Conventional Neutrino Beams
Lecture II

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Neutrino Physics Summer School
Fermilab
July 12, 2007
Question from July 11 Lecture

- How many pions do you make for a given incoming proton at some energy?


Note scale: \( \sim 3-4 \, \pi/\text{POT} \)

Integrated Over all \( x_f \) at 120 GeV

\[ x_f = \frac{p_\pi}{p_p} \]
Question from July 11

- How many pions do you make for a given incoming proton at some energy?
- I lied yesterday: $p_t$ is more like 280MeV, not 200MeV

Question from July 11

- How efficient is this horn focusing?
- Reference: NuMI Technical Design Report
- 3 different beams are from 3 different target/horn positions
- Note famous “GEANT Bump” from problem in hadron production model
Almost a Question from July 11

• How efficient is horn focusing compared to other focusing?
• 500GeV proton-fed beam shown

Question from July 11

- Are the near and far detector fluxes identical? (Example: T2K experiment)
- Remember: $\theta$ depends a lot on whether or not you’ve focused the pions that made those neutrinos

$$\Phi_\nu = BR \frac{1}{4\pi L^2} \left( \frac{2\gamma}{1 + \gamma^2 \theta^2} \right)^2$$
Question from July 11

• How many particles are we talking about here?

<table>
<thead>
<tr>
<th>Protons</th>
<th>$\pi,K$ focus (maybe bend)</th>
<th>$\pi,K,(\mu)$ Let them decay</th>
<th>$\nu_\mu,%\nu_\text{e}$ Shielding</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sim 10^{13}$ per pulse</td>
<td>Few $\pi$ per 120 GeV protons</td>
<td>Depends on decay length: $\sim 1$ per $\pi$</td>
<td>$20$ interactions/ $2 \times 10^{13}$</td>
</tr>
</tbody>
</table>
Getting from Event Rates to $\nu$ Flux

\[N = \phi_{\nu\mu} \sigma_{\nu_x} \varepsilon_x M\]

\[\phi_{\nu\mu} = \frac{N(\text{events})}{\sigma_{\nu_x} (cm^2 / \text{nucleon}) \varepsilon_x M (kton) \times \frac{kton}{10^9 g} \times \frac{g}{6.02 \times 10^{23} \text{nucleons}}}\]

\[\phi_{\nu\mu} = \frac{20}{6 \times 10^{-38} \ cm^2 \times 6 \times 10^{32}}\]

\[\phi_{\nu\mu} = 0.6 \times 10^6 \ \frac{\nu}{cm^2}\]

Or at 1km away, $2 \times 10^{13}$ protons make about $2 \times 10^{10}$ neutrinos (2mx2m)
In the words of Ken Peach

“When I was on an experiment to determine $\varepsilon'/\varepsilon$, once we were close to getting the result out, I realized something:

All the theorists asked ‘what value did you measure?’
and

All the experimentalists asked ‘what uncertainty on the measurement did you end up getting?’ ”

This talk will try to speak to both theorists and experimentalists…

but remember who wrote the talk…”
Goals of Long Baseline Oscillation Measurements

• Measurements of “atmospheric neutrino oscillation parameters”: $\nu_\mu$ disappearance as a function of neutrino energy
• Searches for CP violation and understanding the neutrino mass hierarchy: $\nu_e$ appearance
• Verify Oscillation Framework: $\nu_\tau$ appearance
• Search for Sterile Neutrinos: Neutral Current disappearance, looking for three distinct $\Delta m^2$
Conventional Neutrino Beam Summary

Major Components:
- Proton Beam
- Production Target
- Focusing System
- Decay Region
- Shielding
- Monitoring

Ways to Understand $\nu$ Flux:
- Hadron Production
- Proton Beam measurements
- Pion Measurements
- Muon Measurements
  at angles vs momentum
  at $0^\circ$ versus shielding
Systematic Uncertainties

• Neutrino Flux
  – Hadron Production
    • $\pi/K$ ratio
    • $x$ and $p_t$ spectrum of produced Pions/Kaons
  – Beamline Geometry
    • Focusing uncertainties
    • Alignment Uncertainties
• Neutrino Interactions:
  Background and Signal!
  – Quasi-elastic Uncertainties
  – Resonance (low W) Uncertainties
  – DIS (high W)
  – Nuclear Effects
• Event Selection
• Event Energy Resolution
  – Important especially for measurements versus neutrino energy
  – Narrow Band beams: energy resolution is key to background rejection

Problem: uncertainties all affect the near and far detector both, you can’t always separate one from the other
Two detector experiment (in theory)

\[ N(\text{NC})_n = \Phi_n \sigma^{\text{NC}} \]
\[ N(\text{CC})_n = \Phi_n \sigma^{\text{CC}} \]

- Make two detectors as identical as possible
  - same scintillator, water, steel etc.
- Measure \( \nu \) spectrum in the near detector
- Predict the \( \nu \) spectrum in the far detector
- Cross section uncertainties should cancel…
- Detector efficiency uncertainties should cancel…
- Simple, right?

Near detector

\[ \Phi(L) = \Phi_0 / L^2 \]

Far detector

\[ N(\text{NC})_f = \Phi_f \sigma^{\text{NC}} \]
\[ N(\text{CC})_f = \Phi_f \sigma^{\text{CC}} \]
Two Detector Experiment (in practice)

• Near Detector sees a line source of neutrinos, far detector sees a point source
  – Think: where do $\nu_\mu$’s in beam decay compared to $\nu_e$’s?

• Near Detector will have different event rate
  – Beam-induced rates differ by $10^4$ to $10^5$
  – Cosmic ray rates differ due to different shielding and detector size

• Near Detector Design is different
  – Different electronics, PMT’s, active area coverage…

• $\nu_\mu \rightarrow \nu_\tau$ may be large: $\nu_\tau$ CC suppression large
  – $\nu_\mu$ CC energy distribution is very different
Near Detector Design

• Far detector must be massive: the more instrumented it is, the more $/kton…

• Tradeoff between segmentation and far detector mass

• Near Detector Design options:
  – “Identical” to far detector
    • Argue that detector efficiencies and cross sections are the “same”, you just need independent flux measurements
  – Much more segmented and fine-grained
    • Try to measure fluxes and cross sections as best you can, make far detector prediction

• Ideally, you would do both…
K2K near neutrino detectors (K2K-II)

SciBar detector
Full active scintillator tracker
CH target (9.38t fid. vol.)

Muon range detector
Iron target (330t fid. vol.)

ν beam monitor (momentum & direction.)

ν beam

1kt water
Cherenkov detector
(25t fiducial volume)

μν beam monitor (momentum & direction.)

CCQE identification

water target (25t fiducial volume)

water target (6t fid. vol.)

Scintillating fiber tracker
T2K Near Detector Suite

- What’s interesting here is how it differs from the K2K Near Detector suite: no Cerenkov detector

- **On-axis detector**
  - Measure $\nu$-beam profile
  - $\nu$-beam direction at 1 mrad precision.
  - iron - scintillator stacks $\times$ 14 units

- **Off-axis detector:** In Magnet ($B=0.2T$)
  - Measure $\nu$-flux in SK direction: $\Phi_{\nu}^{ND}(E_{\nu})$.
    - Measure $\nu_{\mu}$, $\bar{\nu}_{\mu}$ and $\nu_{e} + \bar{\nu}_{e}$ fluxes separately.
    - Neutrino Energy $\leftarrow$ CC-QE kinematics.
  - Cross sections of $\nu$ interactions
    - CC-$1\pi$/CC-QE ... BG for $E_{\nu}$ reconstruction
    - NC-$\pi^{0}$ production ... BG for $\nu_{e}$ detection
Detectors located 2km from target sees point source of neutrinos, like Far Detector

**Question:**
what about $\nu_\mu \rightarrow \nu_\tau$ at the 2km detector?

**2km detectors:**
Liquid Argon
Water Cerenkov
Muon Range Detector
MINOS Near Detector (cf Far)

- 1040m from target (735km)
- 103m underground (705m)
- 980 ton mass (5400 ton mass)
- 3.8m x 4.8m x 16m (8m octagon)
- 282 steel + 153 scintillator planes (484 planes)
- Two distinct sections:
  - Front: Calorimeter
    - Every plane instrumented
  - Back: Spectrometer
    - One in five planes instrumented
- Fast QIE electronics
  - Continuous (19ns) sampling in spill
Events in 10μs at Near Detector, for $10^{13}$ Protons on Target

MINOS Near Rates
NOvA Near Detector

- Same segmentation and structure as far detector, but
  - sees line source
  - Needs very tight fiducial cuts
- Designed to operate at several different angles

Can operate between 4-21 mrad Off axis
(Far Detector is 14mrad)
## Near Detector Summary

<table>
<thead>
<tr>
<th>Exp’t</th>
<th>Detector</th>
<th>Near Detector Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>K2K</td>
<td>Water Cerenkov</td>
<td>Several, one “identical”</td>
</tr>
<tr>
<td>MINOS</td>
<td>Steel Scintillator</td>
<td>“Identical”, but faster electronics</td>
</tr>
<tr>
<td>OPERA</td>
<td>Emulsion-Lead</td>
<td>No Near Detector</td>
</tr>
<tr>
<td>T2K</td>
<td>Water Cerenkov</td>
<td>2 at 280m for flux (coarse) and cross sections (fine-grained), 1 at 2km that is “identical+”</td>
</tr>
<tr>
<td>NOvA</td>
<td>Segmented Scintillator</td>
<td>1 that is “identical” but moves, plus fine-grained MINERvA in almost same beam</td>
</tr>
</tbody>
</table>
Remainder of Talk

• $\nu_\mu$ disappearance
  – K2K Near Detector Analysis and Result
  – MINOS Near Detector Analysis and Result

• $\nu_e$ Appearance
  – K2K Result
  – MINOS, NOvA, T2K, OPERA Sensitivity and Background Comparison

• What will we need to take advantage of more statistics?
  – Hadron Production Experiments
  – Dedicated Cross Section Measurements

• Reward for working hard: combining NOvA and T2K
  – Mass Hierarchy
Reminder from Nakaya’s Lecture I

**K2K Neutrino Energy $E_\nu$ Reconstruction**

**CC quasi elastic (QE)**

\[ \nu_\mu + n \rightarrow \mu + p, \quad (E_\mu, p_\mu) \]

**CC inelastic**

\[ \nu_\mu + n \rightarrow \mu + p + \pi, \quad (E_\mu, p_\mu) \]

**Energy Reconstruction Formula**

\[ E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos \theta_\mu} \]

**Event Selection**

- \( \text{Rate}(E_\nu, \text{Near}) \rightarrow \phi(E_\nu, \text{Near}) \)
- \( \sigma(\text{QE}), \sigma(\text{nonQE}) \)

12 July
Constraining Cross Section Model in K2K Near Detector

\[ E_V = \frac{m_N E_\mu - m_\mu^2}{2} \frac{1}{m_N - E_\mu + p_\mu \cos \theta_\mu} \]

\[ \mu^- \rightarrow \mu^- \quad 1 \text{ track} \]

\[ \text{non-QE} \quad 2 \text{ track} \]

\[ \text{You can derive this...} \]

1-ring events at 1kT

\[ p_\mu (\text{GeV/c}) \]

SciBar

1 track

2 track

2 track non-qe

hep-ex/0606032
Measurement of $\nu_\mu \to \nu_\mu$ survival in K2K

Use both Number of events + Spectrum shape

Null oscillation probability is 0.003% (4.19s)

Allowed regions

Best fit parameters (in physical region)

$\sin^2 2\theta = 1.0$
$\Delta m^2 = (2.76 \pm 0.36) \times 10^{-3} \text{eV}^2$

Reconstructed $E_\nu$

- No oscillation
- Best fit point

12 July 2007

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Measurement of $\nu_\mu \rightarrow \nu_\mu$ survival in MINOS

See 10%-40% data-MC differences in near detector: how to extrapolate to Far?

Error envelopes include uncertainties in cross-sections, beam and detector
Near Detector Tuning at MINOS

- By taking data at several horn currents and target positions, MINOS isolated the problem to Hadron Production Model.

\[ \bigcirc \] = pions focused by horns
MINOS $\nu_{\mu}$ Systematic Errors

- Systematic shifts in the fitted parameters are computed using MC “fake data” samples for $\Delta m^2=2.7 \times 10^{-3}$ eV$^2$ and $\sin^2 2\theta=1.0$
- The uncertainties considered and shifts obtained:

<table>
<thead>
<tr>
<th>Preliminary Uncertainty</th>
<th>Shift in $\Delta m^2$ (10$^{-3}$ eV$^2$)</th>
<th>Shift in $\sin^2 2\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near/Far normalization $\pm 4%$</td>
<td>0.050</td>
<td>0.005</td>
</tr>
<tr>
<td>Absolute hadronic energy scale $\pm 11%$</td>
<td>0.060</td>
<td>0.048</td>
</tr>
<tr>
<td>NC contamination $\pm 50%$</td>
<td>0.090</td>
<td>0.050</td>
</tr>
<tr>
<td>All other systematic uncertainties</td>
<td>0.044</td>
<td>0.011</td>
</tr>
<tr>
<td>Total systematic (summed in quadrature)</td>
<td>0.13</td>
<td>0.07</td>
</tr>
<tr>
<td>Statistical error (data)</td>
<td>0.36</td>
<td>0.12</td>
</tr>
</tbody>
</table>

- Magnitude of systematic error is $\sim 40\%$ of statistical error for $\Delta m^2$
- Several systematic uncertainties are data driven → improve with more data and study

Chris Smith, FNAL Seminar

12 July 12007

Debbie Harris, Conventional Neutrino Beams II
MINOS $\nu_\mu$ Survival Results

\[ |\Delta m^2_{32}| = 2.74^{+0.44}_{-0.26} \text{ (stat + syst)} \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2 2\theta_{23} = 1.00^{+0.13}_{-0.13} \text{ (stat + syst)} \]

Normalisation = 0.98
Challenges to $\nu_e$ Appearance

Problem: looking for a $\nu_e$ in a beam of $\nu_\mu$'s

- Intrinsic beam $\nu_e$
  - K decays
    \[ K \rightarrow \pi e \nu_e \]
  - $\mu$ decays
    \[ \pi \rightarrow \mu \rightarrow e\nu_e \nu_\mu \]

- Neutral Current events

- $\nu_\mu$ charged current events

- $\nu_\tau$ charged current events
Probabilities

\[ N_{\text{far}} = \phi_{\nu_{\mu}} \sigma_{\nu_{x}} P(\nu_{\mu} \rightarrow \nu_{x}) \varepsilon_{x} M_{\text{far}} + B_{\text{far}} \]

\( \phi = \text{flux}, \sigma = \text{cross section} \quad \varepsilon = \text{efficiency} \quad M = \text{mass} \)

\[ P(\nu_{\mu} \rightarrow \nu_{x}) = \frac{N_{\text{far}} - B_{\text{far}}}{\phi_{\nu_{\mu}} \sigma_{\nu_{x}} \varepsilon_{x} M_{\text{far}}} \]

\( B_{\text{far}} = \text{Backgrounds at far detector, from any flux} \)

\[ B_{\text{far}} = \sum_{i=\mu,e} \phi_{\nu_{i}} (P) \sigma_{\nu_{i}} \varepsilon_{ix} M_{\text{far}} \]
Probabilities, continued

\[
\left( \frac{\delta P}{P} \right)^2 = \left( \frac{N_{\text{far}} + (\delta B_{\text{far}})^2}{(\phi_{\nu_{\mu}} \sigma_{\nu_{x}} \epsilon_{\nu_{x}} M_{\text{far}})^2} \right) + \frac{N_{\text{far}} - B_{\text{far}}}{(\phi_{\nu_{\mu}} \sigma_{\nu_{x}} \epsilon_{\nu_{x}})^2} \left[ \delta(\phi_{\nu_{\mu}} \sigma_{\nu_{x}} \epsilon_{\nu_{x}}) \right]^2
\]

\[
\left( \frac{\delta P}{P} \right)^2 = \left( \frac{N_{\text{far}} + (\delta B_{\text{far}})^2}{(\phi_{\nu_{\mu}} \sigma_{\nu_{x}} \epsilon_{\nu_{x}} M_{\text{far}})^2} \right) + \left( N_{\text{far}} - B_{\text{far}} \right) \left[ \frac{\delta \phi_{\nu_{\mu}}}{\phi_{\nu_{\mu}}} \right]^2 + \left( \frac{\delta \sigma_{\nu_{x}}}{\sigma_{\nu_{x}}} \right)^2 + \left( \frac{\delta \epsilon_{\nu_{x}}}{\epsilon_{\nu_{x}}} \right)^2
\]

2 Regimes:

\[
N_{\text{far}} \approx B_{\text{far}}
\]

\[
N_{\text{far}} \gg B_{\text{far}}
\]

Problem:
Don’t always know \textit{a priori} which regime you are in
---depends on $\Delta m^2$
---depends on $\sin^2 2\theta_{13}$
Near Detector Strategy

\[ B_{\text{far}} = \sum_{i=\mu, e} \phi_{\nu_i \text{ far}} (P) \sigma_{\nu_i} \varepsilon_{ix} M_{\text{far}} \]

Backgrounds come from several sources

\[ N_{\text{near}} = \sum_{i=\mu, e} \phi_{\nu_i \text{ near}} \sigma_{\nu_i} \varepsilon_{ix} M_{\text{near}} \]

Build near detector with same \( \varepsilon \)

\[ B_{\text{far}} = N_{\text{near}} \frac{\sum_{i=\mu, e} \phi_{\nu_i \text{ far}} (P) \sigma_{\nu_i} \varepsilon_{ix} M_{\text{far}}}{\sum_{i=\mu, e} \phi_{\nu_i \text{ near}} \sigma_{\nu_i} \varepsilon_{ix} M_{\text{near}}} \]

Simulations better at predicting ratios absolute levels

\[ B_{\text{far}} = \sum_{i=\mu, e} N_{\text{near, } i} \frac{\phi_{\nu_i \text{ far}} \sigma_{\nu_i} \varepsilon_{ix} M_{\text{far}}}{\phi_{\nu_i \text{ near}} \sigma_{\nu_i} \varepsilon_{ix} M_{\text{near}}} \]
Near Detector Strategy (cont’d)

\[ B_{\text{far}} = \int dE_v \sum_{i=\mu,e} N_{\text{near},i}(E_v) \left( \frac{\phi_{v_{i,\text{far}}}}{\phi_{v_{i,\text{near}}}} \right) (E_v) \left( \frac{\sigma_{v_i}}{\sigma_{v_i}} \right) (E_v) \left( \frac{\epsilon_{ix}}{\epsilon_{ix}} \right) (E_v) \frac{M_{\text{far}}}{M_{\text{near}}} \]

• But ratios don’t cancel everything
• Underlying problem: fluxes are different
  – Near detector: line source, far detector: point source
  – But even if that is solved, still \( \nu_\mu \) CC oscillations
• All of these terms are functions of energy
  – Uncertainties in energy dependence of cross sections translate into far detector uncertainties…
Search for $\nu_\mu \rightarrow \nu_e$ oscillation in K2K

As a result,

# of expected BG 1.63 events

(1.25 from $\nu_\mu$ & 0.38 from beam $\nu_e$)

# of observed events 1 event

Signal candidate event

RUN: 21858
EVENT: 2240771
$E_{\gamma 1}$: 266.7MeV
$E_{\gamma 2}$: 170.8MeV
$q_{\gamma \gamma}$: 22.5 deg.
$M_{\gamma \gamma}$: 83.1MeV/c$^2$

Though, this event looks like multi-ring…

Slide courtesy Y. Hayato
Search for $\nu_\mu \rightarrow \nu_e$ oscillation in K2K

Expected # of electron candidates ($N_{SK}$)

$$N_{SK} = N_{\nu\mu}^{BG} (\Delta m^2) + N_{BEAM\nu_e}^{BG} + N_{OSC\nu_e}^{SIG} (\sin^2 2\theta, \Delta m^2)$$

- **Expected BG**: 1.63
- **Observed**: 1

**Upper limit on $\sin^2 2\theta_{\mu e}$**

- $(90\% \, CL)$
  - $0.18@\Delta m^2=2.8\times10^{-3} eV^2$
  - $(0.25@\Delta m^2=2.0\times10^{-3} eV^2)$
  - $0.16@\Delta m^2=3.0\times10^{-3} eV^2$

**Chooz limit**

*Slide courtesy Y. Hayato*
Search for $\nu_\mu \rightarrow \nu_e$ oscillation in MINOS

- How to discriminate between electrons and $\pi^\pm\mu^\pm$?
  - Longitudinal, transverse event shape…
- How to discriminate between electrons and $\pi^0$?
  - Less obvious in MINOS…

**Neural Net MC example**

- Oscillation parameters:
  \[
  \sin^2(2\theta_{13}) = 0.1 \\
  |\Delta m_{32}|^2 = 2.7 \times 10^{-3} \text{eV}^2 \\
  \sin^2(2\theta_{23}) = 1
  \]

- POT = $16 \times 10^{20} \times 12$ what has already collected

<table>
<thead>
<tr>
<th>$\nu_\mu$ CC</th>
<th>NC</th>
<th>$\nu_e^{\text{beam}}$</th>
<th>$\nu_\tau$ CC</th>
<th>Total</th>
<th>$\nu_e^{\text{osc}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6</td>
<td>39.0</td>
<td>8.7</td>
<td>4.7</td>
<td>58.0</td>
<td>29.1</td>
</tr>
</tbody>
</table>
Today’s signal is tomorrow’s background…

- OPERA: main goal is to see $\nu_\tau$ CC events through $\tau \rightarrow e$ decay channel, so should be sensitive to

$$\Delta m^2_{23} = 2.5 \times 10^{-3} \text{ eV}^2.$$
People writing proposals much prefer to be in the situation where you have <1 event background.

Then sensitivity $\propto$ time

Note: $\nu_e$ searches are already at 1 or more background events:
- K2K: 1.6 background events per $10^{20}$
- MINOS: 3.6 background events per $10^{20}$ POT
- OPERA: 13 background events per $10^{20}$ POT

Need to improve
- Intrinsic $\chi$ in the beam: use Off-axis trick
  - $\nu_\mu$ peaked in energy. Electron neutrinos over a broad spectrum.
  - $\nu_e$ CC/NC event separation: use lower energy, or better detector, or off axis beam (since NC events reconstruct with energy lower than the peak)
- Statistics: more detector mass or proton power or both

Next Generation $\nu_e$ searches:
- T2K: 23 background events in 5-year run
- NOvA: 19 background events in 6-year run
How well do new designs do?

<table>
<thead>
<tr>
<th></th>
<th>$\nu_\mu$ CC</th>
<th>NC</th>
<th>Beam $\nu_e$</th>
<th>$\nu_\tau$ CC</th>
<th>Total Background</th>
<th>Signal</th>
<th>$S/\sqrt{(S+B)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>K2K</td>
<td>0</td>
<td>1.3</td>
<td>0.4</td>
<td>0</td>
<td>1.7</td>
<td>~1</td>
<td>0.6</td>
</tr>
<tr>
<td>MINOS</td>
<td>5.6</td>
<td>39</td>
<td>8.7</td>
<td>4.7</td>
<td>58</td>
<td>29.1</td>
<td>3.1</td>
</tr>
<tr>
<td>OPERA</td>
<td>1</td>
<td>5.2</td>
<td>18</td>
<td>4.5</td>
<td>28.7</td>
<td>10</td>
<td>1.6</td>
</tr>
<tr>
<td>T2K</td>
<td>1</td>
<td>9</td>
<td>13</td>
<td>0</td>
<td>23</td>
<td>103</td>
<td>9.2</td>
</tr>
<tr>
<td>NOvA*</td>
<td>0.5</td>
<td>7</td>
<td>11</td>
<td>0</td>
<td>18.5</td>
<td>148</td>
<td>11.5</td>
</tr>
</tbody>
</table>

Assume $\sin^2\theta_{13}=0.1$, $\delta=0$, *normal hierarchy, but not all same $\Delta m^2$

How does MiniBooNE compare?

<table>
<thead>
<tr>
<th></th>
<th>$\nu_\mu$ $\bar{\nu}_\mu$</th>
<th>NC</th>
<th>Beam $\nu_e$</th>
<th>$\bar{\nu}_e$ $\bar{\nu}_e$</th>
<th>Total Bkgrnd</th>
<th>Sgnl</th>
<th>$S/\sqrt{(S+B)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mini-BooNE</td>
<td>23</td>
<td>89</td>
<td>229</td>
<td>0</td>
<td>358</td>
<td>163</td>
<td>7.1</td>
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MiniBooNE Signal assumes mixing angle is factor of ~20 lower than the that of the other experiments
Reference: FNAL Seminar, April 2007

Total Background above 475MeV:
358 events
Total signal for 0.26% probability:
163 events

See also Richard Van De Water’s Lecture II
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Now that we have reduced backgrounds and increased mass...

- Remember, just because your simulation says it is true, that doesn’t mean the simulation is right
- Need to measure neutrino interactions better
  - What really comes flying out of the nucleus when it is hit by a neutrino?
- Need to measure hadron production better
  - What really comes flying out of the target when it is hit by protons?
$\nu_e$ Appearance Analysis

Summary:
Event Samples are different
Near to far, so
Uncertainties
In cross sections
Won’t cancel

If signal is small,
Worry about background
Prediction ($\nu_e$ flux and nc xsection), if signal is
Big, worry about signal cross sections
How much do cross section errors cancel near to far?

- **Toy analysis:** start with old NOvA detector simulation, which had same $\nu_e$/NC ratio, mostly QE & RES signal events accepted, more $\nu_\mu$ CC/NC accepted.

- Near detector backgrounds have $\sim$3 times higher $\nu_\mu$ CC!

- Assume if identical ND, can only measure 1 background number: hard to distinguish between different sources.

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
<th>QE</th>
<th>RES</th>
<th>COH</th>
<th>DIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta\sigma/\sigma$</td>
<td></td>
<td>20%</td>
<td>40%</td>
<td>100%</td>
<td>20%</td>
</tr>
<tr>
<td>Signal $\nu_e$, $\sin^22\theta_{13}=0.1$</td>
<td>175</td>
<td>55%</td>
<td>35%</td>
<td>n/i</td>
<td>10%</td>
</tr>
<tr>
<td>NC</td>
<td>15.4</td>
<td>0</td>
<td>50%</td>
<td>20%</td>
<td>30%</td>
</tr>
<tr>
<td>$\nu_\mu$ CC</td>
<td>3.6</td>
<td>0</td>
<td>65%</td>
<td>n/i</td>
<td>35%</td>
</tr>
<tr>
<td>Beam $\nu_e$</td>
<td>19.1</td>
<td>50%</td>
<td>40%</td>
<td>n/i</td>
<td>10%</td>
</tr>
</tbody>
</table>

For large $\sin^22\theta_{13}$, statistical=8%
For small $\sin^22\theta_{13}$, statistical=16%

Assume post-MINERvA, $\sigma$’s known at:
- $\Delta$QE $= 5\%$, $\Delta$RES $= 5\%$, 10% (CC, NC)
- $\Delta$DIS $= 5\%$, $\Delta$COH$_{Fe} = 20\%$
Nuclear effects at MINOS

- Visible Energy in Calorimeter is NOT $\nu$ energy!
  - $\pi$ absorption, rescattering
  - final state rest mass

Toy MC analysis:

Nuclear Effects Studied in Charged Lepton Scattering, from Deuterium to Lead, at High energies, but nuclear corrections may be different between e/μ and $\nu$ scattering
Dedicated Neutrino Interaction Measurements

- MINERvA: exclusive final state measurements, 3 nuclear targets, to run in NuMI beamline in time for MINOS and NOvA (and T2K’s) data

- T2K 280m Off axis detector: inclusive $\pi^0$ measurements and some exclusive states, water target

- SciBooNE: use SciBAR in MiniBooNE beam to look at anti-$\nu$’s NOW!
Need Dedicated Hadron Production Experiments!

Example: NuMI: Absolute rates known only to 20% in high energy tail, Far/near ratio known better, but still only at 5% ratio without MIPP
Hadron Production Experiment
Case Study: MIPP

FNAL expt E907, ran with NuMI Target for MINOS Will run with thin targets as well

Figures courtesy M. Messier

HARP is CERN H.P. experiment that looked at K2K and MiniBooNE targets
What should you take away from this course?

<table>
<thead>
<tr>
<th></th>
<th>Experimentalist</th>
<th>Theorist</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beams</strong></td>
<td>Conventional Neutrino Beams are a critical and challenging problem.</td>
<td>Beams aren’t flavor eigenstates, and contamination depends on which detectors your friends use.</td>
</tr>
<tr>
<td></td>
<td>Need targets, horns, decay regions and lots of Design work!</td>
<td></td>
</tr>
<tr>
<td><strong>Systematics</strong></td>
<td>Don’t believe it’s true just because the Monte Carlo says so. Don’t be caught by</td>
<td>You can’t do % or better measurements without spending all your time worrying about systematics.</td>
</tr>
<tr>
<td></td>
<td>surprise... the other measurements you need (cross-sections, hadron production,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>test beam) may take years.</td>
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</tbody>
</table>
### Last Words…

<table>
<thead>
<tr>
<th></th>
<th>Experimentalist</th>
<th>Theorist</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ appearance</td>
<td>Find a may to make experimental efforts compliment each other.</td>
<td>Help the experimentalists do this, but only in a way that is realistic!!!</td>
</tr>
<tr>
<td>$\nu_\mu$ disappearance</td>
<td>Don’t ignore the difficulty of this measurement if it is important!</td>
<td>Tell experimentalists again how critical it is to know if $\theta_{23}$ is 45°</td>
</tr>
<tr>
<td>$\nu_\tau$ appearance</td>
<td>Everything comes to those who can wait.</td>
<td>Don’t assume you know the answer. And what if the answer is not what you expected?</td>
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</tbody>
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