Neutrino and Antineutrino Charged-Current Inclusive Cross Sections & Flux Measurements in MINERvA

Jeff Nelson
Fermilab JETP Seminar, 1/8/16
A MINERvA “natural hat trick” on interrelated topics …

<table>
<thead>
<tr>
<th>Date</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec. 11</td>
<td>Phil Rodrigues</td>
<td>Identification of Multinucleon Effects in Neutrino-Carbon Interactions at MINERvA</td>
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<tr>
<td></td>
<td>U. of Rochester</td>
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<tr>
<td>Dec. 18</td>
<td>Leo Aliaga</td>
<td>Flux Results from MINERvA</td>
</tr>
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<td></td>
<td>William &amp; Mary</td>
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<tr>
<td>Dec. 25</td>
<td>No Seminar</td>
<td>Happy Holidays!</td>
</tr>
<tr>
<td>Jan 1</td>
<td></td>
<td>Happy New Year!</td>
</tr>
<tr>
<td>Jan 8</td>
<td>Jeff Nelson</td>
<td>Neutrino and Antineutrino Charged Current Inclusive Cross Sections and Flux Measurements in MINERvA</td>
</tr>
<tr>
<td></td>
<td>William &amp; Mary</td>
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</tbody>
</table>

BONUS:
“Measurement of Neutrino Flux from Neutrino-Electron Elastic Scattering”
[arXiv:1512.07699]
Outline

• Introduction
  > Neutrino interactions
  > Status of charged-current inclusive scattering
  > The low-ν method

• The analysis
  > MINERvA/NuMI
  > Analysis design
  > Systematic uncertainties

• Results
  > Fluxes and comparisons
  > Cross sections and comparisons
Goals of the long-baseline program

• Targets
  > Quadrant of $\theta_{23}$ (most uncertain of the angles)
  > Hierarchy of neutrino mass spectrum
  > CP violation in the neutrino sector

• Later two driven by electron appearance measurements at long baselines at few–GeV energies
  > Comparisons of neutrino/antineutrino appearance
  > Understanding background systematic uncertainties
  > Oscillation parameters (esp. the quadrant) have significant impact on parameter measurements

• Pushes most systematics to regimes we’ve never achieved!
  > Flux, interactions, energy scales, background, near/far extrapolation…
  > e.g. Both NOvA and T2K report 11% syst on their sample backgrounds
State of scattering (ca. 2016)

- Final SPS and TeVatron results
  > Many GeV to hundreds of GeV
- Final results from MINOS
  > Down into the few GeV region
- Final results from MiniBooNE, K2K, and SciBooNE
  > All these are for $E < \sim 1$ GeV
  > Dearth of antineutrino data starting to be addressed
- MINERvA, ArgoNeut, T2K results rolling in
  > Dozens of papers
  > Starting to get the right nuclei
  > Can’t fit it all on one plot anymore… a good thing!!!
Neutrino event generators

- Neutrino experiments have are few *in situ* physics handles
  - MIP/muon, muon decay (Michel) electrons, neutral pions
  - Only know the incoming neutrino direction accurately
- We rely heavily on full simulations of neutrino interactions to understand:
  - Signal selection
  - Background rejection
  - Energy reconstruction
  - Near/far extrapolation
- In the US program we most often use **GENIE**
  - C. Andreopoulos et al, NIM A, 614, 87 (2010)
  - We will use version v2r6p2 as the reference today
- Many other generators exist
  - Some with fully specified final states
  - Some only with computed physics distributions
- Central values for the generators are fits to scattering data
Our generators (models) do not accurately reflect recent exclusive cross section data

Adapted from PRD 81, 092005 (2010) by P. Rodrigues

These examples are all charge pion production

Adapted from PRD 83, 052007 (2011) by P. Rodrigues
We now, however, know a lot more about what works well and what doesn’t

- QE–like and nuclear effects analyses favor a 2p2h process and RPA–type nuclear effects
- Pion data shows reasonable agreement on the strength of effects of intranuclear rescattering
The role of inclusive scattering

- Generators require data to tune their models
  > They/We need more/better data!
- The current and future long-baseline neutrino program focuses on the few GeV region
- This region offers a particularly interesting mix of processes “it’s complicated”
- In that context, one particularly useful constraint for tuning is the inclusive (total) charged-current scattering cross section

![Graph showing GENIE's predicted composition in NuMI LE flux]
World inclusive cross section measurements for neutrinos & antineutrinos

\[ \frac{\sigma_{CC}}{E_{\nu}} \times 10^{-38} \text{ cm}^2 / \text{GeV} \]

Note: \( \sigma/E \) approaches a well-determined asymptotic value at high energies

PDG 2016 Preview!

Thanks Sam!

She says this is the first unveiling!
Neutrino flux measurement
Neutrino flux critical for any absolute cross section measurement

\[
\sigma(E) = \frac{U(D - B)}{\epsilon \Phi T \times \Delta E}
\]

- D is data event yield
- B is background estimate
- \(U(\ )\) unfolding operation
- \(\Phi\) is flux (AKA the hardest part)
- \(\epsilon\) is efficiency/acceptance correction
- \(\Delta E\) is the bin width
- T is number of targets
How to know your neutrino flux?

- **Ex situ via Hadron production data**
  - External thin & thick target hadron production data can be used to modify off-the-shelf simulation packages
  - Subject of previous JETP by Leo Aliaga (more later)

- **Measuring muon spectra at the end of the decay volume**
  - Get a muon for each muon neutrino so sampling the muon rate at various ranges allows evaluation of flux
  - NuMI has three thresholds for its muon counters (not very finely grained)

- **Can also use standard-candle cross sections**
  - Neutrino-electron scattering (more later)
  - Low recoil event rates: subject of the seminar
The principle of the low-$\nu$ method

- $\nu$ is the energy transferred to the recoil system

  \[ \nu = E - E_\mu \]

- In the limit of small $\nu$, the charged-current cross section for neutrinos and antineutrinos is approximately constant as a function of neutrino energy (will show this shortly)
  > That this is constant is needs to be true because we know that cross sections can be expressed by a set of structure functions

- A measurement of the low-$\nu$ interaction rate as a function of neutrino energy is equivalent to a measurement of the shape of the neutrino flux as a function of energy
The cross section for charged-current inclusive neutrino–nucleon scattering ...

\[
\frac{d^2\sigma}{dx dy} = \frac{G_F^2 ME}{\pi} \left( \left[ 1 - y \left( 1 + \frac{Mx}{2E} \right) + \frac{y^2}{2} \left( 1 + \frac{(2Mx/Q)^2}{1 + R_L} \right) \right] F_2 \pm \left[ y - \frac{y^2}{2} \right] x F_3 \right)
\]

- Where the “+” is for neutrino scattering; “−” is for antineutrino
- \(E\) is the neutrino energy, \(M\) is the mass of the nucleon, \(x\) (scaling variable) and \(y\) (inelasticity) are given by

\[
y = \frac{\nu}{E} \quad x = \frac{Q^2}{2M\nu}
\]

- The internal structure of the nucleon is described by structure functions \(F_2(x,Q^2)\), \(xF_3(x,Q^2)\), and \(R_L(x,Q^2)\).
- \(R_L\) is the ratio of the cross section for scattering from longitudinally polarized \(W\) bosons to transversely polarized and is defined in terms of \(F_1\) and \(F_2\)

\[
R_L(x, Q^2) = \frac{F_2(x, Q^2)(1 + 4M^2x^2/Q^2) - 2xF_1(x, Q^2)}{2xF_1(x, Q^2)}
\]
Then some algebra happens...

- Substitute $y = \nu/E$ and $Q^2 = 2Mvx$, group terms into $\nu/E$, and integrate over $x$

\[
\frac{d\sigma}{d\nu} = \frac{G_F^2 M}{\pi} \left( \int_0^1 F_2 \, dx - \frac{\nu}{E} \int_0^1 [F_2 \mp xF_3] \, dx \right.
\]

\[
+ \frac{\nu}{2E^2} \int_0^1 \left[ \frac{Mx(1 - R_L)}{1 + R_L} F_2 \right] \, dx + \frac{\nu^2}{2E^2} \int_0^1 \left[ \frac{F_2}{1 + R_L} \mp xF_3 \right] \, dx \right)
\]

- Integrating this to low $\nu$ (i.e. $\nu_0 << E$) causes the terms proportion $\nu/E$, $\nu/E^2$ and $\nu^2/E^2$ to be vanishingly small
- Therefore $\sigma(\nu<\nu_0,E)$ is approximately constant
- It deviates modestly due to $Q^2$ dependence of the structure functions (Bjorken scaling violation)
Game plan...

- The charged–current cross section for events with low hadronic recoil (ν) is nearly energy independent
  > The low–ν cross section is a (nearly) standard–candle process!
- Due to the energy independence, the interaction rate is proportional to the flux:

\[
N(\nu < \nu_0, E) = \Phi(E) \times \sigma(\nu < \nu_0, E) \propto \Phi(E)
\]

- Use the extracted event rates to measure the neutrino and antineutrino fluxes
- Then extract inclusive scattering cross sections using those fluxes
This picture isn’t quite so simple

• Can’t cut at exactly $\nu=0$
• So you have to put in corrections from other structure functions

$$S(\nu_0, E) = \frac{\sigma(\nu < \nu_0, E)}{\sigma(\nu < \nu_0, E \to \infty)}$$

• For this analysis, these are calculated using the GENIE model
• You have to normalize the flux somewhere
  • Can use precision external measurements as an anchor
  • Can use GENIE (which itself is based on data)
Some recent examples of the low-$\nu$ technique in action

- **NuTeV (and CCFR before them)**
  > They examined neutrino energies from 30 to 360 GeV and used a 5 – 20 GeV low-$\nu$ cut so all their “flux sample” events firmly in the DIS regime
  > These energies mean the recoil systems have fairly high multiplicity and fairly linear calorimetric responses with Gaussian resolutions

- **MINOS**
  > They examined neutrinos (antineutrinos) energies from 3(5) to 50 GeV and used low-$\nu$ cuts as low as 1 GeV
  > The lowest energy application of the technique to date
But isn’t your low-\(\nu\) cross section is part of you the CC cross section you wish to measure?!?

- **Successful history of the method in CCFR, NuTeV, MINOS**
- **Seems like a circular argument ...**
  - Your standard candle is also part of the inclusive sample (at the tens of percent level in MINOS)
  - One must use the simulation and external normalization to correct for this part of the sample
- **Leads to a balancing act...**
  - Try to keep the fraction of low-\(\nu\) events small by decreasing the \(\nu\) cut
  - Try to keep the statistical uncertainty of the flux low by increasing the \(\nu\) cut
  - Try to keep away from the lowest energy recoils where the uncertainties in the models “blows up”
Why use Low-$\nu$ in MINERvA?

- **MINERvA**
  - It is a fine-grained detector with better hadron energy resolution
  - Ran in both neutrino and antineutrino enhanced sample
  - Extend down to neutrinos energies as low as 2 GeV

- **To go this low in energy ...**
  - Need to extend the low-$\nu$ limit to as low as 300 MeV
  - Recoil systems with single particle final states are a significant probability so we get non-Gaussian response that depends on details of initial state
  - Pushes into areas that were fully murky in 2009

- **How to address?**
  - We evaluate the uncertainties in this method based on the data/mc discrepancies that we do see in these other channels and using new models for the effects people think we’re seeing.
  - New results and theoretical progress give us better, model-motivated systematic uncertainties (both nuclear effects and process models)
  - New generators (like GENIE) have better tools to do more complete analysis of theoretical uncertainties
  - Study of using low-$\nu$ method in MINERvA was performed
At the 12/11 MINERvA JETP seminar...

- A theory based description of unmolded effects in GENIE (Valencia model) that improves agreement at the lowest emerges (top)
- Neutrino cross sections (bottom) in bins of momentum transfer as a function of recoil energy ($\nu$)
  > Shows us where the issues are lurking
- From earlier in the year we also saw that the modern final-state interaction (FSI) model in GENIE works better too

See arXiv:1511.05944 & Carrie McGivern’s 6/26/15 for pion based tests of FSI models
The MINERvA neutrino–nucleus scattering experiment
The MINERvA Collaboration
- Finely segmented solid scintillator (CH) detector on axis in NuMI
  - Active tracker is all scintillator
  - Calorimeters are scintillator w/ Fe or Pb
- MINOS detector for muon spectrometer
- Test beam program for energy scale/detector model
NuMI Neutrino Beam

\[
p + C \rightarrow \pi \rightarrow \mu + \nu_{\mu}
\]

- 120 GeV protons impinge on a 2 interaction length graphite target
- Mesons produced in the target are focused by two magnetic horns
- The beam composition is selected by the polarity of the current in the horns
  - Forward Horn Current (FHC) focuses \( \pi^+ \) creating a neutrino-enhanced beam
  - Reverse Horn Current (RHC) focuses \( \pi^- \) creating an antineutrino-enhanced beam
- Can also change the target–horn configuration (and horn current) to focus different energy pions & change the neutrino energy spectrum

Image courtesy of Z. Pavlovic
The data set

- NuMI low–energy tune (LE) data collected from 2010–2012
- RHC $1.09 \times 10^{20}$ POT
- FHC $3.18 \times 10^{20}$ POT
- Since then we have been collecting data in NuMI’s medium energy (ME) tune
MINERvA analysis chain
A MINERvA event

In this plot the color reflects the energy recorded in the strip
Muon reconstruction

- For this analysis we require that the muon track be matched to a track in MINOS
  - Imposes a roughly 1.5 GeV threshold to punch through the MINERvA calorimeters and be above the MINOS tracking threshold
  - Limits the maximum muon angle to be within roughly 20° of the beam direction
- MINOS returns momentum based on either range or curvature and charge based on curvature
- Systematic uncertainties in MINOS muons
  - 2% uncertainty on muon momentum from range due to mass model and dE/dx model in MINOS
  - 0.6% (2.5%) uncertainty on muon momentum from curvature for momentum below (above) 1.5GeV
    - Based on comparing magnetic field maps to magnetic induction measurements
    - Based on comparisons between range and curvature for tracks stopping
    - Added in quadrature to range uncertainty
Calorimetry

Energy not on the muon road (or on the road and too energetic to be a muon) within a timing window in the tracker/downstream ECAL/ downstream HCAL
Low energy calorimetric response constrained by test beam experiment

- This analysis uses a preliminary MC to the test beam response
  - 10% proton uncertainty
  - 5% pion uncertainty
  - 3% for electron–magnetic response (also tested using Michel electrons and the neutral pion peak)
  - n.b. errors are 3%/5%/3% with tuning

- Other particle responses were validated by comparing GEANT to external inelastic scattering data
  - Sample samples also used to validate GENIE final-state interaction model
  - 15% neutron response uncertainty
  - Higher energy inelastic pion/proton data

NIM A 789, 28 (2015)
Average energy carried by particle type in the CC inclusive recoil system (MINERvA flux/GENIE)

Deficit at low energy is due to FSI, binding energy, and excitation of the nucleus

From simulation
Fractional recoil system energy resolution (neutrino CC inclusive)

\[ \frac{\sigma}{\nu} = 0.132 + \frac{0.329}{\sqrt{\nu}} \]

\[ \frac{\sigma}{\bar{\nu}} = 0.163 + \frac{0.283}{\sqrt{\nu}} \]

From simulation
Uncertainty on calorimetric reconstruction of the recoil system

From simulation

Systematic error on recoil energy vs. True recoil energy, $E$ (GeV)

PRELIMINARY
The analysis
Low-$\nu$ method for flux determination

The absolute normalization of the flux is set such that the extracted cross section matches a target value at high neutrino energy.

\[ \Phi(E) = \eta \frac{U(D_\nu - B_\nu)}{\epsilon \sigma_\nu T \times \Delta E} \]
Many $\nu$'s

Three $\nu$ cuts are used: 300 MeV, 800 MeV and 2 GeV.
“Overlap” is the fraction of the inclusive data sample with $\nu$ less than the cut.
Event yields (inclusive)

\[ \sigma(E) = \frac{U(D - B)}{\epsilon \Phi T \times \Delta E} \]

\[ \Phi(E) = \eta \frac{U(D_{\nu} - B_{\nu})}{\epsilon \sigma_{\nu} T \times \Delta E} \]
Event yields (lowest of the 3 low $\nu$ cuts)

$\nu_\mu$ in FHC, $\nu < 0.3$ GeV

$\bar{\nu}_\mu$ in RHC, $\nu < 0.3$ GeV

$$\sigma(E) = \frac{U(D - B)}{\epsilon \Phi T \times \Delta E}$$

$$\Phi(E) = \eta \frac{U(D_\nu - B_\nu)}{\epsilon \sigma_\nu T \times \Delta E}$$
Unfolding

Unfolding removes the effects of detector resolution on a distribution using a simulated model of detector response.

\[
\sigma(E) = \frac{U(D - B)}{\epsilon \Phi T \times \Delta E}
\]

\[
\Phi(E) = \eta \frac{U(D_\nu - B_\nu)}{\epsilon \sigma_\nu T \times \Delta E}
\]
Unfolding

\[ \sigma(E) = \frac{U(D - B)}{\epsilon \Phi T \times \Delta E} \]

\[ \Phi(E) = \eta \frac{U(D_{\nu} - B_{\nu})}{\epsilon \sigma_{\nu} T \times \Delta E} \]
Acceptance correction

The acceptance correction accounts for the acceptance of muons into MINOS, which requires a forward trajectory and at least 1.5 GeV energy.

\[ \sigma(E) = \frac{U(D - B)}{\epsilon \Phi T \times \Delta E} \quad \Phi(E) = \eta \frac{U(D_\nu - B_\nu)}{\epsilon \sigma_\nu T \times \Delta E} \]
Acceptance correction

\[ \sigma(E) = \frac{U(D - B)}{\epsilon \Phi T \times \Delta E} \]

\[ \Phi(E) = \frac{U(D_\nu - B_\nu)}{\epsilon \sigma_\nu T \times \Delta E} \]
Low-$\nu$ correction

$\nu_\mu$ in FHC

\[ \sigma(E) = \frac{U(D - B)}{\epsilon \Phi T \times \Delta E} \]

$\bar{\nu}_\mu$ in RHC

\[ \Phi(E) = \eta \frac{U(D_\nu - B_\nu)}{\epsilon \sigma_\nu T \times \Delta E} \]
Normalization technique

Normalize fitting lower-cut sample to the upper-cut sample up to 22 GeV

Merge the higher-cut sample with the new normalized points

Fit error is a uncertainty on the lower-cut samples

This is a shape measurement: The flux is normalized such that the extracted inclusive cross section matches an external target value at high neutrino energy

\[ \Phi(E) = \frac{U(D_\nu - B_\nu)}{\epsilon \sigma \tau \times \Delta E} \]
Systematic uncertainties
Systematic uncertainties

- **Flux**
  - Hadron production, focusing
    - Largely unimportant since, in this analysis, we derive our own flux based on the low-$\nu$ sample
  - Will address this assertion in a bit

- **Detector**
  - Muon energy scale
  - Hadronic energy scale
  - Saturation and cross talk
  - Efficiency/normalization

- **Interaction model**
  - GENIE gives a recommended set of parameter variations for systematic uncertainties
    - c.f. GENIE Collaboration, arXiv:1510.05494
  - In light of the “nuclear effects” analysis we have updated these for the low-recoil region
  - More on this in a bit...

- Will show breakdowns of these uncertainties with results
Low recoil reconstruction – validation

- Off-track “muon fuzz” on rock muons
  - Knock-on electrons and brems can feed into the recoil
  - Tests accidental and cross talk models too
  - We find our GEANT model doesn’t produce muon fuzz often enough

- Add in fuzz from real rock muons to MC to make the spectrum agree with data
  - Take 50% of the correction as an uncertainty
Standard GENIE parameter “knobs”
(Not really meant to be read!)

<table>
<thead>
<tr>
<th>Description</th>
<th>±1σ Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged-current quasi-elastic (CCQE) axial mass, $M_{A^{CCQE}}$</td>
<td>-15% $\pm$ 25%</td>
</tr>
<tr>
<td>CCQE electromagnetic form factor</td>
<td>BBBA2005 (default) or dipole</td>
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<tr>
<td>Charged-current resonance axial mass, $M_{A^{CRCRES}}$</td>
<td>±20%</td>
</tr>
<tr>
<td>Charged-current resonance vector mass, $M_{V^{CRCRES}}$</td>
<td>±20%</td>
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<tr>
<td>Non-resonance 1π production in $\nu p$ interactions</td>
<td>±50%</td>
</tr>
<tr>
<td>Non-resonance 1π production in $\nu n$ interactions</td>
<td>±50%</td>
</tr>
<tr>
<td>Non-resonance 2π production in $\nu p$ interactions</td>
<td>±50%</td>
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<tr>
<td>Non-resonance 2π production in $\nu n$ interactions</td>
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<tr>
<td>Intrannuclear absorption probability for nucleons</td>
<td>±20%</td>
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<tr>
<td>Intrannuclear absorption probability for pions</td>
<td>±20%</td>
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<tr>
<td>Intrannuclear charge exchange probability for nucleons</td>
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<tr>
<td>Intrannuclear charge exchange probability for pions</td>
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<td>Intrannuclear elastic scattering probability for nucleons</td>
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<td>Intrannuclear inelastic scattering probability for pions</td>
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<td>Intrannuclear π-production probability for nucleons</td>
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<tr>
<td>Intrannuclear π-production probability for pions</td>
<td>±20%</td>
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<tr>
<td>Intrannuclear mean free path for nucleons</td>
<td>±20%</td>
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<tr>
<td>Intrannuclear mean free path for pions</td>
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<tr>
<td>Feynman $x_\pi$ distribution in 1π states in AGKY model</td>
<td>±20%</td>
</tr>
<tr>
<td>$\pi$ angular distribution in $\Delta \rightarrow \pi N$</td>
<td>isotropic (default) or Rein-Sehgal</td>
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<tr>
<td>Radiative decay branching ratio, $\Delta \rightarrow \gamma X$</td>
<td>±50%</td>
</tr>
<tr>
<td>Random phase approximation model</td>
<td>off (default) or on</td>
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<tr>
<td>Random phase approximation and meson exchange currents model</td>
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<tr>
<td>Effective nuclear radius for intrannuclear interactions</td>
<td>±0.6 fm</td>
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<tr>
<td>Formation zone time (when a quark is free in the nucleus)</td>
<td>±50%</td>
</tr>
<tr>
<td>Hadronization model with more isotropic final states</td>
<td>off (default) or on</td>
</tr>
</tbody>
</table>

arXiv:1510.05494
Model–based estimate of the uncertainties in QE–like events

- In normal analyses we use a large (GENIE recommended) $M_A$ (axial mass) uncertainty as an effective uncertainty to encompass uncertainties in QE–like processes
- For this analysis we implemented a different systematic uncertainty on QE–like events based on the modified version of GENIE used in our nuclear effects analysis
  > Sets of weights to account for RPA and MEC effects in QE events based in the Valencia model
- Use difference between standard GENIE and the “Valencia” GENIE as the uncertainty due to unmodeled QE–like effects
  > Ran the analysis both ways and used the difference as an uncertainty
  > It is not implemented as a central–value weight for this analysis (use standard GENIE)
- Residual uncertainty on $M_A$ is based on NOMAD and bubble chamber data (3%)
Examples of QE–like uncertainty vs the rest of the uncertainties

Selected data events (black squares stat errors)
Simulation from standard GENIE (pink/squares)
Valencia–weighted GENIE (blue)
Uncertainty implemented as: red–blue

Also shown: Acceptance corrected data and true GENIE (green/triangles)

We have these plots for each point in the analysis (see Josh’s thesis)
the two points that go beyond the envelop are the worst in any distribution
Flux results
Extracted neutrino flux by subsample (there ARE points under the pink and blue)

Normalization WRT GENIE (at 9–12 GeV bin)

<1 means data favors a lower low-$\nu$ cross section than modeled in GENIE

Statistical uncertainties in table

<table>
<thead>
<tr>
<th>$\nu$ cut</th>
<th>FHC $\nu_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu &lt; 2$ GeV</td>
<td>0.925 ± 0.009</td>
</tr>
<tr>
<td>$\nu &lt; 800$ MeV</td>
<td>0.958 ± 0.009</td>
</tr>
<tr>
<td>$\nu &lt; 300$ MeV</td>
<td>0.946 ± 0.012</td>
</tr>
</tbody>
</table>
NuMI on-axis neutrino flux from the low-ν method (merged)
Extracted antineutrino flux by subsample

\[ \bar{\nu}_\mu \text{ in RHC} \]

Normalization WRT GENIE (at 9–12 GeV bin)

<1 means data favors a lower low-\(\nu\) cross section than modeled in GENIE

Statistical uncertainties in table

<table>
<thead>
<tr>
<th>(\nu) cut</th>
<th>RHC (\bar{\nu}_\mu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu &lt; 2,\text{GeV})</td>
<td>0.943 (\pm 0.021)</td>
</tr>
<tr>
<td>(\nu &lt; 800,\text{MeV})</td>
<td>1.085 (\pm 0.019)</td>
</tr>
<tr>
<td>(\nu &lt; 300,\text{MeV})</td>
<td>1.200 (\pm 0.020)</td>
</tr>
</tbody>
</table>
NuMI on-axis antineutrino flux from the low-$\nu$ method (merged)
Fluxes of neutrinos from defocused pions

\( \bar{\nu}_\mu \) in FHC

\( \nu_\mu \) in RHC

\( \bar{\nu}_\mu \) in FHC

\( \nu_\mu \) in RHC

MINERvA Preliminary

fractional uncertainty

neutrino energy (GeV)

neutrino energy (GeV)

MINERvA

Total

Statistical

MCStatistical

GENIE

Flux

RecoilReconstruction

MuonReconstruction

CrossNormalization

MassModel

Normalization

MINERvA Low \( \nu \), Nelson/W&M
Comparisons between low-$\nu$ fluxes and other MINERvA flux constraints
**MINERvA a priori flux estimation**

- Leo provided a comprehensive JETP seminar (12/18/15) on the MINERvA flux
- Central value is based on *ex situ* data
  - Using GEANT4 simulations
  - Corrected using external hadron production data
  - Errors based on experimental data
- Errors due to the beam line geometry evaluated using beam simulations and assumed survey/geometry errors
The MINERvA flux program has been a multi-year effort (some history)

MINERvA physics program produced physics results based on 2 prior snapshots of the flux and the newly-unveiled flux

GEN0
  > Used for our 2013 quasi-elastic scattering papers

GEN1
  > This flux was used for most MINERvA analyses
  > This is the central-value flux used on the slides in this seminar

GEN2
  > Subject of Leo’s dissertation and seminar
  > Completed this Fall
  > Used for the recent nuclear-effects analysis
  > Two versions a version using only thick-target data (GEN2thick) and one also using thick-target data (GEN2thin)
  > We’ll compare this flux to the low-ν flux results
Low-$\nu$ flux and GEN2 (thin target) neutrino comparison

FHC neutrinos

L. Aliaga, 12/18/15 FNAL JETP seminar
Low-$\nu$ flux and GEN2 (thick target) neutrino flux comparison

FHC neutrinos

L. Aliaga, 12/18/15 FNAL JETP seminar
Low-$\nu$ flux and GEN2 (thin-target) antineutrino flux comparison

RHC antineutrinos

L. Aliaga, 12/18/15 FNAL JETP seminar
Low-$\nu$ flux and GEN2 (thick target) antineutrino flux comparison

RHC antineutrinos

L. Aliaga, 12/18/15 FNAL JETP seminar
Results of flux comparisons

- Full covariance comparison (2–22 GeV)
  - Both are systematics limited for these focused samples
  - The uncertainties on these two fluxes are uncorrelated

<table>
<thead>
<tr>
<th></th>
<th>Low-$\nu$ vs GEN2 (thin)</th>
<th>Low-$\nu$ vs GEN2 (thick)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2 / \text{DoF}$</td>
<td>4.8/10</td>
<td>18.6/10</td>
</tr>
</tbody>
</table>

- Low-$\nu$ flux is more compatible with the flux derived from thin-target hadron production data than that obtained from replica target (thick-target data)
  - Thin-target data method is also directly applicable for other target geometries
  - Thick-target data is, in general, more precise
  - Hence, the US–NA61 program for NuMI/LBNE
Signal is a single electron moving in beam direction
- Purely electro-weak process
- Cross section is smaller than nucleus scattering by ~2000
- 123 ±17(stat) ±9(syst) events

Independent *in situ* flux constraint
- Important proof of principle for future experiments
- Statistically limited in the MINERvA LE sample (~8% error)
- Results are consistent with new flux calculations
- Results are consistent with the *a priori* GEN2 (THIN) flux (~2%) and with the low ν flux

Further confidence in flux!
- Three independent methods yield consistent results
Cross section results
Neutrino cross section by low-$\nu$ cut (plot is before data-to-data cross normalization)

Data plotted with stat+syst errors

GENIE normalized

$\sigma/E$ ($10^{-38}$ cm$^2$ / GeV / nucleon)

$\nu_\mu$ in FHC

neutrino energy (GeV)

$\nu < 0.3$ GeV
$\nu < 0.8$ GeV
$\nu < 2.0$ GeV

MINERvA Preliminary
Antineutrino cross section by low-$\nu$ cut (plot is before data-to-data cross normalization)

Data plotted with stat+syst errors

MINERvA Preliminary

GENIE normalized
Neutrino cross section – Normalized and merged

\( \nu_\mu \text{ in FHC} \)

\[ \frac{\sigma}{E} \left( 10^{-38} \text{ cm}^2 / \text{ GeV} / \text{ nucleon} \right) \]

- Data plotted with stat+syst errors
- GENIE normalized

MINERvA Preliminary

1/8/16

MINERvA Low \( \nu \), Nelson/W&M
Antineutrino cross section – Normalized and merged

Data plotted with stat+syst errors

MINERvA Low ν, Nelson/W&M
NOMAD–normalized inclusive neutrino cross section

- NOMAD 9–12 GeV bin has 3.7% uncertainty
- GENIE systematic uncertainty in that bin is 6.5%
- NOMAD data point is 3.0% higher than the GENIE model
A data-driven normalization for the antineutrino cross section?

- Unfortunately there are no sufficiently precise external measurements (like NOMAD) in small enough bins in our normalization region
- Stick with GENIE value in the 9 – 12 GeV bin (superimposed as orange dot)
  > GENIE’s systematic uncertainty is 10.6%
  > Normalization drives the errors
- Forthcoming analysis on neutrino/antineutrino cross section ratio will refine antineutrino normalization
Cross checks

- Show that the extracted flux is not significantly dependent on the assumed initial flux
  > Also can think of this as a closure test
  > Use the extracted flux as the central value flux on MC and redo the entire low-$\nu$ analysis again

  ✓ Point-by-point the fluxes all agree to <1% level

- Redo the entire analysis and extract cross sections from “defocused” samples and compare
  > RHC neutrinos and FHC antineutrinos
  > Defocused pions in the beam so much different phase space for hadron production (and beam optics) hence much different fluxes
  > MINOS magnetic field defocuses muons in these samples so most much different acceptances
  > These are a small minority of the beam, so they are a stringent test of the backgrounds subtraction
  > Tests unfolding with radically different energy spectra
It doesn’t matter if the pions were focused or defocused, the measured cross sections are consistent!

Data with statistical uncertainties only
Comparison to world data
Comparison to world data
(the Big Picture)

A. Schukraft, G. Zeller

Thank you for this personalized plot!
MINERvA results from select low-energy world data

\[ \nu_\mu \text{ in FHC} \]

\[ \bar{\nu}_\mu \text{ in RHC} \]

All points are isoscalar corrected

Simulation is GENIE
Summary

- Using the low-ν method, we extracted NuMI low-energy tune neutrino fluxes for muon neutrinos and antineutrinos or both focused and defocused samples
  > 1st time this has been done for NuMI fluxes in the antineutrino-enhanced (RHC) beam
  > Lowest energy application of this technique
  > Lower than prior studies due to MINERvA’s better resolution resolution
  > These fluxes are consistent with the new MINERvA “GEN2” a priori fluxes & with our neutrino–electron scattering data
  > These low-ν results helped to: validate the flux, pick the flux to use as our central value, and to validate revised horn conductor model

- Using the low-ν fluxes we extracted muon neutrino and antineutrino inclusive CC cross sections
  > Extends inclusive data to lower energies (esp. antineutrinos)
  > A forthcoming analysis will also measure the neutrino–antineutrino cross-section ratio with lower uncertainties