Cross-section measurement program in NOvA

**Leonidas Aliaga** (on behalf of the NOvA Collaboration)

New Directions in Neutrino-Nucleus Scattering (NUSTEC Workshop)

March 15, 2021
The NOvA experiment

» NOvA is a long-baseline neutrino experiment

» 2 detectors: 14 mrad off-axis and 810 km apart

» Designed to measure for $\nu_\mu \rightarrow \nu_e$: detectors provide excellent imaging of both $\nu_\mu$ and $\nu_e$ CC events

Neutrino mode

» 96% pure $\nu_\mu$ beam, 1% $\nu_e$ and $\bar{\nu}_e$

» High neutrino flux at the Near Detector provides a rich data set for cross-section measurements
NOvA Near Detector

The ND is 1 km from source, underground at Fermilab.

PVC cells filled with liquid scintillator, 193 ton fully active mass and 97 ton downstream muon catcher

Alternating planes of orthogonal views

Low-Z, fine-grained: 1 plane ~ 0.15 $X_0$

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Cl</th>
<th>H</th>
<th>O</th>
<th>Ti</th>
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<tbody>
<tr>
<td></td>
<td>65.9%</td>
<td>16.1%</td>
<td>10.7%</td>
<td>3.0%</td>
<td>2.4%</td>
</tr>
</tbody>
</table>
Neutrino cross-section measurements at NOvA

Energy range
Detector technology
Statistics

Unique environment for cross-section measurements

νμ CC
Long, straight track

νe CC
Short, wider, fuzzy shower

NC
Diffuse activity from nuclear recoil system
Neutrino cross-section measurements at NOvA

Energy range
Detector technology
Statistics

Unique environment for cross-section measurements

This talk
» Inclusive analyses
» Exclusive analyses
  ▶ CC low hadronic activity
  ▶ Pion production
    • $\nu_\mu$ - CC $\pi^0$
» Other analyses

Long, straight track
Short, wider, fuzzy shower
Diffuse activity from nuclear recoil system

νµ CC
νe CC
NC
Inclusive CC analyses
$\nu_\mu$ CC Inclusive

\[
\left( \frac{d^2 \sigma}{d \cos \theta_\mu d T_\mu} \right)_i = \sum_k \left( \frac{\sum_j U_{ijk}^{-1} (N_{\text{sel}}(\cos \theta_\mu, T_\mu, E_{\text{avail}})_j P(\cos \theta_\mu, T_\mu, E_{\text{avail}})_j)}{N_t \Phi(\cos \theta_\mu, T_\mu, E_{\text{avail}})_{ik} \Delta \cos \theta_\mu \Delta T_\mu} \right)
\]

Analysis is done in $(T_\mu, \cos \theta_\mu, E_{\text{avail}})$ and then projected to muon kinematics

$E_{\text{avail}}$: total energy of all observable final state hadrons
\[ \left( \frac{d^2 \sigma}{d \cos \theta_\mu d T_\mu} \right)_i = \sum_k \left( \frac{\sum_j U_{ijk}^{-1} (N_{\text{sel}}(\cos \theta_\mu, T_\mu, E_{\text{avail}})_j P(\cos \theta_\mu, T_\mu, E_{\text{avail}})_j)}{N_t \Phi(i_k \Delta \cos \theta_\mu, \Delta T_\mu)} \right) \]

\[ = \sum_k \left( \frac{\sum_j U_{ijk}^{-1} (N_{\text{sel}}(\cos \theta_\mu, T_\mu, E_{\text{avail}})_j P(\cos \theta_\mu, T_\mu, E_{\text{avail}})_j)}{N_t \Phi(i_k \Delta \cos \theta_\mu, \Delta T_\mu)} \right) \]

**NOvA Preliminary**

Typical total [shape] uncertainties ~12% [8%] in each bin.

**Flux**
- Calibration and Detector Response
- \(\nu\text{-A modeling}\)
- Muon Energy Scale
- Muon Angle - Alignment
- Neutron modeling
- Statistical

**Total**
- Normalization+Shape Uncertainties
- Shape-only Uncertainties

**Average Fractional Uncertainties**

0.02 0.04 0.06 0.08 0.1 0.12

**Analysis bins**

**Reconstructed \(T_\mu\) (GeV)**
- 0.5
- 1
- 1.5
- 2
- 2.5

**Reconstructed \(\cos \theta_\mu\)**
- 0.5
- 0.6
- 0.7
- 0.8
- 0.9
- 1

**Events/(8.09E+20 POT)**
- 1
- 10
- 10^2
- 10^3
- 10^4
\( \nu_\mu \) CC Inclusive: Example of 2 cosine slices

*Draft publication is under Collaboration review*

**NOvA Preliminary**

\[ 0.80 \leq \cos \theta_\mu \leq 0.85 \]

\[ 0.99 \leq \cos \theta_\mu \leq 1.00 \]

**Generators**

- **GENIE 2.12.2 - Tuned**
  - p-value = 0.93
- **GENIE 2.12.2 - Untuned**
  - p-value = 0.24
- **GENIE 3.00.06**
  - p-value = 0.26
- **GiBUU 2019**
  - p-value = 0.03
- **NEUT 5.4.0**
  - p-value = 0.52
- **NuWro 2019**
  - p-value = 0.22

*G18_10j_02_11a*

**Analysis bins**

Presented in Fermilab JETP Seminar, July, 2020
First ever $\nu_e$ CC double differential

\[
\frac{d^2\sigma}{d\cos\theta_e dE_e} \bigg|_i = \sum_j \left( \frac{U_{ij}^{-1}(N_{sel}^{\nu_e}(\cos\theta_e, E_e)_j - N_{bkg}^{\nu_e}(\cos\theta_e, E_e)_j)}{N_t \Phi \epsilon(\cos\theta_e, E_e)_{ik} \Delta\cos\theta_e \Delta E_{ei}} \right)
\]

Cross section as a function of the electron kinematics

Background estimate in each electron kinematic bin is done via a template fit of the ElectronID distribution

Electron ID uses deep convolutional network, reconstructed shower width and gap to reconstructed vertex

NuMI beam at the NOvA near detector

Neutrino mode

1% $\nu_e + \bar{\nu}_e$

Neutrino energy (GeV)

Events / 8.09 $\times 10^{20}$ POT

ElectronID

NOvA Simulation
First ever $\nu_e$ CC double differential

$$\left( \frac{d^2\sigma}{d\cos\theta_e dE_e} \right)_i = \sum_j \left( \frac{U^{-1}_{ij} (N_{\text{sel}}(\cos\theta_e, E_e)_j - N_{\text{bkg}}(\cos\theta_e, E_e)_j)}{N_t \Phi_e(\cos\theta_e, E_e)_{ik} \Delta \cos\theta_e \Delta E_e} \right)$$

Typical uncertainties $\sim 18\%$ in each bin

$123456$ (GeV)

$0102030405060$ (GeV)

$0.85 < \cos\theta_e \leq 0.90$

$0.97 < \cos\theta_e \leq 1.00$

$\theta$

» p-values ranging from 0.3 to 0.99.

Presented in Fermilab JETP Seminar, August, 2020
Inclusive analyses in the antineutrino beam

» $\bar{\nu}_\mu$ CC Inclusive
  - We are investigating a measurement in 3D: $(T_\mu, \cos \theta_\mu, E_{\text{avail}})$

» $\bar{\nu}_e$ CC Inclusive
  - We plan to measure in 2D: $(E_e, \cos \theta_e)$

NOvA Simulation

Antineutrino mode

Ratios $\bar{\nu}_\mu / \nu_\mu$ and $\bar{\nu}_e / \bar{\nu}_\mu$ will be calculated
Inclusive analyses in the antineutrino beam

- $\nu_\mu$ CC Inclusive
  - We are investigating a measurement in 3D: $(T_\mu, \cos\theta_\mu, E_{\text{avail}})$

- $\bar{\nu}_e$ CC Inclusive
  - We plan to measure in 2D: $(E_\mu, \cos\theta_e)$

Ratios $\bar{\nu}_\mu / \nu_\mu$ and $\bar{\nu}_e / \nu_\mu$ will be calculated
Exclusive analyses
Beyond the inclusive measurements

I showed the status of the inclusive CC cross sections in NOvA

$\sigma_{\text{CC}}^{\text{inclusive}}(E_\nu) = \sigma_{\text{CC}}^{\text{QE}} + \sigma_{\text{CC}}^{\text{MEC}} + \sigma_{\text{CC}}^{\text{Res}} + \sigma_{\text{CC}}^{\text{DIS}} + \sigma_{\text{CC}}^{\text{Coh}}$

**NOvA is actively working on different exclusive channels with neutrino and antineutrino for CC and NC**

By T. Golan
Beyond the inclusive measurements

I showed the status of the inclusive CC cross sections in NOvA

\[ \sigma_{CC}^{\text{inclusive}}(E_\nu) = \sigma_{CC}^{\text{QE}} + \sigma_{CC}^{\text{MEC}} + \sigma_{CC}^{\text{Res}} + \sigma_{CC}^{\text{DIS}} + \sigma_{CC}^{\text{Coh}} \]

**NOvA is actively working on different exclusive channels with neutrino and antineutrino for CC and NC**

There are two areas of analyses:

- **\( \nu_\mu \)-CC with low hadronic activity (\( \nu_\mu \)-CC low-had):** suitable for nuclear effect studies

- Different channels of semi in[ex]clusive pion / pion-less / proton production for CC and NC

*By T. Golan*
\( \nu_\mu \)-CC low-had: why is this measurement interesting?

- It is sensitive to MEC contributions
- It characterizes neutrino interactions with pion and proton with low kinetic energies

We plan to measure

- Cross sections of \( \nu_\mu \)-CC interactions with low hadronic activity in 3D: \((\cos\theta_\mu, T_\mu, E_{\text{avail}})\)
  - Total and shape comparison of measurements with generators
  - Close examination to the phase space regions that are sensitive to MEC

- Test of nuclear effects by comparing the energy estimation using the QEL hypothesis w.r.t the calorimetric calculation on the selected sample (QEL and MEC enriched distribution)
**νμ-CC low-had: selection of low hadronic activity**

For this sample:

- **QE and MEC are enhanced**
- **Res is reduced**
- **DIS is almost negligible**

### Composition in percentages

<table>
<thead>
<tr>
<th>Selection</th>
<th>QE</th>
<th>MEC</th>
<th>Res</th>
<th>DIS</th>
<th>COH</th>
</tr>
</thead>
<tbody>
<tr>
<td>νμ-CC Incl.</td>
<td>20.9%</td>
<td>18.9%</td>
<td>38.7%</td>
<td>19.8%</td>
<td>1.8%</td>
</tr>
<tr>
<td>νμ-CC 1-track</td>
<td>39.7%</td>
<td>33.7%</td>
<td>23.0%</td>
<td>2.5%</td>
<td>1.1%</td>
</tr>
</tbody>
</table>

### Selection:

**νμ CC with 1 track**

**NOvA Simulation**

- Events / (8.09x10^{20} POT)
- νμ CC Inclusive selection
- QE, Res, DIS, MEC, Other
- Kalman Tracks: all, only 1, only 2, only 3, > 3

**Fermilab**

03-15-2021    Leo Aliaga

NUSTEC Workshop
νµ-CC low-had: interaction modes

We defined low hadronic activity by optimizing the minimum uncertainty on the total cross section:

<table>
<thead>
<tr>
<th>Signal: νµ CC with</th>
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<tr>
<td>$T_{\text{proton}}^{\text{max}} = 250 \text{ MeV}, \ T_{\text{pion}}^{\text{max}} = 175 \text{ MeV}</td>
</tr>
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</table>
νμ-CC low-had: MEC component

MEC fraction increases with the $E_{\text{avail}}$ bins

The cross sections will have regions of enhanced MEC

Total and shape comparisons will help to test different models
νµ-CC low-had: testing the QE hypothesis

Another study we can perform with this MEC + QE enhanced sample is to test the QE hypothesis.

We want to observe the differences between the neutrino energy estimated by our calorimetric technique (Cal) vs the QE hypothesis.

- **We want to compare this ratio using different models with the ratio using real data**

**Work on the low hadronic activity channel is in progress and we expect results soon**
We plan to measure: cross sections of $\bar{\nu}_\mu$ - CC interactions with at least 1 $\pi^0$ w.r.t. $P_{\pi^0}$ and $\theta_{\pi^0}$.

Motivation

» It provides insight on background to $\nu_e$ / $\bar{\nu}_e$ appearance

» It constrains systematic uncertainties for neutrino interaction models
$\nu_\mu$ CC $\pi^0$: invariant mass distribution

$$m_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1 - \cos \theta_{\gamma\gamma})}$$

**NOvA Simulation**

- **Signal:** $\bar{\nu}_\mu$ CC with primary $\pi^0$
- **CC $\pi^0$ Background**
  - Wrong sign: $\nu_\mu$ CC $\pi^0$
  - $\bar{\nu}_\mu$ CC with secondary / tertiary… $\pi^0$
- **Non-CC or Non—$\pi^0$ Background**
  - $\nu_\mu$ CC with zero-$\pi^0$
  - NC
  - Other

**Selected event components**

- $\nu_\mu$ CC primary $\pi^0$
- $\nu_e$ CC primary $\pi^0$
- $\nu_\mu/\nu_e$ CC secondary $\pi^0$
- $\nu_e/\nu_\mu$ CC 0$\pi^0$
- NC
- Other

Mean of the Gaussian fit

**Invariant mass peak cut — [62, 222] MeV**
$\nu_\mu$ CC $\pi^0$: resolution and particle id

Cross sections w.r.t

$\pi^0$ momentum and angle

$l \bar{p}_{\pi^0} = l \bar{p}_{EM1} + \bar{p}_{EM2}$

$\cos \theta_{\pi^0} = \cos(\bar{p}_{\pi^0}, Beam)$
$\nu_{\mu} CC \pi^0$: resolution and particle id

Cross sections w.r.t $\pi^0$ momentum and angle

$| \vec{P}_{\pi^0} | = | \vec{P}_{EM1} + \vec{P}_{EM2} |$

$\cos \theta_{\pi^0} = \cos(\vec{P}_{\pi^0}, Beam)$

Work is in progress finalizing selection and completing the cross-section calculation chain
νμ CC π⁰: resolution and particle id

Cross sections w.r.t π⁰ momentum and angle

\[ |P_{π⁰}| = |P_{EM1} + P_{EM2}| \]

\[ \cos(θ_{π⁰}) = \cos(P_{π⁰}, Beam) \]

Work is in progress finalizing selection and completing the cross-section calculation chain

» We are improving the particle identification for all analyses by using Convolutional Visual Network (CVN):
  ▶ It is trained in single particle candidates as an attempt to minimize model bias
  ▶ We use uniform distributions (momentum, angle, position) of e, γ, π⁺⁻, p, μ
NOvA is pursuing other analyses

- $\nu_\mu$ and $\bar{\nu}_\mu$ CC excess events (2p2h)
- NC $\pi^0$ production in neutrino and antineutrino beam
- $\nu_\mu$ CC exclusive final state with pions and without pions
- $\nu_\mu$ CC Coherent pion production
- Neutrino-electron scattering
- CC low hadronic activity in antineutrino beam
Summary and conclusions

» The NOvA experiment has an excellent opportunity to make a high precision and a broad set of neutrino-nucleus cross-section measurements

» The $\nu_\mu$ - CC and $\nu_e$ - CC were recently presented and the publications will follow soon

» Exclusive channels such as $\nu_\mu$ - CC with low hadronic activity and $\bar{\nu}_\mu$ - CC $\pi^0$, and other pion final states measurements are actively being analyzed and we expect results in a short term

» We will calculate ratios of inclusive channels and exclusive over inclusive measurements
Summary and conclusions

» In parallel, we are making improvements to allow more precise measurements:

  ▶ Improvement in the particle identification by CVN, dedicated neutron and pion reconstruction groups, etc

  ▶ The NOvA Test Beam experiment, currently in-progress, aims to reduce the calibration and detector response uncertainties

» We are collecting more neutrino and antineutrino data. We expect to have good statistics and finer resolution to make higher dimensional cross-section measurements
Thank you!
Backup
Systematic uncertainties coming from each of these steps are assessed and propagated to the final results.
Begin with Geant4 simulation of neutrino beam production and transport.

Hadron production model is constrained with external measurements on thin target data (mainly from NA49, CERN).

- Same technique developed by MINERvA (Phys. Rev. D94, 092005)
- The uncertainty based on these external measurements results in a ~10% normalization uncertainty.

Beam misalignment is sub-dominant around the peak (~2GeV)
The NOvA 2019 GENIE Tune

- We use NOvA and external data to tune interaction model.
- These analyses use GENIE 2.12.2

- Correct QE to account for low $Q^2$ suppression.
- Apply low $Q^2$ suppression to Res baryon production.
- Nonresonant inelastic scattering (DIS) at $W>1.7$ GeV/c^2) weighted up 10% based on NOvA data.
- “Empirical MEC” based on NOvA ND data to account for multinucleon knockout (2p2h).

Same tune that was used in the NOvA 2019 analysis (arXiv:2006.08727)
Cross-section measurements

Differential cross-section measurement recipe:

\[
\frac{d\sigma}{dx_i} = \sum_j U_{ij}^{-1} \left( N_{sel}^j \times P_j \right) \times \Phi \Delta x_i
\]

We rely on simulations for optimizing the selection, applying corrections for the background, smearing and efficiency and for the flux normalization.

1. **Selection** of the reconstructed signal event candidates optimally with minimal model bias.
2. Subtraction of the **backgrounds** in the selection.
3. Correction of the **detector smearing** to move from reconstructed to true distributions.
4. Correction of the **efficiency** in the selection.
5. Normalization by the **neutrino flux**.
6. Normalization by the number of targets.
Selected signal events: 4 $E_{\text{avail}}$ slices

Good statistics for forward-going muons
$\nu_\mu$-CC low-had: efficiency and purity for $75 < E_{\text{avail}} < 150$ MeV

- Efficiency drops as the muon energy and angle increase due to containment.
- Purity $> 0.9$ in the whole phase space.