Status of the $\nu_\mu$ CC Coherent $\pi^+$ Production in the NOvA Near Detector

On behalf of the NOvA collaboration
The NOvA Experiment

- A neutrino oscillation experiment with 810 km baseline, two structurally identical detectors, NuMI $\nu_\mu$ 700 kW beam, off-axis

Main physics goals:
- $\nu_\mu \rightarrow \nu_e$ Oscillations
- Cross-section studies
- Sterile Neutrino studies
- Exotics
- More...

High statistics collected at the Near Detector can be used to study neutrino cross sections!
NOvA Beam Flux

- flux has a peak between 1 and 5GeV
- receives high neutrino flux contains 96% pure $\nu_\mu$ beam and 1% of $\nu_e$ and $\bar{\nu}_e$
- provides a rich data set for measuring cross-sections.
The NOvA Near Detector

A cell contains a single loop of wavelength shifting fiber

Wavelength shifting fibers read out by a single pixel on Avalanche Photodiode

Alternating horizontal and vertical planes for 3D reconstruction

An array of wavelength shifting fibers ends that goes to avalanche photo diode interface

NOvA Near Detector located at the MINOS underground facility

Detector Composition

<table>
<thead>
<tr>
<th>Element</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-H</td>
<td>77%</td>
</tr>
<tr>
<td>Cl</td>
<td>16%</td>
</tr>
<tr>
<td>TiO₂</td>
<td>6%</td>
</tr>
</tbody>
</table>

Side view of the NOvA Near Detector and Muon catcher
NOvA Simulation

Beamline and flux: G4NuMI

ν-A modelling: GENIE

Detector response: GEANT4

Readout electronics and DAQ: Custom simulation routines
Charged Current Coherent Interaction

- An inelastic interaction produces a lepton and a pion in the forward direction.
- Nucleus (A) stays in its initial state.

\[ \nu_l + A \rightarrow l^- + \pi^+ + A \]
\[ \overline{\nu}_l + A \rightarrow l^+ + \pi^- + A \]

- The square of the four-momentum exchanged with the nucleus, |t|, must be small.

\[ Q^2 = (P_\nu - P_{\mu})^2 \]
\[ |t| = \left| (P_\nu - P_{\mu} - P_{\pi}) \right| \]

\[ Q^2 = W^+ \]
\[ t = IP \]
\[ \pi^+ \]

\[ A \rightarrow A \]
Motivation

- **Theoretical Interests:**
  
  Charged Current Coherent models are not very well understood.

  Provides detailed tests for hypothesis such as:
  
  - CVC
  - PCAC
  - HDM

- **Experimental Interests:**
  
  Reconstructing $E_{\nu}$ is more accurate compared to other channels. (i.e. $E_{\nu} = E_{\mu} + E_{\pi}$)

  NOvA cross-section results will be useful for the upcoming DUNE experiment.

  Coherent pion production can be mistaken for quasi-elastic scattering when the $\pi^+$ is misidentified as a proton or is not detected.

  For isoscalar nuclei coherent $\pi^+$ and $\pi^-$ cross sections are same.
Signal and Background Definitions

- Scaled down to POT 1.42e21

- Signal definition:
  \( \nu_\mu \) CC coherent interactions formed within the fiducial volume. (Currently using same fiducial volume defined in NuMi CC inclusive analysis.)

- Background definition:
  Interactions other than signal will be treated as Background. (!signal)
**Currently analyzing golden event sample**

<table>
<thead>
<tr>
<th>Number of 2D Prongs</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of 3D Prongs</td>
<td>1583</td>
<td>7281</td>
<td>1082</td>
<td>825</td>
<td>840</td>
</tr>
<tr>
<td>1583</td>
<td>5770</td>
<td>2165</td>
<td>1906</td>
<td>3193</td>
<td>1604</td>
</tr>
<tr>
<td>7638</td>
<td>7809</td>
<td>1887</td>
<td>2165</td>
<td>3743</td>
<td>3139</td>
</tr>
<tr>
<td>1583</td>
<td>7281</td>
<td>1082</td>
<td>825</td>
<td>986</td>
<td>586</td>
</tr>
</tbody>
</table>

Note: **Prong** is a reconstructed particle candidate that has directional and reconstructed information.

Charged Current Coherent event reconstructed as two 3D prongs and one 2D prong.
Event Selection

- Created following cuts to separate Signal and the Background
  - Data Quality Cut
  - Fiducial Cut
  - Containment Cut
  - Muon ID Cut (optimized $\mu_{\text{onID}} > 0.615$)
  - Two Prong Cut (Only use clean events)
  - Pion ID Cut ($\text{PionID} > 0.7$) (using single particle cvn)
  - Vertex Energy Cut (Extra $\text{VertexE10} > -0.079$)
  - Loose $|t|$ Cut $\leq 0.2\text{GeV}$

From NuMu CC Inclusive analysis

Efficiency confusion matrix for the 5label network evaluated on FHC genie prongs
Estimating Muon K.E.

\[ \mu^- K.E. = 0.00206646 \times (\mu^- \text{ Prong Length}) + 0.0201737 \]

Mean: 5.87918e-03
Sigma: 3.22632e-02
Estimating Pion K.E.

NOvA Simulation

![Diagram showing polynomial fit and data points with mean and sigma values](image)

- Mean: 0.0585206
- Sigma: 0.215871
Reconstructed $|t|$ (Signal Vs Background)

**NOvA Simulation**

- **COH**
- **RES**
- **QE**
- **DIS**
- **MEC**

**Graphs:**

- Left graph: Reconstructed $|t|$ $(\text{GeV}^2)$ vs. Number of Events / $(1.42 \times 10^5 \text{ POT})$
- Right graph: Reconstructed $|t|$ $(\text{GeV}^2)$ vs. Number of Events / $(1.42 \times 10^5 \text{ POT})$

**Graph Legend:**

- **CC COH**
- **Backgrounds**
- **Signal+Backgrounds**

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Fermilab New Perspectives 2021
Summary

- Energy of the Muon can be successfully estimated by using Muon prong length.
- Energy of the Pion can be estimated by using Pion CalE but, requires more improvements.
- Reconstructed |t| can be used to separate Coherent events from dominating backgrounds.
- After implementing loose |t| cut (i.e. |t| < 0.2 GeV$^2$) the cut table (POT Normalized) can be summarized as follows:

<table>
<thead>
<tr>
<th>Cut Name</th>
<th>CC COH</th>
<th>CC RES</th>
<th>CC QE</th>
<th>CC MEC</th>
<th>CC DIS</th>
<th>NC</th>
<th>TOTAL Bkg.</th>
<th>Eff %</th>
<th>Relative Eff.</th>
<th>Purity %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Quality</td>
<td>29312.4</td>
<td>364007.8</td>
<td>1214097.2</td>
<td>100434.4</td>
<td>326609.6</td>
<td>2625084.3</td>
<td>9305263.6</td>
<td>99.8</td>
<td>99.8</td>
<td>0.31</td>
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<tr>
<td>Fiducial</td>
<td>28645.1</td>
<td>1971807.1</td>
<td>630035.9</td>
<td>529390.7</td>
<td>1672683.7</td>
<td>1443259.8</td>
<td>4885034.2</td>
<td>97.72</td>
<td>97.7</td>
<td>0.58</td>
</tr>
<tr>
<td>Containment</td>
<td>19966.1</td>
<td>1753343.8</td>
<td>434417.2</td>
<td>331591.3</td>
<td>1611071.3</td>
<td>1438900.8</td>
<td>4206645.8</td>
<td>68.11</td>
<td>69.7</td>
<td>0.47</td>
</tr>
<tr>
<td>Muon ID</td>
<td>17713.5</td>
<td>777508.6</td>
<td>291175.5</td>
<td>279690.4</td>
<td>405887.6</td>
<td>123259.1</td>
<td>1766796.5</td>
<td>60.43</td>
<td>88.7</td>
<td>0.99</td>
</tr>
<tr>
<td>Two Prong</td>
<td>2066.7</td>
<td>32327.4</td>
<td>60441.2</td>
<td>12786.6</td>
<td>5475.0</td>
<td>3033.6</td>
<td>112382.3</td>
<td>7.05</td>
<td>11.7</td>
<td>1.81</td>
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<td>Pion ID</td>
<td>1421.4</td>
<td>9695.0</td>
<td>5821.1</td>
<td>1325.7</td>
<td>2006.6</td>
<td>887.0</td>
<td>19486.9</td>
<td>4.8</td>
<td>68.8</td>
<td>6.8</td>
</tr>
<tr>
<td>Vertex Energy</td>
<td>1388.6</td>
<td>6243.0</td>
<td>5610.4</td>
<td>1040.4</td>
<td>1633.1</td>
<td>797.5</td>
<td>14981.7</td>
<td>4.7</td>
<td>97.7</td>
<td>8.5</td>
</tr>
<tr>
<td>Loose</td>
<td>t</td>
<td></td>
<td>1239.8</td>
<td>3266.5</td>
<td>197.1</td>
<td>115.8</td>
<td>673.9</td>
<td>361.1</td>
<td>4.2</td>
<td>89.3</td>
</tr>
</tbody>
</table>
Next Steps

- Finalizing Pion energy estimator by using multivariate method trained by single pions
- Finalizing event selection by adding final cut based on multivariate event classifier
- Hand scanning event display views to find out ways to further separate dominating background: RES from signal events
- Creating an enhanced sample and considering signal events other than golden event sample to address low efficiency
Thank you!
Backups
Estimating Muon K.E.

\[
\mu^- K.E = 0.00206646 \times (\mu^- \text{ Prong Length}) + 0.0201737
\]
Estimating Pion K.E.

polynomial fit
Reconstructing $|t|$:

$$|t| = \left| (p_\nu - p_\mu - p_\pi)^2 \right|$$

$$\approx \left( \sum_{i=\mu,\pi} E_i - p_{i,L} \right)^2 + \left| \sum_{i=\mu,\pi} \vec{p}_{i,T} \right|^2,$$

(Measurement of Total and Differential Cross Sections of Neutrino and Antineutrino Coherent pion Production on Carbon by MINERVA Collaboration [arXiv:1409.3835])

- Assumptions:
  - The recoiling nucleus only takes momentum and no energy (infinitely heavy nucleus)
  - The transverse momentum of the incoming neutrino is zero (w.r.t. beam coordinates system)

$$\therefore p_v = \begin{pmatrix} E_\mu + E_\pi \\ 0 \\ 0 \end{pmatrix}, p_\mu = \begin{pmatrix} E_\mu \\ p_{\mu_x} \\ p_{\mu_y} \end{pmatrix} \text{ and } p_\pi = \begin{pmatrix} E_\pi \\ p_{\pi_x} \\ p_{\pi_y} \\ p_{\pi_z} \end{pmatrix}$$
Determining $P_t$ and $P_l$

\[
\hat{P} \cdot \hat{U} = P_l
\]

\[
P^2 = p_x^2 + p_y^2 + p_z^2
\]

\[
P^2 = P_t^2 + P_l^2 \text{ (By considering OAB Right Angle Triangle)}
\]

\[
p_t^2 = p^2 - p_l^2
\]

\[
\therefore P_t = \sqrt{p_x^2 + p_y^2 + p_z^2 - p_l^2}
\]

Here, $P_t$ and $P_l$ are transverse and longitudinal momenta calculated w.r.t. the beam direction.

Here, $P_x, P_y$ and $P_z$ are momentum components of the neutrino observed w.r.t. the detector coordinate system.

Here, $\hat{U} = (0.0011401229, -0.06190152, 0.99807253)$ i.e. Average Beam Direction.