Flux measurements in MINERvA

September 7, 2021

Mike Kordosky
The MINERvA Experiment
The MINERvA Experiment

- NuMI hall at Fermilab, upstream of MINOS ND
- Fully active scintillator tracker
- Embedded C, Fe, Pb, He, and H$_2$O targets
The MINERvA Experiment

- Ran between 2009-12 in the NuMI low energy (LE) configuration: $E \approx 3.5$ GeV
- 2013-19 in the medium energy (ME) configuration: $E \approx 6$ GeV
- Huge dataset, especially in the ME configuration
  - Neutrino mode: $4.3 \times 10^6 \nu_\mu$-CC interactions with MINOS acceptance.
  - Anti-neutrino mode $2.5 \times 10^6 \bar{\nu}_\mu$-CC interactions
Motivation for measuring flux and cross-sections: Oscillation Experiments

The event rate at a near detector is a convolution of three terms

\[ \Gamma_{ND}(E_{reco}) = \int \Phi_{ND}(E_{true}) \sigma_{ND}(E_{true}) R_{ND}(E_{true}, E_{reco}) \, dE_{true} \]

- Predicted, *a priori*, from a beam simulation (g4NuMI, g4LBNE)
- Hadron production data (NA49, NA61, MIPP, etc) used to improve the simulation. Incorporated via event by event reweighting.
- Uncertainties from the HP data, physics model, & beam optics propagated via many universes (a.k.a. multi-sim) approach.
- Some systematic control by changing horn currents, target position, or off axis position

Neutrino Flux
Motivation for measuring flux and cross-sections: Oscillation Experiments

The event rate at a near detector is a convolution of three terms*:

\[ \Gamma_{ND}(E_{reco}) = \int \Phi_{ND}(E_{true}) \sigma_{ND}(E_{true}) R_{ND}(E_{true}, E_{reco}) \, dE_{true} \]

- Nucleus, and hence detector, dependent
- Usually the FD and ND have the same nuclei, so the cross-sections are the same at the two detectors
- Or the ND has a variety
- Various final states, some easier to measure than others.

* Mis-identified events / backgrounds complicate this but in a non-essential way. Let’s ignore them.
Motivation for measuring flux and cross-sections: Oscillation Experiments

The event rate at a near detector is a convolution of three terms

\[ \Gamma_{ND}(E_{reco}) = \int \Phi_{ND}(E_{true}) \sigma_{ND}(E_{true}) R_{ND}(E_{true}, E_{reco}) \, dE_{true} \]

- Encodes the relationship between true and reconstructed energy
- Includes kinematic acceptance & smearing
- Predicted by a MC simulation: event generator + GEANT
- Depends on the scattering channel / final state
What if you get $\sigma \times R$ wrong?

- DUNE study where missing energy due to neutrons was not understood
- Model was tuned but using the wrong mechanism
What if you get $\sigma \times R$ wrong?

- DUNE study where pion multiplicity (and a few other things) are not modeled correctly.
  - Mock data is NuWro, model is GENIE
- Affects $R$ since one needs to correct for pion mass to get $E_{\text{reco}}$
- Large bias in $\delta_{\text{cp}}$ can be mitigated by cross-section measurements in the ND

DUNE ND CDR
arXiv:2103.13910
Motivation for measuring flux and cross-sections: Oscillation Experiments

The far detector has an additional term:

$$\Gamma_{FD}(E_{reco}) = \int \Phi_{FD}(E_{true}) \sigma_{FD}(E_{true}) R_{FD}(E_{true}, E_{reco}) P_{osc}(E_{true}; \theta, \Delta m^2) \, dE_{true}$$

- The goal is to extract the oscillation parameters
- Beam simulations predict $\Phi_{FD}/\Phi_{ND}$ fairly well (% level uncertainties) without oscillations.
- Constructing the two detectors out of the same nuclei gives the same $\sigma$ at the FD and ND
- Functionally similar ND and FD can reduce the difference between $R_{FD}$ and $R_{ND}$
- But the integral and unknown $P_{osc}$ spoils direct cancellation
- Oscillation analyses end up being model dependent at some level
- Need to understand the models and/or reduce/remove dependency

$$\Gamma_{ND}(E_{reco}) = \int \Phi_{ND}(E_{true}) \sigma_{ND}(E_{true}) R_{ND}(E_{true}, E_{reco}) \, dE_{true}$$
MINERvA: a ND without a pesky FD

\[ \Gamma_{ND}(E_{\text{reco}}) = \int \Phi_{ND}(E_{\text{true}}) \sigma_{ND}(E_{\text{true}}) R_{ND}(E_{\text{true}}, E_{\text{reco}}) dE_{\text{true}} \]

- MINERvA’s goal is to tease apart this integral
- Factorize it into three parts:
  - Flux
  - Cross-section
  - Response
- I’ll spend a good bit of time talking about the flux.
  - It’s the first thing you’d like to get right.
  - MINERvA’s flux campaign has unique elements enabled by the fined grained scintillator tracker and the large dataset.
    - Lessons and techniques apply directly onto future experiments (e.g., DUNE),
- The starting point is the NuMI beam simulation corrected with hadron production data.
- Then a series of in situ measurements are used to reduce uncertainties.
The NuMI Beam

“Horns Of Plenty”
Simon van der Meer

NuMI @ FNAL
Target
Horns
π^+

Decay Pipe

10 m 30 m 675 m

Muon Monitors

Hadron Monitor

Rock

12 m 18 m

Energy (GeV)

#CC Events/GeV/kton/3.8x10^{20}pot

focusing peak

high energy tail
Getting to a precise flux

Geant 4 Beam MC
“g4numi”

Beamline Geometry & Focusing

Physics: hadron interactions

Surveying, material assay, details, details, details

Hadron Production Data
“thick” & “thin”
in situ measurements
Focusing uncertainties

$\nu_{\mu}$ Focusing Uncertainties

- Horn 1 Position
- Horn Current
- Proton Beam Spot Size
- POT Counting
- Proton Beam Position
- Target Position
- Horn 2 Position
- Horn Water Layer

Small details matter!
Hadronic interactions

What a mess!

- Many neutrinos have multiple interactions in their “ancestry”
  - Strong interactions & hadronization at low $Q^2$ in nuclei. Don't expect the MC to get it right!
Constraining the simulation

Our Strategy

1) Carefully tabulate interactions and material in each n's ancestry

2) Find some relevant hadron production data

3) Weight interactions

4) Assign and propagate uncertainties

\[ f_{\text{Data}} = \frac{1}{\sigma_{\text{inel}}} E \frac{d^3 \sigma}{dp^3} \]

\[ w(x_F, p_T, E) = \frac{f_{\text{Data}}(x_F, p_T, E)}{f_{\text{MC}}(x_F, p_T, E)} \]

Data from NA49 @ CERN
Thin target $\pi$ production data

NA49 data: $pC \rightarrow pX @ 158$ GeV/c

Stat. Uncertainty
- <2.5%
- 2.5 – 5.0%
- >5.0%

This is the major data-set used to make our flux prediction
The *a priori* flux prediction

- Uncertainty < 10% over most of the range.
**in situ** data: the low-nu technique

Cross-section as a function of the energy transfer $\nu$

Becomes constant for small $\nu/E$, resulting in a measurement of the flux shape.

Normalized to well measured high energy neutrino CC cross-section

Data indicates a warping of the flux shape around the focusing peak. Best hypothesis is a $3.6\%$ ($1.8\sigma$) shift in the muon energy scale.

\[
\frac{d\sigma}{d\nu} = A \left(1 + \frac{B}{AE_{\nu}} \frac{\nu}{E_{\nu}} - \frac{C}{AE_{\nu}^2} \frac{\nu^2}{E_{\nu}^2} \right)
\]

- “Use of Neutrino Scattering Events with Low Hadronic Recoil to Inform Neutrino Flux and Detector Energy Scale” A. Bashyal et al (MINERvA), 2021 *JINST* **16** P08068
in situ data: the low-nu technique

Data indicates a warping of the flux shape around the focusing peak. Best hypothesis is a 3.6% (1.8σ) shift in the muon energy scale.

Weakness of this method is the potential circularity with cross-section measurements and model dependence.

As ever, the problem is the nucleus.

\[ \frac{d\sigma}{d\nu} = A \left( 1 + \frac{B \nu}{A E_\nu} - \frac{C \nu^2}{A E_\nu^2} \right) \]

- “Use of Neutrino Scattering Events with Low Hadronic Recoil to Inform Neutrino Flux and Detector Energy Scale” A. Bashyal et al (MINERvA), 2021 *JINST* **16** P08068
in situ data: the low-nu technique

Data indicates a warping of the flux shape around the focusing peak. Best hypothesis is a 3.6% (1.8σ) shift in the muon energy scale.

Weakness of this method is the potential circularity with cross-section measurements and model dependence.

As ever, the problem is the nucleus. So, let’s get rid of it.
Neutrino electron scattering

- Cross-section is extremely well predicted by the SM
- ~4000 times smaller than inclusive CC cross-section
- Radiative corrections important at the few % level
Neutrino electron scattering

- Kinematics requires that $E_e \theta_e^2 < 2m_e$
- The signature is a very forward energetic electron with no hadronic recoil.
- Electron can radiate real photons. Important to include them in the cross-section.
Neutrino electron scattering

data from ME anti-neutrino beam

- Two most important variables:
  - $E_e \theta_e^2 < 0.0032 \text{ GeV } \cdot \text{ radian}^2$
  - $\frac{dE}{dx} < 4.5 \text{ MeV/1.7cm}$
- Backgrounds constrained with a sideband fit in $E_e \theta_e^2$ and $\frac{dE}{dx}$ space
Neutrino electron scattering

- Two most important variables:
  - $E_{\theta}^2 < 0.0032 \text{ GeV/radian}^2$
  - $dE/dx < 4.5 \text{ MeV/1.7cm}$
- Backgrounds constrained with a sideband fit in $E_{\theta}^2$ and $dE/dx$ space
Neutrino electron scattering

- Two most important variables:
  - $E_e \theta_e^2 < 0.0032 \text{ GeV/radian}^2$
  - $dE/dx < 4.5 \text{ MeV/1.7cm}$
- Backgrounds constrained with a sideband fit in $E_e \theta_e^2$ and $dE/dx$ space

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nu_e</td>
<td>$1.02 \pm 0.02$</td>
</tr>
<tr>
<td>Nu_mu</td>
<td>$0.93 \pm 0.03$</td>
</tr>
<tr>
<td>Numu coherent 1</td>
<td>$1.63 \pm 0.20$</td>
</tr>
<tr>
<td>Numu coherent 2</td>
<td>$2.12 \pm 0.29$</td>
</tr>
<tr>
<td>Numu coh 3</td>
<td>$1.81 \pm 0.22$</td>
</tr>
<tr>
<td>Numu coh 4</td>
<td>$2.11 \pm 0.36$</td>
</tr>
<tr>
<td>Numu coh 5</td>
<td>$1.24 \pm 0.71$</td>
</tr>
<tr>
<td>Numu coh 6</td>
<td>$0.80 \pm 0.60$</td>
</tr>
</tbody>
</table>

Coherent $\pi^0$ production in 6 energy bins
Neutrino electron scattering

distributions after sideband fit and signal selection

- **Two most important variables:**
  - $E_e \theta_e^2 < 0.0032$ GeV/radian$^2$
  - $dE/dx < 4.5$ MeV/1.7cm

- **Backgrounds constrained with a sideband fit in $E_e \theta_e^2$ and $dE/dx$ space**
Neutrino electron scattering

After background subtraction and efficiency correction.

- Uncertainty dominated by statistics. But, systematics < 10 %, especially at low electron energy where most events are.
Constraining the flux

Bayes’ theorem allow us to infer a new prediction of the flux given a measurement that uses our current prediction

\[ P(M|N_{\nu e \rightarrow \nu e}) \propto P(M)P(N_{\nu e \rightarrow \nu e}|M) \]

- **New prediction, given the observed measurement**
- **a-priori model of the flux**
- **Likelihood of our data given the a-priori model**
Constraining the flux

Likelihood of our data

\[ P(N_{\nu e \rightarrow \nu e} \mid M) = \frac{1}{(2\pi)^{K/2}} \frac{1}{|\Sigma_N|^{1/2}} e^{-\frac{1}{2}(N-M)^T \Sigma_N^{-1}(N-M)} \]

- \( N \) is a vector containing the bin content of the measured energy spectrum of given process
- \( M \) is the same as \( N \) but for the MC prediction
- \( \Sigma_N \) is the covariance matrix of the uncertainties of \( N \)
- \( K \) is the number of bins of the spectrum

This is calculated for each universe of the flux error band
Constraining the flux

- These plots have a single constraint from neutrino electron scattering in the ME anti-neutrino beam configuration
- We also have a similar measurement in the ME neutrino beam configuration
- And, there is one more thing too...
One last thing: inverse muon decay

Similar to the neutrino electron elastic scattering, but with a very forward muon in the final state.

- Threshold is ~11 GeV, so this process constrains the high energy component of the flux. Only sensitive to muon neutrinos.

https://arxiv.org/abs/2107.01059
One last thing: inverse muon decay

\[ \nu_\mu e^- \rightarrow \mu^- \nu_e \]

- Similar to the neutrino electron elastic scattering, but with a very forward muon in the final state.
- Threshold is \( \sim 11 \text{ GeV} \), so this process constrains the high energy component of the flux. Only sensitive to muon neutrinos.

https://arxiv.org/abs/2107.01059

127 (56) IMD events in the FHC (RHC) beams.
A combined constraint

- We combine the following to form a joint constraint
  - Neutrino electron scattering in the ME neutrino focused beam (a.k.a. Forward horn current = “FHC”)
  - Neutrino electron scattering in the ME anti-neutrino focused beam (reversed horn current = “RHC”)
  - Inverse muon decay in the ME beam
Covariance matrix
The effect of different constraints

Label indicates constraint applied

- **Unconstrained**
  - FHC Number of ∇e events vs. RHC Number of ∇e events
  - Measured number of events

- **FHC Constraint**
  - Measured number of events

- **Combined nue with IMD**
  - RHC Number of ∇e events vs. FHC Number of ∇e events

- **RHC Constraint**
  - Measured number of events
Combined results

- Flux: $\nu$, FHC
  - Weight: FHC+RHC+IMD
  - Before Constraint
    - Mean: 66.0
    - RMS: 5.1
    - RMS/Mean: 7.7%
  - After Constraint
    - Mean: 60.0
    - RMS: 2.0
    - RMS/Mean: 3.3%

- Flux: $\nu$, RHC
  - Weight: FHC+RHC+IMD
  - Before Constraint
    - Mean: 49.0
    - RMS: 3.9
    - RMS/Mean: 7.8%
  - After Constraint
    - Mean: 46.0
    - RMS: 2.2
    - RMS/Mean: 4.7%
Constrained flux
Constrained flux
## Post-constraint uncertainties (%)

<table>
<thead>
<tr>
<th>Constraint applied</th>
<th>anti-$\nu$</th>
<th>$\nu$</th>
<th>anti-$\nu_e$</th>
<th>$\nu_e$</th>
<th>anti-$\nu$</th>
<th>anti-$\nu$</th>
<th>$\nu_e$</th>
<th>anti-$\nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A priori Uncertainty</td>
<td>7.76</td>
<td>11.12</td>
<td>7.81</td>
<td>11.91</td>
<td>7.62</td>
<td>12.17</td>
<td>7.52</td>
<td>11.73</td>
</tr>
<tr>
<td>FHC</td>
<td>6.11</td>
<td>6.30</td>
<td>5.811</td>
<td>8.50</td>
<td>3.90</td>
<td>8.37</td>
<td>3.94</td>
<td>8.68</td>
</tr>
<tr>
<td>RHC</td>
<td>4.92</td>
<td>8.07</td>
<td>4.98</td>
<td>9.19</td>
<td>5.88</td>
<td>8.36</td>
<td>5.68</td>
<td>8.64</td>
</tr>
<tr>
<td>FHC+RHC</td>
<td>4.68</td>
<td>5.56</td>
<td>4.62</td>
<td>7.80</td>
<td>3.56</td>
<td>7.15</td>
<td>3.58</td>
<td>7.84</td>
</tr>
<tr>
<td>FHC+RHC+IMD</td>
<td>4.66</td>
<td>5.20</td>
<td>4.56</td>
<td>6.08</td>
<td>3.27</td>
<td>6.98</td>
<td>3.22</td>
<td>7.54</td>
</tr>
</tbody>
</table>

**anti-$\nu$ focused beam (“RHC”)**

**$\nu$ focused beam (“FHC”)**
Conclusions

- MINERvA’s flux constraint uniquely combines a sophisticated and well tuned beam-line MC with in-situ data.
- First ever joint constraint of a neutrino and anti-neutrino beam using neutrino electron scattering and inverse muon decay.
- Uncertainties beaten down to 3.3% and 4.7% for numu and anti-numu in the FHC and RHC beams, respectively.
- Statistics limited.
- Little shape information.
- A detector with very good angle and energy resolution will be able to do even better by constraining the shape of the flux.
  - Huge sample. 22000 events events in 30t of LAr in 5 years of running.
- This is effectively the end of MINERvA’s long flux campaign. Plan is to release results for NuMI on-axis (shown today) as well as off-axis locations.
- In principle, these results could also be rephrased to constrain the flux for LBNF/DUNE. That may be something we will try.