Neutral Current $1\pi^0$ Production at MiniBooNE
Sixth International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region

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Yale

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The Measurement

- Isolating the NC $1\pi^0$ Sample
- Cross Section Calculation
  - Background Subtraction
  - Unsmearing
  - Efficiency Correction, Flux

- Coherent Production Models
- Resonant Production Measurement
What Was Measured

We measured the cross section for NC interactions resulting in one $\pi^0$ exiting the target nucleus and no other mesons

- Includes production from the initial interaction as well as production from final state interactions in the nucleus
- Excludes interactions in which an initially produced $\pi^0$ was lost to final state interactions
- $d\cos\theta_{\pi^0}$, $dp_{\pi^0}$ differential cross sections measured for neutrino and antineutrino induced production

Direct $\pi^0$ Production Interactions

- Resonant
  \[ \nu_\mu N \rightarrow \nu_\mu + (\Delta \rightarrow N + \pi^0) \]

- Coherent/diffractive
  \[ \nu_\mu A \rightarrow \nu_\mu + A + \pi^0 \]
NC $\pi^0$ Production

What Was Measured

We measured the cross section for NC interactions resulting in one $\pi^0$ exiting the target nucleus and no other mesons:

- Includes production from the initial interaction as well as production from final state interactions in the nucleus.
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- $d\cos\theta_{\pi^0}, dp_{\pi^0}$ differential cross sections measured for neutrino and antineutrino induced production.

Models Used in MC

- **Resonant**
  - Rein-Sehgal (Annals Physics, 133, 79 (1981))
  - $M_A = 1.1$ GeV
  - Includes $\Delta(1232)$ and 17 higher mass resonances
  - Non-isotropic $\Delta$ decay

- **Coherent**
  - $M_A = 1.03$ GeV
  - NUANCE FSI model used in lieu of $F_{abs}$ term

- **Diffractive**
  - Rein (NP B278, 61 (1986))
What Was Measured

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Signature

- $\pi^0$ decays to two $\gamma$s that induce electromagnetic showers via pair-production
Filling the $\pi^0$ Box

Cuts

- Preliminary Cuts
  - One subevent
    *Eliminates events with decays, which we do not expect from most NC $\pi^0$ events*
  - Veto hits < 6
  - Tank hits > 200

- Analysis Cuts
  - Fiducial volume cut
  - Choose events with $e - \mu$ fit likelihood difference favoring $e$-like hypothesis
  - Choose events with $e - \pi$ fit likelihood difference favoring $\pi$-like hypothesis
  - Choose events with two-track invariant mass similar to $\pi^0$ mass
Filling the $\pi^0$ Box

Cuts

- **Preliminary Cuts**
  - One subevent
  - _Veto hits < 6_
    - *Eliminates cosmics, uncontained events (which disproportionately eliminates muon containing events)*
  - Tank hits > 200

- **Analysis Cuts**
  - Fiducial volume cut
  - Choose events with $e - \mu$ fit likelihood difference favoring $e$-like hypothesis
  - Choose events with $e - \pi$ fit likelihood difference favoring $\pi$-like hypothesis
  - Choose events with two-track invariant mass similar to $\pi^0$ mass
Filling the $\pi^0$ Box

Cuts

- Preliminary Cuts
  - One subevent
  - Veto hits < 6
  - Tank hits > 200

  *Eliminates substantial portion of NC elastic events*

- Analysis Cuts
  - Fiducial volume cut
  - Choose events with $e - \mu$ fit likelihood difference favoring $e$-like hypothesis
  - Choose events with $e - \pi$ fit likelihood difference favoring $\pi$-like hypothesis
  - Choose events with two-track invariant mass similar to $\pi^0$ mass
Filling the $\pi^0$ Box

Cuts

- Preliminary Cuts
  - One subevent
  - Veto hits $< 6$
  - Tank hits $> 200$

- Analysis Cuts
  - Fiducial volume cut
    *Eliminates events subject to poor reconstruction at the edge of the detector*
  - Choose events with $e - \mu$ fit likelihood difference favoring $e$-like hypothesis
  - Choose events with $e - \pi$ fit likelihood difference favoring $\pi$-like hypothesis
  - Choose events with two-track invariant mass similar to $\pi^0$ mass
Filling the $\pi^0$ Box

Cuts

- **Preliminary Cuts**
  - One subevent
  - Veto hits $< 6$
  - Tank hits $> 200$

- **Analysis Cuts**
  - Vertex within 500 cm
  - Choose events with $e - \mu$ fit likelihood difference favoring $e$-like hypothesis
  - Choose events with $e - \pi$ fit likelihood difference favoring $\pi$-like hypothesis
  - Choose events with two-track invariant mass similar to $\pi^0$ mass

![Graph showing $\nu$ Mode log($L_e/L_\mu$) Distribution By Channel](image-url)
Filling the $\pi^0$ Box

Cuts

- **Preliminary Cuts**
  - One subevent
  - Veto hits $< 6$
  - Tank hits $> 200$

- **Analysis Cuts**
  - Vertex within 500 cm
  - Choose events with $e - \mu$ fit likelihood difference favoring $e$-like hypothesis
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Cuts

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  - Vertex within 500 cm
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  - Choose events with two-track invariant mass similar to $\pi^0$ mass
# Filling the $\pi^0$ Box

## In The Box

<table>
<thead>
<tr>
<th>Events Passing Cuts</th>
<th>Purity</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino Mode</td>
<td>21542 w/ 6.461E20 POT</td>
<td>73%</td>
</tr>
<tr>
<td>Data/MC = 1.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antineutrino Mode</td>
<td>2305 w/ 3.386E20 POT</td>
<td>58%</td>
</tr>
<tr>
<td>Data/MC = 0.94</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Signal Composition

<table>
<thead>
<tr>
<th>$\nu$</th>
<th>$\bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC Res.</td>
<td>77% (77%)</td>
</tr>
<tr>
<td>NC Coh.</td>
<td>18% (17%)</td>
</tr>
<tr>
<td>NC $\pi^\pm$</td>
<td>2% (3%)</td>
</tr>
<tr>
<td>NC El.</td>
<td>2% (2%)</td>
</tr>
<tr>
<td>$N,DIS$</td>
<td>&lt; 1% (&lt; 1%)</td>
</tr>
</tbody>
</table>

After Cuts% (Before Cuts%)

## Background Composition

<table>
<thead>
<tr>
<th>$\nu$</th>
<th>$\bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC $\pi^\pm$</td>
<td>23%</td>
</tr>
<tr>
<td>NC El.</td>
<td>13%</td>
</tr>
<tr>
<td>$N,\pi$</td>
<td>12%</td>
</tr>
<tr>
<td>CC $\pi^\pm$</td>
<td>13%</td>
</tr>
<tr>
<td>CC $\pi^0$</td>
<td>10%</td>
</tr>
<tr>
<td>$\nu_e$ Induced</td>
<td>7%</td>
</tr>
<tr>
<td>Wrong-sign</td>
<td>5%</td>
</tr>
</tbody>
</table>

C.E. Anderson

NC 1$\pi^0$ Production
Background Subtraction

First step is to subtract background contamination from the $\pi^0$ box.

- MC predicted background is relatively normalized and subtracted.
Unsmearing

- Effects in the detector and reconstruction scatter measured values from the true value
- Need to deconvolve these experiment-specific effects to produce externally useful results

- Angle is measured very well
- Momentum has a tendency to be overestimated
Differing characteristics of each measurement, e.g. statistics, smearing behavior, distribution shape, call for different smearing techniques

Choose the least biased (estimated) result after applying various tested techniques\(^a\)\(^b\) which includes not unsmearing at all

\(^a\) G. D'Agostini, NIM A 362 (1995) 487

\(^b\) A. Hocker and V. Kartvelishvili, NIM A 372 (1996) 469
Correcting to the Cross Section

- Correct for events lost to cuts using efficiency

\[ \nu \text{ Mode NC } 1\pi^0 p_{\pi^0} \text{ Cut Efficiency} \]

\[ \text{Anti-}\nu \text{ Mode NC } 1\pi^0 p_{\pi^0} \text{ Cut Efficiency} \]

\[ \nu \text{ Mode NC } 1\pi^0 \cos\theta_{\pi^0} \text{ Cut Efficiency} \]

\[ \text{Anti-}\nu \text{ Mode NC } 1\pi^0 \cos\theta_{\pi^0} \text{ Cut Efficiency} \]

- Divide by number of targets in detector and integrated flux to get cross section

  - \( 4.88 \times 10^{32} \) nucleons in fiducial volume
  - \( 3.36(43) \times 10^{11} \ \nu_{\mu}/\text{cm}^2 \) at \( \langle E_{\nu} \rangle = 808 \text{ MeV} \) in neutrino running
  - \( 9.0(12) \times 10^{10} \ \bar{\nu}_{\mu}/\text{cm}^2 \) at \( \langle E_{\nu} \rangle = 630 \text{ MeV} \) in antineutrino running

These are cross sections for inclusive NC $\pi^0$ production per nucleon, averaged over MiniBooNE flux, and uncorrected for FSI.

MC prediction generated with NUANCE v3 using Rein-Sehgal for $\pi^0$ production with coherent production scaled by 0.65;

- Measurement is more forward peaked than prediction.
- More production is measured in neutrino mode than predicted and vice versa in antineutrino mode.
Systematic errors are calculated by measuring the covariance matrix of the cross section under random, correlated variations of the underlying parameters of the MC thrown according to their uncertainties.

Systematic errors include uncertainty in the integrated flux, cross section uncertainties on background model, and detector response uncertainties including bias introduced by unsmearing.

Measurements largely systematics dominated.

<table>
<thead>
<tr>
<th></th>
<th>$\nu_\mu$</th>
<th>$\bar{\nu}_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux</td>
<td>11.3%</td>
<td>12.9%</td>
</tr>
<tr>
<td>X-Sec.</td>
<td>9.3%</td>
<td>9.4%</td>
</tr>
<tr>
<td>Detector</td>
<td>4.3%</td>
<td>4.2%</td>
</tr>
<tr>
<td>Total</td>
<td>15.3%</td>
<td>16.5%</td>
</tr>
</tbody>
</table>
Cross Sections

Total NC $1\pi^0$ Production
Cross Sections

- $\nu_\mu$ Induced $\sigma = (4.54 \pm 0.04_{\text{stat}} \pm 0.71_{\text{sys}}) \times 10^{-40}$ cm$^2$/nucleon
- $\bar{\nu}_\mu$ Induced $\sigma = (1.43 \pm 0.03_{\text{stat}} \pm 0.23_{\text{sys}}) \times 10^{-40}$ cm$^2$/nucleon

First absolute differential cross sections measured for NC $\pi^0$ production
Coherent Production Models

- Models for NC coherent $\pi^0$ production demonstrate wide variabilities in their predictions.
- Forward angular distribution (particularly for antineutrino mode) is very sensitive to predictions.
- Calculated rate of events passing cuts using MiniBooNE default coherent production and predictions from Hernandez, et al$^a$, and Alvarez-Ruso, et al$^b$

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$^a$ arXiv:0903.5285v1; thanks to Juan Nieves for predictions

$^b$ Phys. Rev. C 76, 068501 (2007); thanks to Luis Alvarez-Ruso for predictions
Previous absolute measurements of NC $\pi^0$ productions measured only resonant production

- Hawker - Reanalysis of GGM data (Krenz et al., Nucl. Phys. B135, 45 (1978)) producing separate $\nu_\mu$ cross sections on protons and neutrons

We can subtract the additional background and correct for FSI to produce an absolute total resonant cross section for comparison

- Calculated using each of the coherent production models mentioned previously
Conclusions

- MiniBooNE has collected the largest sample of both neutrino and antineutrino induced NC $\pi^0$ events to date ($\sim 20k$ events in neutrino running and $\sim 2k$ events in antineutrino running)
- We have calculated the first differential NC $1\pi^0$ cross sections and the first absolute NC $1\pi^0$ total cross section
  - Measurement is systematics dominated
  - Angular cross sections will be invaluable in testing models of coherent production
  - Measurements will be published in the coming months