Cross-section measurements at the NOvA near detector

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Outline

• Overview of the NOvA beam, detector and simulation
• Inclusive measurements
• Pion production measurements
• NC coherent $\pi^0$ results
• Summary and outlook
Beam at NOvA

- NOvA detectors are 14 mrad off the NuMI beam axis.
- Narrow 2-GeV spectrum
- Small flux shape uncertainties (hadron production uncertainties are mostly normalisation effect)
- 95% pure $\nu_\mu$ beam

\[
E_\nu = \frac{1 - (m_\mu / m_\pi)^2}{1 + \gamma^2 \tan^2 \theta} E_\pi
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- $E_\nu$ vs $E_\pi$ plot
- $\nu_\mu$ vs $\bar{\nu}_\mu$ vs $\nu_e$ vs $\bar{\nu}_e$ vs $\nu_\tau$ vs $\bar{\nu}_\tau$

\[E_\nu = \frac{1 - (m_\mu / m_\pi)^2}{1 + \gamma^2 \tan^2 \theta} E_\pi
\]

- $10^6 \nu_\mu$ CC / 6E20 POT / kton / 0.1 GeV
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- On-Axis
- 14.6 mrad Off-Axis (NOvA)

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Beam at NOvA

- NOvA is sensitive to many different nu+A interaction channels.
- Cross sections in NOvA’s energy range suffer from high uncertainties in neutrinos and no measurements below 3 GeV for antineutrinos.
- Nice overlap with currently running experiments, as well as future experiments in the US.
The NOvA Near Detector

- Tracking calorimeter
- 77% hydrocarbon by mass, 16% chlorine, 6% TiO$_2$
- Muon catcher (steel + NOvA cells) at downstream end to range out $\sim$2GeV muons.
- $O(10)$ ns single hit timing resolution.

Wavelength-shifting fibres routed to a single cell on an Avalanche Photodiode

~1 hour of data!

10 $\mu$s NuMI pulse

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Simulation

Beamline+Flux: G4NuMI

nu interactions & FSI modelling: GENIE

Detector response: GEANT4

Readout electronics & DAQ: Custom simulation routines
\( \nu_\mu \) CC inclusive

- \( \sigma(E) \) and flux-averaged double differential cross section in muon kinematics variables

\[
\left( \frac{d^2\sigma}{d \cos \theta_\mu dT_\mu} \right)_i = \frac{\sum_j U_{ij} (N^{sel}(\cos \theta_\mu, T_\mu)_j - N^{bkg}(\cos \theta_\mu, T_\mu)_j)}{\epsilon(\cos \theta_\mu, T_\mu)_i (\Delta \cos \theta_\mu)_i (\Delta T_\mu)_i N_{\text{target}} \phi}
\]

- \( \sigma(E) \) measurements are kinematically restricted this phase space due to limited statistics and low efficiency

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\( \nu_\mu \) CC inclusive: Reco + Selection

- Hits associated in time and space are used to form a candidate interaction.
- Vertices, tracks and showers are reconstructed from these hits.
$\nu_\mu$ CC inclusive: Reco + Selection

- Solid box is Fiducial Volume
- Containment uses nearest projected distance to an edge (dashed box is rough approximation).
- Events with hadronic activity in or near the muon catcher are excluded
$\nu_\mu$ CC inclusive: PID

- Use a $kNN$ to separate signal and background tracks based on 4 variables:
  - track length
  - dE/dx along track
  - scattering along track
  - fraction of track planes w/ single particle dE/dx

![Graphs and plots illustrating the analysis of neutrino CC inclusive events with PID.](image-url)
\( \nu_\mu \) CC inc: efficiency and background

- Selection efficiency is dominated by containment cut.
- Backgrounds are small near the 2 GeV peak, larger in the tails of the spectrum.
- Uncertainties are at the level of a few %. 

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Statistical uncertainties are typically <2%.

Systematics are still being assessed, but we expect for the differential measurement ~10% highly correlated (normalisation) flux uncertainties, and all the other systematics combined to be 5-8%.

σ(E) measurement systematics will be similar, although systematics from energy scale uncertainties will be larger on the rising and falling edges of the spectrum.
ν_\text{e} CC inclusive: Overview

- Challenging because (by design) there are ~1% of ν_\text{e}.
- We have shown preliminary results on this channel in the past. That analysis is now superseded with a different event identification developed in the oscillation analysis.

\[
\frac{d\sigma}{dX_i} = \frac{\sum_j U_{ij}(N^{\text{sel}}(X_j) - N^{\text{bkg}}(X_j))}{\epsilon(X_i)\Delta X_i N_{\text{target}} \Phi}
\]

σ(E) and flux-averaged single differential cross-section as a function of the electron kinematics for energies between 1 and 3 GeV.
\( \nu_e \) CC inclusive: CVN

• NOvA uses a Convolutional Neural Network (CNN) where a series of image filters are applied to hit map images to extract features associated with an interaction
• Not limited to features chosen a priori
• CNNs extract features of varying complexity and learn correlations

30\% effective increase in exposure

First CNN implementation on a HEP result

Inputs are image representations of our events where "RGB" calibrated hit information

Does not require previous reconstruction: no reconstruction inefficiencies

Inspired by animal visual cortex

Kernels, Filters or Convolutional Layers extract features of varying levels of complexity
\( \nu_e \) CC inclusive: CVN

- A convolutional visual network (CVN) is then trained on these filters.
- 30% effective increase in exposure in the Far Detector for the oscillation analysis.
Currently using a cut (CVN > 0.85) that optimises the FoM of $S/\sqrt{(S+B)}$

- Backgrounds are significant, and we are investigating potential driven data constraints.
\[ \nu_e \text{ CC incl: Efficiency and Purity} \]

- Xsec, FSI and calibration systematics included in error bands.
- Uncertainties on efficiency and backgrounds is between 5-10%.
- Data-driven constraints on the efficiency and backgrounds are being explored.
\( \nu_\mu \text{ CC} \pi^0 \)

- Signal: \( \nu_\mu\)-CC events with at least one primary \( \pi^0 \) in the final state.
- \( \pi^0 \) production vital for \( \nu_e \) appearance searches
- Flux-averaged differential cross sections in final state kinematics
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.
\[ \nu_\mu \text{ CC } \pi^0 \]

- Signal is dominantly RES (38.3%) and DIS (61.3%).
- Uncertainty (~15%) is systematic dominant.

Plan to report flux-averaged differential cross section in final state muon and pion kinematics.
- At final stage of internal review.

Results soon!
NC Coherent $\pi^0$

- Neutrino coherent scattering = small momentum transfer.
- Single forward-going pion, without other pions or nucleons.

To identify the NC $\pi^0$ sample:
- Absence of muon.
- Two showers identified as photons by dE/dx-based likelihoods.
- Cut on invariant mass to select $\pi^0$s

Main background is RES and DIS $\pi^0$s.
NC Coherent $\pi^0$

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).

![Control Sample](image1.png)

![Signal Sample](image2.png)
NC Coherent $\pi^0$

- Fit the backgrounds to control sample data in $\pi^0$ energy vs angle 2D space.
- Background fit result are applied to the backgrounds in the signal sample.
Renormalised background using energy and angle 2D space.

Measured flux-averaged cross-section using background subtraction:

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

Total uncertainty 16.7%, systematic dominant.
Summary and future plans

• The NOvA experiment has excellent opportunities to make high precision measurements of neutrino-nucleon/nucleus interactions

• $8 \times 10^{20}$ POT neutrino ND dataset:
  • systematics-limited inclusive and CC neutral pion production measurement to be released this year
  • CC charged pion production and NC neutral pion production measurements are in progress

• $3 \times 10^{20}$ POT antineutrino ND dataset $\rightarrow$ inclusive measurement are high priority for NOvA

• Stay tuned for results soon!
Thank you!
Neutrino beam

NuMI Beam

- 120 GeV protons extracted from the Main Injector at Fermilab in 10 μs spills
- Focus secondary pions using magnetic horns
  - Positive hadrons for neutrino beam
  - Negative hadrons for antineutrino beam
- Decay kinematics mean a detector at 14.6 mrad sees a narrowly peaked energy spectrum
- Beam 97.5% $\nu_\mu$ with 0.7% $\nu_e$ and 1.8% wrong-sign
• Present results data collected between February 6, 2014 and May 2, 2016

• Equivalent to $6.05 \times 10^{20}$ protons-on-target in a full 14 kT detector

• Beam had been running at 560 kW

• **Achieved 700 kW design goal, most powerful neutrino beam in the world**
NOvA detectors

- Two functionally identical detectors
- Extruded plastic cells alternating vertical and horizontal orientation filled with liquid scintillator
- Charged particles passing through cells produce light which is collected.
Cell hits coloured by recorded charge (~photoelectrons)
Far Detector 10 $\mu$s NuMI Beam Window

Cell hits coloured by recorded charge (~photoelectrons)
Far Detector Neutrino Interaction

Cell hits coloured by recorded charge (~photoelectrons)

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Event topologies

\[ \nu_\mu \text{ CC} \]

\[ \nu_e \text{ CC} \]

\[ \text{NC} \]
Muon neutrino selection

- Separate $\nu_\mu$ CC interactions from NC and cosmic-ray backgrounds
- Use 4 variable k-Nearest Neighbour to select $\mu$
- Selection is 81% efficient and 91% pure
- Containment cuts remove activity near walls
- Additional Cosmic rejection from event topology and Boosted Decision Tree

![Graphs and diagrams related to Muon ID and dE/dx Log-likelihood](images)

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Electron neutrino selection

- 73% $\nu_e$ CC selection efficiency, 76% purity with CVN classifier
- Good ND Data/MC agreement
- CVN provides better cosmic rejection and similar systematics to 2015 classifiers
- Bin analysis in 3 bins of CVN and 4 bins of energy
NC Coherent \pi_0

Fit the backgrounds to control sample data in \pi_0 energy vs angle 2D space.

Apply the background tuning to the signal sample.
The Bragg Peak Identifier (BPI) is a measure of the increase in dE/dx towards the end of a prong. The BPI value is defined for prongs with Nhit ≥ 4 as the ratio of average energy deposit in the furthest min(6, Nhit/2) hits from the prong start point to the average energy deposit in the rest of the prong. Here, Nhit/2 is always rounded down.