Hadron Production Tuning

Patricia Vahle
University College, London
Uncertainties in a Neutrino Beam

1. **Hitting the target with proton beam**
   - Position/size of beam
   - Scraping
2. **Production of hadrons from collisions in the target**
3. **Focusing/decay of those hadrons to make a neutrino beam**
   - Misalignment of beam elements
   - Uncertainties in horn current
   - Mis-modeling of horn current distribution
“Dead Reckoning” the ND spectrum

- “Easy”
- Can evaluate uncertainties with simulation
- Secondary beam monitors give another handle
Hadron Production

Recent HARP, NA49 results, and MIPP expected results improve the coverage.

External Data is extrapolated to NuMI Beam energy, target thickness, and target material.
Simulating hadron production

Different state of the art shower cascade models predict very different fluxes

Predicted ND Flux

Fluka 2005
Mars

• 10% difference < 5 GeV
• 20-50% difference 5-10 GeV
• > 50% difference > 10 GeV

Predicted F/N ratio

• ~1% difference in peak
• Up to 10% differences above

Using spread of 4 models: 8% uncertainty in peak, 15% in tail

(ND dead reckoning)
Energy Spectra in ND

- 15% data/MC discrepancies in peak
- Up to 40% discrepancy in tail
- Discrepancies change with beam configuration
Flexibility of NuMI

- Changing position of target and horns changes neutrino beam energy
- Focus different regions of parent hadron $p_T$ vs. $p_z$ phase space
- We can use this extra information to try to constrain hadron production
Distorting Hadron Production

- Start by parameterizing Fluka pt vs. pz distributions
- Distort the parameters in the model to fit our data

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

\[ A(x) = a_1(1 - x)^{a_2}(1 + a_3x)x^{-a_4} \]
\[ B(x) = b_1(1 - x)^{b_2}(1 + b_3x)x^{-b_4} \]
\[ C(x) = c_1/x^{c_2} + c_3 \text{ (for } x < 0.22\text{)} \]
\[ = c_1e^{c_2(x-c_3)} + c_4x + c_5 \text{ (for } x > 0.22\text{)} \]
\[ \text{where } x = p_z/120 \]

\[ A' = (k_1 + k_2x)A \]
\[ B' = (k_3 + k_4x)B \]
\[ C' = (k_5 + k_6x)C \]

\[ W = \frac{[A' + B'p_T]}{[A + Bp_T]} \exp\left(-C' - C) p_T^{3/2}\right) \]

Full fit function: 6 had. prod., 1 Kaon scale, 5 targeting+focusing, and 3 “detector” parameters
- Initial $\chi^2$/NDF=3146/360
- After fit $\chi^2$/NDF=569/345
- Agreement between data and MC improves in every configuration
- Discrepancies after fit at 5% level
Hadron Production Tuning

- Weights ~20% in region of $p_T$ vs $p_z$ that produces MINOS neutrinos
- Hadron production tuning changes mean $p_T$ less than model spread

<table>
<thead>
<tr>
<th>Model</th>
<th>$&lt;p_T&gt;$ (GeV/c)</th>
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<tbody>
<tr>
<td>GFLUKA</td>
<td>0.37</td>
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<tr>
<td>Sanf.-Wang</td>
<td>0.42</td>
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<tr>
<td>CKP</td>
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<tr>
<td>Malensek</td>
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<tr>
<td>MARS – v.14</td>
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<td>MARS – v.15</td>
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<td>Fluka 2001</td>
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<tr>
<td>Fluka 2005</td>
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<tr>
<td>Fluka2005 Tuned</td>
<td>0.355</td>
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</tbody>
</table>

Region of LE10 Beam
Summary

- Errors in neutrino flux prediction come primarily from
  - Targeting
  - Hadron production
  - Focusing
- Hadron production errors difficult to quantify, potentially large
- Using flexibility of NuMI beam, we can place further constraints on hadron production, tune model to match our data
- After tuning, reduce data/MC discrepancies to ~5% level in 6 different beam configurations
- Errors in ND spectrum reduced to < 10% after fit
Prediction of FD spectrum

- Neutrino Energy depends on angle wrt original pion direction
- Angular distributions different between Near and Far

Far Spectrum without oscillations is similar, but not identical to the Near spectrum!
Prediction of FD spectrum

Far/Near ratio depends on beam line geometry, decay kinematics, beam divergence, but it’s well understood.
## Targeting and Focusing

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
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<tbody>
<tr>
<td>POT</td>
<td>2%</td>
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<tr>
<td>Horn Offset</td>
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<tr>
<td>Horn Angle</td>
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<tr>
<td>Chase</td>
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<tr>
<td>Horn Current Offset</td>
<td>1.0%</td>
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<tr>
<td>Horn Current distribution</td>
<td>Difference in model between skin depth=6mm vs infinite</td>
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<tr>
<td>Baffle scraping</td>
<td>0.25%</td>
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</table>