Flux and cross-section measurements in MINERvA

- How to predict the flux from a wideband neutrino beam...
- and what that buys you!

Mike Kordosky
The NuMI Beam

NuMI @ FNAL

• π,K production off a graphite target
• Wide range of $p_T$, $p_z$
• Cross-sections not well known

Important decay modes

$\pi^+, K^+ \rightarrow \mu^+ \nu_{\mu}$
$K^+ \rightarrow \pi^0 \mu^+ \nu_{\mu}$
$\rightarrow \pi^0 e^+ \nu_e$
$K^0_L \rightarrow \pi^- e^+ \nu_e$
$\rightarrow \pi^- \mu^+ \nu_{\mu}$
$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_{\mu}$
The NuMI Beam

NuMI @ FNAL

The diagram shows the layout of the NuMI beam with key components labeled:
- Target
- Horns
- Decay Pipe
- Absorber
- Muon Monitors
- Hadron Monitor
- Rock

The focusing peak and high energy tail are highlighted in the inset graph, which plots the number of events per GeV/GeV/tons against energy (GeV) with different focusing conditions indicated.

“Horns Of Plenty”
Simon van der Meer
Getting to a precise flux

- Geant 4 Beam MC “g4numi”
  - Beamline Geometry & Focusing
  - Surveying, material assay, details, details, details
  - Physics: hadron interactions
  - Hadron Production Data “thick” & “thin”

Focus on LE beam 2005-12
Focusing uncertainties

Small details matter!

±0.25% of beam
±2%
±1%
±1cm
±1mm
complicated, ask me
±0.5mm

Neutrino Energy (GeV)

Fractional Uncertainties
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!

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### # of interactions per $\nu_\mu$ (x100)

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<thead>
<tr>
<th>Projectile</th>
<th>C</th>
<th>Fe</th>
<th>Al</th>
<th>Air</th>
<th>He</th>
<th>H$_2$O</th>
<th>Be</th>
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<td>117.5</td>
<td>2.9</td>
<td>1.0</td>
<td>1.1</td>
<td>1.5</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>$\pi^+$</td>
<td>8.1</td>
<td>1.3</td>
<td>1.8</td>
<td>0.2</td>
<td></td>
<td>0.4</td>
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<tr>
<td>$\pi^-$</td>
<td>1.3</td>
<td>0.2</td>
<td>0.2</td>
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<td>$K^\pm$</td>
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<td>0.1</td>
<td>0.1</td>
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</tr>
<tr>
<td>$K^0$</td>
<td>0.6</td>
<td></td>
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<tr>
<td>$\Lambda/\Sigma$</td>
<td>1.0</td>
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<td></td>
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</table>

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### Average Number of Interactions /$\nu_\mu$

- g4numi simulation
- Geant 4.9.2.p3 FTFP-BERT
Absorption in the beamline

Particles traverse a significant amount of material

NuMI Low Energy Beam, $\nu_\mu$

![Graph showing material traversed vs. neutrino energy](image)

- $\pi^+$ - C
- $K^+$ - C
- primary p - C
- $\pi^+$ - Al
- $K^+$ - Al
- others - C
- $\pi^+$ - Fe
- $K^+$ - Fe
- others - no C
- $\pi^+$ - He
- $K^+$ - He
- total

6 mol/cm$^2$ of graphite $\approx$ 40cm
Constraining the simulation

Our Strategy

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

2) Find some relevant hadron production data

3) Weight interactions

4) Assign and propagate uncertainties

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

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

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

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

This is the major data-set used to make a “thin target” flux prediction
**NuMI target π production data**

MIPP data: π yields from a NuMI target

Stat. Uncertainty
- ● <2.5%
- ○ 2.5 – 5.0%
- ▲ >5.0%

This is the major data-set used to make a “thick target” flux prediction
Constraining Kaons

- **Thin target:** pC → K±X data from NA49 (G. Tinti PhD Thesis, Oxford 2010) and K/π ratio from MIPP (A. Lebedev PhD thesis, Harvard 2007) cover most of the region \( x_F < 0.5 \)

- **Thick Target:** MIPP's measurements of the K/π yield from a NuMI target (S. Seun PhD thesis, Harvard 2007).
We account for everything

Additional constraints applied to both thin and thick target predictions

- Neutral K production predicted from charged K data via quark counting
  \[ N(K^0) = \frac{1}{4}N(K^+) + \frac{3}{4}N(K^-) \]

- We use pC → pX, nX data from NA49

- nC → πX data corrected with pC → π+X data and vise versa.

- We use FLUKA to scale data to lower projectile energies.

- We compare measured absorption cross-sections with the MC to derive corrections and uncertainties for p, n, π, K projectiles

- We constrain pA → π, K X interactions with pC data, adding 10-30% uncertainty

- Processes without data constraints are characterized by projectile and produced particle. Assign a 40% uncertainty to each in 4 xF bins from 0 to 1

Thin target results

ratio to g4numi uncorrected prediction
Thick target results

ratio to g4numi uncorrected prediction
A conundrum

Thick / Thin $\nu_\mu$ flux ratio

The curve ought to agree with 1
Comparison to *in situ* data

$\nu_e \rightarrow \nu_e$ scattering
Well known cross-section.
2000x smaller than $\nu N$.
Cleanly identified events.

J. Park Ph.D (FNAL-thesis-2013-36)

**Thin:** 106 events
**Thick:** 105 events
**Data:** 96.6 events

Good agreement seen for both flux predictions.

Used to tune our final flux prediction.
Reduces flux and unc. by $\sim 1\%$.
Medium Energy Flux

An aside....

Now, carrying on with the LE beam...

NuMI Medium Energy Beam

MINERvA Preliminary

NuMI Medium Energy Beam, HP Uncertainties,
Comparison to *in situ* data

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

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

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

Normalized to well measured high energy neutrino CC cross-section

Result agrees with the thin target flux prediction ($\chi^2$/NDF = 7.3/15) better than the thick target prediction (61.3/15)

We have adopted the thin target flux, corrected by $\nu_e \rightarrow \nu_e$, as the official prediction.
MINERvA

Selected cross-section results: quasi-elastics
Quasi-elastic scattering

Quasi-elastic (QE) CC scattering dominates charged-current (and therefore oscillation signals) at ~1 GeV.

QE on nucleons is thought to be well understood.

But scattering on nuclei is complicated by final state interactions that introduce “quasielastic-like” zero-pion final states.

And by the possibility of interactions with multi-nucleon bound states (frequently called 2p2h interactions).
New measurements are in dimensions of muon $p_T$ and $p_z$.

Improved systematics and reconstruction.

Data indicates extra strength in cross section at moderate transverse momentum.
A new way of studying QE

**Idea:** Look at inclusive scattering in 2 kinematic dimensions. Split $Q^2$ into energy transfer $q_0$ and 3 momentum transfer $q_3$. Different scattering channels appear as bands.

Models for scattering off of two nucleons tend to increase the cross-section in this area.
νμ data in the (q₀,q₃) plane


Adding in models of RPA (a charge screening effect) and 2p2h improves agreement in some regions, but not in others — excess in similar kinematic region to excess in antineutrino QE

\[ E_{\text{avail}} = \sum p \text{ and } \pi^\pm \text{ K.E.} + \text{total energy of all other particles except n} \]
Uncertainty on $\nu_e$ CC cross-section relative to $\nu_{\mu}$ has a strong impact on DUNE's physics reach.

$\nu_e$ QE-like

$\nu_e$ makeup only $\sim 1\%$ of the NuMI beam but can be readily identified.

Goal: measure $\nu_e$ QE and compare to $\nu_{\mu}$
$\nu_e$ QE-like

$\nu_e$ VS $\nu_\mu$

Summary

- MINERvA's flux prediction is as precise as has ever been made for a wide band beam like NuMI.
- That prediction enables precision absolute cross-sections
- A multi-faceted study of QE and other low recoil channels is now bearing significant fruit.
- Many other exclusive channels I couldn't cover! (Single $\pi^{\pm,0}$ production, CC and NC K production, coherent p production, diffractive $\pi^0$ production). Plus inclusive scattering on different nuclear targets!
- Next talk → Meson production
Backups
MINERvA Publications

MINERvA Physics Publications so far:

“Evidence for neutral-current diffractive neutral pion production from hydrogen in neutrino interactions on hydrocarbon”, accepted for publication, in press
“First evidence of coherent K+ meson production in neutrino-nucleus scattering”, accepted for publication, in press

Two more recently went to the arXiv

Cross sections for neutrino and antineutrino induced pion production on hydrocarbon in the few-GeV region using MINERvA
Neutrino Flux Predictions for the NuMI Beam

Several public results in paper preparation

Antineutrino Quasielastic Scattering
Neutrino Quasielastic Scattering
Charged current neutrino and antineutrino inclusive cross sections via the “Low-nu” method
Systematic Uncertainties

In practice we shift multiple knobs simultaneously: “many universes” “multi-sims”
The “Many Universes” method

• Each hadron production data point, including absorption cross-sections, is treated as a random variable with a central value and uncertainty.

• Points can be correlated.

• Random MC universes created by throwing new values for the data points, recomputing weights.

• For any distribution, can compute the bin-to-bin covariance matrix.
Applying pC to pA

- Subdominant portion of the ancestry is interactions on nuclei that are not carbon. Most common are He, Fe and Al.
- We constrain these interactions with pC data when possible.
- An additional uncertainty was derived:
  1) Measurements of $K^0$, and $\Lambda^0$ production off Be, Cu and Pb targets by a 300 GeV proton beam are used to derive an A-dependent scaling in bins of momentum and angle
  2) The scaling is applied to $pA \rightarrow pX$ and $pA \rightarrow KX$ data collected at 100 GeV on C, Al, Cu, Ag, and Pb targets. Agreement at ~10% level.
  3) The scaling is then applied to the MC, and unscaled vs scaled MC are compared
  4) The level of agreement for both scaled data and MC is used to assign the eventual error.
- Results in an additional 10-30% error
**p absorption**

Inelastic = meson or heavy baryon production

Absorption = inelastic + quasi-elastic

MC underestimates inelastic by ~5%. We correct and take 5% as the error.

The QEL cross-section is taken to be 29±4 mb

For neutrons, and for protons colliding with He, Al, Fe we assume a 40% uncertainty. No other materials are relevant.
**π absorption**

MC agrees well with the data. Error set by residuals.

C: 10 mb (~5%)
Al: 24 mb
MC agrees not-so-well with the data. Error set by residuals.

K+ with p<2 GeV
C: 68 mb
Al: 83 mb

K- with p<2 GeV
C: 80 mb
Al: 49 mb

K+ with p>2 GeV
C: 13 mb
Al: 31 mb

K- with p>2 GeV
C: 20 mb
Al: 31 mb
A new way of studying QE

Just looking at $d\sigma/dQ^2$ integrates across the bands, obscuring things

![Diagram showing energy transfer and momentum transfer with color-coded regions for $Q^2 = 0.2$ GeV$^2$ and $Q^2 = 1.0$ GeV$^2$.](image)
GENIE vs low recoil data

Default* GENIE

* includes a MINERvA tune which lowers non-resonant $\nu_\mu n \rightarrow 1\pi^+ + $nucleons production by 76% and the total rate of $\pi^+$ production for $W<1.8$ GeV by an additional 10%. Coherent $\pi^\pm$ production also lowered by 50% for $E_{\pi} < 450$ MeV.
GENIE vs low recoil data

Default* GENIE + RPA correction

* includes a MINERvA tune which lowers non-resonant $\nu_\mu n \rightarrow 1\pi + \text{nucleons}$ production by 76% and the total rate of $\pi$ production for $W<1.8$ GeV by an additional 10%. Coherent $\pi^\pm$ production also lowered by 50% for $E_\pi < 450$ MeV.
GENIE vs low recoil data

Default* GENIE + RPA correction + MEC

* includes a MINERvA tune which lowers non-resonant \( \nu_\mu n \rightarrow 1\pi + \text{nucleons} \) production by 76% and the total rate of \( \pi \) production for \( W < 1.8 \text{ GeV} \) by an additional 10%. Coherent \( \pi^\pm \) production also lowered by 50% for \( E_{\pi} < 450 \text{ MeV} \).
NuMI Running

Total NuMI protons

Antineutrinos

560 kW!

Major Milestone!

<table>
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<tr>
<th></th>
<th>Tmp</th>
<th>NuMI</th>
<th>NuMI Pwr</th>
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<td></td>
<td>86.1 F (30.0 C)</td>
<td>48.6 E12</td>
<td>701.0 kW</td>
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<tr>
<td>BNB</td>
<td>0.0 p/hr</td>
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Beam to NUMI(6+6), S

MINOS

MINOS+

MINERvA

NOvA

10.56x10^{20} PoT MINOS neutrino-mode
5.80x10^{20} PoT MINOS+ neutrino-mode
3.36x10^{20} PoT MINOS antineutrino-mode

Aug 6, 2016 Mike Kordosky, Wm & Mary
The MINERνA detector

* 200 finely segmented scintillator planes (CH) in 3 views
* Calib: FEB bench tests, source mapper, LI, rock $\mu$, Michel electrons, test-beam
* 4% channel to channel variations after calibration

Aug 6, 2016

Mike Kordosky, Wm & Mary