Neutral Current Coherent $\pi^0$ Measurement in the NOvA ND

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For the NOvA Collaboration
Introduction to Coherent Pion Production

- Neutrinos can coherently scatter off target nucleus via charge/neutral current interaction and produce pions:
  \[ \nu \mathcal{A} \rightarrow \nu \mathcal{A} \pi^0 \]
- The target nucleus stays in ground state.
- Small momentum transfer. No quantum number (charge, spin, isospin) exchange.
- Single forward-going pion in the final state, no other pions or nucleons or vertex activity.

- Coherent \(\pi^0\) is an important background to \(\nu_e\) appearance measurement.
- Physics in its own right: Partially Conserved Axial Current (PCAC) hypothesis, used in Rein-Seghal model and in most neutrino event generators such as GENIE.
The NOvA Near Detector

- 0.3 kton, 4.2mX4.2mX15.8m,
- 1 km from source, underground at Fermilab.
- PVC cells filled with liquid scintillator.
- Alternating planes of orthogonal view.
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Ryan Patterson, Caltech

The NOvA Near Detector Construction

- Detector construction and instrumentation completed Aug. 2014
- Neutrinos observed within seconds of turning on!

Beam

PVC cells filled with liquid scintillator.
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<table>
<thead>
<tr>
<th>Component</th>
<th>Mass Weight</th>
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<tbody>
<tr>
<td>C12</td>
<td>66.8%</td>
</tr>
<tr>
<td>Cl35</td>
<td>16.4%</td>
</tr>
<tr>
<td>H1</td>
<td>10.5%</td>
</tr>
<tr>
<td>Ti48</td>
<td>3.3%</td>
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<tr>
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</tr>
<tr>
<td>Others</td>
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Results

- The measured inclusive cross section from Gargamelle, T2k, and NOvA as shown.
- There is also shown the predicted cross section for nue on carbon from GENIE.
- There is large correlation between the energy bins for NOvA results (see Top table).
- Our detector material is dominant by the carbon, chlorine, and hydrogen.
The NOvA Near Detector

- 0.3 kton, 4.2m×4.2m×15.8m,
- 1 km from source, underground at Fermilab.
- PVC cells filled with liquid scintillator.
- Alternating planes of orthogonal view.

### Nuclear Cross Sections

- Beam

### Near Detector

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- Low-Z, fine-grained (1 plane ~ 0.15X₀), highly-active tracking calorimeter
- Optimized for EM shower measurement, including the π⁰s
Coherent $\pi^0$ in The NOvA ND

- Signature of COH $\pi^0$ in the NOvA ND is one single forward-going $\pi^0$.
- Photons from neutral pion decay make EM showers.
- Reconstructing both photons provide additional constraint on background and energy scale.
• Narrow band neutrino beam $1\sim3\text{GeV}$ peak at $\sim2\text{GeV}$, Dominated by $\nu_\mu$ (94%)
• Neutrino flux uncertainty comes form hadron production and beam focusing.
• Hadron production uncertainty constraint by external hadron production data (PPFX).
Analysis Strategy

- Select **NC $\pi^0$ sample**: no muon track, two photon showers, no other particles. Reconstruct the invariant mass.
- Using kinematics, further select a **signal sample** with most of the coherent signal.
- Define a **control sample (sideband)**, dominated by non-coherent $\pi^0$s, to constrain background modeling.
- Apply the background fit result to the signal sample.
- Get a flux-averaged cross-section measurement from the signal sample as the data event excess over background prediction in the coherent region.
Photon Shower Identification

- Look for $\pi^0 \rightarrow \gamma \gamma$ and both photons are reconstructed.
- Identify EM showers by likelihoods build upon shower longitudinal and transverse $dE/dx$ information.
Identify the NC $\pi^0$ sample
- Absence of muon.
- Two showers identified as photons by dE/dx-based likelihoods.
- Reconstruct invariant mass.
- Background dominated by RES and DIS $\pi^0$s.
- Cut on invariant mass further reduces background.
- Also serve as a check of photon reconstruction and energy scale.
Signal Sample and Control Sample

NOvA Preliminary
• Divide the NC $\pi^0$ into two sub-samples:
  • **Signal sample**: events with most of their energy in the 2 photon-showers and low vertex energy: it has >90% of the signal.
  • **Control sample**: the events with extra energy other than the photons or in the vertex region, dominated by non-coherent $\pi^0$ s (RES and DIS).
The control sample is used to fit background to data in $\pi^0$ energy vs angle 2D space.
Fit the backgrounds to control sample data in \( \pi^0 \) energy vs angle 2D space.
• Fit the backgrounds to control sample data in $\pi^0$ energy vs angle 2D space.

• Apply the background tuning to the signal sample.
• Background fit result are applied to the backgrounds in the signal sample.

• Coherent signal measurement by subtracting normalized background from data in the coherent region of the energy and angle 2D space.
Cross-Section Measurement And Uncertainties

\[ \sigma = \frac{N_{Data, selected} - N_{Bkg, norm}}{\epsilon \times N_{Target} \times \phi} \]

- Selected data
- Normalized Background
- Signal efficiency
- Number of target nucleus
- Flux

Uncertainty to this analysis comes from both statistics and systematics. To reduce the statistic uncertainty, we want to reduce the number of background \( N_{Bkg} \) while keeping relatively high signal efficiency \( \epsilon \). Systematic uncertainty mainly comes from the measured number of background \( N_{Bkg} \) and flux. Coherent modeling and detector simulation also contribute to the uncertainty through \( \epsilon \). The uncertainty to \( N_{Bkg} \) is constrained by the control sample as described above. External data (MIPP/NA49) are used to constrain the flux uncertainty from hadron production.

The neutrino flux, data and MC used in this analysis will be discussed in section 2 and 3. Section 4 focuses on the selection of NC \( \pi^0 \) sample, including both coherent signal and non-coherent background. Section 5 present the selection of coherent signal sample and non-coherent control sample, and the data-driven method of background constraint. Systematic uncertainties will be discussed in section 6.
Cross-Section Measurement And Uncertainties

6.7% statistical uncertainty with 3.7E20POT data

\[ \sigma = \frac{N_{\text{Data,selected}} - N_{\text{Bkg,norm}}}{\epsilon \times N_{\text{Target}} \times \phi} \]

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Cross-Section Measurement And Uncertainties

6.7% statistical uncertainty with 3.7E20POT data

10.4% systematic uncertainty from background modeling, constrained by control sample data

\[
\sigma = \frac{N_{\text{Data, selected}} - N_{\text{Bkg, norm}}}{\epsilon \times N_{\text{Target}} \times \phi}
\]

Selected data

Normalized Background

Signal efficiency

Flux

Number of target nucleus
The cross-section of coherent $\pi^0$ production is calculated as:

$$\sigma = \frac{N_{Data, selected} - N_{Bkg,norm}}{\epsilon \times N_{Target} \times \phi}$$

where

- $N_{Data, selected}$ is the number of selected data in the coherent (low-$\bar{\nu}$) region of the signal sample,
- $N_{Bkg,norm}$ is the normalized MC background,
- $\epsilon$ is the efficiency of coherent signal selection calculated by MC,
- $N_{Target}$ is the number of target nucleus in the fiducial volume,
- $\phi$ is the muon neutrino flux.

6.7% statistical uncertainty with 3.7E20POT data

10.4% systematic uncertainty from background modeling, constrained by control sample data

3.7% Uncertainty from signal modeling and 1% from EM shower modeling

Flux

Number of target nucleus

Cross-Section Measurement And Uncertainties
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Selected data

\[ \sigma = \frac{N_{Data, selected} - N_{Bkg, norm}}{\epsilon \times N_{Target} \times \phi} \]

Normalized Background

Signal efficiency

3.7% Uncertainty from signal modeling and 1% from EM shower modeling

<1% uncertainty from detector simulation

10.4% systematic uncertainty from background modeling, constrained by control sample data

Flux

Number of target nucleus

3.7% Uncertainty from signal modeling and 1% from EM shower modeling

<1% uncertainty from detector simulation
The strategy of the coherent $\pi^0$ analysis is as follows. First, we select single $\pi^0$ events in the NC sample defined by the absence of a reconstructed muon in the final state. Both photons from $\pi^0$ decay should be reconstructed as 3D prongs. The sample is composed of both coherent and non-coherent (Resonance and DIS) interactions. Next, using kinematics, we define a control sample, entirely dominated by non-coherent $\pi^0$, and a signal sample containing coherent and non-coherent events. The control sample is used to tune the normalization and shape of the non-coherent $\mu$ background, which is then applied to the non-coherent background in the signal sample. Finally, the coherent signal is measured in the low-$\mu$ region of the coherent signal sample as the excess over non-coherent prediction.

The cross-section of coherent $\pi^0$ production is calculated as:

$$\sigma = \frac{N_{Data, selected} - N_{Bkg, norm}}{\epsilon \times N_{Target} \times \phi}$$

where $N_{Data, selected}$ and $N_{Bkg, norm}$ are the number of data and normalized MC background in the selected coherent (low-\mu) region of the signal sample, $\epsilon$ is the efficiency of coherent signal selection calculated by MC, $N_{Target}$ is the number of target nucleus in the fiducial volume, and $\phi$ is the muon neutrino flux.

Uncertainty to this analysis comes from both statistics and systematics. To reduce the statistical uncertainty, we want to reduce the number of background ($N_{Bkg}$) while keeping relatively high signal efficiency ($\epsilon$). Systematic uncertainty mainly comes from the measured number of background ($N_{Bkg}$) and flux. Coherent modeling and detector simulation also contribute to the uncertainty through $\epsilon$. The uncertainty to $N_{Bkg}$ is constrained by the control sample as described above. External data (MIPP/NA49) are used to constrain the flux uncertainty from hadron production.

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Cross-Section Measurement And Uncertainties

- 6.7% statistical uncertainty with 3.7E20POT data
- 10.4% systematic uncertainty from background modeling, constrained by control sample data
- 3.7% Uncertainty from signal modeling and 1% from EM shower modeling
- <1% uncertainty from detector simulation
- 9.4% uncertainty from external hadron production data
Cross-Section Measurement And Uncertainties

6.7% statistical uncertainty with 3.7E20POT data

\[
\sigma = \frac{N_{Data, selected} - N_{Bkg, norm}}{\epsilon \times N_{Target} \times \phi}
\]

10.4% systematic uncertainty from background modeling, constrained by control sample data

• 16.7% total uncertainty (stat + syst): a very competitive result.
Cross Section Result
NOvA Preliminary

- Coherent signal measurement by subtracting normalized background from data in energy and angle 2D space.
- Measured flux-averaged cross-section:
  \[ \sigma = 14.0 \pm 0.9\text{(stat.)} \pm 2.1\text{(syst.)} \times 10^{-40}\text{cm}^2/\text{nucleus} \]
- Total uncertainty is 16.7%, systematic dominant.

<table>
<thead>
<tr>
<th>Source</th>
<th>(\delta(%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calorimetric Energy Scale</td>
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<tr>
<td>Background Modeling</td>
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<tr>
<td>Control Sample Selection</td>
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<tr>
<td>EM Shower Modeling</td>
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<td>Coherent Modeling</td>
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<td>Rock Event</td>
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<tr>
<td>Alignment</td>
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<tr>
<td>Total Systematics</td>
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<tr>
<td>Signal Sample Statistics</td>
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<tr>
<td>Control Sample Statistics</td>
<td>4.1</td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td>16.7</td>
</tr>
</tbody>
</table>
Summary

• Coherent is an important interaction mode for neutrino oscillation measurement, and also has its own physics interest.
• NOvA near detector is good for $\pi^0$ measurements.
• Large dataset leads to a small statistic uncertainty.
• Data-driven methods to constrain most of the systematic uncertainty.
• We measured the cross-section of NC coherent $\pi^0$:

$$\sigma = 14.0 \pm 0.9\text{(stat.)} \pm 2.1\text{(syst.)} \times 10^{-40}\text{cm}^2/\text{nucleus}$$

Total uncertainty is 16.7%.
• A very precise measurement in the few-GeV region.
Thank you!
Back up slides
Muon-Removed Brem Showers

• Rock muons induce EM showers in the detector via bremsstrahlung radiation.
• A muon-removal (MR) technique is developed to isolate those EM showers.
• Provide a data-driven method to check detector performance and benchmark EM shower modeling and likelihoods.
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Provide a data-driven method to check detector performance and benchmark EM shower modeling and likelihoods.
Muon-Removed Brem showers provide a photon control sample to benchmark the modeling and selection efficiency of EM showers.

- Very good agreement between data and MC.
- 1% difference in selection efficiency taken into systematic uncertainty.
Coherent $\pi^0$: World Measurement

There are relatively few coherent $\pi^0$ measurement, most suffer from large uncertainty.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>A</th>
<th>$&lt;E_\nu&gt;$ (GeV)</th>
<th>$\sigma$ ($10^{-40} cm^2/N$)</th>
<th>$\sigma/\sigma(\nu_\mu\text{-CC})$</th>
<th>$\sigma/\sigma(\text{RS})$</th>
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<tbody>
<tr>
<td>Aachen-Padova</td>
<td>27</td>
<td>2</td>
<td>29±10</td>
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<tr>
<td>Gargamelle</td>
<td>31</td>
<td>3.5</td>
<td>31±20</td>
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<tr>
<td>CHARM</td>
<td>20</td>
<td>30</td>
<td>96±42</td>
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<tr>
<td>SKAT</td>
<td>30</td>
<td>7</td>
<td>79±28</td>
<td>4.3±1.5</td>
<td>0.65±0.14</td>
</tr>
<tr>
<td>15’ BC</td>
<td>20</td>
<td>20</td>
<td>72.6±10.6</td>
<td>0.20±0.04</td>
<td>0.9±0.20</td>
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<tr>
<td>NOMAD</td>
<td>12.8</td>
<td>24.8</td>
<td>72.6±10.6</td>
<td>3.21±0.46</td>
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<tr>
<td>MiniBooNE</td>
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<td>0.8</td>
<td>77.6±15.8</td>
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<td></td>
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<tr>
<td>SciBooNE</td>
<td>12</td>
<td>0.8</td>
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<td></td>
<td></td>
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<tr>
<td>MINOS</td>
<td>48</td>
<td>4.9</td>
<td></td>
<td></td>
<td></td>
</tr>
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</table>

Results scaled to Carbon (A=12) Target
A “measured” angular resolution in data by comparing the reconstructed EM shower direction to the muon direction.

The NOvA ND has good angular resolution (~0.02rad) for EM shower measurement.

Important to the coherent $\pi^0$ cross-section measurement.
Select the coherent region in energy vs angle 2D space
DFR $\pi^0$
Coherent $\pi^0$ Candidate in the NOvA ND

A coherent $\pi^0$ candidate events with 2 photons from $\pi^0$ decay.
Group hits together in time and space for each neutrino interaction.
Reconstruction: Vertexing

Find particle paths, and use the intersection to form vertex
Reconstruction: Clustering

Group hits from each shower together using clustering algorithm.