Probing Neutrino Oscillations at The NOvA Experiment

55th Annual Fermilab Users Meeting

Adam Lister, on behalf of the NOvA Collaboration

University of Wisconsin – Madison

16 June 2022
Neutrino Oscillations

The three-flavour model of neutrino oscillations ($\nu_e$, $\nu_\mu$, $\nu_\tau$) has been very successful.

- $\Delta m^2_{21}$, $\Delta m^2_{32}$ control frequency
- $\theta_{12}$, $\theta_{13}$, $\theta_{23}$ control magnitude
- $\delta_{CP}$ controls $\nu-\bar{\nu}$ differences
- $L$ (baseline)
- $E$ (neutrino energy)
Open Questions

What is the Neutrino Mass Ordering?
Normal or inverted?
Implications for $\nu0\beta\beta$, cosmology!

Based on Phys.Rev.D 69 (2004), 117301
Open Questions

What is the Neutrino Mass Ordering?
Normal or inverted?
Implications for $\nu^0\beta\beta$, cosmology!

![Diagram showing normal and inverted neutrino mass orderings](image)

What is the octant of $\theta_{23}$?
For $\nu_3$, does $\nu_\mu = \nu_\tau$?
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Is CP violated?
Non-conservation of CP important for matter-antimatter asymmetry
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Is three-flavour the full picture?
Additional neutrino states?
Non-standard interactions?

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Adam Lister, University of Wisconsin - Madison
55th Annual Fermilab Users Meeting, 16 June 2022
In this talk
NOvA’s oscillation analyses can probe these open questions!

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New Bayesian treatment of NOvA's three-flavour analysis

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A new search for sterile neutrinos in the NOvA data

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An Introduction to The NOvA Experiment
The NOvA Experiment

NOvA is a long baseline neutrino experiment.
- **Near Detector** ~1 km, **Far Detector** ~810 km
- Detectors 14 mrad off-axis of the NuMI beamline
  - Neutrino energy peaked around 2 GeV

Collected $37 \times 10^{20}$ protons-on-target (*Thank you Fermilab!*)

*Used in these analyses:*
- $13.6 \times 10^{20}$ POT $\nu$-beam data
- $12.5 \times 10^{20}$ POT $\bar{\nu}$-beam data

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The NOvA Detectors

Functionally identical **Near** and **Far** detectors
- Segmented tracking calorimeters
- Extruded PVC cells filled with liquid scintillator

Alternating plane orientation → **two views per event**

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Cells! The Building Block of NOvA

- **Near Detector**
  - 3.9 m
  - 0.3 kT – 20,192 channels

- **Far Detector**
  - 15.6 m
  - 14 kT – 344,064 channels

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At New Perspectives:

"NOvA in 10 Minutes" - Maria Manrique Plata

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Neutrino Interactions in NOvA

The NOvA detectors are optimised for surface running in a 2 GeV beam!
Neutrino Interactions in NOvA

The NOvA detectors are optimised for surface running in a 2 GeV beam!

- Have ~10 ns timing
  - Select $\nu$ from overwhelming cosmic backgrounds (FD)
  - Separate $\sim$10s $\nu$ per spill (ND)
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  - Separate \(~10\)s $\nu$ per spill (ND)

A single cosmic left over in the whole of the FD using only beam timing!

...and our neutrino!

* still need a lot of cosmic rejection after applying timing requirements
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- **Have ~10 ns timing**
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- **Small atomic mass provides radiation length ~ 40 cm**
  - ~6 samples per radiation length $\rightarrow$ **electrons** easy to disambiguate from **muons**
  - Large photon conversion distance help with $\pi^0$ background rejection
Neutrino Interactions in NOvA

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- Have ~10 ns timing
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  - Large photon conversion distance help with $\pi^0$ background rejection
- Machine Learning algorithms used for particle ID and event ID
Results!
2020 Far Detector Spectra

Very high purity selection for both $\nu$ and $\bar{\nu}$ modes

Backgrounds primarily from $\nu_e$ intrinsic to the beam (irreducible)

>4$\sigma$ $\bar{\nu}_e$ appearance

Disfavour strong asymmetry in $\nu_e$-$\bar{\nu}_e$ appearance
A New Bayesian Strategy!

Different statistical techniques help us probe our data in different ways!

We’ve developed a new Bayesian analysis in the context of our three-flavour analysis.

Main Take Away

The probability distribution can be used to quickly produce credible intervals for new parameters!
Bayesian Analysis Results

Conclusions drawn from the data are the same as in previous frequentist analysis

Exclude $\delta_{CP} = \pi/2$ at $>3\sigma$ (IO)

Less strong constraint on $\delta_{CP}$ in the NO, but disfavour region around $\delta_{CP} = 3\pi/2$

Weak preference for NO, Upper octant
Bayesian analysis allows us to report a measurement of $\theta_{13}$:

$$\sin^2(2\theta_{13}) = 0.085^{+0.020}_{-0.016}$$

When reporting measurements of other parameters, we **constrain $\theta_{13}$ using reactor neutrino results** (yellow, hashed).

Good agreement with reactor experiments!
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24th June

Fermilab Wine & Cheese Seminar

A Bayesian Look at 3-flavor Oscillations in NOvA: Drilling Deeper into PMNS

Artur Sztuc
Several anomalous results potentially explained by oscillations with $\Delta m^2 >> \Delta m^2_{21}, \Delta m^2_{31}$ (not predicted by three-flavour!)

Previous NOvA analyses use NC disappearance to probe the possibility of a 3+1 model

**Limitation** was using ND data to predict far detector spectrum, using a dedicated tune of the cross-section models to NOvA data.
**Analysis Strategy**

**Two Detector Fit**

- No NOvA cross-section tune
- Tailored systematic uncertainties
- This allows us to increase our $\Delta m^2_{41}$ range

**Analysis Samples**

**νμ sample**

Constrains $\Delta m^2_{32}$, $\theta_{23}$ and size of $\theta_{24}$

**νμ sample**

Constrains $\Delta m^2_{32}$, $\theta_{23}$ and size of $\theta_{24}$

**NC sample**

Any oscillation in ND is governed
entirely by sterile parameters

Oscillations at FD are at
atmospheric frequency and give
us access to $\theta_{24}$, $\theta_{34}$, $\delta_{24}$
Sterile Neutrinos at NOvA

Pre-fit distributions
(No NOvA cross-section tune)

Neutrino Beam

NOvA Preliminary

$\nu_\mu$, ND

Observed 209 events

$\bar{\nu}_\mu$, FD

Observed 469 events

$\bar{\nu}_e$, ND

$\bar{\nu}_e$, FD

NC ND

NC FD

Events $\times 10^3$ / 1 GeV

Events / 1 GeV

Reconstructed Neutrino Energy (GeV)
Sterile Neutrinos at NOvA

Pre-fit distributions
(No NOvA cross-section tune)

Three-flavour prediction
lays almost perfectly under
our
3+1 best fit

This data can be well
described by 3-flavour
oscillations within our
systematic uncertainties
Sterile Neutrino Results

NOvA data shows no evidence for sterile neutrinos under 3+1 model

Sensitivity at high $\Delta m^2_{41}$ driven by the Near Detector, and is systematics limited

Sensitivity at low $\Delta m^2_{41}$ driven by the Far Detector, and is less systematics limited

Limits on $\theta_{24}$ are competitive around $\Delta m^2_{41} = 10$ eV$^2$

→Limits come from both $\nu_\mu$ and NC samples
Sterile Neutrino Results

NOvA data shows no evidence for sterile neutrinos under 3+1 model

Sensitivity at high $\Delta m^2_{41}$ driven by the Near Detector, and is systematics limited

Sensitivity at low $\Delta m^2_{41}$ driven by the Far Detector, and is less systematics limited

NC disappearance gives us direct access to $\theta_{34}$ → This has generally been accessed by short baseline $\nu_\tau$ appearance searches, which give access to $\theta_{\mu\tau}$

[Diagram showing exclusion contours for $\Delta m^2_{41}$ and $\sin^2 \theta_{34}$]
NOvA Into The Future

● New analyses
  ○ $\nu_{\mu}$ CC low-hadronic activity
    ▪ [Poster, Leo Aliaga]
  ○ $\nu_{\mu}$ CC coherent pion production
    ▪ [Poster, Chatura Kuruppu]
    ▪ [New Perspectives talk, Chatura Kuruppu]
  ○ Studies towards $\nu$-$e$ elastic scattering
    ▪ [New Perspectives talk, Barnali Brahma]
  ○ NOvA-T2K joint fit! 🌟
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- NOvA Test Beam

3-flavour analysis
NOvA Into The Future

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  ○ $\nu_\mu$ CC low-hadronic activity ★
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  ○ Studies towards $\nu$-e elastic scattering ★
    ■ [New Perspectives talk, Barnali Brahma]
  ○ NOvA-T2K joint fit!

● NOvA Test Beam

● New MW-capable target and MW-capable horn installed
  ○ New power record 893 kW!
Future Sensitivities

Expect > 2x **current protons-on-target** (both $\nu/\bar{\nu}$!)

Mass hierarchy determination depends on the **true value of $\delta_{CP}$** and statistics.

For **MH = Normal**

- $\delta_{CP} = 0.82\pi$ (**NOvA best fit**)
  - $\sim 2.5\%$ chance of $3\sigma$ MH determination

- $\delta_{CP} = 1.37\pi$ (**T2K best fit, $\sim$most favourable params**)
  - $>50\%$ chance at $4\sigma$ MH determination

Statistical uncertainties only
Measurement uncertainty still statistics-dominated with full dataset
Conclusions

NOvA has an extensive physics program!

- Three-flavour oscillation physics
- Oscillation physics with alternate models
- Neutrino cross-sections
- Exotic phenomena searches

From this talk:

- New Bayesian techniques: new measurement of $\theta_{13}$
- We find no evidence for sterile neutrinos in the NOvA data (under the 3+1 model)

Many more exciting results to come in the future!
Thank you from the collaboration

April 2022
Additional Slides
The NuMI Beam

Collected $3.7 \times 10^{20}$ protons-on-target to date

Current analysis dataset uses

$1.36 \times 10^{20}$ POT neutrino-beam data and $1.25 \times 10^{20}$ POT antineutrino-beam data
2020 Frequentist Analysis

Normal Ordering 90% CL

- NOvA
- MINOS+ 2020
- T2K Nature 580
- IceCube 2018
- SK 2018

Best fit

$\Delta m_{32}^2 \times 10^3 \text{ eV}^2$

$\sin^2 \theta_{23}$
Asymmetry

\[ A_{CP} = \frac{P_{\nu_\mu \rightarrow \nu_e} - P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}}{P_{\nu_\mu \rightarrow \nu_e} + P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}} \]

NOvA Preliminary

Energy / Distance (10^{-3} GeV/km)

Reconstructed neutrino energy (GeV)
Matter Effects & Asymmetry

NOvA Preliminary

E = 2 GeV
No Matter Effects

$\delta_{CP} = 0 \quad \delta_{CP} = \pi/2$
$\delta_{CP} = \pi \quad \delta_{CP} = 3\pi/2$

NOvA Preliminary

E = 2 GeV
w/ Matter Effects

$\delta_{CP} = 0 \quad \delta_{CP} = \pi/2$
$\delta_{CP} = \pi \quad \delta_{CP} = 3\pi/2$
2020 Far Detector Spectra

Very high purity selection for both $\nu$ and $\bar{\nu}$ modes

<table>
<thead>
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<th>$\nu_\mu$</th>
<th>Obs.</th>
<th>Best Fit</th>
<th>Bg.</th>
</tr>
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<tbody>
<tr>
<td>$\nu$</td>
<td>211</td>
<td>222.3</td>
<td>8.2</td>
</tr>
<tr>
<td>$\bar{\nu}$</td>
<td>105</td>
<td>105.4</td>
<td>2.1</td>
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<tr>
<td>$\nu$</td>
<td>82</td>
<td>85.8</td>
<td>26.8</td>
</tr>
<tr>
<td>$\bar{\nu}$</td>
<td>33</td>
<td>33.2</td>
<td>14.0</td>
</tr>
</tbody>
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Backgrounds primarily from $\nu_e$ intrinsic to the beam (irreducible)

>$4\sigma$ $\bar{\nu}_e$ appearance

Disfavour strong asymmetry in $\nu_e$-$\bar{\nu}_e$ appearance
3F Oscillation Analysis Strategy

ND DATA

DATA-DRIVEN CORRECTION
Data-driven correction to signal/backgrounds in ND

DATA-DRIVEN PREDICTION
Use corrected ND simulation to predict spectra at the FD (constrains uncertainties)

FIT FOR OSCILLATIONS
Best Fit: fit all parameters NOvA is sensitive to
- $\Delta m^2_{32}, \theta_{23}, \delta_{\text{CP}}$
- $\theta_{13}$ constrained from reactor experiments
- Solar parameters fixed

CONFIDENCE INTERVALS
- Choose parameter(s) (eg $\delta_{\text{CP}}, \sin^2\theta_{23}$)
- For each point in space, minimise $\chi^2$
- Frequentist correction for coverage

CHOOSE ANOTHER SPACE
A New Bayesian Strategy!

DATA

*stays the same!

DATA-DRIVEN CORRECTION
Data-driven correction to signal/backgrounds in ND

DATA-DRIVEN PREDICTION
Use corrected ND simulation to predict spectra at the FD (constrains uncertainties)

PRODUCE POSTERIOR PROBABILITY SPACE
Use our current (“prior”) understanding of parameter values to construct a multi-dimensional “posterior” probability distribution.

CREDIBLE INTERVALS
Use probability distribution to produce credible intervals for parameters we’re interested in, marginalising over other parameters

\[ \Delta m^2_{32} \]
\[ \delta_{CP} \]
\[ \theta_{23} \]

(Example for three dimensions)

Posterior probability distribution means quick to produce credible intervals in new parameters

DONE!
Additional Bayesian Plots

Weak preference for normal ordering, upper octant

Bayesian Cred. Int.: $1\sigma$ $2\sigma$ $3\sigma$

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

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

NOvA Preliminary
Additional Bayesian Plots

When taking both orderings into account, we have no strong preference for $\delta_{CP}$
Additional Bayesian Plots

- No tension between NOvA and T2K for $\theta_{13}$
- No tension with measurements from reactor experiments
Additional Bayesian Plots

Slightly higher preference for NO with reactor constraint
Sterile $\nu_\mu$ Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{24} \Delta_{41} + 2 \sin^2 2\theta_{23} \sin^2 \theta_{24} \sin^2 \Delta_{31} - \sin^2 2\theta_{23} \sin^2 \Delta_{31}$$

Oscillations at atmospheric frequency, notably does not depend on $\theta_{34}$, $\delta_{24}$

$\nu_\mu$ sample constrains atmospheric parameters and size of $\theta_{24}$
Sterile NC Disappearance

\[ 1 - P(\nu_\mu \to \nu_s) \approx 1 - \cos^4 \theta_{14} \cos^2 \theta_{34} \sin^2 2\theta_{24} \sin^2 \Delta_{41} \]

\[ - \sin^2 \theta_{34} \sin^2 2\theta_{23} \sin^2 \Delta_{31} \]

\[ + \frac{1}{2} \sin \delta_{24} \sin \theta_{24} \sin 2\theta_{23} \sin \Delta_{31} \]

ND Oscillations from $\Delta m^2_{41}$

Oscillations at atmospheric frequency, gives us access to $\theta_{24}, \theta_{34}, \delta_{24}$
Citations

What Are Those Arrows?

The arrows are because these three experiments report either

$$|U_{\tau 4}|^2 = \cos^2 \theta_{24} \sin^2 \theta_{34}$$

Or $\theta_{34}$ directly for a given value of $\Delta m^2_{41}$.

Anomalous $\nu_\tau$ appearance searches measure

$$\sin^2 2\theta_{\mu\tau} = \cos^4 \theta_{14} \sin^2 2\theta_{24} \sin^2 \theta_{34}$$
NOvA-T2K Joint Analysis

Different best fit points, but still overlap at 1σ.

Made good progress, hoping for public results this year.
Future Sensitivities

NOvA Preliminary

- $\sin^2\theta_{13} = 0.085$
- $13.60 \times 10^{20}$ POT-equiv (v)
- $12.50 \times 10^{20}$ POT (\bar{v})

Total events - antineutrino beam

- $\delta_{CP} = 0$
- $\delta_{CP} = \pi/2$
- $\delta_{CP} = \pi$
- $\delta_{CP} = 3\pi/2$

Total events - neutrino beam

NOvA 2020 Best Fit
- $\nu 31.5 \times 10^{20} + \nu 31.5 \times 10^{20}$ POT

Full-dataset Sensitivity
- 2020 Syst.
- Inverted
- Normal