New neutrino oscillation results from NOvA

Luke Vinton
Introduction

• Overview of the NOvA experiment setup
• Improvements for this round of analysis
• Muon neutrino disappearance result
• Electron neutrino appearance result
• Joint disappearance and appearance fit
The NOvA experiment

Studying oscillations of neutrinos within the NuMI beam over a 810km baseline with two functionally identical off-axis detectors
The NuMI beam

• 8.85 e20 POT in 14 kton equivalent detector
• 50% more exposure than the 2016 analysis

• Now running in anti-neutrino mode
• Running at design target of 700 kW since June 2016
The Detectors

- Designed to identify electrons:
  - Fine segmentation
  - Low Z
  - 62% active

- 14 kton
  - 810 km from source

- 330 ton
  - 1 km from source

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Detector Components

- PVC extrusions + Liquid Scintillator (mineral oil + 5% pseudocumene)
- Readout via WLS fibre to APD

- Layered planes in orthogonal views for 3D reconstruction
Event topologies

1 radiation length =
- 38 cm
- 6 cell depths
- 10 cell widths
Analysis Improvements

• 50% more data! 9 e20 POT

• **Improved analysis techniques:**
  • improved selections using deep learning,
  • separating events by energy resolution to better exploit the existing data

• Retuned cross-section modelling
  • Particularly important for multi-nucleon processes

• Detector sim improvements

• Data driven flux estimates
Previous results

Previous appearance and disappearance results
6.05 e20 protons on target

arXiv:1701.05891

arXiv:1703.03328
Deep learning inspired PID

Deep learning methods used to identify muons and electrons using features of the event topology.
$\nu_\mu$ Disappearance

- Select and measure $\nu_\mu$ events in both detectors
- Extrapolate beam expectation to far detector
- Measure cosmic background expectation using far detector data outside the beam spill window
- Compare measured far detector energy spectrum with expectation
$\nu_\mu$ Disappearance

- New selection using deep learning selector and retuned cosmic BDT
- Equivalent background rejection with 11% more signal selected
$\nu_\mu$ Energy Estimator

Final reconstructed energy combines $E_{\text{had}}$ and $E_\mu$ via a piecewise linear fit.
Resolution Binning

4 quantiles in the far detector split by hadronic energy fraction for each reconstructed neutrino energy bin

Energy resolution best for lower hadronic energy fraction

- Resolution varies from 6% to 12% from best to worst resolution bins
Resolution Binning

NOvA Preliminary

Simulated Selected Events
Simulated Background
Data
Shape-only 1-σ syst. range
ND area norm., $8.09 \times 10^{20}$ POT
Data mean: 1.77 GeV
MC mean: 1.76 GeV

NOvA Preliminary

Simulated Selected Events
Simulated Background
Data
Shape-only 1-σ syst. range
ND area norm., $8.09 \times 10^{20}$ POT
Data mean: 1.75 GeV
MC mean: 1.76 GeV

NOvA Preliminary

Simulated Selected Events
Simulated Background
Data
Shape-only 1-σ syst. range
ND area norm., $8.09 \times 10^{20}$ POT
Data mean: 1.73 GeV
MC mean: 1.74 GeV

NOvA Preliminary

Simulated Selected Events
Simulated Background
Data
Shape-only 1-σ syst. range
ND area norm., $8.09 \times 10^{20}$ POT
Data mean: 1.71 GeV
MC mean: 1.71 GeV
$\nu_\mu$ Systematics

- Systematics assessed using sets of shifted MC
- Impact on the result of each systematic is assessed by allowing the systematic uncertainty to shift as a penalty term in the fit
In the absence of oscillations we expect 763 events, 126 were observed.

<table>
<thead>
<tr>
<th>Events</th>
<th>126</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>Expected</td>
<td>129</td>
</tr>
<tr>
<td>Total Background</td>
<td>9.24</td>
</tr>
<tr>
<td>Cosmic</td>
<td>5.82</td>
</tr>
<tr>
<td>Neutral Current</td>
<td>2.50</td>
</tr>
<tr>
<td>Other Beam</td>
<td>0.96</td>
</tr>
</tbody>
</table>
$\nu_\mu$ Far Detector Events

[Graphs showing event distributions for different quantiles with reconstructed neutrino energy on the x-axis and events per 0.1 GeV on the y-axis. Each graph includes data, prediction, 1-σ syst. range, beam background, and cosmic background.]
Joint fit

UO preferred at 0.2\(\sigma\)

\[ \sin^2\theta_{23} = \]

UO: \(0.558^{+0.041}_{-0.033}\)
LO: \(0.475^{+0.036}_{-0.044}\)

\[ \Delta m^2_{32} = 2.444^{+0.079}_{-0.077} \times 10^{-3} \text{ eV}^2 \]
$\nu_e$ Appearance

- Measure ND and FD $\nu_e$ and $\nu_\mu$ energy Spectra
- Break down ND $\nu_e$ selected events to separately extrapolate background components
- Extrapolate ND $\nu_\mu$ selected events estimate to the FD
- Use FD data from outside of the beam spill to estimate cosmic backgrounds
- Compare measured FD spectrum to expectation
Optimized to maximally exploit the power of our CVN ID. Select down to low PID values to recover as many signal events as possible. Binning in PID to retain the full power of the high purity subsample of events.
$\nu_e$ Systematics
$\nu_e$ Predicted Events

NOvA Simulation

$\sin^2 2\theta_{13} = 0.082$

$\sin^2 \theta_{23} = 0.43 - 0.60$

NOvA FD

$8.85 \times 10^{20}$ POT eq.

Total events expected

$\nu_e$

NH: $\Delta m_{32}^2 = +2.44 \times 10^{-3}$ eV$^2$

IH: $\Delta m_{32}^2 = -2.48 \times 10^{-3}$ eV$^2$

$\delta_{CP}$
\( \nu_e \) Selected Events

Observe **66 events in FD**
Background Expectation \( 20.5 \pm 2.5 \)

**NOvA Preliminary**

- **FD data**
- **Best Fit prediction**
- **Total Background**
- **Cosmic Background**

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

Reconstructed Neutrino Energy (GeV)

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Joint Best Fit

IH at $\delta_{cp} = \pi/2$ disfavoured at greater than 3$\sigma$

Approaching IH rejection at 2$\sigma$
Conclusions

• At 8.85 e20 POT, NOvA finds:
  • **Muon neutrinos disappear:** Competitive measurement of $\Delta m^2_{32}$, new analysis prefers mixing near-maximal
  • **Electron neutrinos appear:** Inverted Hierarchy at $\delta_{cp} = \pi/2$ disfavoured at greater than 3$\sigma$. Approaching 2$\sigma$ IH rejection

• **Excellent detector and beam performance**
• **Significant improvement in our analysis tools.** Expected to continue, benefiting from efforts like the NOvA test beam.
• Looking forward to opening the box on our first antineutrino data this summer!
• Expect NOvA to continue to contribute to key questions:
  • Is $\delta_{cp}$ nonzero?
  • What is the mass hierarchy?
Thank you!
Tuned interaction modelling

- Nuclear effects on the initial state (nuclear charge screening/"RPA" effect) and reactions themselves (multi-nucleon ejection e.g. 2p2h via Meson Exchange Currents (MEC)) are important components of our interaction model, particularly of the hadronic energy component.
- Theory for these effects and how they fit together remains incomplete.
- Important that we not just have the best possible central value tune, but also appropriately conservative uncertainties.
\( \nu_\mu \) Result

NOvA Preliminary

NOvA Normal Hierarchy

90% C.L. \( 8.85 \times 10^{20} \) POT-equiv.

\[ \Delta m^2_{32} \quad (10^{-3} \text{ eV}^2) \]

\[ \sin^2 \theta_{23} \]

\( \nu_\mu \) only
Future

Normal $\delta_{CP} = \frac{3\pi}{2}$, $\sin^2 \theta_{23} = 0.500$

$\Delta m^2_{32} = 2.45 \times 10^{-3} \text{eV}^2$, $\sin^2 \theta_{13} = 0.082$

NOvA Simulation

NOvA joint $\nu_e + \nu_\mu$

- Hierarchy
- CPV

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

All projected beam intensity and analysis improvements

Year

2016 2018 2020 2022 2024