Recent results from the NOvA neutrino experiment

HIGH ENERGY PHYSICS SEMINAR

Gavin S. Davies
Indiana University
Hello, neutrino

Neutrinos are abundant; 2nd only in the universe to photons

Interact via the weak force carriers
  - Enrico Fermi coined the name neutrino (1933): “the little neutral one”, spin-1/2

Neutrinos are produced in the sun, supernovae and cosmic rays.

Small cross sections (they rarely interact).
Interactions are flavor conserving

“I have done a terrible thing, I have postulated a particle that cannot be detected”
Wolfgang Ernst Pauli, 1930
Neutrino Oscillations

1956: F. Reines and C. Cowan report the first evidence for neutrinos
- Detection of the free neutrino: A Confirmation
  *Science* 124:103-104 (1956)
- Nobel Prize in Physics, 1995: F. Reines
  “for the detection of the neutrino”

1998: Super-Kamiokande reports first evidence for neutrino oscillations → neutrinos have mass
- Evidence for oscillation of atmospheric neutrinos
  5300+ citations to date, #22 of all time

Neutrino oscillation is a well-established, well-described phenomenon over the last 20 years
- Nobel Prize in Physics, 2015
  “for the discovery of neutrino oscillations, which shows that neutrinos have mass”
- Fundamental Physics Breakthrough Prize, 2016
  “awarded to five experiments investigating neutrino oscillation”
  - Daya Bay, K2K/T2K, Super-K, KamLAND, SNO
Neutrino Oscillations

Create in one flavour, but detect in another

\[ \nu = \sum_{m=1}^{3} U_{\ell m} \nu_m \]

Flavor eigenstates: \( \nu_e, \nu_\mu, \nu_\tau \) (interactions)

Mass eigenstates: \( \nu_1, \nu_2, \nu_3 \) (propagation)

Flavor eigenstate oscillations described by the 3 x 3 PMNS matrix
Neutrino Oscillations

Neutrino oscillation is much like a double slit experiment; the neutrino mass eigenstates propagate differently, and interfere.

Given an initial flavor eigenstate of $\nu_\alpha$, observation some time later will yield a combination which:

1) has maximal $\nu_\beta$ (constructive interference)
Or 2) has only $\nu_\alpha$ (destructive interference)

The amount of interference is governed by the mixing matrix, $U$.
The PMNS Mixing Matrix

Pontecorvo

*Sov. Phys. JETP* **6**:429 (1957)
*Sov. Phys. JETP** 26:984-988 (1968)

Maki, Nakagawa, Sakata


\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-\sin \theta_{13} e^{-i\delta} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

atmospheric and reactor and solar and
long-baseline long-baseline reactor

\[\Delta m_{32}^2 \sim \pm 2 \times 10^{-3} eV^2\]

\[\Delta m_{31}^2 \approx \Delta m_{32}^2, \quad \Delta m_{21}^2 \sim 8 \times 10^{-5} eV^2\]

\[
P_{\alpha\beta} = \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 [eV^2] \frac{L [km]}{E [GeV]}\right)
\]

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

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

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

\[
\sqrt{P_{\text{atm}}} = \sin (\theta_{23}) \sin (2\theta_{13}) \frac{\sin (\Delta_{31} - aL)}{\Delta_{31} - aL} \Delta_{31}
\]
The PMNS Mixing Matrix

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\end{pmatrix} \]

atmospheric and reactor and solar and long-baseline long-baseline reactor

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

\[ \Delta m^2_{31} \approx \Delta m^2_{32} \]

\[ \Delta m^2_{21} \sim 8 \times 10^{-5} \text{eV}^2 \]
Open Questions

Neutrino mixing very different from quark sector mixing
Masses are really small compared to the rest of the Standard Model (SM)

Open Questions

Neutrino mixing very different from quark sector mixing
Masses are really small compared to the rest of the SM

Do neutrino oscillations violate charge-parity (CP) symmetry?

- $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$?

CP Violation

---

Neutrino

NOvA: L=810 km

Anti-Neutrino

NOvA: L=810 km

CP conserved

No matter effects

$sin^2 2\theta_{13} = 0.085$

$|\Delta m^2_{32}| = 2.44 \times 10^{-3} eV^2$

$sin^2 \theta_{23} = 0.5$

- NH $\delta = 0$
Open Questions

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\[ \delta = \frac{\pi}{2} \]

CP Violation

CP conserved

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Do neutrino oscillations violate CP symmetry?

- $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$?
- If CP violation is near maximal, $\delta_{CP}$ can create matter/anti-matter asymmetry via leptogenesis
- “Why are we here

**CP Violation**

**CP conserved**

### Neutrino

NOvA: L=810 km

<table>
<thead>
<tr>
<th>Neutrino energy (GeV)</th>
<th>$P(\nu_\mu \rightarrow \nu_e)$ %</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>1</td>
<td>1.5</td>
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<td>4</td>
<td>4.5</td>
</tr>
<tr>
<td>5</td>
<td>5.5</td>
</tr>
</tbody>
</table>

No matter effects

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$\sin^2 \theta_{23} = 0.5$

### Anti-Neutrino

NOvA: L=810 km

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Do neutrino oscillations violate CP symmetry?

Is the mass hierarchy (ordering) “normal” or “inverted”?
i.e. is the most $\nu_e$ state the lightest?
  ◦ Enhancement or suppression of oscillation probability depending on hierarchy

$\nu_e$ $\nu_\mu$ $\nu_\tau$

$\Delta m^2_{\text{atm}}$ $\Delta m^2_{\odot}$

Normal Hierarchy

Inverted Hierarchy

CP Violation

Mass Hierarchy
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\[ P(\nu_\mu \rightarrow \nu_e) \% \]

**Neutrino**
NOvA: $L=810 \text{ km}$

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**Anti-Neutrino**
NOvA: $L=810 \text{ km}$

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---

**CP Violation**

**Mass Hierarchy**
Open Questions: Mass Hierarchy

NOvA: L=810 km, E=2.0 GeV

\[ \sin^22\theta_{13} = 0.085 \]
\[ |\Delta m^2_{32}| = 2.44 \times 10^{-3} \text{eV}^2 \]
\[ \sin^2\theta_{23} = 0.5 \]

Inverted hierarchy

Normal hierarchy

UVA HEP seminar, Sep. 26\textsuperscript{TH} 2018
G. S. Davies (Indiana U.), NOvA
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Is the mass hierarchy (ordering) “normal” or “inverted”?

What is the octant of $\theta_{23}$?

- Governs $\nu_\mu/\nu_\tau$ split in $\nu_3$. More muon- or tau-like?
- If equal, imply some underlying symmetry?
Open Questions: $\theta_{23}$ Octant

NOvA: L=810 km, E=2.0 GeV

$\sin^2 2\theta_{13} = 0.085$
$|\Delta m^2_{32}| = 2.44 \times 10^{-3} \text{eV}^2$
$\sin^2 \theta_{23} = 0.404, 0.623$

Inverted hierarchy
Upper octant
Lower octant
Normal hierarchy

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e \%)$
$P(\nu_\mu \rightarrow \nu_e \%)$

$\delta = 0$  $\bullet \delta = \pi/2$
$\delta = \pi$  $\square \delta = 3\pi/2$
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Is the mass hierarchy (ordering) “normal” or “inverted”?

What is the octant of $\theta_{23}$?

“The existence of non-zero neutrino masses, inferred from neutrino oscillation experiments, is the only lab-based evidence of physics beyond the standard model.”

P.A.N. Machado
**NuMI Off-axis $\nu_e$ Appearance**

- Start with **world’s most powerful neutrino beam**
- NuMI $\nu_\mu$ beam at Fermilab
The NuMI Neutrino beam

- Target
- Focusing Horns
- $\pi^-$
- $\pi^+$
- $\nu_\mu$ / $\bar{\nu}_\mu$
- $\nu_\mu$

$8.85 \times 10^{20}$ POT Neutrino Beam

$> 700 \text{ kW operation}$
The NuMI Antineutrino beam

- Target
- Focusing Horns
- Decay Pipe

$\pi^+ \rightarrow \pi^0 \rightarrow \nu_\mu / \bar{\nu}_\mu$

$p \rightarrow > 700 \text{ kW operation}$

- Weekly neutrino beam
- Weekly antineutrino beam
- Accumulated beam
- Accumulated neutrino beam
- Accumulated antineutrino beam

8.85x10$^{20}$ POT Neutrino Beam

New! 6.9x10$^{20}$ POT Antineutrino Beam
Detectors

Far Detector

15 x 15 x 60 m

Near Detector

4 x 4 x 15 m

WLS fibers

PVC extrusions filled with liquid scintillator.

APD module
NOvA Far Detector

The Rotunda is ~77 feet ~ 23m in diameter and height
NOvA FD is 15m x 15m x 60m
~2/3 height, x 2.5 length

UVA designed and fabricated NOvA Power Distribution System
NOvA Physics Program

Primary Goal:
Measurement of 3-flavour oscillations via:

- Disappearance of $\nu_\mu$ CC events
  - $\nu_\mu \rightarrow \nu_\mu$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
  - Precision measurements of: $\sin^2(\theta_{23})$ & $|\Delta m_{32}^2|$

- Appearance of $\nu_e$ CC events
  - $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - Determine mass hierarchy
  - Search for $\delta_{CP} \neq 0$
    - $\theta_{13}$ & $\theta_{23}$ & $\delta_{CP}$

Other goals include:
- Searches for sterile neutrinos
- Neutrino cross sections
- Supernova neutrinos
- Cosmic ray physics
- Upwards-going muon (dark matter) analysis (UVA)

New 2018 oscillation analyses including antineutrino oscillations for the first time on NOvA

http://novaexperiment.fnal.gov/publications/

UVA HEP seminar, Sep. 26TH 2018  G. S. Davies (Indiana U.), NOvA
NOvA’s last *neutrino-only* oscillation results published in PRD at the weekend

Next frontier is *antineutrino oscillations*

http://novaexperiment.fnal.gov/publications/
Events are 550 μs readouts around the neutrino beam spill
Time-space separation

neutrino beam window
Neutrino Interactions at NOvA

Low-Z to enhance electron photon separation, each plane is \( \sim 0.18 X_0 \)
Molière radius is \( \sim 10 \) cm, 2.5 NOvA cells

- \( \nu_\mu \) CC: Long, straight track
  - \( \sim 5 \) m

- \( \nu_e \) CC: Shorter, wider, fuzzy shower
  - \( \sim 2.5 \) m

- NC: Diffuse activity from nuclear recoil system
Traditional reconstruction

Use the topology and magnitude of the energy depositions.
Takes advantage of the granularity and time resolution of our detectors.

**ISOLATE THE EVENT**
We isolate individual interactions using time and space correlation of the hits

**DEFINE CLUSTERS**
Groups of hits can be clustered as following the path of same particle starting at the interaction point

**FIT TRAJECTORIES**
When necessary we can fit an assumed trajectory for each cluster of hits
Reconstruction with deep learning

Instead of selecting a set of features a priori, let a deep learning network extract features and draw correlations.

Use “images” of our events to train Convolutional Neural Networks (CNNs) to identify neutrino interactions.

Instead of training with a weight for each pixel, convolve kernel operations across the image to extract features.

Inspired by the visual cortex.
CVN Event Classifier

We use a convolutional neural network based on the GoogLeNet. Calibrated hit maps are inputs to this: Convolutional Visual Network (CVN)

Successive layers of “feature maps” create variants of the original image, which enhance different features at growing levels of abstraction

Extracted features used as inputs to a “feed-forward” neural network to create a multi-label classifier

NOvA’s 2016 $\nu_e$ appearance analysis was the first implementation of convolutional neural networks in a HEP result

Network produces multi-dimensional classification output, normalized to 1. Reduces processing time running one network for many analyzes.
Updated CVN

New for this analysis:

A shorter, simpler architecture trained on updated simulation.

Replaced Genie truth labels with final state labels.
  ○ Exploring using final states with protons to constrain WS backgrounds.

Separate training for the neutrino and antineutrino beams.
  ○ Wrong-sign treated as signal in training.
  ○ 14% better efficiency for $\bar{\nu}_e$ with a dedicated network.
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Simulation tuning

We tune our simulation to get a better central value and to set systematic uncertainties.

Beam flux is tuned using the Package to Predict the FluX using external data.


We tune our cross-section model primarily to account for nuclear effects.

- Backstory: disagreements are seen in cross sections as measured on a single nucleons vs. in more complex nuclei.
- Nuclear effects are a likely solution, but the theory for them remains incomplete.
- So, we tune using a combination of external theory inputs and our own ND data.

$\nu_\mu (\bar{\nu}_\mu) \text{ disappearance}$
$\nu_\mu$ and $\bar{\nu}_\mu$ at the ND

Select muon neutrino and antineutrino CC events in ND
- Wrong sign contamination \( \sim 3\% \) for neutrino (11\% antineutrino)

Reconstructed neutrino energy is estimated from muon length and hadronic energy
- \( E_\nu = E_\mu + E_{\text{had}} \)

Data is split in 4 equal populations (quartiles) based on hadronic energy fraction as a function of reconstructed neutrino energy
- Energy resolution varies from 5.8\% (5.5\%) to 11.7\% (10.8\%) for neutrino (antineutrino) beam

Systematic uncertainties shown are shape only, 1.3\% and 0.5\% offset for neutrinos and antineutrinos respectively is removed for display purposes
Predict $\nu_\mu$ and $\bar{\nu}_\mu$ at the FD

<table>
<thead>
<tr>
<th>Neutrino beam</th>
<th>NOvA Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events / 0.1 GeV</td>
<td>FD Data</td>
</tr>
<tr>
<td>All Quartiles</td>
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</tr>
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</table>

<table>
<thead>
<tr>
<th>Events</th>
<th>113</th>
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<tbody>
<tr>
<td>Total Observed</td>
<td>113</td>
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<tr>
<td>Best fit prediction</td>
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<tr>
<td>Cosmic Bkgd.</td>
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<td>Beam Bkgd.</td>
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<td>Unoscillated</td>
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<table>
<thead>
<tr>
<th>Events</th>
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<tbody>
<tr>
<td>Total Observed</td>
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<tr>
<td>Best fit prediction</td>
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<tr>
<td>Cosmic Bkgd.</td>
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<td>Beam Bkgd.</td>
<td>0.6</td>
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<tr>
<td>Unoscillated</td>
<td>266</td>
</tr>
</tbody>
</table>
$v_e (\bar{v}_e)$ appearance
\( \nu_e \) and \( \bar{\nu}_e \) at the ND

Select electron neutrino and antineutrino CC events using particle ID in the ND for each beam mode

- Separate into low and high particle ID (purity)

For the neutrino beam constrain:
- the beam electron neutrinos using the muon neutrino spectrum
- the muon neutrino background using Michel electrons
- remaining data/MC discrepancy is assigned to the neutral current component

For the antineutrino beam, scale all components evenly to match the data.
Predict $\nu_e$ and $\bar{\nu}_e$ at the FD

We use the ND data to predict the background in the FD.

Each component is propagated independently in bins of energy and particle ID bins.

Add a one-bin peripheral signal sample. This sample has a less stringent containment selection, adds a different cosmic rejection boosted decision tree and high particle ID cut.

ND wrong sign component is 22% (32%) of the electron neutrino background for the high (low) PID bin.

Data-based cross-checks using identified protons and event kinematics within systematic uncertainty.
$\nu_e$ and $\bar{\nu}_e$ expectations

Event counts in neutrino and antineutrino mode vary according to the oscillation parameters.

Ellipses as a function of CP are drawn for normal and inverted hierarchy (NH and IH) as well as upper and lower octant (UO and LO).

10-22 Expected for $\bar{\nu}_e$

30-75 Expected for $\nu_e$
Event counts in neutrino and antineutrino mode vary according to the oscillation parameters.

Ellipses as a function of CP are drawn for normal and inverted hierarchy (NH and IH) as well as upper and lower octant (UO and LO).
$\nu_e$ and $\overline{\nu}_e$ at the FD

**Neutrino beam**

<table>
<thead>
<tr>
<th>Events / $8.85 \times 10^{20}$ POT-equiv</th>
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<tbody>
<tr>
<td>Reconstructed Neutrino Energy (GeV)</td>
</tr>
</tbody>
</table>

- **FD data**
- **2018 Best Fit**
- **Wrong Sign Bkg.**
- **Total Beam Bkg.**
- **Cosmic Bkg.**

**NOvA Preliminary**

<table>
<thead>
<tr>
<th>Total Observed</th>
<th>58</th>
<th>Range</th>
</tr>
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<tbody>
<tr>
<td>Total Prediction</td>
<td>59.0</td>
<td>30-75</td>
</tr>
<tr>
<td>Wrong-sign</td>
<td>0.7</td>
<td>0.3-1.0</td>
</tr>
<tr>
<td>Beam Bkgd.</td>
<td>11.1</td>
<td></td>
</tr>
<tr>
<td>Cosmic Bkgd.</td>
<td>3.3</td>
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<tr>
<td>Total Bkgd.</td>
<td>15.1</td>
<td>14.7-15.4</td>
</tr>
</tbody>
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**Antineutrino beam**

<table>
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<th>Events / $6.91 \times 10^{20}$ POT-equiv</th>
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**NOvA Preliminary**

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<tbody>
<tr>
<td>Total Prediction</td>
<td>15.9</td>
<td>10-22</td>
</tr>
<tr>
<td>Wrong-sign</td>
<td>1.1</td>
<td>0.5-1.5</td>
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<td>Beam Bkgd.</td>
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<tr>
<td>Cosmic Bkgd.</td>
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<tr>
<td>Total Bkgd.</td>
<td>5.3</td>
<td>4.7-5.7</td>
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G. S. Davies (Indiana U.), NOvA
$\nu_e$ and $\bar{\nu}_e$ at the FD

**Total Observed** | 58 | Range
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**Total Prediction** | 59.0 | 30-75
Wrong-sign | 0.7 | 0.3-1.0
Beam Bkgd. | 11.1 |
Cosmic Bkgd. | 3.3 |
Total Bkgd. | 15.1 | 14.7-15.4

**Total Observed** | 18 | Range
---|---|---
**Total Prediction** | 15.9 | 10-22
Wrong-sign | 1.1 | 0.5-1.5
Beam Bkgd. | 3.5 |
Cosmic Bkgd. | 0.7 |
Total Bkgd. | 5.3 | 4.7-5.7
Joint $\nu_e$ appearance $+$ $\nu_\mu$ disappearance
Systematic uncertainties

Most important systematics:

Detector Calibration
- Will be improved by the 2019 test beam program

Neutrino cross sections
- Particularly nuclear effects (RPA, MEC)

Muon energy scale

Neutron uncertainty – new with \( \nu \bar{\nu} \)’s
Allowed oscillation parameters

**Best Fit**

Normal hierarchy

Upper Octant

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

\[ \sin^2 \theta_{23} = 0.58 \pm 0.03 \]

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

\[\sin^2 \theta_{23}\]
Allowed oscillation parameters

Consistent with other long-baseline and atmospheric experiments.
Significance of maximal

Prefer non-maximal at $1.8\sigma$.
Exclude lower octant at similar level.
Allowed oscillation parameters

Best Fit

Normal hierarchy
Upper Octant

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

\[ \sin^2 \theta_{23} = 0.58 \pm 0.03 \]

\[ \delta_{CP} = 0.17\pi \]

Exclude IH, \( \delta = \pi/2 \) at > 3\( \sigma \)
Allowed oscillation parameters

Note: you cannot read the rejection of the MH from this plot.

- This is an FC-corrected plot of significance for rejecting particular sets of values: $(\delta, \text{octant, hierarchy})$.

- It is not a likelihood surface, so it cannot be profiled to remove $\delta$ and the octant.

Consistent with all $\delta_{\text{CP}}$ values in NH at $< 1.6\sigma$. 
2σ sensitivity to CP violation in 2024 for favorable parameters

\[
\sin^2\theta_{23} = 0.4 - 0.6, \quad |\Delta m^2_{32}| = 2.5 \times 10^{-3} \text{eV}^2, \quad \sin^2 2\theta_{13} = 0.082
\]
Into the future

$\sin^2 \theta_{23} = 0.4-0.6$, $|\Delta m^2_{32}| = 2.5 \times 10^{-3} \text{eV}^2$, $\sin^2 2\theta_{13} = 0.082$

**2σ sensitivity to CP violation** in 2024 for favorable parameters

**3σ sensitivity to the hierarchy** possible in 2020 with favorable parameters
The test beam program is how we will realize those analysis improvements

Reduced systematics

Additional validation of DL techniques

Simulation improvements

Installation and commissioning starting this summer

Beam in the first half of 2019, planning on 2 million particles
Deep Learning Prospects

Particle classification – thus far shown CVN as an event classifier

Single particles are separated using geometric reconstruction methods

“Prong” CVN: (4-views)
Data check: $\pi^0$ mass peak
12% purity improvement over traditional selection

Classify particles using both views of the particle and both views of the event
Deep Learning Prospects

Full event reconstruction is the dream

Cluster and classify particles simultaneously using instance aware semantic segmentation.

A network reconstructs an event hit by hit

Bounding Boxes - builds bounding boxes aiming to contain a single particle.
Labels - A softmax function is used to classify the particle in each box.
Clustering - Pixel by pixel clusters are defined to closely contain single particles.


A network for full event reconstruction is in development; promising avenue for future improvements
The Next Generation

Many questions will not be firmly established by current LBL experiments

Need new neutrino experiments with larger exposures and better precision

1st Generation

- K2K

2nd Generation

- T2K

3rd Generation

- HyperK
- DUNE

HyperK seed funding approved Sept 19th 2018
http://www.hyperk.org/?p=387

DUNE: First particle tracks seen in protoDUNE
Summary

We have begun the measurement of antineutrino appearance at long baseline

- Analyzed the **first NOvA antineutrino beam** dataset $6.9 \times 10^{20}$ POT plus $8.9 \times 10^{20}$ POT of neutrino beam data

We have **strong evidence for $\bar{\nu}_e$ appearance at long baseline**

- $> 4\sigma$ above background, including wrong-sign
- Achieved in our first antineutrino result thanks to outstanding beam performance and support from Fermilab!
- Training on neutrinos and anti-neutrinos separately yields the largest improvement for event classification – several deep learning avenues explored on NOvA

A joint analysis of $\nu_\mu/\bar{\nu}_\mu$ disappearance and $\nu_e/\bar{\nu}_e$ appearance prefers:

- The Normal Hierarchy at $1.8\sigma$ and excludes IH, $\delta CP = \pi/2$ at $>3\sigma$
- Non-maximal mixing at $1.8\sigma$ and similarly prefers the upper-octant

NOvA can reach $3\sigma$ sensitivity to the hierarchy by 2020 for the most favorable $\delta$, and $>30\%$ of the $\delta$ range by 2024

- Thanks to extended running, accelerator improvements, and analysis improvements thanks to the test beam

http://novaexperiment.fnal.gov
Thank you.
Questions?

http://novaexperiment.fnal.gov
Easter Egg

http://nusoft.fnal.gov/nova/public/nova-events

Can you beat our neural nets?
Backup
• If fit separately, the $\bar{\nu}_\mu$ data prefers non-maximal while $\nu_\mu$ prefers maximal.
  – Consistent with joint oscillation parameters to >4%.

• Matter effects introduce a small asymmetry in the point of maximal disappearance.

• Gives a $\sim1\sigma$ preference for the Upper Octant from just the $\nu_\mu + \nu_{\bar{\mu}}$ fit in NH.
  – The asymmetry is flipped in the Inverted Hierarchy, so there is a similar preference for the lower octant there.
Into the future

\[ \sin^2 \theta_{23} = 0.4-0.6, \ |\Delta m_{32}^2| = 2.5 \times 10^{-3} \text{eV}^2, \ \sin^2 2\theta_{13} = 0.082 \]

2σ sensitivity to CP violation in 2024 for favorable parameters

2018 analysis techniques and projected beam exposure improvements

UVA HEP seminar, Sep. 26TH 2018  G. S. Davies (Indiana U.), NOvA
Into the future

\[ \sin^2 \theta_{23} = 0.4 - 0.6, \quad |\Delta m_{32}^2| = 2.5 \times 10^{-3} \text{eV}^2, \quad \sin^2 2\theta_{13} = 0.082 \]

- **2\sigma sensitivity to CP violation** in 2024 for favorable parameters
- **3\sigma sensitivity to the hierarchy** possible in 2020 with favorable parameters

2018 analysis techniques and projected beam exposure improvements.
Near detector spills

USB HEP seminar, Sep. 26th 2018  
G. S. Davies (Indiana U.), NOvA
Near detector spills

- Multiple events in ND per NuMI spill
  - Over 2 million/year fiducial events collected

- Events separated using topology and timing
  - Color in display denotes time
  - Blue hits are early in spill, red are late

Top view

Beam direction

Side view

Color denotes time
Production cross section is a little higher for $\pi^+ \rightarrow \nu_\mu$ than for $\pi^- \rightarrow \bar{\nu}_\mu$

- $p^+$ colliding with $p^+$ and $n^0$ in the target

Wrong-sign: $\nu$ in the $\bar{\nu}$ beam (or vice versa).

Off-axis beam reduces the wrong-sign.

- WS primarily would primarily come from the unfocused high-energy tail.

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UVA HEP seminar, Sep. 26TH 2018  G. S. Davies (Indiana U.), NOvA
NOvA Simulation

Neutrino Beam

NOvA Far Detector

Flux 1-5 GeV

96.3% $\nu_\mu$

2.5% $\bar{\nu}_\mu$

1.1% $\nu_e + \bar{\nu}_e$

Antineutrino Beam

NOvA Far Detector

Flux 1-5 GeV

15.2% $\nu_\mu$

83.5% $\bar{\nu}_\mu$

1.3% $\nu_e + \bar{\nu}_e$

How to study disappearance

Compare the measured spectrum to the unoscillated prediction...

But there are large uncertainties from the neutrino flux and cross-section.

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

\[ \Delta m^2 \]
How to study appearance

Still start from the unoscillated $\nu_\mu$ prediction based on ND measurements.

$\nu_\mu \rightarrow \nu_e$ oscillations are sub-dominant (a few %)

Need ND measurements to constrain both signal and background.
How to detect a neutrino

Observe the charged particles after a neutrino interacts with a nucleus:

- **Lepton**
  - CC $\nu_{\mu} \rightarrow \mu^{-}$, CC $\nu_{e} \rightarrow e^{-}$
  - NC $\rightarrow$ no visible lepton

- **Hadronic shower**
  - Neutrinos typically produce a proton
  - Antineutrinos typically produce a neutron
  - May one or more $\pi^{\pm}$, additional $p$, $n$, etc.
  - May also contain EM from $\pi^{0} \rightarrow \gamma\gamma$
**Reconstruction**

**Vertexing:** Find lines of energy depositions w/ Hough transform CC events: 11 cm resolution

**Clustering:** Find clusters in angular space around vertex. Merge views via topology and prong dE/dx

**Tracking:** Trace particle trajectories with Kalman filter tracker. Also, cosmic ray tracker: lightweight, fast, and for large calibration samples, online monitoring.
Reconstruction

Event Separation: Coarse event-level time-space clustering, or ‘slicing

Utilize density-based DBSCAN clustering algorithm

Reconstruction

**Vertexing:** Find lines of energy depositions w/ Hough transform

CC events: 11 cm resolution
NC events: 29 cm resolution
Reconstruction

Prong Clustering: Given a seed vertex, look for **clusters in angular space** around vertex.

Merge views via topology and prong dE/dx
Reconstruction

Excellent reconstruction capabilities

Reconstruct $\pi^0$ peak – used as a calibration cross-check

- Demonstrates ability to reconstruct NC events

<table>
<thead>
<tr>
<th>Data $\mu$</th>
<th>MC $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>134.2 ± 2.9 MeV</td>
<td>136.3 ± 0.6 MeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data $\sigma$</th>
<th>MC $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.9 ± 2.1 MeV</td>
<td>47.0 ± 0.7 MeV</td>
</tr>
</tbody>
</table>
NOvA FD on the surface

Surface far detector, rate is driven by cosmic ray muons. Rate of 148 kHz.

Record 10 $\mu$s beam window $\pm$ 270 $\mu$s side band.
Cosmic ray rejection

- FD is on the surface; exposed to 150 kHz of cosmic rays
- 10 μs spill window at ~ 1 Hz gives $10^5$ rejection
- Cosmic background rate measured from data adjacent in time to the beam spill window

550 μs exposure of FD
Deep learning on NOvA

The edge-finding kernel below is man-made.

CVN (Convolutional Visual Network), the kernels are learned from the training data.

Edge-finding Kernel

-1 -1 -1
-1 8 -1
-1 -1 -1
Event Classification

Classify neutrino events using two tower network, Convolutional Visual Network.

Each view of the event is examined separately for most of feature extraction.

New this analysis:

Updated simulation.

Classification is done using final states.

Network optimizations.

Separate neutrino and antineutrino training.

Particle classification

Showing the network the entire event teaches the network **contextual** information.

Particularly useful in the classification of photons.

The change in efficiency for each category from removing context information.

UVA HEP seminar, Sep. 26th 2018
Extrapolation

\( \nu_e \) extrapolation

\( \nu_\mu \) extrapolation

UVA HEP seminar, Sep. 26\textsuperscript{TH} 2018
G. S. Davies (Indiana U.), NOvA
Cross-section tuning

From external theory:

- Valencia RPA model† of nuclear charge screening applied to QE.
- Same model applied to resonance.

From NOvA ND data:

- 10% increase in non-resonant inelastic scattering (DIS) at high $W$.
- Add MEC interactions
  - Start from Empirical MEC*
  - Retune in ($q_0$, $|q|$) to match ND data
  - Tune separately for $\nu/\bar{\nu}$


MEC uncertainties

We also determine uncertainties on the MEC component we introduce.

- Both on shape and total rate.

Repeat the tuning procedure with shifts in the Genie model.

- Turn Genie systematic knobs coherently to push the non-MEC x-sec more QE-like or more RES-like.
Cross-section tune

We also determine uncertainties on the MEC component we introduce.

- Both on shape and total rate.

Repeat the tuning procedure with shifts in the Genie model.

- Turn Genie systematic knobs coherently to push the non-MEC x-sec more QE-like or more RES-like.

Independently, Minerva* has also tuned a multi-nucleon component to their data.

The resulting tune is \(\sim 1\sigma\) away from the NOvA tune.

---

Cross-check: Muon-removed, electron-added

We can create a control sample of “electron neutrino” events by removing the muon and replacing it with a simulated electron.

Compare the efficiency between MRE events with real and simulated hadronic showers. – Allows us to focus on the effect of the hadronic shower on efficiency.

Efficiency agrees between data and MC at the 2% level for both neutrino and antineutrino beams.
**Cross-check:**
Muon-removed from bremsstrahlung

Bremsstrahlung showers in cosmic ray muons provide a sample of known electron showers in data at the Far Detector.

Efficiency of data and simulated brem showers agrees within systematics for neutrino and antineutrino CVN.
Cross-check: Muon-removed from bremsstrahlung

Bremsstrahlung showers in cosmic ray muons provide a sample of known electron showers in data at the Far Detector.

Efficiency of data and simulated brem showers agrees within systematics for neutrino and antineutrino CVN.
Other analysis selections

Some basic additional cuts: Contained, fiducial events, well-reconstructed, reasonable energy range

An additional $\nu_\mu$ requirement: a track identified as a muon

CVN identifies events with a muon, but it does not identify the muon track

Identify muons in reconstructed tracks using a kNN
Track length, dE/dx, scattering, fraction of track-only planes

![Graph](image)
Cosmic rejection at FD

Additional cosmic rejection needed at the Far Detector. – 11 billion cosmic rays/day in the Far Detector on the surface. – $10^7$ rejection power required after timing cuts are applied.
The $\nu_\mu$ sample uses a BDT based on: – Track length and direction, distance from the top/sides, fraction of hits in the muon, and CVN.
Cosmic rejection for the $\nu_e$ sample is in 2 stages: – Core sample: require contained events, beam-directed events, away from the detector top – Peripheral sample: events failing the core selection can pass a BDT cut plus a tight CVN cut.

Different BDT from $\nu_\mu$
Oscillation sensitivity depends on spectrum shape

Improve sensitivity by separating high-resolution and low-resolution events.

Split into 4 quantiles by hadronic energy fraction. – Muon energy resolution (3%) is much better than hadronic energy resolution (30%)
Improving energy resolution

Data
Area-normalized MC
Shape-only systematics
Wrong-sign

Quartile 1
Best Resolution ~6%

Quartile 4
Worst Resolution ~12%

Data/MC shape agrees well per quartile
Data vs. MC

Good agreement in FD data distributions of muon and hadronic energy and inelasticity.
Far detector backgrounds to $\nu_e$

14.7 – 15.4 total $\nu_e$ background, 4.7 – 5.7 total $\bar{\nu}_e$ background

Wrong sign depends on oscillation parameters
Didn’t you say there are 3 neutrinos?

From LEP, invisible width of Z-boson very strongly measured there are 3 “light” neutrinos

- $N_\nu = 2.984 \pm 0.008$

“light” means $m_\nu < \frac{1}{2} m_Z$ and additional neutrino must not couple to Z

- Hence “sterile” neutrino:
  - no SM charge; no SM interactions

Cosmological constraints:

- $N_{\text{eff}} = 3.2 \pm 0.5$
- $\Sigma m_\nu < 0.32$ eV
  - 90%, Planck TT+lowP+lensing+BAO

3+1 formalism

Extend PMNS matrix with an additional sterile neutrino ($\nu_s$), three new mixing angles and two new CP phases.

Three new mass-splittings; one is independent $\Delta m^2_{41}$

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\nu_s
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_4
\end{pmatrix}
\]
3+1 formalism

Extend PMNS matrix with an additional sterile neutrino ($\nu_s$), three new mixing angles and two new CP phases

Three new mass-splittings; one is independent $\Delta m^2_{41}$

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U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_4
\end{pmatrix}$

$1 - P(\nu_\mu \to \nu_s) \approx 1 - \frac{1}{2} \cos^4 \theta_{14} \cos^2 \theta_{34} \sin^2 2\theta_{24} + \sin^2 \theta_{34} \sin^2 2\theta_{23} \sin^2 \Delta_{31}$

$\nu_e \to \nu_e$ at short baselines (reactor)

$|U_{e4}|^2 = \sin^2 \theta_{14}$

$|U_{\mu4}|^2 = \cos^2 \theta_{14} \sin^2 \theta_{24}$

$4 \cdot |U_{e4}|^2 \cdot |U_{\mu4}|^2 = \sin^2 \theta_{14} \sin^2 \theta_{24} \equiv \sin^2 2\theta_{\mu e}$

$|U_{\tau4}|^2 = \cos^2 \theta_{14} \cos^2 \theta_{24} \sin^2 \theta_{34}$

$\nu_\mu \to \nu_\mu$ at short/long baselines

$\nu_\mu \to \nu_s$ at long baselines (NCs)

$\nu_\mu \to \nu_\mu$ at short/long baselines

$\nu_{e} \to \nu_{e}$ at short baselines (reactor)

$\Delta_{ij} \equiv \frac{\Delta m^2_{ji} L}{4E}$
Why NC’s?

Do any $\nu_\mu$ oscillate to a sterile state?

- $\nu_\mu \rightarrow \nu_s$ mixing causes energy-dependent depletion of NC

![Graph showing neutrino energy versus L/E (km/GeV) with different mixing probabilities and energy levels.](image)
Searching for $\nu_s$ in NOvA

- NC interactions unaffected by 3-flavour oscillations but mixing between active and sterile neutrinos reduces the rate of NC events
  - NC rate is the same for all 3 active flavours
- Compare number of Neutral Current events between Near and Far Detectors
  - Select high statistics ND sample to predict expected rate at the FD
  - Select FD events to search for reduced rate due to sterile oscillations
- Null result would allow NOvA to set limits on sterile mixing angles and further increase the exclusion region

Search for a depletion of NC events at the Far Detector

This is a rate-only analysis

NC disappearance relative to 3-flavour predictions is model independent
Anomaly #1a

LSND (1993 – 1998) observed a 3.8sigma excess of $\bar{\nu}_\mu \to \bar{\nu}_e$, could be interpreted as oscillations at high mass-splitting scale $\sim 1\text{eV}^2$

KARMEN2 experiment, however, saw results consistent with expectation

MiniBooNE investigated
- $\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$

Anomaly #1b

MiniBooNE saw excess appearance in both neutrino and anti-neutrino channels.

Data consistent with antineutrino oscillations for $0.01 < \Delta m^2 < 1.0 \text{ eV}^2$.

Some overlap with regions of phase-space from LSND.
Anomaly #2

Solar neutrino experiments: GALLEX and SAGE

Calibrated using radioactive sources

Measured rates from the calibration sources displayed consistent deficits

…consistent with a 1 eV$^2$ mass-splitting
Anomaly #3?

A suite of reactor neutrino experiments have seen a deficit of $\nu_e$

...consistent with a 1 eV$^2$ mass-splitting. Hang tight, there’s more...
So, not an anomaly?

Daya Bay released results in 2017 after studying their flux as a function of reactor fuel cycles to extract information on the uranium (U…) and plutonium component.

Flux deficit appears to only come from the uranium flux.

Sterile neutrino hypothesis is incompatible with Daya Bay’s observation at 2.6 sigma.
Super-K exclusion in $|U_{\mu 4}|^2$, $|U_{\tau 4}|^2$ parameter space

$|U_{\mu 4}|^2 < 0.041$ for $\Delta m^2_{41} > 0.1 \text{ eV}^2$

$|U_{\tau 4}|^2 < 0.18$ for $\Delta m^2_{41} > 0.1 \text{ eV}^2$

Super-K only experiment with measurement on $|U_{\tau 4}|^2$ directly comparable to NOvA
NC Disappearance

NOVA’S FIRST PUBLIC 2017 DATASET
RESULT
2016 Sterile mixing angle limits

In 3+1 analysis, for $\Delta m^2_{41} = 0.5 \text{ eV}^2$

$$|U_{\mu 4}|^2 = \sin^2 \theta_{14} = 0, \cos^2 \theta_{14} = 1$$

$$|U_{\tau 4}|^2 = \cos^2 \theta_{14} \sin^2 \theta_{24}$$

$$|U_{\tau 4}|^2 = \cos^2 \theta_{14} \cos^2 \theta_{24} \sin^2 \theta_{34}$$

$$|U_{\mu 4}|^2 < 0.126 \text{ at } 90\% \text{ C.L.}$$

$$|U_{\tau 4}|^2 < 0.268 \text{ at } 90\% \text{ C.L.}$$
Constrain NOvA’s degenerate best fit points for $\sin^2(\theta_{23})$, $|\Delta m_{32}^2|$, and $\delta_{CP}$ (NH)

Profile $\sin^2(\theta_{23})$, $\delta_{24}$

Perform a shape-based fit for $\theta_{24}$ and $\theta_{34}$

In a 3+1 analysis, for $\Delta m_{41}^2 = 0.5$ eV$^2$:

$\theta_{24} < 16.2$ at 90% C.L.

$\theta_{34} < 29.8$ at 90% C.L.
The future for NOvA $\nu_s$ searches

**NOvA short-baseline $\nu_e$ appearance-$\nu_\mu$ disappearance joint fit**

Probe LSND and MiniBooNE allowed regions with one NOvA year

**NOvA short-baseline $\nu_\tau$ appearance**

![Graph showing $\Delta m^2$ vs. $\sin^2 2\theta_{\mu\tau}$ with NOvA Realistic Sel., NOvA Perfect Sel., NOMAD, CHORUS, E531, CCFR, and CDHS data points.]

- $\nu_\mu \rightarrow \nu_\tau$ 90% C.L.
- $18 \times 10^{20}$ POT

Probing $\delta_{14}$ & $\delta_{13}$ with $\nu_e$ long-baseline

Black line shows NOvA sensitivity to $\nu_\tau$ appearance; rate-only fit to two flavor model

NOvA will be competitive with previous experiments after 3 years of running
DUNE will be the premier long-baseline neutrino experiment

- Multi-megawatt, high intensity, wide band neutrino beam
  - Produced at Fermilab, directed towards the Sanford Underground Research Facility (SURF)
  - 40 kT (fiducial mass) Liquid Argon Time Projection Chamber (LArTPC) far detector
    - Four 10kT modules located at the 4850 level
- Highly capable neutrino near detector
  - High statistics neutrino cross-section measurements and capability to fully characterize the spectrum and flavor composition of the beam
Physics of DUNE

Would like to have $> 5\sigma$ determination for all 3ν questions
- and sensitive searches beyond 3ν paradigm

Neutrino Oscillations; Proton Decay; Supernova Neutrinos

UVA HEP seminar, Sep. 26TH 2018
First ProtoDUNE tracks
HyperK:
“Seed funding” just approved Sept 19\textsuperscript{th} 2018
Project construction could begin as soon as 2020

Detector(s):
FD – bigger version of SK with better PMTs
\(~190~kT~\) fiducial mass (10x SK)

ND – continue to use ND280
still uses JPARC beam (upgraded to \(~\)MW level)

Physics:
double proton decay sensitivity (see \(~10~\) if lifetime is at current limits)
could see \(~50k~\) SNe events (out to 10 kpc)
expect > 2k appearance events in 10 years
Hierarchy determination “possible” after \(~5~\) yr

M. Shiozawa (Neutrino 2018)