New Results from the NOvA Experiment

Erica Smith, on behalf of the NOvA Collaboration
Indiana University

NuFACT 2019
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NOvA

- NOvA is a long-baseline neutrino oscillation experiment
- Study neutrinos from the NuMI beam at Fermilab
- Two functionally identical detectors:
  - Far Detector (FD) 14 kton; on the surface
  - Near Detector (ND) 0.3 kton; underground
- Off axis position provides narrow band beam that peaks around 2 GeV
Physics Goals

- What is the neutrino mass hierarchy?
- Is there a $\nu_\mu - \nu_\tau$ symmetry?
- Is CP violated in the lepton sector?
- Is the large mixing angle maximal, and if not, what is the octant?
- Are there other neutrinos beyond the three active flavors?
- Is there a $\nu_3 - \nu_e$ hierarchy?

\[ \theta_{23} > 45^\circ \quad \theta_{23} < 45^\circ \]

\[ \Delta m^2_{atm}, \Delta m^2_{\odot} \]
Physics Goals

• What is the neutrino mass hierarchy?
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  • Is the large mixing angle maximal, and if not, what is the octant?
• Is CP violated in the lepton sector?
• Are there other neutrinos beyond the three active flavors?
The NuMI Neutrino Beam

Flux 1-5 GeV
- 95% $\nu_\mu$
- 4% $\overline{\nu}_\mu$
- 1% $\nu_e$

Weekly neutrino beam
Weekly antineutrino beam
Accumulated beam
Accumulated neutrino beam
Accumulated antineutrino beam

NOvA far detector exposure, NuMI beam


Date

8.85x10^{20} POT

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The NuMI Antineutrino beam

Target

Focusing Horns

Decay Pipe

$\pi^-$

$\pi^+$

$p$

The NuMI Antineutrino beam

Flux 1-5 GeV

- $6\% \, \nu_\mu$
- $93\% \, \bar{\nu}_\mu$
- $1\% \, \nu_e$

Weekly neutrino beam
Weekly antineutrino beam
Accumulated beam
Accumulated neutrino beam
Accumulated antineutrino beam

NOvA far detector exposure, NuMI beam

2014
2015
2016
2017
2018
2019

Date

8.85x10^{20} \text{ POT}

12.33x10^{20} \text{ POT}

Erica Smith
NOvA Detectors

- Detectors are fine-grained, low-Z, highly-actively tracking calorimeters
- Cells are PVC, filled with liquid scintillator
- Read out via wavelength shifting fiber to APD
- Orthogonal layers of cells → top and side view for each event
Near Detector Event Display

Beam

(colors show hit times)
Far Detector Event Display – 550 μs

(colors show charge)
Far Detector Event Display – 10 μs

(colors show charge)
Selected Events from Near Detector Data
Cross section Measurements

How well do we understand neutrino interactions in our detector?

See talk: H. Duyang, WG2, Aug 27
Motivation

• High statistics datasets in our ND
• Cross section uncertainty is one of our largest systematics in the oscillation analyses
• Understanding nuclear effects is important to be able to reconstruct neutrino energy
  • i.e. do we model neutrino scattering well enough to be able to predict $E_{\text{true}} \rightarrow E_{\text{reco}}$
Measurements in Progress

In neutrino and antineutrino modes –

• Charged current measurements:
  • \( \nu_\mu \) CC 0\( \pi \)
  • \( \nu_\mu \) CC \( \pi^0 \)
  • \( \nu_\mu \) CC \( \pi^\pm \)
  • \( \nu_\mu \) CC inclusive
  • \( \nu_e \) CC inclusive

• Neutral current measurements:
  • NC \( \nu \) COH \( \pi^0 \)
  • NC \( \nu \) \( \pi^0 \) semi-inclusive
NC Coherent $\pi^0$

$\pi^0$s slightly more forward going than predicted

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

consistent with model prediction

arxiv:1902.00558, submitted to PRD
$\nu_\mu$ CC Semi-inclusive $\pi^0$

$\nu_\mu + A \rightarrow \mu^- + \pi^0 + X$

3.72$\times 10^{20}$ POT

- Reporting result as differential cross section as a function of $Q^2$ and muon and pion kinematics
- Generally consistent with GENIE

Paper in preparation
Fermilab JETP seminar

NOvA Preliminary
\( \nu_\mu \text{CC Inclusive} \)

Double differential cross section as a function of muon kinematics

Uncertainties driven by flux, energy scale

Mock data study. Real data coming soon
Neutral Current Analysis

Are there other neutrinos beyond the three known active flavors?

See talk: A. Aurisano, WG1+5, Aug 30
Long Baseline Neutral Current Disappearance

- NC interaction rate is the same for 3 active neutrino flavors – insensitive to 3 flavor oscillations
- Oscillations to sterile neutrino states will result in deficit in NC interaction rate
- Sensitive to mixing parameters $\theta_{24}, \theta_{34}, \Delta m_{41}^2$
Neutrino Beam

Predict 191.2 ± 13.8 (stat) ± 22.0 (syst) events
Observed 214

No evidence for NC disappearance

Antineutrino Beam

Predict 69 ± 8 (stat) ± 10 (syst) events
Observed 61
Limits

Neutrino Beam

NOvA 8.85 × 10^{20} POT-eqv.
\[ \Delta m^2_{43} = 2.57 \times 10^{-3} \text{ eV}^2 \]
\[ \theta_{13} = 8.5^\circ, \sin^2 \theta_{23} = 0.624 \]
\[ \Delta m^2_{11} = 0.5 \text{ eV}^2, \delta_{13} = 0.74\pi \]

valid for \( 0.05 < \Delta m^2_{41} \text{ (eV}^2) < 0.5 \)

\[ \theta_{24} < 16.2^\circ, \theta_{34} < 29.8^\circ \text{ (90}\%\text{CL)} \]

Antineutrino beam

NOvA Fit, 12.51 × 10^{20} POT
\[ \sin^2 \theta_{23} = 0.542, \Delta m^2_{32} = 2.44 \times 10^{-3} \text{ eV}^2 \]
\[ \Delta m^2_{41} = 0.5 \text{ eV}^2 \]
\[ \delta_{13} = 1.37\pi \]

valid for \( 0.05 < \Delta m^2_{41} \text{ (eV}^2) < 0.5 \)

\[ \theta_{24} < 24.7^\circ, \theta_{34} < 31.7^\circ \text{ (90}\%\text{CL)} \]
Future

- Currently using data-driven near-to-far ratio approach which assumes no oscillations at the ND
- In the future, use covariance matrix technique to perform joint ND-FD fit to produce contours
  - Allows for oscillations in the ND
  - Extends reach to higher $\Delta m^2_{41}$
- Short baseline oscillation results from the ND
Three Flavor Analysis

Is there $\nu_\mu - \nu_\tau$ symmetry?
What is the mass hierarchy?
Is CP violated in the lepton sector?

See talk: S. Calvez, WG1, Aug 29
Event Identification
• Event ID is done by our CNN, called Convolutional Visual Network (CVN)
  • Employs a deep convolutional network in the “image recognition” style
  • Trained on two dimensional views of the event’s calibrated hits
  • Information of each view is combined in the final layer of the network
• Trained separately on neutrinos and antineutrinos
• Effective exposure increase of 30% for $\nu_e$ selection (JINST 11, P09001)
Simulation Tuning

- Beam flux is tuned using the Package to Predict the FluX using external data
- We tune our cross-section model primarily to account for nuclear effects
  - First apply corrections based on external theory and/or data
  - Use ND data to constrain remaining pieces
Correct QE component to account for effect of long-range nuclear correlations using model of València group via work of R. Gran (MINERvA) [https://arxiv.org/abs/1705.02932]
Cross Section Tuning

Apply same long-range effect as for QE to resonant (RES) baryon production as a stand-in for nuclear effects we see at low $Q^2$ - difference between modified and unmodified as uncertainty.
Nonresonant inelastic scattering (DIS) at high invariant mass ($W > 1.7 \text{ GeV/c}^2$) weighted up 10% based on NOvA data.
Tune weights for empirical MEC in true 4-momentum transfer to get agreement with ND data in reconstructed 4-momentum transfer.
Constraints from ND Data

- Use reco-to-true migration for signal extrapolation
- $\nu_e$ backgrounds use the Far/Near ratio in bins of reconstructed energy
- Other (small) beam backgrounds are taken from simulation
Muon Neutrinos at the ND

- Selected muon neutrino and antineutrino charged current interactions in ND.
- Used in the signal extrapolation
- Wrong sign contamination is estimated to be 3% (11%) for neutrino (antineutrino) beam.
Electron Neutrinos at the ND

• ND $\nu_e$-like sample has no appearance – all background
• To constrain backgrounds in the neutrino beam we use two data-driven techniques
• For the antineutrino beam we scale all components proportionally

<table>
<thead>
<tr>
<th>Neutrino</th>
<th>Antineutrino</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam $\nu_e/\bar{\nu}_e$</td>
<td>55%</td>
</tr>
<tr>
<td>NC</td>
<td>24%</td>
</tr>
<tr>
<td>CC $\nu_\mu/\bar{\nu}_\mu$</td>
<td>21%</td>
</tr>
</tbody>
</table>
$\nu_\mu$ and $\bar{\nu}_\mu$ data at the Far Detector

**Neutrino beam**

- **Total Observed**: 113
- **Best fit prediction**: 124
- **Cosmic Bkgd.**: 2.1
- **Beam Bkgd.**: 2.1

**Antineutrino beam**

- **Total Observed**: 102
- **Best fit prediction**: 96
- **Cosmic Bkgd.**: 0.8
- **Beam Bkgd.**: 1.4
Defining Neutrino beams and the Far Detector data. 

- **Neutrino Beam**
  - Low PID
  - High PID
  - Data: 
    - FD Data
    - Oscillation Fit
    - 1-σ Syst Range
    - Wrong Sign Bkg
    - Total Beam Bkg
    - Cosmic Bkg

- **Anti-Neutrino Beam**
  - Low PID
  - High PID
  - Data: 
    - FD Data
    - Oscillation Fit
    - 1-σ Syst Range
    - Wrong Sign Bkg
    - Total Beam Bkg
    - Cosmic Bkg

Events / $8.85 \times 10^{20}$ POT-equiv

Energy (GeV) vs. Events / 12.33 $\times 10^{20}$ POT
$\nu_e$ and $\bar{\nu}_e$ data at the Far Detector

**Neutrino Beam**
- **Total Observed**: 58
- **Total Prediction**: 59.0
- **Wrong**
  - **sign**: 0.7
- **Beam Bkgd.**: 11.1
- **Cosmic Bkgd.**: 3.3
- **Total Bkgd.**: 15.1

**Anti-Neutrino Beam**
- **Total Observed**: 27
- **Total Prediction**: 27
- **Wrong**
  - **sign**: 2.2
- **Beam Bkgd.**: 7.0
- **Cosmic Bkgd.**: 1.1
- **Total Bkgd.**: 10.3

4.4$\sigma$ evidence of $\bar{\nu}_e$ appearance
Maximal mixing disfavored at 1.2σ.
Lower octant disfavored at 1.6σ..
Consistent with other long-baseline and atmospheric experiments.
Best Fit

$$\Delta m^2 = (2.48^{+0.11}_{-0.06}) \times 10^{-3} \text{ eV}^2$$

$$\sin^2 \theta_{23} = 0.56^{+0.04}_{-0.03}$$

$$\delta_{CP} = 0.0^{+1.3}_{-0.4} \pi$$

NHUO: All values of $\delta$ ruled out at 1.1$\sigma$.

IH: $\delta = \pi/2$ ruled out $> 4\sigma$. 
NOvA Preliminary

Feldman-Cousins corrected significances

<table>
<thead>
<tr>
<th></th>
<th>IH LO</th>
<th>IH UO</th>
<th>NH LO</th>
<th>NH UO</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO</td>
<td>Disfavored 1.6σ</td>
<td>Disfavored 1.8σ</td>
<td>Disfavored 2.0σ</td>
<td></td>
</tr>
<tr>
<td>NH</td>
<td>Disfavored 1.6σ</td>
<td>Best fit</td>
<td>NH preferred</td>
<td></td>
</tr>
</tbody>
</table>

IH Disfavored 1.9σ

NH preferred at 1.9σ

NOvA FD
8.85×10^{20} POT-equiv (ν)
12.33×10^{20} POT (ν)

\( \sin^2 \theta_{13} = 0.082 \)
\( \sin^2 \theta_{23} = 0.48 \)
\( \Delta m_{32}^2 = -2.54 \times 10^{-3} \text{eV}^2 \)
\( \Delta m_{32}^2 = +2.48 \times 10^{-3} \text{eV}^2 \)

Total events - antineutrino beam

Total events - neutrino beam

2019 best fit
• Calibration and energy scale are two of the largest systematic uncertainties
• Will be reduced with the test beam program
• Beam run in fall 2019
Future

• Expected to run through 2025
• Run plan: 50-50 neutrinos/antineutrinos

• Potential 3-5σ sensitivity to hierarchy
• Possible > 2σ sensitivity to CP violation

• Proposed accelerator improvements and test beam program enhance NOvA’s reach
• Improvements in simulation will improve analysis robustness

• Joint T2K-NOvA analysis coming soon
Summary

• Cross section program:
  • Dedicated measurements using ND data
  • Integration of new measurements and theoretical work from the community

• Consistent with three flavor picture:
  • No evidence for NC disappearance

• Constraints on three flavor oscillation parameters:
  • $4.4\sigma$ evidence for electron antineutrino appearance in a muon antineutrino beam
  • $1.9\sigma$ preference for the Normal Hierarchy
  • $1.6\sigma$ preference for $\theta_{23}$ in the Upper Octant (maximal mixing disfavored at $1.2\sigma$)
Thank you!
Backups
Muon Neutrino Energy

\[ E_\nu = E_\mu + E_{\text{had}} \]

- Muon energy is calculated with a conversion from track length.
- Hadronic energy is the summed calorimetric energy of the non-muon hits, converted to true energy.
- Muon energy resolution (3%) is much better than hadronic energy resolution (30%).
Muon Neutrinos at the ND

Muon neutrino sample divided into four quartiles based on hadronic energy fraction.

Each quartile extrapolated separately to the FD.
Electron Neutrino Energy

\[ E_\nu = A^* E_{EM} + B^* E_{had} + C^* E_{EM}^2 + D^* E_{had}^2 \]

- Detector response is different for EM energy and hadronic energy
- To take this into account we separate the EM and hadronic depositions with a CVN variant
Other Selections

- Some basic additional cuts:
  - Contained, fiducial events, well-reconstructed, reasonable energy range
  - An additional $\nu_\mu$ requirement: a track identified as a muon.
- CVN identifies events with a muon, but it does not identify the muon track.
- Identify muons in reconstructed tracks using a kNN
  - Track length, dE/dx, scattering, fraction of track-only planes
• Additional cosmic rejection needed at the Far Detector.
  • 11 billion cosmic rays/day in the Far Detector on the surface.
  • $10^7$ rejection power required after timing cuts are applied.

• The $\nu_\mu$ sample uses a BDT based on:
  • Track length and direction, distance from the top/sides, fraction of hits in the muon, and CVN.

Cosmic rejection for the $\nu_e$ sample is in 2 stages:
• Core sample: require contained events, beam-directed events, away from the detector top
• Peripheral sample: events failing the core selection can pass a BDT cut plus a tight CVN cut.
  • Different BDT from $\nu_\mu$ based on the same containment variables used for cuts in the core sample.
• Additional cosmic rejection needed at the Far Detector.
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**Core Sample**

**Peripheral Sample**

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**Additional notes:**

- Black – Cosmic data
- Color – $\nu_e$ Signal MC
- $\bar{\nu}_e$ beam
$\nu_e$ Decomposition

- $\nu_e$ and $\nu_\mu$ events come from the same parents:
  - Lower energy neutrinos come primarily from $\pi$ decay.
  - Higher energy neutrinos come primarily from $K$ decay.
- Use contained $\nu_\mu$ data to constrain the $\pi$ flux
- Use higher energy uncontained events to constraint the $K$ flux.
**$\nu_e$ Decomposition**

The CC/NC constrained using the number of observed Michel electrons.

- Determine the fraction of the two components in each analysis bin.

**Change in Total**

- $\nu_e$ CC: +3%
- $\nu_\mu$ CC: +7%
- NC: -4%
Cross Section Tuning - QE

GENIE 2.12 default:
global relativistic Fermi gas
(+ “Bodek-Ritchie tail”)  

Local Fermi gas
+ Nuclear polarization / long-range collective response (“RPA”)

Supported by eA data; MINERvA vA data (PRD 116, 071802; PRL 121, 022504), T2K vA data (PRD 98, 032003), ...
Cross Section Tuning - QE

GENIE 2.12 default:
- global relativistic Fermi gas
  (+ “Bodek-Ritchie tail”)

Applying the IFIC València group's calculation (LFG + RPA) via reweights for GENIE by R. Gran (MINERvA)

[R. Gran, arXiv:1705.02932]

Local Fermi gas
+ Nuclear polarization / long-range collective response (“RPA”)

CV correction
(other colors show uncertainties)
Apparent suppression at low momentum transfer \((Q^2)\) relative to model... (except in \(\nu A \rightarrow \mu^+\pi^-\))

No theory guidance here. Reminiscent of LFG+RPA correction in elastic though....

![Diagram of particle interactions]
Cross Section Tuning – \( \pi^\pm \)

Adapt elastic long-range correlation model ("RPA")
Use difference between modified and unmodified as uncertainty

MINERvA studies in pion production suggest alternate empirical correction we may consider in future

Apply \( Q^2 \)-based Valencia LFG+RPA weight from QE to resonant production
Cross Section Tuning – 2p2h

“2p2h”
Knock out two nucleons with an elastic-like interaction

València group’s MEC model best available in GENIE 2.12

Despite success for lower energies, leaves something to be desired for 2 GeV on $^{12}$C

NOvA Preliminary

Valencia MEC
Neutrino Beam $\nu_\mu + \bar{\nu}_\mu$ CC Selection

$10^4$ Events

Visible $E_{\text{had}}$ (GeV)
Cross Section Tuning – 2p2h

Refit empirical “model”* to ND data

* T. Katori, NuInt12 Proceedings, arXiv:1304.6014
Re-perform fitting procedure with alternate non-MEC model (shifts within uncertainties) to establish uncertainty bounds for MEC fit.
Cross Section Tuning - Future

Topological selections give us other windows into the performance of our model
NOvA FD $\times 10^{20}$ POT equiv $\nu + \times 10^{20}$ POT $\bar{\nu}$

Significance ($\sigma$) vs $\delta_{CP}$

- NH Lower octant
- NH Upper octant
- IH Lower octant
- IH Upper octant

NOvA Preliminary
Systematics Reduced with Extrapolation

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What’s new with $\bar{\nu}$’s? Wrong-sign contamination

- ~10% systematic uncertainty on wrong-sign from flux and cross section
  - Does not include uncertainties from detector effects.
- Confirm using data-driven cross-checks
  - 11% WS in the $\nu_\mu$ sample checked using neutron captures.
  - 22% WS in beam $\nu_e$ checked using identified protons and event kinematics.
New neutron response systematic

\[ \bar{\nu}_l \rightarrow W \rightarrow n \]

\[ \bar{\nu}_l \rightarrow W \rightarrow p \]

- \( \bar{\nu} \)'s have neutrons where \( \nu \)'s have protons.
  - Often several hundred MeV of energy.
  - Modeling these fast neutrons is known to be challenging.
- See some discrepancies in an enriched sample of neutron-like prongs.
- New systematic introduced:
  - Scales the amount of deposited energy of some neutrons to cover the low-energy discrepancy.
  - Shifts the mean \( \nu_\mu \) energy by 1\% in the antineutrino beam and 0.5\% in the neutrino beam.
- Negligible impact was seen on selection efficiencies.
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Systematics – $\sin^2\theta_{23}$

NOvA Preliminary

- Neutron Uncertainty
- Detector Calibration
- Neutrino Cross Sections
- Near-Far Differences
- Detector Response
- Muon Energy Scale
- Normalization
- Beam Flux
- Total syst. error
- Statistical error

Uncertainty in $\sin^2\theta_{23}$
Systematics - $\delta_{CP}$

- Near-Far Differences
- Neutrino Cross Sections
- Detector Response
- Detector Calibration
- Normalization
- Neutron Uncertainty
- Beam Flux
- Muon Energy Scale
- Total syst. error
- Statistical error

Uncertainty in $\delta_{CP}/\pi$
Reach – Hierarchy Resolution, IH

$$\sin^2 \theta_{23} = 0.45-0.60, \ \Delta m^2_{32} = -2.54 \times 10^{-3} \text{eV}^2, \ \sin^2 2\theta_{13} = 0.082$$

![Graph showing hierarchy resolution](image)

- IH $\delta_{CP} = 3\pi/2$
- IH $\delta_{CP} = \pi$
- IH $\delta_{CP} = 0$
- IH $\delta_{CP} = \pi/2$

2019 analysis techniques

56$\times 10^{20}$ POT($\nu$) + 36$\times 10^{20}$ POT($\bar{\nu}$) by 2025

Erica Smith
Reach – Maximal Mixing Rejection

\[ \delta_{\text{CP}} \in [0,2\pi], \Delta m_{32}^2 = +2.48 \times 10^{-3} \text{eV}^2, \sin^2 \theta_{13} = 0.082 \]

Max. mixing rejection

- NH \( \sin^2 \theta_{23} = 0.60 \)
- NH \( \sin^2 \theta_{23} = 0.45 \)
- IH \( \sin^2 \theta_{23} = 0.60 \)
- IH \( \sin^2 \theta_{23} = 0.45 \)

Significance \( \sigma = \sqrt{\Delta \chi^2} \)

2019 analysis techniques

36\times10^{20} \text{POT}(\nu) + 36\times10^{20} \text{POT}(\bar{\nu}) \text{ by 2025}
Reach - $\delta_{CP}$

$\sin^2\theta_{23} = 0.45 - 0.60$, $\Delta m^2_{32} = +2.48 \times 10^{-3} \text{eV}^2$, $\sin^2\theta_{13} = 0.082$

CP violation

NOVA Simulation

$\sigma = \sqrt{\Delta \chi^2}$

2019 analysis techniques
$36 \times 10^{20} \text{POT}(v) + 36 \times 10^{20} \text{POT}(\bar{v})$ by 2025

NOVA Simulation

$\sin^2\theta_{23} = 0.45 - 0.60$, $\Delta m^2_{32} = -2.54 \times 10^{-3} \text{eV}^2$, $\sin^2\theta_{13} = 0.082$

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