Charged-Current Inclusive Cross Section Ratios with $\theta_\mu < 17^\circ$ at MINERvA

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CC Inclusive Events Introduction

- Neutrino CC Inclusive: all neutrino events with a nucleon as a target mediated by the $W^+$ boson, regardless of specifics of the final state of the nucleus.

- Sum of CCQE + resonance + transition + DIS.

- Inclusive cross sections are commonly used for detector calibrations and to cross-check event generators.

- You need to understand the inclusive cross section before you understand specific channels!
Nuclear Effects in Neutrino Scattering

- One common theme of contemporary neutrino experiments: they rely on large $A$ materials to supply adequate event rates (Fe, Ar, C, etc.)

- Problem: nuclear effects caused by nucleons being bound in a nucleus distort the energy reconstruction of the neutrinos.

- Two detectors does not solve your problem! Nuclear effects are $E_\nu$ dependent, and the energy spectrum between near/far detectors is not the same.

- Effects not well understood in neutrino physics. General strategy has been to adapt electron scattering effects into neutrino event generators.
Neutrino Nuclear Effects

Traditional methods to incorporate $x$ dependent nuclear effects into neutrino event generators is to adapt existing $e^-$ scattering data... (Bodek-Yang)

...or use existing neutrino data + predicted pdfs to fit underlying structure functions (CTEQ).

$$x = \frac{Q^2}{2ME_{had}}$$


In both cases, need more neutrino data to correctly model these effects!
Charged Lepton Scattering Nuclear Effects

• However, there are some difficulties incorporating charged lepton data...

• For example, neutrinos are sensitive to the axial component of $x F_3$ and $F_2$.

• Charged lepton nuclear effects still not fully explained.

• Despite ~30 years of active research, EMC effect still not fully understood.

• Moral: $\nu + A$ data is needed not only to model the nuclear effects, but also understand the fundamental physics.
Planes of scintillator strips, surrounded by steel outer frames make up hexagonal modules.

Nuclear targets in the same neutrino beam (as in EMC) allow MINERvA to make A-dependent physics measurements. MINOS near detector used for escaping muon ID and reconstruction.
Active Scintillator Modules

He Target

250 kg Liquid He: not used

Water: Not used in today's analysis

1" Pb / 1" Fe
266kg / 323kg

3" C / 1" Fe / 1" Pb
166kg / 169kg / 121kg

0.3" Pb
228kg

.5" Fe / .5" Pb
161kg / 135kg

500kg Water: Not used in today's analysis

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Neutrino Energy Range

- Neutrinos are generated by the NuMI beam line at Fermilab.

- Today's presentation uses the “low energy” (peak 3 GeV) $\nu_\mu$ NuMI configuration. Neutrinos with an energy between 2 and 20 GeV are analyzed.

- For more details on the NuMI beamline and how we estimate our flux, see D. A. Harris's talk on Friday.
Event Selection

Inclusive event: an event with at least one track (outgoing muon) + possible extra detector activity.

Events are selected in the passive material in the nuclear target region to form a sample of Fe, Pb and C events.

To reduce systematic uncertainties, the σ ratio of C/CH, Fe/CH and Pb / CH are measured.
Reconstruction Overview

Event is reconstructed with a vertex in a nuclear target (target 3). Both tracks in this case are used to fit the vertex.

Additional detector energy summed and corrected calorimetrically.

Long muon track matched to MINOS near detector.
Recoil Reconstruction

- Recoil energy = all non muon energy in a -25, 30 ns window of the vertex time.

- Calibrated energy deposits \((E_i)\) in the detector weighed by the energy lost in passive material \(c_i\); see table.

\[
E_{\text{had}} = \alpha \times \sum_i c_i E_i
\]

### Energy lost by a mip in each material

<table>
<thead>
<tr>
<th>Material</th>
<th>CH</th>
<th>C</th>
<th>Fe</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>dE/dx (MeV/g/cm²)</td>
<td>1.96</td>
<td>1.74</td>
<td>1.45</td>
<td>1.12</td>
</tr>
</tbody>
</table>

### Overall scale factor (\(\alpha\)) computed from simulation

<table>
<thead>
<tr>
<th>vertex</th>
<th>Tgt 2</th>
<th>Tgt 3</th>
<th>Tgt 4</th>
<th>Tgt 5</th>
<th>Trk</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha)</td>
<td>1.78</td>
<td>1.67</td>
<td>1.59</td>
<td>1.57</td>
<td>1.60</td>
</tr>
</tbody>
</table>
One-track vertex events occasionally truly occur in the scintillator surrounding the nuclear target, but are reconstructed to the passive target. This makes up the largest background.

True vertex (green star) is in the same material as the reconstructed vertex (orange star).

Vertex is reconstructed in the Pb (blue). However, the true vertex of the event is in the scintillator (yellow).
Background Subtraction

- We subtract this background by measuring the event rates in the downstream tracker, and extrapolating these events upstream to the nuclear target region.

- Downstream events are weighted for MINOS acceptance based on $E_{\mu}$, $\theta_{\mu}$ and a $E_{\text{had}}$ based weight which accounts for tracking inefficiency.

- Extrapolation is done by matching the same transverse section of the detector between modules.
Background Subtraction Accuracy

- Top plot shows the true BG from MC / estimated BG.

- Additional uncorrelated uncertainty added to this fraction until the $\chi^2 / \text{dof} = 1$.

- Background extracted separately for data and MC, shows good agreement (bottom plot).

- Other backgrounds (wrong sign, neutral current) are < 1 %, and originate as muons mis-identified in MINOS.
Event Composition

\[ Q^2 = 2E_\nu(E_\mu - p_\mu \cos(\theta_\mu)) \]

\[ W = \sqrt{M^2 + 2ME_{had} - Q^2} \]

\[ x = \frac{Q^2}{2ME_{had}} \]

- Not truly “Inclusive” due to the \( \theta_\mu \) cut
- \( Q^2 \) region sculpted by MINOS acceptance: low \( \theta_\mu \) → low \( Q^2 \).
- Dominated by CCQE and low \( W \) events (resonance + transition).
CAUTION: Low $Q^2$ Ahead

- X-dependent nuclear effects are traditionally measured in an highly inelastic region ($Q^2 > 1 \text{ GeV}^2$, $W > 2 \text{ GeV}$).

- This is not the kinematic region of the MINERvA data set, which has a mean $Q^2$ between 0.23 and 1.0 GeV$^2$.

- This is, however, the energy and $Q^2$ region typical of oscillation experiments.

- What we end up measuring is a mixture of nuclear effects from CCQE, Resonance, transition and traditional DIS.

<table>
<thead>
<tr>
<th>$x$</th>
<th>QE (%)</th>
<th>Res. (%)</th>
<th>DIS (%)</th>
<th>Soft DIS (%)</th>
<th>Non-res. Inelastic (%)</th>
<th>Generated $Q^2$ (GeV$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0–0.1</td>
<td>11.3</td>
<td>42.5</td>
<td>5.9</td>
<td>19.2</td>
<td>15.7</td>
<td>0.23</td>
</tr>
<tr>
<td>0.1–0.3</td>
<td>13.6</td>
<td>36.4</td>
<td>16.7</td>
<td>9.1</td>
<td>23.0</td>
<td>0.70</td>
</tr>
<tr>
<td>0.3–0.7</td>
<td>32.7</td>
<td>32.8</td>
<td>11.8</td>
<td>1.4</td>
<td>21.1</td>
<td>1.00</td>
</tr>
<tr>
<td>0.7–0.9</td>
<td>55.1</td>
<td>25.4</td>
<td>4.3</td>
<td>0.5</td>
<td>14.6</td>
<td>0.95</td>
</tr>
<tr>
<td>0.9–1.1</td>
<td>62.7</td>
<td>21.6</td>
<td>2.8</td>
<td>0.5</td>
<td>12.3</td>
<td>0.90</td>
</tr>
<tr>
<td>1.1–1.5</td>
<td>69.6</td>
<td>18.1</td>
<td>1.9</td>
<td>0.4</td>
<td>9.9</td>
<td>0.82</td>
</tr>
<tr>
<td>&gt; 1.5</td>
<td>79.1</td>
<td>12.8</td>
<td>0.6</td>
<td>0.3</td>
<td>7.1</td>
<td>0.86</td>
</tr>
</tbody>
</table>
X Migration

- Migration in x is severe, especially in the x > 0.3 bins.

- Poor x resolution in this region stems from CCQE events, where calorimetry is an inappropriate technique for recoil energy reconstruction.

- Typical unfolding methods (Bayesian) do not converge with migration this severe.

- Solution is to “fold” the generated MC x distribution using the smearing matrix rather than unfold data.

Each cell is the percent of events generated in that x bin

<table>
<thead>
<tr>
<th>x bin</th>
<th>0.0–0.1</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>
<th>1.1–1.5</th>
<th>overflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0–0.1</td>
<td>73</td>
<td>23</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.1–0.3</td>
<td>12</td>
<td>60</td>
<td>23</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>0.3–0.7</td>
<td>4</td>
<td>20</td>
<td>47</td>
<td>9</td>
<td>5</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>0.7–0.9</td>
<td>2</td>
<td>11</td>
<td>30</td>
<td>11</td>
<td>9</td>
<td>10</td>
<td>26</td>
</tr>
<tr>
<td>0.9–1.1</td>
<td>2</td>
<td>8</td>
<td>30</td>
<td>12</td>
<td>6</td>
<td>10</td>
<td>31</td>
</tr>
<tr>
<td>1.1–1.5</td>
<td>3</td>
<td>7</td>
<td>21</td>
<td>8</td>
<td>8</td>
<td>14</td>
<td>38</td>
</tr>
</tbody>
</table>
Absolute Cross Sections

• Absolute cross sections on CH, C, Fe and Pb are measured, but we present measurements of the *ratios* of C / CH, Fe / CH and Pb / CH.

• Ratio measurements reduce the systematic uncertainty substantially, especially the normalization error which is primarily the uncertainty on the flux prediction.

![Graph showing Uncertainties on $\sigma^{Fe}$ and Errors on Ratio of $\sigma^{Fe} : \sigma^{CH}$ over Neutrino Energy (GeV).]
Results: $\sigma(E_\nu)$

- MC is based on GENIE version 2.6.2
- $E_\nu$ unfolded to true kinematics.
- We see good agreement between our data and MC as a function of $E_\nu$ at the 1 GeV level.
- GENIE's treatment of nuclear effects for total cross section appears to agree with data.
- However, the kinematics of the individual events could be still altered by effects not modeled in GENIE.
Results: $d\sigma /dx$

- Story very different in terms of Bjorken $x$.
- We observe a *deficit* of events at $0 < x < 0.1$ which grows with $A$. The size of this deficit is too large to be consistent with shadowing measured from $e^-$ scattering.
- We observe an excess of events from $0.9 < x < 1.1$ which grows with $A$.
- Neither effect is modeled by our simulation. Indicates GENIE nuclear effects are insufficient.
Modeling Nuclear Modifications

- GENIE's default nuclear model is based on BY 2003, and simulates the same \( x \) dependent nuclear effects for C, Fe and Pb.

- Alternate models / calculations:
  - Kulagin-Petti. Theoretical calculation based on computed \( 2xF_1 \), \( F_2 \) and \( xF_3 \) for each nucleus A.

- Calculations of the ratios agree with GENIE at the ~ 1\% level (see table).

<table>
<thead>
<tr>
<th>( x )</th>
<th>C/CH</th>
<th>Fe/CH</th>
<th>Pb/CH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( G )</td>
<td>( \sigma_{st} )</td>
<td>( % )</td>
</tr>
<tr>
<td>0.0–0.1</td>
<td>1.050</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>0.1–0.3</td>
<td>1.034</td>
<td>0.7</td>
<td>-0.3</td>
</tr>
<tr>
<td>0.3–0.7</td>
<td>1.049</td>
<td>0.8</td>
<td>-0.1</td>
</tr>
<tr>
<td>0.7–0.9</td>
<td>1.089</td>
<td>1.8</td>
<td>-0.1</td>
</tr>
<tr>
<td>0.9–1.1</td>
<td>1.133</td>
<td>2.3</td>
<td>-0.1</td>
</tr>
<tr>
<td>1.1–1.5</td>
<td>1.111</td>
<td>2.2</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Future Nuclear Target Analyses

- Future analysis: isolate a DIS region from the inclusive sample.

- Should improve the x resolution by removing 99% of CCQE events, allows comparison of the data to models preferring higher $Q^2$.

- Initial investigation into a CCQE removed “inelastic” region has shown poor statistics. Considering increasing the energy range of analyzed events.

- Currently taking higher intensity ME energy data, will shift more of our events into the DIS region and improve overall statistics.
Conclusions

- MINERvA has recently measured the total and differential (as a function of $x$) cross section ratios of C/CH, Fe/CH and Pb / CH.
- Total cross section ratios agree well with the simulation, differential ratios show disagreements at low and high $x$.
- This disagreement cannot be explained by the alternate models we investigated.
- Further DIS measurements will allow cleaner comparisons at low $x$ in the near future.
Thank you for listening!
But Wait! There's More!

- More MINERvA Talks!
  - C. Patrick and C. McGivern, CCQE results Weds.
  - B. Eberly, Resonance Pion production. Fri.
  - A. Mislivec Coherent Pion production. Fri.
  - D. Harris, Neutrino Flux. Fri.

- MINERvA Posters!
  - C. Patrick, CCQE results
  - J. Mousseau, Inclusive Ratios (if you're not sick of me)

- ArXiv reference of Inclusive Ratio paper: 1403.2103v1
Backup Slides
Background Subtraction Acceptance Weights

Muon-only Geant4 simulation measures probability muon will hit MINOS

\[ RW = \frac{f_{\text{target}}(E_\mu, \theta_\mu)}{f_{\text{tracker}}(E_\mu, \theta_\mu)} \]
$E_{\text{had}}$ Dependent Correction

Correction Applied to BG Prediction, Iron of Target 2

Pink band is statistical error

Correction accounts for tracking inefficiency due to high energy hadron showers.
Wrong Sign and Neutral Current Background

![Graph showing the fraction of events in a channel versus neutrino energy. The graph includes two data sets: Neutral Current and Wrong Sign (\(\n\)). The y-axis represents the fraction of events in the channel, ranging from $10^{-5}$ to $10^{-1}$, and the x-axis represents the neutrino energy in GeV, ranging from 2 to 20. The data points are connected by lines to show trends.]
Content of Final States

Sources of Visible Energy for $E_{\text{had}} = [0.0,0.2]$ GeV

- x-talk: 19.1%
- $e + \gamma + \pi^0$: 4.6%
- $\pi^\pm + K$: 45.0%
- $p$: 7.3%
- n: 23.5%

Sources of Visible Energy for $E_{\text{had}} = [0.2,1.0]$ GeV

- $\mu$: 8.2%
- $e + \gamma + \pi^0$: 26.9%
- $\pi^\pm + K$: 8.3%
- $p$: 44.2%
- n: 6.7%

Sources of Visible Energy for $E_{\text{had}} = [1.0,2.5]$ GeV

- x-talk: 19.0%
- $e + \gamma + \pi^0$: 6.6%
- $\pi^\pm + K$: 9.4%
- $p$: 27.2%
- n: 33.0%

Sources of Visible Energy for $E_{\text{had}} = [2.5,5.0]$ GeV

- $\mu$: 24.3%
- $e + \gamma + \pi^0$: 39.4%
- $\pi^\pm + K$: 8.7%
- $p$: 15.3%
- n: 9.3%
Detector Technology