Muon-neutrino charged-current interactions at the NOvA near detector

Leonidas Aliaga (on behalf of the NOvA Collaboration)

The 22nd International Workshop on Neutrinos from Accelerators (NuFact 2021)

September 9, 2021
The NOvA experiment

» NOvA is a long-baseline neutrino oscillation experiment
» 2 detectors: 14.6 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
The NOvA experiment

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

- NOvA Simulation

- 94% pure $\nu_\mu$, 5% $\bar{\nu}_\mu$, and 1% $\nu_e + \bar{\nu}_e$ in neutrino mode
- 92% pure $\bar{\nu}_\mu$, 7% $\nu_\mu$, and 1% $\nu_e + \bar{\nu}_e$ in antineutrino mode

*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>
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<tr>
<td>%</td>
<td>67%</td>
<td>16%</td>
<td>11%</td>
<td>3%</td>
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Neutrino interactions at the few-GeV region

NOvA flux peaks between 1 and 5 GeV: it is the transition region between interaction processes.
Neutrino interactions at the few-GeV region

These interactions happen inside the nuclear media. **nuclear physics is important (and hard).**

The theory to describe this process is incomplete. Models are still under construction.

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**Meson Exchange Currents (MEC)**

**Quasi-Elastic (QE)**

**Resonant (RES)**

**Deep Inelastic Scattering (DIS)**
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
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This talk

\( \nu_\mu - CC \text{ Inclusive} \)

\( \nu_\mu - CC \text{ with low hadronic activity} \)

See also next talk

Interactions with electromagnetic shower in the NOvA ND (B. Ramson)
We rely on simulations for optimizing the selection, applying corrections for the background, smearing and efficiency and for the flux normalization.
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NuMI beam prediction

Hadron production model is constrained with external measurements on thin target data (NA49)

» Same technique developed by MINERvA (Phys. Rev. D94, 092005)

» The uncertainty based on these external measurements results in a ~10% normalization uncertainty

Beam focusing uncertainty is sub-dominant around the peak (below 2.5 GeV)
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.
- Non resonant 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 multi-nucleon knockout (2p2h).

Same tune that was used in the NOvA 2019 analysis

Our analyses are constructed to be insensitive to this tuning
$\nu_\mu$ - CC Inclusive
**Containment and fiducial**

**Muon candidates** should be contained in the **active region + Muon Catcher** and any other track only in the active region to avoid shower leaking.

`Top View`

`Side View`

Colors show time

These **preselection criteria** select 23% of signal events

**Vertices** should be inside a **fully active** (fiducial) region to cut rock muons
Muon identification

(Tracks reconstructed by the Kalman algorithm)

- **Preselection**: events fully contained and with vertex in fiducial volume.

- **Muon ID** calculated with a Boosted Decision Tree
Muon identification

NOvA Simulation

- **Preselection**: events fully contained and with vertex in fiducial volume.
- **Muon ID** calculated with a Boosted Decision Tree.
- Cut value corresponds to minimum uncertainties on cross section measurement.
- Sample has 97% purity and ~98% efficiency with respect to preselection.
\( \nu_\mu \) CC Inclusive

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

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
\[
\left( \frac{d^2 \sigma}{d \cos \theta_\mu d T_\mu} \right)_i = \sum_k \left( \frac{\sum_j U^{-1}_{ijk}(N^\text{sel} \cos \theta_\mu, T_\mu, E_\text{avail})_j P(\cos \theta_\mu, T_\mu, E_\text{avail})_j}{N_t \Phi \epsilon(\cos \theta_\mu, T_\mu, E_\text{avail})_{ik} \Delta \cos \theta_\mu \Delta T_\mu} \right)
\]
$\nu_\mu$ CC Inclusive: Example of 2 cosine slices

Draft publication is under Collaboration review

Out of the box generator comparisons.

All generators reproduce well the shape of our data.

We notice an overall normalization difference in GiBUU.

*G18_10j_00_000 and G18_10b_02_11a*
$\nu_\mu$ CC Inclusive: $E_\nu$ and $Q^2$

Draft publication is under Collaboration review

-presented in Fermilab JETP Seminar, July, 2020

Data (Stat. + Syst.)
- GENIE 3.00.06*
- GiBUU 2019
- NEUT 5.4.0
- NuWro 2019

\begin{itemize}
  \item $E_\nu$ and $Q^2$ are extracted only over the range of muon kinematics reported in the differential measurements.
  \item Good agreement between data and predictions for $E_\nu$
  \item We observe a low $Q^2$ suppression that is not well modeled by any generator
\end{itemize}

*\text{N18\_10j\_02\_11a: G18\_10j\_00\_000 and G18\_10b\_02\_11a}
\( \bar{\nu}_\mu \) CC Inclusive

- Analysis is similar to the muon-neutrino

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

- Ratios \( \bar{\nu}_\mu / \nu_\mu \) and \( \bar{\nu}_e / \nu_\mu \) will be calculated

\( \sigma / E_\nu (\text{cm}^2 / \text{GeV} / \text{nucleon} \times 10^{-4}) \)

\( \frac{d \sigma}{d Q^2} (\text{cm}^2 / \text{GeV}^2 / \text{nucleon} \times 10^{-4}) \)

- \( E_\nu \) and \( Q^2 \) are extracted only over the range of muon kinematics reported in the differential measurements.

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

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**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 neutral and charged pion / pion-less / proton production for CC and NC

*By T. Golan*
$\nu_\mu$ - CC with low hadronic activity
νμ-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 νμ - CC interactions with low hadronic activity in 2D: (cosθμ, Tμ)
  - Total and shape comparison of measurements with generators
  - Close examination to the phase space regions that are sensitive to MEC

» Additionally, we want to test nuclear effects by comparing $E_{νQE}$ (assuming QE interactions and using muon kinematics) vs $E_{νCal}$ (using calorimetry on all detected particles)
$\nu_\mu$-CC low-had: interaction modes

Fraction of interactions to total selected events

Selection: $\nu_\mu$ CC with 1 track

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Selection criteria:
- $\nu_\mu$ CC with 1 track

**QE**

- Fraction of interactions to total selected events

**MEC**

- Fraction of interactions to total selected events

**Res**

- Fraction of interactions to total selected events

**DIS**

- Fraction of interactions to total selected events
**ν_µ-CC low-had: interaction modes**

Fraction of interactions to total selected events

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Low hadronic activity is defined by finding the minimum uncertainty on the total cross section:

**Signal: ν_µ CC with**

\[ T_{\text{proton}}^{\text{max}} = 250 \text{ MeV}, \ T_{\text{pion}}^{\text{max}} = 175 \text{ MeV} \]

Purity is > 80% in most of the analysis bins
Cross section using mock-data

» The expected uncertainties are small enough to make cross-section measurements

» The full analysis chain has been built

Analysis is currently under Collaboration review

Selected events

Analysis bins
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.

This talk showed:

- $\nu_\mu$ - CC Inclusive was recently presented and the publication will follow soon
- $\nu_\mu$ - CC with low hadronic activity is actively being analyzed and we expect results in a short term

$\nu_e$ - CC and exclusive CC and NC channels including pion final states measurements have quick progress.

Stay tuned!
Thank you!
Backup
Available energy and interaction modes

NOvA Simulation

Events / 8.09 x 10^{20} POT

Reco available energy (GeV)

NOvA Simulation

Ratio to total

Reco available energy (GeV)

Selected events
QE
Res
DIS
MEC
Others