NOvA's latest results on three-flavor neutrino oscillations

Miami 2018, December 16th 2018
NOvA in a nutshell

- **Long-baseline** neutrino oscillation experiment.
- Two **functionally similar** detectors 809 km apart.
  - Near detector (ND) ~100 m underground, at Fermilab.
  - Far detector (FD) on surface in northern Minnesota.
- Muon (anti)neutrino disappearance and electron (anti)neutrino appearance
  - Study oscillation parameters.
- Additional searches including (sterile) neutrinos beyond the three active flavors.

See next talk by Jeremy Hewes!
Neutrino oscillations

\[
\begin{pmatrix}
\nu_e \\
\nu_{\mu} \\
\nu_{\tau}
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{-i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[s_{ij} \equiv \sin \theta_{ij}, \quad c_{ij} \equiv \cos \theta_{ij}\]

- Neutrinos oscillate because each of the flavor states is a superposition of the three mass states.
- The PMNS matrix describes the relationship → calculate probability of transition between states.
- Characterised by:

  3 angles: \(\theta_{12}, \theta_{13}, \theta_{23}\),
  1 phase: \(\delta_{CP}\),
  2 mass splittings: \(\Delta m_{21}, \Delta m_{32}\).
Open questions

• Is $\theta_{23}$ maximal (exactly 45°)? If not which octant is it in?

• What is the value of $\delta_{CP}$? Is there CP violation in the lepton sector?

• Is $\nu_3$ the heaviest (normal hierarchy) or lightest (inverted hierarchy)?
Muon neutrino disappearance

Survival probability:

\[ P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2 \left( \frac{1.27 \Delta m_{32}^2 L}{E} \right) \]
Electron neutrino appearance

\[ P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{\text{atm}}} e^{-i(\Delta_{32} + \delta_{CP})} + \sqrt{P_{\text{sol}}} \right|^2 \]

\[ \approx P_{\text{atm}} + P_{\text{sol}} + 2 \sqrt{P_{\text{atm}} P_{\text{sol}}} \left( \cos \Delta_{32} \cos \delta_{CP} \mp \sin \Delta_{32} \sin \delta_{CP} \right) \]

\[ P_{\text{atm}} = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} (\Delta_{31})^2 \]

\[ P_{\text{sol}} = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \frac{\sin^2(-aL)}{(-aL)^2} (\Delta_{21})^2 \]

\[ \Delta_{ij} = (1.27 \Delta m_{ij}^2 L)/E \]

\[ a = G_{F} N_{e}/\sqrt{2} \]

\[ N_{e} = \text{Earth's electron density} \]

- Gives us access to every oscillation parameter
- Density of Earth causes yields different effects for neutrinos and antineutrinos.
Why do we need neutrinos and antineutrinos?

- IH → slight suppression compared to NH.
- CP violation causes **opposite effects** in neutrinos and antineutrinos.
- Matter effects also produce opposite effects in neutrinos and antineutrinos.
- The **octant of \( \theta_{23} \)** causes either a suppression or enhancement.
How do we produce neutrinos?

NuMI is the world’s most powerful neutrino beam → running at 700 kW design power since January 2017

Recorded $8.85 \times 10^{20}$ protons on target (POT) in neutrino mode
How do we produce neutrinos?

**How do we produce neutrinos?**

**NuMI** is the world’s most powerful neutrino beam → running at 700 kW design power since January 2017.

**Recorded $6.9 \times 10^{20}$ protons on target (POT) in antineutrino mode**
NOvA detectors

- Orthogonal layers of segmented PVC extrusions filled with liquid scintillator.
  - 63 % active mass.
  - Allows for 3D reconstruction.
- Readout → wavelength-shifting fiber to avalanche photodiodes (APDs)
- Both positioned off-axis from beam → narrow energy spectrum.
Two-detector experiments

- Sample unoscillated beam data at ND.
- **Data-driven methods** tweak simulated ND spectrum.
- Propagate to improve our **FD prediction**.
- Technique allows us to reduce key systematic uncertainties:
  - Neutrino beam **flux**.
  - Neutrino **interaction cross-section** models
Deep-learning particle classification

- Event classification is done by our **CVN** (Convolutional Visual Network) classifier.
- CVN employs a Deep Convolutional Network in the "image recognition" style.
- The network is trained on two dimensional views of the event's calibrated hits.
  - Information of each view is combined in the final layers of the network.
- We also train the network separately on a neutrino and antineutrino beam samples.
Muon (anti)-neutrino disappearance
Predicting the far detector spectrum

- Basic quality and selection cuts.
- CVN particle ID cut.
- Boosted decision tree (BDT) for cosmic rejection.
- Split into four samples by hadronic energy fraction.
Far detector observed events

<table>
<thead>
<tr>
<th>Neutrino beam</th>
<th>NOvA Preliminary</th>
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<tbody>
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**Total observed**  | 113
---|---
Integral at best fit  | 121
Cosmic background  | 2.1
Beam background  | 1.2
Unoscillated prediction  | 730

**Total observed**  | 65
---|---
Integral at best fit  | 50
Cosmic background  | 0.5
Beam background  | 0.6
Unoscillated prediction  | 266
Electron (anti)-neutrino appearance
Far detector predictions

- Basic selection and quality cuts.
- CVN particle ID cut, split into two samples.
- Third peripheral sample gives a second chance to events that fail basic selection cuts but are very pure electron-like events.
Far detector observed events

Total observed 58
- Integral at best fit 59.04
- Electron neutrino 43.97
- Electron antineutrino 0.66
- Total beam background 11.07
- Cosmic background 3.33

Total observed 18
- Integral at best fit 15.90
- Electron antineutrino 10.59
- Electron neutrino 1.13
- Total beam background 3.48
- Cosmic background 0.71

> 4σ evidence of electron antineutrino appearance
Neutrino vs. antineutrino beam

- Observed neutrino and antineutrino events hint at a slight preference for the upper octant and normal hierarchy.
- More sophisticated fit allows us probe oscillation parameters.
Systematic uncertainties

- Limited by statistical uncertainty.
- Key uncertainties: **detector calibration** and **neutrino interactions**.
- Neutron uncertainty is also large in antineutrino mode.
Joint fit results

- *Slight* preference for NH, upper octant $\theta_{23}$
- Prefer non-maximal $\theta_{23}$ at 1.8 $\sigma$
- Favor $\theta_{23}$ upper octant at a similar level

**Best-fit:**

\[
\Delta m^2 = 2.51^{+0.12}_{-0.08} \times 10^{-3} \text{ eV}^2
\]

\[
\sin^2 \theta_{23} = 0.58 \pm 0.03
\]
Comparison with other experiments

- NOvA’s 90% CL region is consistent with other long-baseline and atmospheric neutrino experiments
Joint fit results

- For IH, exclude $\delta = \pi/2$ at $> 3\sigma$

Best-fit:
$\delta_{CP} = 0.17\pi$
$\sin^2 \theta_{23} = 0.58 \pm 0.03$
$\Delta m^2 = 2.51^{+0.12}_{-0.08} \times 10^{-3} \text{ eV}^2$
Future sensitivities

- Future run plan → continue in antineutrino mode until **spring 2019**, then 50 % neutrino mode, 50 % antineutrino mode to 2024.

- Proposed **accelerator improvements** and projected improvements in analysis techniques, including input from NOvA’s **test beam program**.

- Assuming NH and $\delta_{CP} = 3\pi/2$, project **3σ sensitivity** to all value of $\theta_{23}$ by 2020.

- By 2024 expect **3σ sensitivity** 30-50 % $\delta_{CP}$ values.
Conclusions

- First analysis with joint-fit of neutrino and antineutrino beam.
- Observe $> 4\sigma$ evidence of electron antineutrino appearance.
- Slight preference for NH at $1.8\sigma$ and exclude IH at $> 3\sigma$ around $\delta_{\text{CP}} = \pi/2$.
- Reject maximal mixing at $1.8\sigma$ and the lower octant at a similar level.