Neutrino Cross Section Measurements in the NOvA Near Detector

Hongyue Duyang
University of South Carolina

For the NOvA Collaboration

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• Introduction to the NOvA ND and flux.
• Neutral pion measurements
• Inclusive Measurements
• Summary
Outline

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The NOvA Near Detector

- NOvA is a Long-baseline neutrino oscillation experiment:
  - See Erica Smith and Steven Calvez’s talk for the latest oscillation results!
- The ND is 1 km from source, **underground** at Fermilab.
- PVC cells filled with **liquid scintillator**.
- Alternating planes of orthogonal view.
- **193 ton** fully active mass.
- 97 ton downstream muon catcher.

- **Low-Z, fine-grained**
  - 1 plane ~0.15X₀ (38 cm).

<table>
<thead>
<tr>
<th>Elements</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>C</td>
<td>65.9%</td>
</tr>
<tr>
<td>Cl</td>
<td>12.0%</td>
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<tr>
<td>H</td>
<td>10.7%</td>
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<td>4.1%</td>
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<tr>
<td>O</td>
<td>3.0%</td>
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<tr>
<td>Ti</td>
<td>2.4%</td>
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</table>
EM showers from $\pi^0$ decay can mimic $\nu_e$-CC signal
Motivation

• Cross-sections are rich in **physics themselves**.
• Also important to **oscillation systematic uncertainties**:
  • **Signals** and **backgrounds** to the oscillation analysis.
  • Oscillations are measured as function of neutrino energy: need to reconstruct $E_\nu$ correctly.
  • **Nuclear effects** (fermi motion, nucleon correlation, final-state interaction…) are important.

![Graph showing near-far differences and uncertainties]

**We want to understand those issues in our own detector**

**Tomasz Golan**

MC generators @ NuSTEC

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NOvA Cross-Section Measurements Overview

- Both neutrino and anti-neutrino modes.
- Excellent statistics from 193 ton of fully-active tracking region.
- Inclusive measurements:
  - $\nu_\mu$-CC inclusive
  - $\nu_e$-CC inclusive
- Neutral pion measurements:
  - Neutral current coherent $\pi^0$ (Submitted to PRD).
  - Charged current semi-inclusive $\pi^0$ (paper in preparation).
  - NC $\pi^0$ inclusive.
- Charged pion measurements
- Others
  - $\nu_\mu$-CC 0\pi
  - $\nu_\mu$-CC 2p2h
  - And more
The Neutrino Flux

- Narrow band neutrino beam 1~3GeV peak at ~2GeV, dominated by $\nu_\mu$ (94%).
- Right on the DUNE 1st oscillation maximum.
- Both neutrino mode and anti-neutrino mode.
- Hadron production uncertainty constraint by external hadron production data.
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Neutrinos coherently scatter on whole nucleus and produce pions.

Background to $\nu_e$ appearance

Small cross section compares with other pion production channels.

Data-driven background prediction:

- A control sample defined by large vertex energy and extra energy deposition than the photon showers.
- A template fit method to normalize backgrounds.
• 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 16.7%, systematic dominant.

• For more details see arXiv: 1902.00558 (submitted to PRD).
\[ \nu_\mu\text{-CC } \pi^0 \]

Signal: \( \nu_\mu\text{-CC} \) events with at least one primary \( \pi^0 \) in the final state.

- Use non-muon shower variables to form a \( \pi^0 \) identifier:
  - Bragg peak identifier.
  - Energy per hit.
  - Photon gap from vertex.
  - Number of missing planes.
- Fit signal and background MC to data in each kinematic bin.
• Reporting result as differential cross section as function of Q2 and muon/pion kinematics.
• In general consistent with GENIE.
• Paper in preparation. For more details see https://theory.fnal.gov/events/event/results-from-nova-2/
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\( \nu_\mu - CC \) Inclusive

- Goal: double differential cross section as function of muon kinematics.
- Backgrounds: neutral current events and \( \nu_e \).

- A boosted decision tree (BDT) based upon dE/dx and scattering information is trained to identify the muons.
- Cut value optimized by minimizing uncertainties.
• Muon energy measured by range.
• Perform unfolding and efficiency correction in \((\cos\theta_\mu, T_\mu, E_{avail})\) 3D space to take into account correlations between lepton and hadron kinematic variables.
• Projection to 1D or 2D space for the differential cross-section measurement.
• Showing a mock data study. Real result coming soon.
\(\nu_e\)-CC Inclusive

- Signal of \(\nu_e\) appearance oscillation measurement.

- Challenge: \(\nu_e\) is only 1\% of the flux. Overwhelming background from \(\nu_\mu\) CC and NC.

- A convolutional neural network (CVN) trained to identify the signal by topology features.

- Cut optimized by minimizing uncertainties.
A template fit method is used to measure signal and background.

- Templates: signal, $\nu_\mu$-CC, NC.
- Fit to data as function of CVNe in each measurement bin.
\(\nu_e\)-CC Inclusive

- High and flat signal efficiency thanks to CVNe and the template fit method.
- The goal is to report double differential cross sections as function of electron kinematics which has never been measured before.
- Also very interesting to see the ratio to \(\nu_\mu\) inclusive.
- Work under internal review.

\[\text{Efficiency vs \text{True Electron Energy (GeV)}}\]

\[\text{Efficiency vs \text{Cos} \theta_e}\]

\[\text{Efficiency vs \text{True \text{Cos} \theta_e}}\]

\[\text{Efficiency vs \text{Electron Energy, } E_e \text{ (GeV)}}\]
Summary

• The NOvA ND has an very active cross section physics program.
• 2 publications coming:
  • NC coherent $\pi^0$
  • CC $\pi^0$
• Inclusive measurements in the final stage.
• Lots of other measurements.
• And expect more in the near future.
Back up slides
The NOvA Experiment

- Long-baseline neutrino oscillation measurements:
  - $\nu_\mu$ to $\nu_e$ appearance & $\nu_\mu$ disappearance
  - Mass hierarchy, $\theta_{23}$ octant, $\delta_{CP}$
  - NC disappearance sterile neutrino search
  - See Erica Smith and Steven Calvez’s talk for the latest oscillation results!
$\nu_\mu$-CC Inclusive Systematic Uncertainties

![Graph showing fractional uncertainty vs. muon kinetic energy for NOvA Simulation](image)

**NOvA Simulation**

- Flux (HP)
- GENIE
- Light
- Calibration
- Cherenkov
- Calib. Shape
- Mu Energy Scale
- Normalization
- Focusing

**Relative Uncertainty on Cross-section**

![Graph showing relative uncertainty vs. muon ID cut](image)