Details of the NOvA $\nu_\mu$ disappearance analysis

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Outline

• The NOvA experiment
• The Far Detector Extrapolation
• Uncertainties
• Results
• Improvements for future analyses
Motivation

1. $\theta_{23}$ was the first angle to be measured but (prior to NOvA and T2K) was the one known to the least precision.

2. A precision measurement of $\theta_{23}$ can help determine the correct texture for the PMNS matrix.

3. An accurate measurement of $\theta_{23}$ improves the NOvA appearance measurement (and if it is non-maximal, could allow us to resolve the octant.)
The NOvA experiment

- NOvA is a long-baseline neutrino oscillation experiment
- Observes neutrinos from NuMI beamline at Fermilab
- Two functionally identical detectors, situated 14 mrad off axis, 810 km apart
- Near Detector is 300 tons (FNAL)
- Far Detector is 14 ktons (Ash River, MN)

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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.
Near Detector Event Display

Colours show hit times

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Cell hits coloured by recorded charge (~photoelectrons)

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Far Detector 10 μs NuMI Beam Window

Cell hits coloured by recorded charge (~photoelectrons)

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Muon neutrino disappearance

\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - (\sin^2 2\theta_{13} \sin^2 \theta_{23} + \cos^4 \theta_{13} \sin^2 2\theta_{23}) \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]

1. Measure neutrinos at ND
2. Extrapolate measurements to make FD prediction
3. Compare FD data to prediction to find best fit of oscillation parameters
Muon neutrino selection

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

- Muon dE/dx used in length-to-energy conversion
- Hadronic energy estimated from calorimetric sum of non-muon hits
- ~7% resolution on neutrino energy

\[ E_\nu = E_{\mu\text{ range}} + E_{\text{had}} \]
Far detector prediction

Translate ND data/ MC observation to true energy

Oscillate ratio to the FD

Smear back into reconstructed energy

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Far Detector Prediction

NOvA Simulation

Reconstructed Neutrino Energy (GeV)

Events

NOvA Simulation

Reconstructed Neutrino Energy (GeV)

Events

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Systematic uncertainties

- The effect of many large uncertainties is reduced by the near-to-far extrapolation technique (cross sections, beam flux, etc.)

<table>
<thead>
<tr>
<th>Systematic (*)</th>
<th>Effect on $\sin^2(\theta_{23})$</th>
<th>Effect on $\Delta m^2_{32}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalisation</td>
<td>± 1.0%</td>
<td>± 0.2 %</td>
</tr>
<tr>
<td>Muon E scale</td>
<td>± 2.2%</td>
<td>± 0.8 %</td>
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<tr>
<td>Calibration</td>
<td>± 2.0%</td>
<td>± 0.2 %</td>
</tr>
<tr>
<td>Relative E scale</td>
<td>± 2.0%</td>
<td>± 0.9 %</td>
</tr>
<tr>
<td>Cross sections + FSI</td>
<td>± 0.6%</td>
<td>± 0.5 %</td>
</tr>
<tr>
<td>Osc. parameters</td>
<td>± 0.7%</td>
<td>± 1.5 %</td>
</tr>
<tr>
<td>Beam backgrounds</td>
<td>± 0.9%</td>
<td>± 0.5 %</td>
</tr>
<tr>
<td>Scintillation model</td>
<td>± 0.7%</td>
<td>± 0.1 %</td>
</tr>
<tr>
<td>All systematics</td>
<td>± 3.4 %</td>
<td>± 2.4 %</td>
</tr>
<tr>
<td>Stat. Uncertainty</td>
<td>± 4.1 %</td>
<td>± 3.5 %</td>
</tr>
</tbody>
</table>

(*) Relative contribution evaluated at $\sin^2(\theta_{23}) = 0.514$ and $\Delta m^2_{32} = 2.52 \times 10^{-3} \text{ eV}^2$

- The 2015 analysis was dominated by a large systematic uncertainty placed on the hadronic energy component (which has since been significantly reduced.)

- All systematics were evaluated by varying the MC based steps in the extrapolation.
NuMu FD spectrum

- Observed: 78 events
- Predicted with NO oscillation: 473 ± 30 events
- Predicted at the best fit point 82 events
- 3.7 from beam background
- 2.9 cosmic induced events
Oscillation measurement

\[ |\Delta m_{32}^2| = 2.67 \pm 0.11 \times 10^{-3} \text{eV}^2 \]

\[ \sin^2 \theta_{23} = 0.404^{+0.030}_{-0.022} (0.624^{+0.022}_{-0.030}) \]

Maximal Mixing Disfavoured at 2.56 \sigma

Best Fit in NO:

Normal Hierarchy, 90\% CL

- NOvA 2016
- T2K 2014
- MINOS 2014

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Improvement 1: Energy Resolution

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

Mean resolution:
- \( E_\mu = 3.5\% \)
- \( E_{\text{had}} = 25\% \)
- \( E_\nu = 7\% \)

Neutrino energy resolution
\[ \frac{E_{\text{had}}}{E_\nu} \]

Separate well resolved energies by quantiles of hadronic energy fraction

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Improvement 1: Energy Resolution

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

Mean resolution:
- \( E_\mu = 3.5\% \)
- \( E_{\text{had}} = 25\% \)
- \( E_v = 7\% \)

Neutrino energy resolution
\[ \frac{E_{\text{had}}}{E_v} \]

Neutral current systematic impact improves by a factor of 2-4:

\[
\begin{align*}
\sin^2\theta_{23} &\quad +3.3/-6.6\% \quad \longrightarrow \quad +1.4/-2.3\% \\
\Delta m^2_{32} &\quad +9.2/-17\% \quad \longrightarrow \quad +3.3/-4.6\% 
\end{align*}
\]
Improvement 2: PID

- CVN (Convolutional Visual Network) used by the electron neutrino appearance analysis already
- Based on CNN (Convolutional Neural Networks)
- Hit maps are read as images with filters applied to them to extract features

Including CVN in our selections improves efficiency by ~10% while reducing background by nearly 50%
Improvement 3: Binning

Finer binning around the maximum oscillation region could enhance the sensitivity of the analysis

- NOvA's standard energy binning: 20 bins of 0.25 GeV each
- Optimum binning: increased number of bins between 1 and 2 GeV
Combination of the improvements reduces uncertainties and significantly increases our sensitivity:

- Systematic uncertainties reduced from 2.2% to 2.0% on $\Delta m_{32}^2$ and from a 2.1% to 1.5% on $\sin^2\theta_{23}$
- Maximal mixing rejection from 2.51 to 3.25σ equivalent to 75% more data
Outlook

- Analysis of $6.05 \times 10^{20}$ POT of NOvA data (1 nominal year)

  - Best fit to muon-neutrino disappearance data is a non-maximal value of $\theta_{23}$, maximal mixing disfavoured at 2.56σ

- Current analysis improvement will result maximal mixing rejection from 2.56 to 3.25σ (equivalent to 75% more data) for 2017 oscillation analysis parameters.

- Didn’t mention here our electron neutrino appearance, sterile neutrino search, neutrino interaction, supernova, monopoles, and a lot more

- Switched to anti-neutrino running in February and already have $3 \times 10^{20}$ POT - Stay tuned!
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
NuMI beam performance

• 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

Switched to antineutrinos on Feb 20th 2017
Why off-axis?

• NOvA detectors are located 14 mrad off the NuMI beam axis.

• With the medium-energy NuMI configuration, it yields a narrow 2-GeV spectrum at the NOvA detectors due to meson decay kinematics:

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

• Location reduces NC and $\nu_e$ CC backgrounds in the oscillation analyses while maintaining high $\nu_\mu$ flux at 2 GeV.
Event topologies

$\nu_\mu$ CC

$\nu_e$ CC

NC
We expect ~65,000 cosmic rays in-time with the NuMI beam spills per day. The expected number of contained $\nu_\mu$ CC events per day is only a few.

Containment cuts will remove 99% of the cosmics.

We use a boosted-decision-tree (BDT) algorithm that takes input from reconstruction variables to reject the remaining cosmics.

All cuts together give us > 15:1 s:b. Cosmics are reduced by $10^7$!
NuMu disappearance IO

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

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

Inverted Hierarchy

NOvA 6.05\times10^{20} \text{ POT-equiv.}

1-\sigma

2-\sigma

3-\sigma

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- Switched to anti-neutrino running in February 2017 (50% neutrino, 50% anti-neutrino after 2018)
- $3\sigma$ sensitivity to maximal mixing of $\theta_{23}$ in 2018
- $2\sigma$ sensitivity to mass hierarchy and $\theta_{23}$ octant in 2018-2019