NOvA: recent oscillation results and prospects

Erika Catano-Mur

54th Fermilab Users (Virtual) Meeting. August 4th 2021
The NOvA Experiment

• NOvA is a long-baseline accelerator neutrino oscillation experiment
  – Using the NuMI muon neutrino (or anti-neutrino) beam from Fermilab.
• It consists of two detectors (Near, Far)
  – Identical technology
  – Different size and location

• Its primary goal is to constrain neutrino oscillation parameters by measuring
  \[ \nu_e, \nu_\mu, \nu_\tau \]
  
  Electron (anti) neutrino appearance
  Muon (anti) neutrino disappearance
Long-baseline neutrino oscillations
3-flavor neutrino oscillations

- 3-flavor neutrino oscillations are transitions in-flight between the flavor neutrinos $\nu_e \nu_\mu \nu_\tau$
  - Caused by non-zero neutrino masses and neutrino mixing.

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_i U_{\alpha i}^* e^{-i \frac{m_i^2 L}{2E}} U_{\beta i} \right|^2$$

- The oscillation probabilities depend on:
  - Neutrino energy ($E_\nu$)
  - Distance between the source and the detector (“baseline” $L$)
  - Mass squared differences ($\Delta m_{21}^2, \Delta m_{32}^2$)
  - Parameters of the mixing matrix: 3 angles and 1 phase ($\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$)

* See: David Caratelli, “Introduction to neutrinos at Fermilab”

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Oscillation experiments

- Neutrino energy + baseline → which parameters can be measured in an experiment

<table>
<thead>
<tr>
<th>Source</th>
<th>Type of $\nu$</th>
<th>$E$ [MeV]</th>
<th>$L$ [km]</th>
<th>$\text{min}(\Delta m^2)$ [eV$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor</td>
<td>$\bar{\nu}_e$</td>
<td>~1</td>
<td>1</td>
<td>$\sim 10^{-3}$</td>
</tr>
<tr>
<td>Reactor</td>
<td>$\nu_e$</td>
<td>~1</td>
<td>100</td>
<td>$\sim 10^{-5}$</td>
</tr>
<tr>
<td>Accelerator</td>
<td>$\nu_\mu, \bar{\nu}_\mu$</td>
<td>$\sim 10^3$</td>
<td>1</td>
<td>$\sim 1$</td>
</tr>
<tr>
<td>Accelerator</td>
<td>$\nu_\mu, \bar{\nu}_\mu$</td>
<td>$\sim 10^3$</td>
<td>1000</td>
<td>$\sim 10^{-3}$</td>
</tr>
<tr>
<td>Atmospheric</td>
<td>$\nu_{\mu,e}, \bar{\nu}_{\mu,e}$</td>
<td>$\sim 10^3$</td>
<td>$10^4$</td>
<td>$\sim 10^{-4}$</td>
</tr>
<tr>
<td>Solar</td>
<td>$\nu_e$</td>
<td>~1</td>
<td>$1.5 \times 10^8$</td>
<td>$\sim 10^{-11}$</td>
</tr>
</tbody>
</table>

- Our current knowledge:

  $\sin^2 (\theta_{12}) = 0.307 \pm 0.013$
  $\sin^2 (\theta_{13}) = 0.0220 \pm 0.0007$
  $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5} \text{eV}^2$

  $\sin^2 (\theta_{23}) = 0.546 \pm 0.021$
  $\Delta m^2_{32} = (2.453 \pm 0.033) \times 10^{-3} \text{eV}^2$

Source: PDG, 2021 update
NOvA physics goals

- **Atmospheric sector** oscillations: $\Delta m^2_{32}$, $\sin^2\theta_{23}$, $\delta_{\text{CP}}$

- **Key open questions** in oscillations:
  - Is the neutrino mass hierarchy normal or inverted?
  - Is CP violated in the neutrino sector?
    - Charge-Parity symmetry $\nu_\mu \rightarrow \nu_e \overset{\text{CP}}{\leftrightarrow} \bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - Is $\theta_{23}$ mixing maximal?
    - $\nu_\mu - \nu_\tau$ symmetry
    - If not, what is the octant of $\theta_{23}$?
  - Disentangle by measuring...
    - disappearance $P(\nu_\mu \rightarrow \nu_\mu)$ and appearance $P(\nu_\mu \rightarrow \nu_e)$
    - in neutrinos and antineutrinos
    - over a 810 km baseline
$\nu_\mu \rightarrow \nu_\mu$ oscillations

- $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ disappearance can constrain $\sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$

- Strategy:
  - Identify muon neutrinos
  - Reconstruct their energy
  - Compare the data with the unoscillated prediction
    - “Dip” location $\rightarrow |\Delta m^2_{32}|$
    - Amplitude $\rightarrow \sin^2 2\theta_{23}$
\( \nu_\mu \rightarrow \nu_e \) oscillations

- \( \nu_\mu \rightarrow \nu_e \) and \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \) appearance depend on \( \sin^2\theta_{23}, \Delta m^2_{32} \) and \( \delta_{CP} \)

- Strategy:
  - Identify electron neutrinos
  - Analyze neutrino and antineutrino beam data simultaneously
  - Use the relative (a)symmetries between \( \nu_e \) and \( \bar{\nu}_e \) appearance rates to set constraints
Finding neutrino events with the NOvA detectors
The NuMI muon neutrino beam

- NuMI: Neutrinos from the Main Injector
  - Part of the Fermilab Accelerator Complex*
- Two running configurations:
  - Neutrino beam ($\nu_\mu$)
  - Antineutrino beam ($\bar{\nu}_\mu$)

- The NOvA detectors are located off-axis.
- At a 14.6 mrad offset, the flux is narrower and peaked around 2 GeV.
- Small contamination: wrong sign, $\nu_e$

See: Jason St. John, "Introduction to Fermilab's Accelerators and Beams" (link).
David Caratelli, "Introduction to neutrinos at Fermilab"
The 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
Collecting neutrinos

Near detector

20193 channels. 1 km from beam source
~5 contained neutrino events per beam pulse (every 1.33 sec)
Negligible cosmic background (underground)

Far detector

344064 channels. 810 km from source
<1 neutrino event per day
130 kHz cosmic ray background

Beam direction

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Identifying neutrino events

- Neutrino interaction candidates are identified using a convolutional neural network (CNN)
  - A deep-learning technique from computer vision

- In addition to the event CNN selection:
  - Events are contained in the detector
  - In-time with the beam
  - CC $\nu_\mu$ require a well-reconstructed $\mu$ track
  - Reject cosmic rays with BDTs
Estimating the neutrino energy

$E_{\mu}$ from length, $\sim 4\%$ resolution

$E_{\mu}$ events

$E_{had}$ from calorimetry, $\sim 30\%$ resolution

$\nu_\mu$ events

$E_{EM}$ from calorimetry, $\sim 10\%$ resolution

$\nu_e$ events

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3-flavor neutrino oscillation analysis
The NuMI beam dataset

- Daily neutrino beam
- Daily antineutrino beam
- Accumulated beam
- Accumulated neutrino beam
- Accumulated antineutrino beam

- 13.6 \times 10^{20} \text{ POT neutrino} + 12.5 \times 10^{20} \text{ POT antineutrino}

Mi Beam Power Hour Average record: 843 kW on June 15, 2021!

4E20 POT delivered in 2021!

See: Jason St. John, "Introduction to Fermilab’s Accelerators and Beams" (link).
Analysis strategy

1. Simulated predictions

Neutrino flux
GEANT4-based simulations of particle production and transport.
Reweighted to incorporate external measurements ("PPFX")

Neutrino interactions on detector materials
Simulated with GENIE 3.0.6*.
Use a custom configuration, tuned to external data and NOvA ND Data.

Detector response to charged particles and light propagation
Propagation of final state particles simulated with GEANT4*.
Light readout and front-end electronics use a custom simulation.

* Updated for this analysis

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ND $\nu_\mu$-like samples are used to correct the FD $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ signal predictions.

ND $\nu_e$-like samples are used to correct the FD $\nu_e$ background predictions.
Constraints using ND data

- Choice of binning / subsamples → additional power to control systematic uncertainties

- $p_T$ binning (lepton transverse momentum)
  - “Rebalance” ND/FD kinematics

- $\nu_\mu$ binning optimized to see the “dip” in the energy spectrum
- $\nu_e$ binning optimized to separate signal/background

ND constraints reduce systematic uncertainties in the FD prediction from $>15\%$ to $4-5\%$
$\nu_\mu$ and $\bar{\nu}_\mu$ data at the Far Det.

$\nu_\mu$ beam

NOvA Preliminary

- FD data
- 2020 Best-fit
- 1-$\sigma$ syst. range
- Background

**Observed**

<table>
<thead>
<tr>
<th>$\nu_\mu$</th>
<th>$\bar{\nu}_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>211</td>
<td>105</td>
</tr>
</tbody>
</table>

Best fit pred.

<table>
<thead>
<tr>
<th>$\nu_\mu$</th>
<th>$\bar{\nu}_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>222.3</td>
<td>105.4</td>
</tr>
</tbody>
</table>

Signal

<table>
<thead>
<tr>
<th>$\nu_\mu$</th>
<th>$\bar{\nu}_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$214.1^{+14.4}_{-14.0}$</td>
<td>$103.4^{+7.1}_{-7.0}$</td>
</tr>
</tbody>
</table>

Background

<table>
<thead>
<tr>
<th>$\nu_\mu$</th>
<th>$\bar{\nu}_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$8.2^{+1.9}_{-1.7}$</td>
<td>$2.1^{+0.7}_{-0.7}$</td>
</tr>
</tbody>
</table>

3. Comparisons with FD data

- 2.02 GeV candidate
- 2.31 GeV candidate

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$\nu_e$ and $\bar{\nu}_e$ data at the Far Det.

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3. Comparisons with FD data

**Observed**

$82 \nu_e$  $33 \bar{\nu}_e$

**Best fit prediction**

$85.8$  $33.2$

**Signal**

$59.0^{+2.5}_{-2.5}$  $19.2^{+0.6}_{-0.7}$

**Background**

$26.8^{+1.6}_{-1.7}$  $14.0^{+0.9}_{-1.0}$
\( \nu_e/\bar{\nu}_e \) appearance + asymmetry

We don’t see a strong asymmetry between \( \nu_e \) and \( \bar{\nu}_e \) appearance rates

→ Exclude IH \( \delta = \pi/2 \) at >3\( \sigma \)
→ Disfavor NH \( \delta = 3\pi/2 \) at ~2\( \sigma \)

82 candidates (27 bkgd.) \( \rightarrow \nu_e \) appearance ✓
33 candidates (14 bkgd.) \( \rightarrow \bar{\nu}_e \) appearance ✓
Constraints on $\Delta m^2_{32}$ and $\sin^2\theta_{23}$

- Best fit:
  - Normal hierarchy
    $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3} \text{ eV}^2$
    $\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$
    $\delta_{CP} = 0.82\pi$

- Precision measurements of $\Delta m^2_{32}$ (3%) and $\sin^2\theta_{23}$ (6%)
The horizon

Far detector

Near detector
Future 3-flavor measurements

- Upcoming 3-flavor analyses:
  - Additional beam data (FY 2021-2022)
  - Improvements to the simulation, reconstruction, and analysis techniques

- NOvA is expected to take data through 2026, for a projected total of $60-70 \times 10^{20}$ POT
  - We’re half way there!
  - Expect increasingly precise measurements of $\Delta m^2_{32}$ and $\sin^2 \theta_{23}$.
  - We can reach $3\sigma$ hierarchy sensitivity for 30-50% of $\delta$ values, and $\sim 5\sigma$ in the most favorable case.
  - We can also reach a $\sim 2\sigma$ determination of CP violation.

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NOvA: a rich physics program!

NOvA + T2K joint analysis

Sterile neutrino searches

Cosmic ray physics and exotics

Cross-section measurements

Learn more: NOvA publications. Snowmass LOI: NOvA+T2K, Steriles, Exotics, Cross-sections
**NOvA Test Beam**

- A scaled-down 30-ton NOvA detector
- Deployed at the Fermilab Test Beam Facility
- Analyzes tagged charged particles from a tertiary beamline (protons, pions, muons, electrons and kaons) in the 0.2 — 2.0 GeV/c momentum range
- Results could address some of the largest systematic uncertainties in NOvA

* See: Vallary Bhopatkar, “Fermilab Test Beam Facility” (link)
Summary

• NOvA’s primary goal is the study of **3-flavor neutrino oscillations**, via measurements of muon (anti)neutrino disappearance and electron (anti)neutrino appearance

• The most recent oscillation analysis results:
  • **Precision measurements of** $\Delta m_{32}^2 (3\%)$ and $\sin^2 \theta_{23} (6\%)$
  • **No strong asymmetry between** $\nu_e$ and $\bar{\nu}_e$ **appearance rates**

• The data analyzed so far corresponds to ~half of the total expected. There’s still a lot to do!

• **NOvA can explore more physics**: sterile neutrino searches, cross-section measurements, exotic and cosmic-ray studies...
  • A lot of opportunities for young scientists

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NOvA continued recording and analyzing data throughout 2020 and 2021. This was made possible by the extraordinary dedication of the Fermilab community at large.

THANK YOU!! See you next year! 👌