Measuring the NuMI Beam Flux for MINERvA

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Measuring Flux: Introduction

Knowing your flux is difficult, and crosschecks are helpful

- CERN PS: *In situ* measurement using μMons increased predicted flux by 50%
- MiniBooNE and SciBooNE data appear to conflict with NOMAD results at higher energy

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CERN PS particle production expt.
Measuring Flux: Introduction

MINERvA will utilize three methods to understand its flux:

1. **External data** *(ab initio)*
2. **Flexible beam design** for *in situ* measurements
3. **Muon monitors** *(in situ)*

- Neutrino-nucleus interaction experiment in the NuMI beamline at Fermilab
  \[ \sigma = \frac{N(\text{observed})}{\text{Flux}} \]
- Low energy (<10 GeV) precision cross section measurements

*figure courtesy Ž. Pavlović*
Measuring Flux: Focusing Uncertainties

Focusing uncertainties are smaller and easier to model than hadron production uncertainties.

## Measuring Flux: Hadron Production

Relying on Monte Carlo models alone isn’t a good option

<table>
<thead>
<tr>
<th>Model</th>
<th>( \langle p_T \rangle ) (GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFLUKA</td>
<td>0.37</td>
</tr>
<tr>
<td>Sanf.-Wang</td>
<td>0.42</td>
</tr>
<tr>
<td>CKP</td>
<td>0.44</td>
</tr>
<tr>
<td>Malensek</td>
<td>0.50</td>
</tr>
<tr>
<td>MARS – v.14</td>
<td>0.38</td>
</tr>
<tr>
<td>MARS – v.15</td>
<td>0.39</td>
</tr>
<tr>
<td>Fluka 2001</td>
<td>0.43</td>
</tr>
<tr>
<td>Fluka 2005</td>
<td>0.36</td>
</tr>
</tbody>
</table>

![Graph showing comparison of different models](image)
Can’t modern data sets solve our problems?

**Measuring Flux: Hadron Production**

Sadly … no.  **Production data ≠ Flux**

**Thick target effects:**
- Experiments are mostly on thin targets
- NuMI target is is ~2\(\lambda_{\text{int}}\) lengths
- Reinteractions are 20-30% effect

**In situ temporal variations of flux:**
- Target changes
- Focusing changes

**Downstream interactions:**
- Interactions in horns, windows, shielding, etc.

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![Graphs showing production flux data](image_url)
We want an *in situ* measurement of $\phi_f(x_F,p_T)$

Allows us to correct the MC model for parent hadron $x_F$ and $p_T$ off the target

- Focusing and decay kinematics imply: flux $\leftrightarrow$ hadron production
- Shape in $p_T$ and $x_F$ impact flux via focusing channel acceptance
Measuring Flux: Variable Beam

“Low” Energy

\[ \pi^+ p_T = 300 \text{ MeV/c} \] and:
- \( p = 5 \text{ GeV/c} \)
- \( p = 10 \text{ GeV/c} \)
- \( p = 20 \text{ GeV/c} \)

“High” Energy

Moving target in/out of 1st horn varies which pions are focused

Deconvolve systematics:
- Neutrino beam focusing
- \( \pi/K \) production off target
- Neutrino cross sections
Measuring Flux: Variable Beam

We can vary:

- Horn current ($p_T$ kick supplied to pions)
- Target position ($x_F$ of focused particles, where $x_F = p_z/p_o$)

- LE = target @10cm
- pME = target @100cm
- pHE = target @250cm
Measuring Flux: Hadron Production

1\textsuperscript{st} \textit{in situ} flux measurement tool:

Tune MC parameterization of hadron production off the target so that it matches \textbf{MINERvA Detector Data} across several beam configurations
Measuring Flux: Fitting to Data

Flexible beam configurations permit tuning hadron production yields to match data.

Each \((x_F, p_T)\) bin contributes with different weight in each beam configuration.
MINERvA’s “standard candle” data set will be QEL events of moderate $Q^2$

- QEL cross section on nucleons is a function of $Q^2$, independent of neutrino energy (even for extreme values of $M_A$)
- Low $Q^2$ events are excluded because of uncertainties due to nuclear effects
- High $Q^2$ events are excluded because of reconstruction difficulties
- Use inclusive CC sample above ~20GeV and compare to CCFR, CCFRR, and CDHSW data sets to fix the absolute normalization

**Ratio of QE cross section 0.2<$Q^2$<0.9**
(assuming a fixed high energy cross section)
Reference $M_A=1.1$
Range of test $M_A$: 0.9, 1.3, 1.5

**Ratio of cross section of test $M_A$ to reference $M_A$ vs. $E_\nu$**
Measuring Flux: Fitting to Data

Result of fit = set of weights in $(x_F, p_T)$ plane that should be applied to $\pi/K$ yields

Weight = \[ \frac{\left( \frac{d^2N}{dx_F dp_T} \right)_{\text{tuned}}}{\left( \frac{d^2N}{dx_F dp_T} \right)_{\text{Monte Carlo}}} \]

MINOS utilized such fits:
Flux uncertainty at far detector reduced (2-10)% → (1-4)%

MINOS used inclusive event sample for its fits:
• Fine for Far/Near ratio ... but not for xsec measurements
• QEL events provide a well-known process for MINERvA

Measuring Flux: Fitting to Data

What kind of flux errors can MINERvA expect?

**Blue error band** = estimation of flux uncertainty based on “current knowledge”*

*Includes:
- Beam focusing uncertainties
- MC differences in $\pi^+$ production off target
- 5% yield uncertainty for $\pi^+$ production off target

Effort is underway to estimate our post-fit errors by warping the hadron production of Geant4 Monte Carlo to bring simulated Geant4 “data” (across many beam configurations) into agreement with simulated Fluka “data.”

[Graph showing flux distribution]
Measuring Flux: Muon Monitors

2nd *in situ* flux measurement tool:

Tune MC parameterization of hadron production off the target so that it matches **Muon Monitor Data** across several beam configurations.
Measuring Flux: Muon Monitors

- Muon thresholds translate into $\nu$ thresholds
- Allows sampling of different energy regions of the flux
- 3 alcoves = poor granularity per measurement ... but NuMI’s flexible beam offers data from many $(I_{\text{horn}}, Z_{\text{target}})$ combinations
Measuring Flux: Muon Monitors

- 3 arrays of ionization chambers (2m x 2m)
- Plans to install a 4th chamber
- Beam μ’s ionize He gas
- Signal = ionized electrons
- Sampling μ flux = hadrons off target = sampling ν flux
- Technique proven at CCFR, CERN-PS, CERN-SPS
Measuring Flux: Fitting to $\mu$Mon

We can fit muon monitor data to obtain $(x_F, p_T)$ in the same way we fit MINERvA data.
Measuring Flux: Fitting to $\mu$Mon

Successfully tuned MC to match $\mu$Mon data

- Empirical parameterization for hadron production
- Warp $p_T$ and $p_z$ to tune MC to $\mu$Mon data
- Allow $\pi^+$ parameters to float
- Fix $\pi^+ / \pi^-$ ratio to NA49 and fix $K/\pi$ ratio to MC

- Data  Monte Carlo  Tuned Monte Carlo
Largest sources of error:
• Delta-rays
• Scaling pC/µ by ± 10%

Other sources of error:
• Bethe-Block energy deposition by µ in He
• Scaling K/π ratio by ± 10%
• Fixing π⁺/π⁻ ratio to MC value
• Scale non-linearity correction in data ± 1σ
• Scale dump backgrounds ± 1σ

Due to large uncertainties, the flux was normalized to MINOS data for \( E_\nu > 25 \) GeV.

How can MINERvA reduce those uncertainties?

Measuring Flux: Fitting to μMon

Significant backgrounds must be included in the μMon MC

δ-Rays:
• Muons can create knock-on electrons while traveling through the rock, air, etc.
• MC indicates δ-rays can be as much as ~30% of the monitor signal
Experiment to correct MC δ-ray production by comparing it to data in which we deliberately introduced more δ-rays.

- Placed “absorbers” (plates of aluminum) in front of the μMonitors to increase δ-rays.
- Al blocks 15 x 15 x 2.5 cm
- 2 absorbers/curtains (set of 45 blocks): located 24 cm and 42 cm in front of monitor.

δ rays increase with absorber thickness and decrease with separation between absorber and monitor.
MINERvA has multiple tools available to understand its flux:

- *In situ* measurements provide checks against external hadron production measurements
- NuMI’s flexible beam design allows us to map out hadron production in (xF,pT), and we can measure our flux *in situ* using two techniques:
  1. Fits to QEL data in MINERvA
  2. Fits to muon monitor yields
- MINERvA will augment and upgrade our muon monitor system to provide more constraints
- MINERvA’s initial estimated flux uncertainty is ~30%, and by performing these studies we can reduce it to 5-10%
The entire MINERvA collaboration thanks NuInt and its organizers for the opportunity to give these presentations.


L. Loiacono, PhD Thesis, University of Texas, 2010
Backup slides
Each data point is the integral of a flux plot from a given beam configuration.

Data needs various corrections:
• Ambient pressure and temperature corrections
• Correction for chamber non-linearity with muon flux intensity
• Relative correction for helium gas quality

Geant4 Monte Carlo needs various corrections:
• Overall scale factor from pC/μ, which can vary 5-10% due to even 20 ppm O₂ contamination of He gas
• Backgrounds need to be estimated
Measuring Flux: Hadron Production

Flexible beam configurations permit *tuning* hadron production yields.

Use empirical form *similar* to BMPT to parameterize Geant4:

\[
\frac{d^2 N}{dx_F dp_T} = \left\{ A(x_F) + \left[ B(x_F)p_T \right] \right\} e^{-C(x_F)p_T^{3/2}}
\]

\[
A(x_F) = a_1 \ast (1. - x_F)^{a_2} \ast (1. + a_3 \ast x_F) \ast x_F^{-a_4}
\]

\[
B(x_F) = b_1 \ast (1. - x_F)^{b_2} \ast (1. + b_3 \ast x_F) \ast x_F^{-b_4}
\]

\[
C(x_F) = c_1/x_F^{c_2} + c_3
\]

Tune parameters of the fit to match data in multiple different beam configurations

\[
A'(x_F) = (p_1 + p_2 x_F)A(x_F)
\]

\[
B'(x_F) = (p_3 + p_4 x_F)B(x_F)
\]

\[
C'(x_F) = (p_5 + p_6 x_F)C(x_F)
\]