Prospects for Improvements in Neutrino Flux Understanding

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Accelerator-Generated Beams

This talk will primarily focus on improvements for future long-baseline beams, especially LBNE and T2K/HyperK
Outline

• Current Status of Flux Predictions
• In Situ Measurements
  ‣ Muon Monitors
• External Hadron Production Measurements
  ‣ MIPP
  ‣ Future NA61/SHINE Measurements
Disagree with MC predictions by 50% or more in some areas
• Well known that out of the box MC flux predictions do not agree well with data
Flux Tuning

- MINOS used ND and many beam configs
- This strategy will continue to be useful for NOvA oscillation measurements
- But much harder to implement for T2K/HK and LBNE
- Would also like to constrain/tune the hadron production simulation with $\nu$ cross-section independent data
- Independent flux measurement also useful for short baseline sterile $\nu$ and heavy $\nu$ decay searches
Current Hadron Production Data

- protons at 8.9 GeV on Be
- protons at 31 GeV/c on C
- protons at 120 GeV/c on C
- protons at 400-450 GeV/c on Be
Production Data Relevant for 8.9 GeV/c p + Be

<table>
<thead>
<tr>
<th>Data</th>
<th>Experiment</th>
<th>Hadron</th>
<th>Published</th>
</tr>
</thead>
</table>

- MiniBooNE flux predictions, 7-10%  PhysRevD.79.072002
- MicroBooNE will build on 10 years of experience with Booster beam
- Analysis of HARP thick target data currently in progress
## Production Data Relevant for 31 GeV/c p + C

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• Current published T2K flux predictions rely heavily on these datasets
Current Uncertainties - T2K

Phys Rev D 87 012001 (2013)

SK $\nu_{\mu}$ Flux

SK $\nu_{e}$ Flux

- Hadron uncertainties (above) dominate T2K flux errors
  - Lower energies dominated by secondary p,n production
  - Higher energies dominated by kaon production
# Production Data Relevant for 120 GeV p + C

<table>
<thead>
<tr>
<th>Data</th>
<th>Experiment</th>
<th>Hadron</th>
<th>Published</th>
</tr>
</thead>
<tbody>
<tr>
<td>158 GeV/c p + thin C target</td>
<td>NA49</td>
<td>$K^+$</td>
<td>G. Tinti Ph.D. thesis</td>
</tr>
<tr>
<td>120 GeV/c p + thin C</td>
<td>MIPP</td>
<td>$K/\pi$ ratio</td>
<td>A. Lebedev Ph D thesis</td>
</tr>
<tr>
<td>120 GeV/c p + NuMI C target</td>
<td>MIPP</td>
<td>$\pi^\pm$</td>
<td>arXiv: 1404:5882</td>
</tr>
</tbody>
</table>
Current Uncertainties - Minerva

• No ND tuning here

D. Harris, previous session
Production at ~400 GeV/c

<table>
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<tr>
<th>Data</th>
<th>Experiment</th>
<th>Hadron</th>
<th>Published</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 GeV/c p + 10-50 cm Be target</td>
<td>NA20</td>
<td>$\pi^\pm, K^\pm, p, \bar{p}$</td>
<td>CERN 80-70 (1980)</td>
</tr>
<tr>
<td>450 GeV/c p + Be target</td>
<td>NA56/SPY</td>
<td>$\pi^\pm, K^\pm, p, \bar{p}$</td>
<td>Eur. Jour. Phys. C10 (1999) 605</td>
</tr>
</tbody>
</table>

- Accuracies in the 5-10% range
Impact on Future beams

• For LBNE and T2HK
  ‣ Near and far detectors likely will have very different detector technologies
  ‣ Target is (likely) fixed in place
  ‣ MINOS strategy will be difficult to implement here

• Need improvements in in-situ constraints (μ Monitors) and external measurements
Muon Monitors

- Typically gas or solid state ionization counters
- Challenge to interpret since sensitive to e’s
NuMI Muon Monitors

- 4 sets of ionization chambers
- Each alcove sees a different threshold
- Vary horn current and target position to map out hadron $p_t$ and $p_z$ space

From NuMI TDR
Using Muon Monitors to Constrain $\nu$ Flux

- NuMI muon monitors have been used to extract a $\nu_\mu$ flux (L. Loiacono PhD dissertation, UT Austin 2010)

- Flux normalized to $E_\nu > 26$ GeV ND data

- Errors dominated by non-muon backgrounds and mumon ionization scale

@ MINOS ND

\begin{figure}[h]
\centering
\includegraphics[width=0.7\textwidth]{nu_flux_measurement.png}
\caption{Flux measurement from the muon monitors.}
\end{figure}

L. Loiacono, NBI, 2010

\begin{itemize}
  \item Error bars come from...
  \begin{itemize}
    \item Non-linearity correction.
    \item K$^+$/\pi$^+$ and $\pi^+$/\pi$^-$ ratios.
    \item Dump backgrounds.
    \item $\mu$ Monitor ionization scale.
    \item $\delta$-rays.
  \end{itemize}
\end{itemize}

Due to large uncertainty, flux requires normalization to MINOS ND data for $E_\nu \approx 26$ GeV.
New μMon in Alcove 4

- Ionization counters recently placed in μ alcove
- Response for alcove 4 is largely insensitive to horn since it sees the highest energy muons from pions not in focussing peak

Data with variable horn current

M-J. Bustamante-Rosell, 4/14/14 AEM talk
Design Considerations

• Ideally the muon monitors should
  ‣ Discriminate between muons and other sources of ionizing radiation
  ‣ Provide an absolute normalization of the muon flux
  ‣ Provide information about the energy spectrum of the muons
Alternative Designs

• In addition to ionization counters, LBNE also proposing
  ‣ Stopped Muon Counters
  ‣ Threshold Gas Cherenkov Detectors
Stopped Muon Counters

• Muons stop in non-scintillating oil
• Look for muon decay electrons after beam pulse
• Also look for $^{12}$B decay following $\mu^-$ capture on $^{12}$C
• Scintillating veto to reject external n’s
• Place detectors at different depths of shielding to pick out flux at specific energies
Threshold Gas Cherenkov

- Pipe filled with argon at variable pressure
- Light reflects off of a flat mirror to a PMT
- Not sensitive to neutrons
- Apparatus can be rotated to map out angular profile of muons
Prototype Detectors

- Prototype stopped muon and gas Cherenkov detectors currently located in NuMI Alcove 2
Gas Cherenkov Prototype Data

NuMI pulse in Gas Cherenkov

G. Mills, LANL

Cherenkov Response Versus Pressure

• Also plan to place detectors in alcove 1 this year
• Muons that exit absorber originate from pions that contribute to neutrino flux above 4 GeV

Note: LBNE absorber not finalized
External Measurements

• Fermilab E907: Main Injector Particle Production (MIPP)
  ‣ p, π, K beams 5 GeV/c-120 GeV/c on thin LH$_2$, C, Be, Bi, U targets and NuMI LE replica target
  ‣ Collected data from 2004-2006

• CERN NA61: SPS Heavy Ion & Neutrino Experiment (SHINE)
  ‣ p and heavy ion beams, from 31 GeV/c - 350 GeV/c
  ‣ Collecting data since 2007
Improvements at 120 GeV/c from MIPP Data

- Just released p+replica target data @ 120 GeV/c arXiv: 1404:5882
- 5-10% uncertainties
- Forward n measurement too

Density Profile of the NuMI Target

$\pi^+ \text{ data}$

MIPP Preliminary

$N(\pi^+/\text{GeV}/\text{POT})$

$x$ (cm)

$y$ (cm)

Density Profile of the NuMI Target

- Three upstream beam wire chambers give 0.2 mm resolution of the incident beam track position at the front face of the target.
- Center of circle represents measured mean position of reconstructed incident beam particles in selected events.
- Width of circle represents measured 1mm beam width.

Graphs and data showing yields and distributions.
Improvements at 31 GeV/c from NA61/SHINE

<table>
<thead>
<tr>
<th>Data</th>
<th>Year</th>
<th>evts (x10^6)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 cm target</td>
<td>2009</td>
<td>5.4</td>
<td>Preliminary ( \pi^\pm, K^\pm, p, K^0_s, \Lambda ) To be published soon</td>
</tr>
<tr>
<td>full target</td>
<td>2007</td>
<td>0.2</td>
<td>( \pi^\pm ) method: Nucl. Inst. Meth. A701 (2013) 99</td>
</tr>
<tr>
<td>full target</td>
<td>2009</td>
<td>2.8</td>
<td>End of 2014?</td>
</tr>
<tr>
<td>full target</td>
<td>2010</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

- Improved syst. and stat. errors in 2009 data
- T2K using these so far, Syst errors 5-8%, but dominated by stat error
Future Measurements at Higher Energies with SHINE

- Proposal to take p and π data at 60-120 GeV/c to benefit future Fermilab neutrino program
  - Thin Be, C, and Al targets
  - Potentially also NOvA or LBNE replica target data
  - Goal is <5% uncertainties
  - Tentatively plan start collecting data in fall 2015 (subject to SPSC approval)

120 GeV p+C event in NA61
**LBNE Phase Space**

π and K contributions to flux at LBNE far site

- Regions of phase space that contribute to LBNE flux are well matched to NA61 phase space

**NA61 Acceptance**

- 4.63 Tm (80 GeV field)
- 9.0 Tm (158 GeV field)
• Current NA61/SHINE has good coverage of $\pi, K, K_0, p, n, \Lambda_0$ that contribute to LBNE flux (red line).

• With additional forward tracking could be improved (green line).
Figure 6: Reconstruction acceptance of the NA61 spectrometer for charged pions at the indicated magnetic field setting.

Note that the neutrino experiments themselves, particularly those collecting large event samples, provide additional constraints on the flux simulations. However, they do not supply direct information on primary interactions.

Below we present brief comments on how improved beam simulation will impact the ongoing and upcoming Fermilab experiments.

4.1 MINERvA

MINERvA \footnote{30} is a dedicated neutrino-nucleus scattering experiment positioned just upstream of the MINOS near detector in the NuMI neutrino beam at Fermilab. The goal of the experiment is high-statistics, absolute measurements of inclusive and exclusive interaction rates for neutrinos.
Neutron Measurements?

- A new projectile spectator detector (an ECAL) was commissioned for NA61 in 2013
- Could potentially use this to make direct measurements of forward \( n \) production
Need for $\pi$ data

Parents of $\pi^+$ which are created in the target and make $\nu_\mu$ hitting MINOS/MINERvA

- $\pi^+$ from $\pi$ reinteractions are a sig part of $\nu_\mu$ flux

M. Kordosky, William&Mary
Summary

- Better flux predictions are needed for future cross section measurements and oscillation measurements with accelerator beams.
- Requires improved sensitivity with in situ measurements and additional hadron production data.
  - Increased statistics and data analysis improvements from NA61 will improve flux predictions for T2K/T2HK over the next 2 years.
  - Possible opportunity to take data starting in 2015 at in SHINE at 60-120 GeV/c could similarly benefit NuMI and LBNE.