Charged Current Quasi-Elastic Scattering at MINERνA

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Nu Int 14, May 19-24 2014, U.K.
CCQE at MINERvA

* Two papers with quasi-elastic results published since the last NuInt:

* We report neutrino and antineutrino charged-current quasi-elastic cross-sections $d\sigma/dQ^2$ on CH scintillator and comparisons to theoretical models
* Additional model comparisons are being shown here for the first time
* Carrie McGivern’s talk will explain about further quasi-elastic analyses we’re working on right now
* And please come and see the poster describing all of our quasi-elastic studies

$$Q^2_{QE} = 2E^2_{\nu} (E_\mu - p_\mu \cos \theta_\mu) - m_\mu^2$$
MINERvA detector

- **Steel Shield**
  - Scintillator Veto Wall
  - Liquid Helium
- **Nuclear Target Region**
  - (C, Pb, Fe, H₂O)
  - 0.25t
  - 8.3 tons total
- **Active Tracker Region**
- **v-Beam**
- **Side HCAL**
- **Side ECAL**
  - 0.6 tons
- **Electromagnetic Calorimeter**
  - 15 tons
- **Hadronic Calorimeter**
  - 30 tons
- **Side HCAL**
  - 116 tons

Dimensions:
- Width: 5 m
- Height: 2.14 m
- Depth: 2.4 m
Scintillator (CH) tracker allows reconstruction of tracks for one and two-track analyses
MINERvA detector

- Steel Shield
- Scintillator Veto Wall
- Liquid Helium
- Nuclear Target Region (C, Pb, Fe, H2O)
- v-Beam
- Active Tracker Region (8.3 tons total)
- Side HCAL
- Side ECAL
- Electromagnetic Calorimeter (15 tons)
- Hadronic Calorimeter (30 tons)
- MINOS Near Detector (Muon Spectrometer)

Dimensions:
- 5 m width
- 2 m depth
MINERvA detector

MINOS’s magnetized detector allows muon charge and momentum reconstruction, but restricts our angular acceptance.
Switching the horn current selects a beam enriched in neutrinos or antineutrinos

- These studies use data from the low energy run with $E_\nu \sim 3.5$ GeV
- Our sample studies $E_\nu$ from 1.5 to 10 GeV, spanning MiniBooNE’s and NOMAD’s ranges
- See Debbie Harris’s talk for more beam details

For the published analyses:
Antineutrino: $1.01 \times 10^{20}$ POT
Neutrino: $9.42 \times 10^{19}$ POT
# Our Monte Carlo: GENIE 2.6.2

## Interaction models

<table>
<thead>
<tr>
<th>Interaction models</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE: axial form-factor</td>
<td>Dipole with axial mass 0.99 GeV</td>
</tr>
<tr>
<td>CCQE: Vector form-factors</td>
<td>BBBA05</td>
</tr>
<tr>
<td>CCQE: Pseudoscalar form-factors</td>
<td>PCAC/Goldberger-Treiman</td>
</tr>
<tr>
<td>Resonance and coherent</td>
<td>Rein-Seghal</td>
</tr>
<tr>
<td>DIS</td>
<td>GRV94/GRV98 with Bodek-Yang</td>
</tr>
</tbody>
</table>

## Nuclear effects

<table>
<thead>
<tr>
<th>Nuclear effects</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear model</td>
<td>RFG, Fermi momentum=225MeV, Pauli blocking, Bodek-Ritchie tail</td>
</tr>
<tr>
<td>FSI modeling</td>
<td>INTRANUKE-hA (S. Dutman, AIP Conf Proc, 896, pp. 178-184 (2007))</td>
</tr>
<tr>
<td>Formation zone</td>
<td>SKAT</td>
</tr>
</tbody>
</table>

CCQE signal definition

- Our signal is defined as an event in which the primary interaction is quasi-elastic (regardless of final-state particles)
- Incoming (anti)neutrino energy between 1.5 and 10 GeV
- Interaction within our scintillator tracker fiducial region

**QE-like**

- QE
  - $\bar{\nu}_\mu$ (anti)neutrino
  - Recoil neutron
  - $\mu^+$

**Not QE-like**

- Not QE
  - $\bar{\nu}_\mu$ (anti)neutrino
  - $\pi^0$ absorbed by the nucleus
  - Only neutron and muon escape: fakes QE

- $\Delta^0$
  - $\Delta$ resonance is an unstable excited state
  - $\Delta$ decays to neutron and pion

- Recoil neutron interacts with another nucleon
  - Final-state interaction produces a pion: fakes non-CCQE

$\nu_l, l^-$
CCQE signal definition

* Our signal is defined as an event in which the **primary interaction is quasi-elastic** (regardless of final-state particles)
* Incoming (anti)neutrino energy between 1.5 and 10 GeV
* Interaction within our scintillator tracker fiducial region

**QE-like**

1. QE: 
   - \( \bar{\nu}_\mu \) interacts with proton to produce QE-like signal
   - Recoil neutron

2. Not QE: 
   - \( \bar{\nu}_\mu \) interacts with proton to produce non-QE signal
   - \( \Delta^0 \) absorption by nucleus
   - Only neutron and muon escape: fakes QE

**Not QE-like**

1. QE: 
   - Recoil neutron interacts with another nucleon
   - Final-state interaction produces a pion: fakes non-CCQE

2. Not QE: 
   - QE: 
     - \( \Delta^0 \) resonance is an unstable excited state
     - \( \Delta \) decays to neutron and pion
   - Not QE: 
     - \( \Delta^0 \) resonance is an unstable excited state
     - \( \Delta \) decays to neutron and pion
CCQE signal definition

* Our signal is defined as an event in which the primary interaction is quasi-elastic (regardless of final-state particles)
* Incoming (anti)neutrino energy between 1.5 and 10 GeV
* Interaction within our scintillator tracker fiducial region

WE CAN IDENTIFY

- **QE-like**
  - QE
  - Not QE

- **Not QE-like**
  - Recoil neutron interacts with another nucleon
  - Final-state interaction produces a pion: fakes non-CCQE

- Only neutron and muon escape: fakes QE
- \(\pi^0\) absorbed by the nucleus
- \(\Delta^0\) resonance is an unstable excited state
- \(\Delta\) decays to neutron and pion
Event selection: tracks: $\bar{\nu}$

- **Antineutrino mode**
  \[ \bar{\nu}_\mu + p \rightarrow \mu^+ + n \]

- Muon track charge matched in MINOS as a $\mu^+$
- **No additional tracks from the vertex**
- The ejected neutron may scatter, leaving an energy deposit, but it does not make a track from the vertex
Muon track charge matched in MINOS as a $\mu^-$

No requirement on the number of additional tracks from the vertex

The ejected proton may make a track, as in the example

An alternate study requires this proton track - see Carrie McGivern’s talk

Neutrino mode

$$\nu_\mu + n \rightarrow \mu^- + p$$
**Event selection: isolated energy**

- **Antineutrino mode**
  \[ \bar{\nu}_\mu + p \rightarrow \mu^+ + n \]

- Energy deposits outside of the muon track, excluding cross-talk
- Neutron scattering may deposit energy
- Frequently, only the muon track is visible; no isolated deposits
- This cut makes little difference at low \( Q^2 \), but greatly improves purity at high \( Q^2 \)

- **Antineutrino - maximum 1 isolated**
- **Neutrino - maximum 2 isolated deposits**
Event selection: recoil energy

- Exclude vertex region: 
  30 g/cm² for neutrino mode 
  Contains < 225 MeV protons
- Antineutrino mode 
  exclude 10 g/cm² 
  Contains < 120 MeV protons

- Backgrounds typically contain pions, which will deposit energy in the detector
- A cut is therefore made on the total calorimetrically-corrected recoil energy
- The energy is summed over the region shown
- The area around the vertex is excluded, as it is suspected that nuclear effects could lead to additional low-energy nucleons in this area, even in CCQE events
Event selection: recoil

\[ \overline{\nu} \quad \nu \]

QE

Not QE
Summary of cuts

- The muon must be matched to a MINOS track
  - $\mu^-$ for neutrino mode; $\mu^+$ for antineutrino mode
- The event vertex must be within the fiducial volume
  - within the central 110 planes of the scintillator tracking region
  - no closer than 22cm to any edge of the planes
- There must be no tracks apart from the muon (antineutrino mode)
- We limit the number of isolated energy showers
  - maximum 2 (neutrino) or 1 (antineutrino)
- We make the $Q^2$-dependent recoil energy cut
- We cut on reconstructed neutrino energy:
  $1.5<E_{\nu}^{QE}<10\text{GeV}$

$$E_{\nu}^{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos \theta_\mu)}$$

(Formula for antineutrino mode; for neutrino mode switch $m_p$ and $m_n$. $E_b$ is binding energy; this is 30 MeV for antineutrino mode, and 34 MeV for neutrino.)

$\bar{\nu}$: 54% efficiency, 77% purity

$\nu$: 47% efficiency, 49% purity
Backgrounds include events such as

* Quasi-elastic-like resonant events, where the pion is absorbed
* QE-like deep-inelastic scattering events
* Other DIS or resonant events which are not removed by our cuts
We use data to estimate our backgrounds by performing a fraction fit of simulated signal and background recoil energy distributions from our Monte Carlo, in each of 4 $Q^2$ bins.

These plots show data for antineutrinos, before the background fit.
Background subtraction: after

We use data to estimate our backgrounds by performing a fraction fit of simulated signal and background recoil energy distributions from our Monte Carlo, in each of 4 $Q^2$ bins.

These plots show data for antineutrinos, after the background fit.
The background scales are shown for both antineutrinos and neutrinos.
We use four iterations of a Bayesian unfolding method.

The unfolding maps reconstructed $Q^2_{QE}$ to generated $Q^2_{QE}$.

Note: True $Q^2_{QE}$ refers to $Q^2$ as constructed from true muon kinematics in the CCQE hypothesis, NOT to the actual 4-momentum transfer squared.
Efficiency and acceptance

* The MINOS-match requirement limits acceptance at high muon angle
* See Carrie McGivern’s talk for ways to address this
Cross-sections

* To get a final cross-section, we normalize by number of **target nucleons**, number of **protons on target** and integrated (anti)neutrino **1.5-10 GeV flux** per proton on target

<table>
<thead>
<tr>
<th></th>
<th>Antineutrino</th>
<th>Neutrino</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Protons on target</strong></td>
<td>1.01 e20</td>
<td>9.42 e19</td>
</tr>
<tr>
<td><strong>Integrated flux (1.5-10 GeV)</strong></td>
<td>2.43 e-8/cm^2/POT</td>
<td>2.91 e-8/cm^2/POT</td>
</tr>
<tr>
<td><strong>Target nucleons</strong></td>
<td>1.91 e30 protons</td>
<td>1.65 e30 neutrons</td>
</tr>
</tbody>
</table>
Systematic uncertainties ($\bar{\nu}$)

- Plot above shows absolute uncertainties
- Plot to right shows shape-only uncertainties
- **Flux** dominates the absolute uncertainty
- **Uncertainty in flux mostly affects normalization**, not shape
- Statistical uncertainties dominate the shape distribution, and total uncertainty is reduced
Comparing cross-sections to models

We use two frameworks for modeling cross-sections:

- **GENIE**, the Monte Carlo we use to estimate our acceptance
- **NuWro** (see T. Golan's talk at NuInt14)

And the following nuclear models:

- **Relativistic Fermi Gas (RFG) (GENIE and NuWro)**
  - Constant binding energy; Fermi-distributed momenta. $p_F=225$ MeV (GENIE), 221 MeV (NuWro)

- **Spectral functions (SF) (NuWro only)**
  - Takes correlations into account when calculating initial-state momenta and removal energies

- **Local Fermi Gas (LFG) (NuWro only)**
  - Fermi momentum and binding energy are a function of position in the nucleus
  - Pauli blocking is less restrictive than for RFG

- **Random Phase Approximation (RPA) (NuWro only)**
  - Models long-range correlations due to particle-hole excitations
  - RPA suppresses the cross-section at low $Q^2$
Corrections for nuclear effects

* We can simulate interactions between initial-state nucleons by adding a correction term to our nuclear models.

* On our plots, we indicate a cross-section modified in this way by using a dotted line in the same color as the initial nuclear model that was modified.

* We currently have two different simulations for these effects:
  
  * The **transverse enhancement model (TEM)** parameterizes an enhancement seen in electron-nucleus scattering data, by modifying the magnetic form-factor. This is believed to be caused by nucleon-nucleon correlations. It is a correction to nuclear models **without RPA**. A. Bodek, H. Budd, and M. Christy, Eur.Phys.J. C71, 1726 (2011).
  
  * The **Nieves model** includes **meson-exchange current** diagrams. Some of these diagrams correspond to nucleon-nucleon correlations. It is a correction to nuclear models **with RPA**. J. Nieves, I. Ruiz Simo and M. J. Vicente Vacas, Phys. Rev. C 83 (2011) 045501.

Examples of some MEC interactions, based on a more detailed list from J Morfín.
Today’s distributions

- The plots I show today use NuWro version nuwro11p, a newer version that was used in our 2013 papers
- We also use our latest MINERvA reconstruction code, including an improved flux measurement
  - However, systematics have not been recalculated
  - Instead, for these preliminary plots, we use the new central values, with the total uncertainty values as used in our 2013 papers
- In all plots, the inner marker on the error bars represents statistical uncertainty, while the outer marker represents total uncertainty
Cross-section model comparisons

- It’s hard to distinguish between the different curves, especially at high $Q^2$ where the cross-section is small.
- A ratio plot will make it easier to see the differences.

**Preliminary**

- GENIE RFG $M_A=0.99$
- NuWro RFG $M_A=0.99$
- NuWro RFG $M_A=1.35$
- NuWro RFG $M_A=0.99+TEM$
- NuWro SF $M_A=0.99$
Rate model comparisons ($\bar{\nu}$)

- Here, we have taken a ratio to our GENIE Monte Carlo distribution, to make it easier to differentiate between models.
- Due to flux uncertainty, a shape-only fit may be still more valuable.

NEW!

### GENIE RFG $M_A=0.99$
### NuWro RFG $M_A=0.99$
### NuWro RFG $M_A=1.35$
### NuWro RFG $M_A=0.99+TEM$
### NuWro SF $M_A=0.99$
### NuWro LFG $M_A=0.99$
### NuWro LFG+RPA $M_A=0.99$
### NuWro LFG+TEM $M_A=0.99$
### NuWro LFG+RPA+Nieves $M_A=0.99$
Antineutrino: shape-only ratio (RFG)

Data appears to favor TEM, suggesting initial-state nucleon-nucleon correlations
Antineutrino: shape-only ratio (LFG)

Again, the TEM model appears promising, as does RPA. However, we must also consider correlations between bins when evaluating the models.
**χ² for fits to antineutrino data**

<table>
<thead>
<tr>
<th>Preliminary</th>
<th>Model</th>
<th>Rate χ²/d.o.f (8 degrees of freedom)</th>
<th>Shape χ²/d.o.f (7 degrees of freedom)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GENIE RFG M_A=0.99</td>
<td>2.2</td>
<td>2.44</td>
<td></td>
</tr>
<tr>
<td>NuWro RFG M_A=0.99</td>
<td>1.19</td>
<td>1.37</td>
<td></td>
</tr>
<tr>
<td>NuWro RFG M_A=1.35</td>
<td>1.98</td>
<td>1.27</td>
<td></td>
</tr>
<tr>
<td>NuWro RFG M_A=0.99 + TEM</td>
<td>0.667</td>
<td>0.447</td>
<td></td>
</tr>
<tr>
<td>NuWro SF M_A=0.99</td>
<td>1.89</td>
<td>2.61</td>
<td></td>
</tr>
<tr>
<td>NuWro LFG M_A=0.99</td>
<td>3.61</td>
<td>3.97</td>
<td></td>
</tr>
<tr>
<td>NuWro LFG + RPA M_A=0.99</td>
<td>0.771</td>
<td>0.953</td>
<td></td>
</tr>
<tr>
<td>NuWro LFG + TEM M_A=0.99</td>
<td>1.54</td>
<td>1.09</td>
<td></td>
</tr>
<tr>
<td>NuWro LFG + RPA + Nieves M_A=0.99</td>
<td>7.06</td>
<td>4.63</td>
<td></td>
</tr>
</tbody>
</table>
### $\chi^2$ for fits to antineutrino data

<table>
<thead>
<tr>
<th>Model</th>
<th>Rate $\chi^2$/d.o.f (8 degrees of freedom)</th>
<th>Shape $\chi^2$/d.o.f (7 degrees of freedom)</th>
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<tbody>
<tr>
<td>GENIE RFG $M_A=0.99$</td>
<td>2.2</td>
<td>2.44</td>
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<td>NuWro RFG $M_A=0.99$</td>
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<td>1.98</td>
<td>1.27</td>
</tr>
<tr>
<td>NuWro RFG $M_A=0.99 +$ TEM</td>
<td>0.667</td>
<td>0.447</td>
</tr>
<tr>
<td>NuWro SF $M_A=0.99$</td>
<td>2.61</td>
<td></td>
</tr>
<tr>
<td>NuWro LFG</td>
<td>3.97</td>
<td></td>
</tr>
<tr>
<td>NuWro LFG + TEM</td>
<td>0.953</td>
<td></td>
</tr>
<tr>
<td>NuWro LFG + Nieves $M_A=0.99$</td>
<td>1.09</td>
<td></td>
</tr>
<tr>
<td>NuWro LFG + RPA + Nieves $M_A=0.99$</td>
<td>7.06</td>
<td>4.63</td>
</tr>
</tbody>
</table>

While this line does not appear to be a good match to data, negative correlations between bins mean its $\chi^2$ is much lower than it would appear. This is to do with the shape of the line relative to the data, rather than its absolute value.
## $\chi^2$ for fits to antineutrino data

<table>
<thead>
<tr>
<th>Model</th>
<th>Rate $\chi^2$/d.o.f (8 degrees of freedom)</th>
<th>Shape $\chi^2$/d.o.f (7 degrees of freedom)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GENIE RFG $M_A=0.99$</td>
<td>2.2</td>
<td>2.44</td>
</tr>
<tr>
<td>NuWro RFG $M_A=0.99$</td>
<td>1.19</td>
<td>1.37</td>
</tr>
<tr>
<td>NuWro $M_A=0.99$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NuWro LFG $M_A=0.99$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NuWro $+\text{RPA} M_A=0.99$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NuWro LFG $+\text{TEM} M_A=0.99$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NuWro LFG $+\text{RPA} +\text{Nieves} M_A=0.99$</td>
<td>7.06</td>
<td>4.63</td>
</tr>
</tbody>
</table>

This higher $\chi^2$ does not tell us about either the LFG, RPA or Nieves models individually, but rather that the convolution of the three of them does not appear to be a close match to our data.
Rate model comparisons ($\nu$)

MINERvA Preliminary • $\nu$ Tracker $\rightarrow$ CCQE

- GENIE RFG $M_A=0.99$
- NuWro RFG $M_A=0.99$
- NuWro RFG $M_A=1.35$
- NuWro RFG $M_A=0.99$ + TEM
- NuWro SF $M_A=0.99$
- NuWro LFG $M_A=0.99$
- NuWro LFG+RPA $M_A=0.99$
- NuWro LFG+TEM $M_A=0.99$
- NuWro LFG+RPA+Nieves $M_A=0.99$

NEW!
Rate model comparisons ($\nu$)

Again, a **shape-only** comparison with models would avoid misleading results due to flux uncertainty.

- GENIE RFG $M_A=0.99$
- NuWro RFG $M_A=0.99$
- NuWro RFG $M_A=1.35$
- NuWro RFG $M_A=0.99+\text{TEM}$
- NuWro SF $M_A=0.99$
- NuWro LFG $M_A=0.99$
- NuWro LFG+RPA $M_A=0.99$
- NuWro LFG+TEM $M_A=0.99$
- NuWro LFG+RPA+Nieves $M_A=0.99$
Neutrino: shape-only ratio (RFG)
Neutrino: shape-only ratio (LFG)

Again, the TEM model appears promising, but the $\chi^2$ will be able to tell us about how the models compare when we take correlations into account.
**χ² for fits to neutrino data**

<table>
<thead>
<tr>
<th>Preliminary</th>
<th>Model</th>
<th>Rate χ²/d.o.f (8 degrees of freedom)</th>
<th>Shape χ²/d.o.f (7 degrees of freedom)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GENIE RFG Mₐ=0.99</td>
<td>1.86</td>
<td>2.06</td>
<td></td>
</tr>
<tr>
<td><strong>NuWro RFG Mₐ=0.99</strong></td>
<td>1.47</td>
<td>1.66</td>
<td></td>
</tr>
<tr>
<td>NuWro RFG Mₐ=1.35</td>
<td>3.38</td>
<td>1.99</td>
<td></td>
</tr>
<tr>
<td><strong>NuWro RFG Mₐ=0.99 + TEM</strong></td>
<td>2.92</td>
<td>2.26</td>
<td></td>
</tr>
<tr>
<td>NuWro SF Mₐ=0.99</td>
<td>2.64</td>
<td>3.43</td>
<td></td>
</tr>
<tr>
<td>NuWro LFG Mₐ=0.99</td>
<td>4.77</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td><strong>NuWro LFG + RPA Mₐ=0.99</strong></td>
<td>1.73</td>
<td>1.83</td>
<td></td>
</tr>
<tr>
<td>NuWro LFG + TEM Mₐ=0.99</td>
<td>3.53</td>
<td>2.75</td>
<td></td>
</tr>
<tr>
<td><strong>NuWro LFG + RPA + Nieves Mₐ=0.99</strong></td>
<td>5.49</td>
<td>4.1</td>
<td></td>
</tr>
</tbody>
</table>
### Preliminary

**χ^2 for \( \bar{\nu} \) and \( \nu \) rates, combined**

<table>
<thead>
<tr>
<th>Model</th>
<th>Combined rate ( \chi^2/d.o.f ) (16 degrees of freedom)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GENIE RFG ( M_A=0.99 )</td>
<td>2.04</td>
</tr>
<tr>
<td>NuWro RFG ( M_A=0.99 )</td>
<td>1.53</td>
</tr>
<tr>
<td>NuWro RFG ( M_A=1.35 )</td>
<td>3.14</td>
</tr>
<tr>
<td>NuWro RFG ( M_A=0.99 ) + TEM</td>
<td>1.92</td>
</tr>
<tr>
<td>NuWro SF ( M_A=0.99 )</td>
<td>2.22</td>
</tr>
<tr>
<td>NuWro LFG ( M_A=0.99 )</td>
<td>3.88</td>
</tr>
<tr>
<td>NuWro LFG ( M_A=0.99 ) + RPA</td>
<td>1.93</td>
</tr>
<tr>
<td>NuWro LFG ( M_A=0.99 ) + TEM</td>
<td>2.59</td>
</tr>
<tr>
<td>NuWro LFG ( M_A=0.99 ) + RPA + Nieves</td>
<td>5.79</td>
</tr>
</tbody>
</table>
Comments on model fits

* **Correlations** between bins can have a dramatic effect on $\chi^2$ values, and cannot be ignored when determining goodness of fit

* **Shape-only** comparisons help reduce flux uncertainty, but have much more significant bin-bin correlations

* Antineutrino mode, in particular, hints at possible nuclear effects including **nucleon-nucleon correlations**

* Our nuclear models are complex and involve the convolution of several elements (initial state momentum distributions, correlation models etc).
  
  * Our results are due to the combined effect of the elements used in each model
  
  * We do not yet have enough information to draw a conclusion about whether the specific models can reproduce our data
Energy around the vertex

- Transverse enhancement parameterizes a model with **correlated pairs** of nucleons
- If a neutrino interacts with a paired nucleon, its partner may also be ejected

Recall that we neglected an **area around the vertex** when we counted the total recoil energy

We now compare the non-track energy deposited within that region to our Monte Carlo, to look for evidence of **additional nucleons**

Our “vertex region” would contain nucleons with an energy up to 225 MeV (neutrino mode) or 120 MeV (antineutrino mode)
Vertex energy - extra protons

- A harder neutrino-mode energy spectrum is seen in data than Monte Carlo
- It is not seen in antineutrino mode
- We simulated extra protons with kinetic energies up to 225 MeV to see how this would change the Monte Carlo distribution

- Modeling an **additional proton** 25±9% of the time gave the best fit to the data
- Final state protons suggests initial state proton-neutron correlations
- This would explain why no such effect was seen for antineutrino mode; we would expect **low-energy neutrons**, to which we have low sensitivity
Summary

* MINER$\nu$A has measured differential cross-sections $d\sigma / dQ^2$ for both neutrino and antineutrino quasi-elastic scattering from scintillator.
* The data suggest a transverse enhancement model, which parameterizes nucleon-nucleon correlations, may be a good fit.
* We saw evidence of additional low-energy protons around the vertex in neutrino-mode interactions, around 25% of the time.
* This suggests proton-neutron correlations.
* We are keen to work with theorists to compare our data with models as they are developed.
* Several further studies are underway: see Carrie McGivern’s talk.

Thank you!
Backup slides
Event selection: recoil

\[ Q_{QE}^2 = 2E_{\nu}^{QE}(E_\mu - p_\mu \cos \theta_\mu) - m_\mu^2 \]

Energies in GeV; \( Q^2 \) in GeV\(^2\)

Recoil \(< 0.03 + 0.3Q_{QE}^2(Q^2 < 1.4)\)
Recoil \(< 0.45(Q^2 \geq 1.4)\)

Recoil \(< 0.05(Q^2 < 0.166)\)
Recoil \(< -0.05 + 0.64Q^2 - 0.22Q^4 \) \((0.166 \leq Q^2 < 1.61)\)
Recoil \(< 0.41(Q^2 \geq 1.61)\)

\[ \vec{\nu} \]

\[ \nu \]
We use data to estimate our backgrounds by performing a fraction fit of signal and background recoil energy distributions from our Monte Carlo, in each of 4 $Q^2$ bins.

Plots show fits for neutrinos.
We use data to estimate our backgrounds by performing a fraction fit of signal and background recoil energy distributions from our Monte Carlo, in each of 4 $Q^2$ bins.

Plots show fits for neutrinos.
MINOS-match requirement

• MINOS-match requirement limits angular acceptance
Purity

$\overline{\nu}$: 77% purity

$\nu$: 49% purity

$\nu$: 49% purity

$Q^2_{QE}$ (GeV$^2$)

Purity
Unfolding - neutrino mode

* We use four iterations of a Bayesian unfolding method

Subtract background

Unfold
Migration matrices for unfolding
Systematics (neutrino)

Hadron interaction model uncertainty is greater in neutrino mode.
- This refers to GENIE’s modeling of final-state interactions.
- Remember our signal is true CCQE as defined by primary interaction, but all we can identify in our data is QE-like.
Vertex resolution $< 5\text{mm}$
$Q^2_{\text{QE}} \text{ resolution } \sim Q^2_{\text{QE}}/4$
Angular resolution: x-z plane, $\bar{\nu}$

**Energy and Angle Ranges:**
- $E_\mu < 3$ GeV
- $3 - 5$ GeV
- $> 5$ GeV
- $\theta_{\mu,x} < 1^\circ$
- $1 - 4^\circ$
- $> 4^\circ$
Angular resolution: x-z plane, $\nu$

$E_\mu < 3\text{GeV}$, $3 - 5 \text{ GeV}$, $> 5\text{GeV}$

$\theta_{\mu,x} < 1^\circ$, $1 - 4^\circ$, $> 4^\circ$
Angular resolution: y-z plane, \( \bar{\nu} \)

- \( E_\mu < 3 \text{GeV} \),
  - 3 - 5 GeV,
  - \( > 5 \text{GeV} \)

- \( \theta_{\mu,y} < 1^\circ \),
  - 1 - 4°,
  - \( > 4^\circ \)

Note: the beam is in the y-z plane, slightly misaligned from the z axis.
Angular resolution: y-z plane, $\nu$

$E_\mu < 3 \text{GeV}$,  
$3 - 5 \text{ GeV}$, 
$> 5 \text{GeV}$

$\theta_{\mu,y} < 1^\circ$,  
$1 - 4^\circ$,  
$> 4^\circ$

Note: the beam is in the y-z plane, slightly misaligned from the z axis.
Muon energy resolution, $\bar{\nu}$

- $E_\mu < 3\,\text{GeV}$,
- $3 - 5\,\text{GeV}$,
- $> 5\,\text{GeV}$

- $\theta_\mu < 5^\circ$,
- $5 - 10^\circ$,
- $> 10^\circ$
Muon energy resolution, $\nu$

$E_\mu < 3 \text{ GeV}$,
$3 - 5 \text{ GeV}$,
$> 5 \text{ GeV}$

$\theta_\mu < 5^\circ$,
$5 - 10^\circ$,
$> 10^\circ$
### $\chi^2$ for fits to published $\bar{\nu}$ data

<table>
<thead>
<tr>
<th>NuWro model</th>
<th>RFG</th>
<th>RFG +TEM</th>
<th>RFG</th>
<th>SF</th>
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</thead>
<tbody>
<tr>
<td>$M_A$ (GeV)</td>
<td>0.99</td>
<td>0.99</td>
<td>1.35</td>
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<td>Rate $\chi^2$/d.o.f</td>
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<td>Shape $\chi^2$/d.o.f</td>
<td>2.9</td>
<td>0.66</td>
<td>1.73</td>
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</tbody>
</table>
χ² for fits to published ν data

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<tr>
<td>Shape χ²/d.o.f</td>
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<td>1.7</td>
<td>2.1</td>
<td>3.8</td>
</tr>
</tbody>
</table>
Correlation matrix - absolute

MINER vA Preliminary correlations → $\bar{\nu}$ (first 8), $\nu$ (last 8)
Correlation matrices: shape-only

- The strong positive and negative correlations between bins can lead to surprisingly low $\chi^2/NDF$ when data is compared to models that at first glance seem poor fits
- Conversely, a model that appears to be a good fit can have a poor $\chi^2/NDF$

- Red indicates positive correlation
- Blue indicates negative correlation