Latest Oscillation Results from NOvA

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Neutrino Oscillations

A. Radovic, JETP January 2018
Neutrino Oscillations

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = U^* \begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix} \quad P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U_{\beta j}^* e^{-i \frac{m_{ij}^2 L}{2E}} U_{\alpha j} \right|^2
\]

\[
U = \begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{13}e^{-i\delta} \\
s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}
\]
Neutrino oscillations raised as many questions as it answered:

• Why is lepton sector mixing much larger than quark sector mixing? Is $\theta_{23}$ maximal?
• What is the hierarchy of neutrino masses?
• Is there CP violation in the lepton sector?
NOvA Physics Goals

Precise measurements: $\Delta m^2_{32}$ and $\sin^2(2\theta_{23})$ for neutrinos and antineutrinos

Strong Constraints on:
- $\theta_{23}$ octant
- $\delta_{\text{cp}}$
- mass hierarchy
\[ P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2 \left( \frac{1.27 \Delta m^2_{atm} L}{E} \right) \]
NOvA Physics Goals

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Strong Constraints on:
- $\theta_{23}$ octant
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\( \nu_e \) Appearance

By measuring beam muon neutrinos which have oscillated to electron neutrinos we gain the power to constrain:

\( \theta_{23} \) octant

\( \delta_{cp} \)

mass hierarchy

\[
P(\nu_\mu \rightarrow \nu_e) \approx \sqrt{P_{atm}e^{-i\left(\frac{\Delta m_{32}^2 L}{4E} + \delta_{cp}\right)}} + \sqrt{P_{sol}}
\]

\( P_{atm} = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \)

Solar term contributes <1% at \( \sim 400 \) L/E
ν_e Appearance

By measuring beam muon neutrinos which have oscillated to electron neutrinos we gain the power to constrain:

θ_{23} octant
δ_{cp}
mass hierarchy

Electron neutrinos experience an extra interaction as they pass through matter, modifying oscillation probabilities, giving us a window into the mass hierarchy.
Studying oscillations over a 810km baseline with two functionally identical detectors and the world’s most powerful muon neutrino beam, NuMI.
Studying oscillations over a 810km baseline with two functionally identical detectors and the worlds most powerful muon neutrino beam, NuMI.
• 8.85x10^{20} POT in 14 kton equivalent detector
• 50% more exposure than the 2016 analysis
• Currently running in anti-neutrino mode
• Running at 700 kW design goal since June 2016!
The NOvA Detectors

Optimized for electron ID, fine segmentation, Low-Z, and 62% Active.
The NOvA Detectors

ND: 330 ton, 1km from source.
FD: 14 kton, 810km from source.
Detector Technology

• PVC extrusion + Liquid Scintillator
  • mineral oil + 5% pseudocumene
• Read out via WLS fiber to APD
  • FD has ~344,000 channels
• muon crossing far end ~40 PE
• Layered planes of orthogonal views

![Diagram showing scintillator cell with looped WLS Fiber and PVC extrusion.](image-url)
NOvA Event Topologies

νμ CC Signal

νe CC Signal

NC Background

1 radiation length = 38cm (6 cell depths, 10 cell widths)
What’s New?

• **More data**, 50% more than our last oscillation update.

• **Improved analysis**, continued use of deep learning tools for our appearance and now also for our disappearance measurements. Binning in energy resolution that better exploits the information in the existing data.

• **Retuned cross section modeling**, continued development of how we treat cross sections including crucial multi-nucleon effects.

• **Detector simulation improvements**, dramatically reducing some of our largest uncertainties in previous measurements.

• **Data driven flux estimates**, developed by MINERvA.
Deep Learning Inspired PID: $\nu_e$ & $\nu_\mu$ Selection

Previously only used for our $\nu_e$ analysis, now our $\nu_\mu$ analysis also features the same event selection technique based on ideas from computer vision and deep learning.

Additionally now used to reclaim a new class of previously rejected $\nu_e$ events.
Deep Learning Inspired PID: $\nu_e$ & $\nu_\mu$ Selection

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Simulation

- Beam hadron production, propagation, neutrino flux: **GEANT4/External Data**
- Cosmic ray flux: **Data Triggers**
- Neutrino Interactions and FSI modeling: **GENIE v2.12.2**
- Detector Simulation: **GEANT4**
- Readout electronics and DAQ: **Custom simulation routines**

Simulation: Locations of neutrino interactions that produce activity in the Near Detector

NOvA Simulation
Retuned Interaction Modeling

- 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)) remain important components of our interaction model, particularly of the hadronic energy component of our interactions.

- Theory for these effects and how they fit together remains incomplete and model evidence ambiguous.

- Important that we not just have the best possible central value tune, but also appropriately conservative uncertainties.
Retuned Interaction Modeling

- Continue to tune MEC to match the excess in our data, now fit using default empirical MEC’s* model for energy transfer to the hadronic system ($q_0$).
- QE RPA from the Valencia group via Richard Gran** now included in central value tune.
- New MEC and RPA uncertainties that better capture limits of theory & data constraints.

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Improved Detector Simulation

- Previously detector response uncertainties were some of our largest. Reduced by an order of magnitude in new detector simulation, driven by addition of Cherenkov light.
- Absorbed and re-emitted Cherenkov light is a small but important in modeling the detector response to hadronic activity.
- Expected energy resolution for $\nu_\mu$ CC events moves from 7% to 9%.
New Flux

- A new data driven flux, Package to Predict the FluX (PPFX), based on thin target hadron production data from NA49 and MIPP.
- Comes with greatly reduced flux uncertainties.
- Pioneered at MINERvA.

*Neutrino Flux Predictions for the NuMI Beam*  
MINERvA Collaboration (L. Aliaga et al.)  
Phys.Rev. D94 (2016) no.9, 092005
Reconstructed neutrino energy (GeV)

- Simulated selected events
- Simulated background
- Data
- Shape-only 1-σ syst. range

ND area norm., $3.72 \times 10^{20}$ POT

Events / 0.1 GeV

MC mean: 1.74 GeV
Data mean: 1.74 GeV

Old  →  New

NOvA Preliminary
νμ Disappearance

1. Select, measure & characterize ND and FD νμ events.
2. Extrapolate beam expectation to FD and measure cosmic expectation from FD data out of the beam spill window.
3. Compare measured FD energy spectra to expectation.
Improved $\nu_\mu$ Selection

Even with excellent timing resolution cosmogenic activity at the Far Detector remains a challenging background due to raw rate.

NOvA Preliminary

$10^3 \text{ Events} / 0.1 \text{ GeV}$

- Total Predicted
- Cosmic Background
- Beam Background

Reconstructed Neutrino Energy (GeV)
Improved $\nu_\mu$ Selection

Even with excellent timing resolution, cosmogenic activity at the Far Detector remains a challenging background due to raw rate.

NOvA Preliminary

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Improved $\nu_\mu$ Selection

• New selection using CVN, a retuned cosmic rejection BDT, and a new PID cut
• Equivalent background rejection with 11% more signal selected.
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- Equivalent background rejection with 11% more signal selected.

![Diagram showing the selection process and distributions](image-url)
Improved $\nu_\mu$ Selection

- Improvement is most pronounced in key low energy region.
- Expected overlap between old and new PID s is consequentially low, particularly in cosmic background events.
Cosmic Background Prediction

• Cosmic backgrounds are characterized using cosmic activity recorded out of the beam spill.

• Final cosmic rate comes from cosmic activity recorded adjacent to the beam spill, ensuring perfectly matched detector performance.
Final reconstructed energy combines $E_{\text{had}}$ and $E_{\mu}$ via a piecewise linear fit.

Observed ND spectrum is converted to true energy using MC expectation, extrapolated to FD using a Far/Near flux ratio, and then converted to an expected reconstructed energy spectra.
Resolution Bins

• Four bins of equal populations in FD, split in hadronic energy fraction as a function of reconstructed neutrino energy.
• Resolution varies from ~6% to ~12% from the best to worst resolution bins.
Resolution Bins

NOvA Preliminary

Quantile 1

best resolution

\(E_{\text{res}} \approx 6\%\)

Quantile 2

\(E_{\text{res}} \approx 8\%\)

Quantile 3

\(E_{\text{res}} \approx 10\%\)

Quantile 4

worst resolution

\(E_{\text{res}} \approx 12\%\)
Resolution Binned Extrapolation

RPA shape uncertainty extrapolation in one spectra.
RPA shape uncertainty extrapolation in one spectra.
Resolution Binned Extrapolation

A. Radovic, JETP January 2018

NOvA Preliminary

Reconstructed Neutrino Energy (GeV)

Events / 0.1 GeV

Simulated Selected Events
Simulated Background
Data
Full 1-σ syst. range
ND POT norm., 8.09 \times 10^{20} POT

Data

syst. range

σ

Full 1-

POT

ND POT norm., 8.09 \times 10^{20}

A Preliminary
Resolution Binned Extrapolation

A Preliminary

\[ \text{Simulated Selected Events} \]
\[ \text{Simulated Background} \]
\[ \text{Data} \]
\[ \text{Shape-only 1-\( \sigma \) syst. range} \]
\[ \text{ND area norm., 8.09 \times 10^{20} \text{ POT}} \]
\[ \text{Data mean: 1.77 GeV} \]
\[ \text{MC mean: 1.76 GeV} \]

\[ \text{MC mean: 1.74 GeV} \]
\[ \text{Data mean: 1.71 GeV} \]
\[ \text{ND area norm., 8.09 \times 10^{20} \text{ POT}} \]
• Systematics were assessed by generating sets of shifted MC.
• Those shifted datasets were used instead of our nominal MC to assess the impact on our final result.
In the absence of oscillations we expect 763 events. **126 were observed.**

<table>
<thead>
<tr>
<th>All Q Events</th>
<th>Total Observed</th>
<th>Expectation at Best Fit</th>
<th>Total Background</th>
<th>Cosmic</th>
<th>Neutral Current</th>
<th>Other Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>126</td>
<td>129</td>
<td>9.24</td>
<td>5.82</td>
<td>2.50</td>
<td>0.96</td>
</tr>
</tbody>
</table>
In the absence of oscillations we expect 763 events. 126 were observed.
$\nu_\mu$ FD Selected Sample

NOvA Preliminary

Quantile 1
best resolution

NOvA Normal Hierarchy
$8.85 \times 10^{20}$ POT-equiv.

Events/0.1 GeV

NOvA Preliminary

Quantile 2

NOvA Preliminary

Quantile 3

NOvA Preliminary

Quantile 4
worst resolution

NOvA Normal Hierarchy
$8.85 \times 10^{20}$ POT-equiv.

Events/0.1 GeV

NOvA Preliminary
\( \nu_\mu \) Result

- Full joint fit with appearance analysis. Feldman Cousins corrections in 2D & 1D limits.
- All systematics, oscillation pull terms shared.
- Constrain \( \theta_{13} \) using world average from PDG, \( \sin^2 \theta_{13} = 0.082 \)

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

**NOvA Preliminary**

- 90\% C.L. 8.85\times10^{20} POT-equiv.
νμ Result

- Full joint fit with appearance analysis. Feldman Cousins corrections in 2D & 1D limits.
- All systematics, oscillation pull terms shared.
- Constrain θ_{13} using world average from PDG, \( \sin^2\theta_{13} = 0.082 \)

**Best fit:**

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

UO preferred at 0.2σ

\[
\sin^2\theta_{23} = UO: 0.558^{+0.041}_{-0.033} \quad \text{LO: 0.475^{+0.036}_{-0.044}}
\]
**ν_μ Result**

- Full joint fit with appearance analysis. Feldman Cousins corrections in 2D & 1D limits.
- All systematics, oscillation pull terms shared.
- Constrain \( \theta_{13} \) using world average from PDG, \( \sin^2 \theta_{13} = 0.082 \)

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\end{align*}
\]
Our previous result*: 2.6σ

New simulation & Calibration: ~1.8σ

New selection and analysis: ~0.5σ

Full dataset: ~0.4σ

Full dataset*: 0.8σ

Our rejection of maximal mixing has moved from 2.6σ to 0.8σ. This change in the character of our result comes from a few key changes which I’ll break down below.

Driven by updates to energy response model. Drop to 2.3σ expected due to new energy resolution. Additionally we have a <70 MeV> shift in our hadronic energy response. This energy shift would be expected to move 0.5 events out of the “dip” region. However it instead pushes 3 "dip" events past a bin boundary.

For combined analysis changes 5% of pseudo-experiments in a MC study had this size shift or larger. This probability is driven by a low expected overlap in background events, and to second order the addition of resolution bins.

New, 2.8x10^{20} POT, data prefers maximal mixing.

*Feldman-cousins corrected significance.
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New simulation & Calibration: ~1.8σ

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For combined analysis changes 5% of pseudo-experiments in a MC study had this size shift or larger. This probability is driven by a low expected overlap in background events, and to second order the addition of resolution bins.

New, $2.8\times10^{20}$ POT, data prefers maximal mixing.

*Feldman-cousins corrected significance.
• Consistent with world expectation.
• Competitive measurement of $\Delta m^2_{32}$.

Best fit:

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

$\sin^2 \theta_{23} =

\text{UO: } 0.558^{+0.041}_{-0.033}
\text{LO: } 0.475^{+0.036}_{-0.044}$
**$v_e$ Appearance**

1. Measure ND and FD $v_e$ and $v_\mu$ Selected Spectra
2. Break down ND $v_e$ selected events to separately extrapolate background components.
3. Extrapolate ND $v_\mu$ selected events estimate signal at the FD. Use FD data from outside of the beam spill to estimate cosmic backgrounds.
4. Compare measured FD to expectation.
\( \nu_e \) Selection

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.

![Diagram showing the selection process](image)

**DATA**

- **Basic Quality cuts**
- **Preselection cuts**
- **Cosmic Rejection cuts**
- **Peripheral Preselection**
- **CVN PID cut**
- **CVN and BDT cut**

- **Core sample**
- **Peripheral sample**

\( \sim 10^6 \) Events
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.
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\( \nu_e \) Selection

Harsh cosmic rejection cuts also reject some signal events. The addition of a new cosmic rejection BDT and a tight cut on CVN allow us to reclaim some of those events.
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• Signal prediction from the ND selected $\nu_\mu$ spectra used in disappearance analysis.
• Background prediction from ND selected $\nu_e$ data, data driven breakdown of the sample in order to extrapolate each component separately.
• Final background correction: beam $\nu_e$ up by 1%, NC up by 20%, $\nu_\mu$ CC up by 10%.
How to check our performance on our signal sample using the Near Detector?

Try faking appeared electron neutrinos by creating hybrid data/simulation events.
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How to check our performance on our signal sample using the Near Detector?

Try faking appeared electron neutrinos by creating hybrid data/simulation events.
Excellent data/MC agreement in MRE sample. Efficiency difference <2%:
$\nu_e$ Systematics

- As in $\nu_\mu$ systematics were assessed by generating sets of shifted MC.
- Those shifted datasets were used instead of our nominal MC to assess the impact on our final result.
• Extrapolate each component in bins of energy and CVN output.
• Expected event counts depend on oscillation parameters.

Signal events (±9% systematic uncertainty):

<table>
<thead>
<tr>
<th></th>
<th>NH, $3\pi/2$,</th>
<th>IH, $\pi/2$,</th>
</tr>
</thead>
<tbody>
<tr>
<td>48</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

Background by component (±10% systematic uncertainty):

<table>
<thead>
<tr>
<th></th>
<th>Total BG</th>
<th>NC</th>
<th>Beam $\nu_e$</th>
<th>$\nu_\mu$ CC</th>
<th>$\nu_\tau$ CC</th>
<th>Cosmics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20.5</td>
<td>6.6</td>
<td>7.1</td>
<td>1.1</td>
<td>0.3</td>
<td>4.9</td>
</tr>
</tbody>
</table>
Observe **66 events in FD**. Background Expectation $20.5 \pm 2.5$.

**NOvA Preliminary**

- Events / $8.85 \times 10^{20}$ POT-equiv
- Reconstructed Neutrino Energy (GeV)
Joint Best Fits

- Full joint fit with disappearance analysis. Feldman Cousins corrections in 2D & 1D limits.
- All systematics, oscillation pull terms shared.
- Constrain $\theta_{13}$ using world average from PDG, $\sin^2 2\theta_{13} = 0.082$
Joint Best Fits

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

Approaching IH rejection at 2$\sigma$. 

**Diagram:**

- NOvA Preliminary
- NH Upper octant
- NH Lower octant
- IH Upper octant
- IH Lower octant

**Significance (\sigma):**

- NOvA FD
- 8.85 $\times$ $10^{20}$ POT equiv.
The Future

\[ \sin^2 2\theta_{13} = 0.082 \]
\[ \sin^2 \theta_{23} = 0.47, 0.56 \]

\[ \Delta m^2_{32} = -2.51 \times 10^{-3} \text{eV}^2 \]

\[ \Delta m^2_{32} = +2.45 \times 10^{-3} \text{eV}^2 \]

\[ \delta_{\text{CP}} = 0 \quad \bullet \quad \delta_{\text{CP}} = \pi/2 \]

\[ \delta_{\text{CP}} = \pi \quad \diamond \quad \delta_{\text{CP}} = 3\pi/2 \]

2017 best fit

NOvA Simulation

NOvA FD

9.49 \times 10^{20} \text{ POT (v)}

8.1 \times 10^{20} \text{ POT (v)}

\[ \theta_{13}^{\text{2017 fit}} = 0.082 \]

\[ \theta_{23}^{\text{2017 fit}} = 0.47, 0.56 \]

\[ \Delta m^2_{32}^{\text{2017 fit}} = -2.51 \times 10^{-3} \text{eV}^2 \]

\[ \Delta m^2_{32}^{\text{2017 fit}} = +2.45 \times 10^{-3} \text{eV}^2 \]
The Future

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

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

NOvA Simulation

NOvA joint $\nu_e+\nu_\mu$

\[ \sqrt{\Delta \chi^2} \]

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

Hierarchy

CPV

All projected beam intensity and analysis improvements

Year

2016 2018 2020 2022 2024
Conclusions

• At 8.85x10^{20} 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 $\delta_{cp} = \pi/2$ disfavored 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?
Many thanks from the NOvA collaboration to the DOE and to Fermilab National Accelerator Laboratory. Thanks to the NSF for my own funding.