating and analyzing the data.

• We have started taking anti-neutrino data (21 February this year!), which will allow “ν-EMC” ratio measurement vs. Bjorken x at ~5% precision for Fe and Pb

• Stay tuned for our future results!