MINER$\nu$A Cross Section Results

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for the MINER$\nu$A Collaboration

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Physics Goals

Study neutrino-nucleus scattering at the few-GeV region

- Precision measurements on signal and background processes relevant to oscillation experiments
- Study nuclear effects to improve understanding of neutrino-nucleus cross section and modelling
- Demonstrate experimental techniques that benefit current and future oscillation experiments
Rich Physics
Richer than Expected!

Final State Interactions, Multinucleon effects, Coherent ...
Nuclear Effects Affect Oscillation

2-particle-2-hole (2p2h)

Inside nucleus:

- Initial states and nuclear potentials
- Final state interactions, i.e.
  - Pion production
  - Pion absorption
- Multi-nucleon correlation, i.e. 2p2h
Neutrino kinematics are reconstructed from the energy-depositing final states in the detectors. Calorimetric reconstructions can go wrong:

- Pion absorption mimics QE, pion production mimics RES
  - $E_\nu$ reconstructed from the respective hypotheses will be biased, and also inflate systematics
- Many pionless events involve multiple nucleons in the final states,
  - Significant energy and momentum are lost to the extra outgoing nucleon. Invisible to T2K and MINIBooNE and neutron challenging for NOνA.

In either cases, the neutrino/anti-neutrino energy reconstruction will have bias and larger systematic uncertainties
MINER$\nu$A aids in developing more accurate nuclear models with precision measurements and new techniques that disentangle the nuclear mess.
MINERνA Timeline

2007  Begin construction
2009  Begin Low Energy (LE) data run
2012  End LE data run
       first publication
2013  Begin Medium Energy (ME) data run
2019  End ME data run
       33 published papers to date
       more in the pipeline

Data taking is over, but our analyses are not!

Measurement of Muon Neutrino Quasi-Elastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5$ GeV
Updated to reflect constrained flux

Tejin Cai (University of Rochester)
What is MINERνA?  Detector Description

MINERνA is on-axis in the Fermilab’s NuMI beam.

LE flux overlaps with DUNE’s.

ME has higher statistics and access to expanded kinematics region.

- LE $\nu$ POT: $4.0 \times 10^{20}$
- LE $\bar{\nu}$ POT: $1.7 \times 10^{20}$
- ME $\nu$ POT: $12.1 \times 10^{20}$
- ME $\bar{\nu}$ POT: $12.4 \times 10^{20}$

we are here!
High Resolution Scintillator (CH) Detector

CH in tracker
Pb, Fe, C and water in target region
3.1 mm tracking resolution
What is MINERνA? Detector Description

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Sensitivities to Many Final States

- MINERνA’s plastic scintillators are sensitive to small energy deposits.
- Hadronic recoils are measured from calorimetry.
- Tracking threshold (KE) for proton is $\sim 100$ MeV.
- Neutrons can deposit visible energies (albeit small) after recoil inside scintillator.

Figure courtesy of P. Rodrigues
Constraining flux
Flux Normalization: $\nu - e$ Scattering

- MINER$\nu$A pioneered the method
- $\nu - e$ is standard electroweak process with precisely predicted cross section
- 2000x more rare than $\nu - A$ interactions

- Neutral current processes
  $\nu e \rightarrow \nu e$
  $\bar{\nu} e \rightarrow \bar{\nu} e$

- At $m_e \ll E_\nu$, electrons are very forward going

- The total number of $\nu - e$ events provides strong constraint on the flux normalization

![Tracker Region Diagram](image)
Results with NuMI Low Energy Beam

Flux

We’ve performed the first in-situ flux normalization measurements in the few-GeV region.

Phys. Rev. D 93, 112007 (2016)

Paper plot has been updated to reflect our best understanding of the flux.
New Results with NuMI Medium Energy Beam

Reduce normalization uncertainty on integrated NuMI $\nu_\mu$ flux from 7.5% to 3.9%. 8x statistics demonstrates $\nu - e$ analysis is viable for future oscillation experiments such as DUNE.
Flux Shape: the Low-$\nu$ Method for $\nu \ll E_\nu$

$$\frac{d\sigma}{d\nu} = \frac{G_F^2 M}{\pi} \int_0^1 \left( F_2 - \frac{\nu}{E_\nu} \left[ F_2 \mp xF_3 \right] + \frac{\nu}{2E_\nu^2} \left[ \frac{Mx(1 - R_L)}{1 + R_L} F_2 \right] + \frac{\nu^2}{2E_\nu^2} \left[ \frac{F_2}{1 + R_L} \mp xF_3 \right] \right) dx \simeq \text{const}$$

and we can derive the flux for $\nu < \nu_0$:

$$\Phi_\nu = \eta_\nu \frac{U_\nu(D_\nu - B_\nu)}{\epsilon_\nu \sigma_\nu^{\text{GENIE}} \#\text{target} \times \Delta E}$$

$\nu_0 = 0.3, 0.8, 2.0$ GeV
$\epsilon_\nu$: Acceptance correction
$\Delta E$: Energy bin width

$U_\nu(D_\nu - B_\nu)$: Unfolded event rates after background subtraction
Flux Shape: the Low-$\nu$ Method for $\nu \ll E_\nu$

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$\sigma_\nu^\text{GENIE}$: $\sigma(\nu < \nu_0, E_\nu)$ from GENIE
Flux Shape: the Low-$\nu$ Method for $\nu \ll E_\nu$

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$\Delta E$: Energy bin width

$\eta_\nu$: Normalization to $9 < E_\nu < 12$ GeV

NOMAD data
Flux Shape: the Low-$\nu$ Method for $\nu \ll E_\nu$

\[
\frac{d\sigma}{d\nu} = \frac{G_F^2 M}{\pi} \int_0^1 \left( F_2 - \frac{\nu}{E_\nu} \left[ F_2 \mp xF_3 \right] + \frac{\nu^2}{2E_\nu^2} \left[ \frac{Mx(1 - R_L)}{1 + R_L} F_2 \right] + \frac{\nu^2}{2E_\nu^2} \left[ \frac{F_2}{1 + R_L} \mp xF_3 \right] \right) dx \approx \text{const}
\]

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\[
\Phi_\nu = \eta_\nu \frac{U_\nu (D_\nu - B_\nu)}{\epsilon_\nu \sigma_\nu^{\text{GENIE}} \# \text{target} \times \Delta E}
\]

$\nu_0 = 0.3, 0.8, 2.0$ GeV

$\epsilon_\nu$: Acceptance correction

$\Delta E$: Energy bin width

$\Phi_\nu$: Flux shape using low-$\nu$ method
MINERνA has demonstrated in-situ flux constraints:

1. Normalization: $\nu - e$ scattering
2. Shape: low-$\nu$ method

Low-$\nu$ method measured inclusive cross-section and provided an excellent cross check of our flux and agreement with the simulation gives us high confidence in the flux.

MINERνA will extend the low-$\nu$ measurement to the Medium Energy.

We are working on a joint analysis between the Low Energy and Medium Energy sample to constrain the flux for a high-$\nu$ sample.

Stay Tuned!
Model tuning
Glossary

**GENIE**: the neutrino-nucleus interaction generator used to simulate events

**MnvGENIE-v1**: A tuned configuration of **GENIE** based on our Low Energy results

1. Random phase approximation (RPA), the long-range correlation

2. Non-resonant pion production tuned to deuterium bubble chamber data

3. Valencia 2p2h model (incorporated into newer **GENIE** versions)

4. Data-driven tune on the Valencia 2p2h model based on low recoil analysis
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4. **Data-driven tune on the Valencia 2p2h model based on low recoil analysis**
Back to our very first CCQE results

Discrepancies in vertex energy:
- prefer adding proton for $\nu$
- does not prefer adding proton for $\bar{\nu}$
- transverse enhancement model/2p2h needed

But how do we know it’s right?
Low Recoil Analysis

MINER$\nu$A has very good calorimetric responses, but terrible particle ID for low energy final states.

Define a charged hadronic energy estimator in place of $q_0$:

$$E_{\text{avail}} = \sum T_p + \sum T_{\pi \pm} + \sum E_{\text{particles other than neutrons}}$$

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Has all the MINERνA tunes except 2p2h modification:
Has all the MINER$\nu$A tunes except 2p2h modification ... not enough, we tune 2p2h to fill in the deficiencies
We also consider the effects on anti-neutrino.
Neutrino tune works! There seems to be low $Q^2$ suppression
Applying tuning: QE
Applications of MINER$\nu$A Tunes $^{QE}$

Better agreement between data and MC
Applications of MINERνA Tunes

The tune improves agreement between data and MC

ν double differential CCQE-Like measurements
Applications of MINERνA Tunes

\( \nu \) double differential CCQE-Like measurements

- The tune improves agreement between data and MC
Applications of MINER$\nu$A Tunes

$\nu$ double differential CCQE-Like measurements

Discrepancies in the higher vertex energy region—more protons?
Applications of MINERνA Tunes

- More vertex energy in the lowest $p_T$ bins
- More cross section in the lowest $Q^2_{QE}$ bins
- Low $Q^2$ suppression, we think it’s due to pions

$\nu$ double differential CCQE-Like measurements
- Discrepancies at the lowest $Q^2_{QE}$ bins
$\nu$ double differential CCQE-Like measurements

- Discrepancies at the highest $Q_{QE}^2$ bins suggesting non-dipole form factor
Going to higher dimensions dig up hidden discrepancies
Our ME results will feature much more statistics
Seeing neutrons
Neutron Tagging

Bonus background from low recoil analysis: neutrons!

A lot of hadronic energy in anti-neutrino events come from neutron. $E_{\text{avail}}$ treat neutron energies as background. But we can also treat neutrons as the signal!
Large discrepancies in the fraction of the lowest energy candidates, otherwise our simulation reproduces data well.
Neutron candidates multiplicity

Regions are divided according to $E_{\text{avail}}$ and the predicted dominant processes differ:
QE-rich: QE and 2p2h
dip: 2p2h
\(\Delta\)-rich: \(\Delta\) and some 2p2h

Neutron candidate multiplicities have larger discrepancies in the dip and \(\Delta\)-rich region, mainly due to the lowest energy candidates.
Some open questions on neutron detections being explored at MINER$\nu$A

- Apply the same analysis to the nuclear targets?
- Turn candidate multiplicity to neutron multiplicity?
- Estimate the energy carried away by neutrons with direction information?
- Measure proton form factor from $\bar{\nu} H \rightarrow \mu^+ n$?

An angle with respect to free proton scattering
Disentangling the nuclear mess
Comparing the transverse components between the leptonic and hadronic final states offer new insights into nuclear effects.
We can infer the initial neutron momentum from $\delta p_T$ and shift in longitudinal proton momentum.
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Weird “accelerating” FSI turns out to be a bug in GENIE, and we’ve found a solution. arXiv:1906.10576
Turns out the projections of $\delta p_T$ w.r.t. a muon-centric coordinate system are sensitive to different nuclear effects.
In collaboration review

**Final States Interaction**

\[ \delta p_{Ty} \text{ is sensitive to the binding energy implementation in GENIE} \]

Default GENIE implements Relativistic Fermi Gas (RFG) model with the Moniz interaction energy \((\text{Nucl. Phys. B43, 605 (1972)})\), which are incompatible.

Non-zero $\delta p_{Tx}$ should be due to Fermi motion
hints of unmodelled asymmetry that we think are pion absorption events
(arXiv:1907.11212)
$\bar{\nu} \text{ CC} \pi^-$ production, statistically limited disagreements in $\mu$ and $\pi^-$ angles
Summary

MINER$\nu$A has demonstrated:

- in-situ flux constrain
  - $\nu - e$ scattering
  - low-$\nu$
- tune or identify model deficiencies
  - low recoil fits to 2p2h
  - transverse kinematic imbalances
- see the elusive neutrons
- measure cross sections to higher dimensions
Outlook

Low energy side:
- 33 published results
- 2 were submitted for publication
- 3 more Low Energy results almost ready

Medium energy side:
- $\nu - e$ cross section submitted for publication
- CCQE $\nu$ and $\bar{\nu}$ in the tracker
- CCQE analysis in the targets
- Pion productions in the tracker and nuclear targets
- DIS/SIS analysis
ν – e Resolution and Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
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<tr>
<td>Beam</td>
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<tr>
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<tr>
<td>Interaction Model</td>
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<td>Statistical</td>
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<tr>
<td>Total</td>
<td>4.75</td>
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Resolutions (lowest energy to highest energy bin)
Energy resolution: 40 MeV ~ 60 MeV
Angular resolution: 0.7° ~ 0.3°
$\delta p_{Tx}$ and $\delta p_{Ty}$ compared to GENIE and it's event type and QE FSI components
Asymmetry in $\pi^0$ measurements

The asymmetry in the Adler’s $\phi$ angle has been observed in the $\pi^0$ result. Stuck pions could in principle exhibit the same asymmetry and affect the observed final state proton through momentum conservation.