THE NO\textsc{v}A EXPERIMENT

\textit{NuMI Off-Axis Neutrino Appearance}

Neutrinos at the Main Injector

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DEC 2014
The NOvA Neutrino Experiment shared a link.

We're getting a lot of exposure right now. Here we are in Science magazine (subscription may be required).

NOvA's shining moment
www.sciencemag.org

It takes a big snare to catch a subatomic ghost. The newly completed NOvA neutrino detector is the size of a warehouse—five stories tall and more than three times that long—and consists of 896 planes of extruded plastic tubes filled with 10 million liters of mineral oil. "This is the world's largest..."
“Using the current Fermilab accelerator complex, physicists are studying the interactions of neutrinos with matter. Neutrinos only experience the weak nuclear force and can pass through a lot of matter without interacting ... Given this reluctance to interact, the only way to ensure enough neutrino interactions to study is to generate incredibly intense beams and analyze them with massive particle detectors.”
“Long-baseline”

Neutrinos at the Main Injector (NuMI) beam @Fermilab, 2 possible modes
1. Beam mostly $\nu_\mu$
2. Beam mostly $\bar{\nu}_\mu$

Compare Near-detector @Fermilab vs Far-detector @Ash River for $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) oscillations
- #of $\nu_e$ ($\bar{\nu}_e$): “appearance”
- #of $\nu_\mu$ ($\bar{\nu}_\mu$): “disappearance”

Up-and-running since mid-October!
- Review: neutrino masses & mixing
- Main measurement program
  - Mixing parameter $\theta_{13}$
  - CP violation parameter $\delta$
  - Distinguishing the hierarchy
- “Atmospheric $\nu$” measurement program
  - Mixing parameter $\theta_{23}$
  - Mass parameter $\Delta^2 m_{23}$
- BSM: sterile $\nu$ search

- Experimental design
  - Backgrounds
  - Sensitivity
  - Beam
  - Detector positioning
  - Detector construction
  - Prototype detector
REVIEW: NEUTRINO MASSES & MIXING

PMNS MATRIX

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
U = \begin{bmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{bmatrix}
\begin{bmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{bmatrix}
\begin{bmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{bmatrix}
\]
REVIEW: NEUTRINO MASSES & MIXING

PMNS MATRIX

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

- **flavour eigenstates**
- **mass eigenstates**

\[\theta_{23} \text{ “atmospheric”} \quad \theta_{13} \text{ “atmospheric / reactor”} \quad \theta_{12} \text{ “solar”}\]

\[U =
\begin{bmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{bmatrix}
\begin{bmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{bmatrix}
\begin{bmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\[\delta = \text{“CP-violating phase”}\]
Review: Neutrino Masses & Mixing

Mass Hierarchy

Sign of $\Delta m^2_{32}$?
Multiple parameters involved

Note degeneracies

$T_2$ changes sign for anti-neutrinos (CP-violating!)
Matter interactions quantified by $A = G_F \rho_e / \sqrt{2}$

A switches sign for anti-neutrinos
A switches sign for inverted hierarchy
REVIEW: NEUTRINO MASSES & MIXING
MATTER INTERACTIONS

\[ P(\nu_\mu \rightarrow \nu_e) = T_1 + (T_3 - T_2) + T_4 \]

Atmospheric: \[ T_1 = \sin^2(2\theta_{13}) \sin^2\theta_{23} \sin^2\Delta_{13} \quad \Delta_{ab} = \Delta m_{ab}^2 L / (4E) \]

Solar: \[ T_4 = \sin^2(2\theta_{12}) \cos^2\theta_{23} \cos^2\theta_{13} \sin^2\Delta_{12} \]

Interference:
\[ T_2 = \sin\delta \sin(\theta_{23}) \sin(\theta_{12}) \sin(\theta_{13}) \cos\theta_{13} \sin\Delta_{12} \sin\Delta_{13} \sin\Delta_{23} \]
\[ T_3 = \cos\delta \sin(\theta_{23}) \sin(\theta_{12}) \sin(\theta_{13}) \cos\theta_{13} \sin\Delta_{12} \sin\Delta_{13} \cos\Delta_{23} \]

\[ A = G_F \rho_e / \sqrt{2} \quad (-A \text{ for anti-neutrinos or inverted hierarchy}) \]

\[ \sin\Delta_{12} \rightarrow \sin(\Delta_{12} - AL) \Delta_{12} / (\Delta_{12} - AL) \]
\[ \sin\Delta_{13} \rightarrow \sin(\Delta_{13} - AL) \Delta_{13} / (\Delta_{13} - AL) \]
# REVIEW: NEUTRINO MASSES & MIXING
# CURRENT LIMITS ON OSCILLATION PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best-fit [+/− 1σ]</th>
<th>3σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{12}^2$</td>
<td>7.58 [+0.22 / -0.26]</td>
<td>6.99 − 8.18</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{23}^2</td>
<td>$</td>
</tr>
<tr>
<td>$\sin^2(\theta_{12})$</td>
<td>0.306 [+0.018 / -0.015]</td>
<td>0.259 − 0.359</td>
</tr>
<tr>
<td>$\sin^2(\theta_{13})$</td>
<td>0.021 [+0.007 / -0.008]</td>
<td>0.001 − 0.044</td>
</tr>
<tr>
<td>$\sin^2(\theta_{23})$</td>
<td>0.42 [+0.08 / -0.03]</td>
<td>0.34 − 0.64</td>
</tr>
<tr>
<td>$\delta$</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

[5]
Take existing best-fit $|\Delta m^2_{23}|$, $\sin^2(\theta_{23})$

From NOνA $\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$), constrain $\theta_{13}$ as function of $\delta$

- Different for normal vs inverted hierarchy!

- CP-violation and Matter effects same sign ("convenient $\delta$‘‘): can determine which hierarchy
  - Otherwise: inherent ambiguity. Higher $\theta_{13}$ $\rightarrow$ higher chance of convenient $\delta$
MAIN MEASUREMENT PROGRAM

\( \theta_{13}, \delta, \) HIERARCHY

- How small a \( \theta_{13} \) will NOvA be able to accurately measure?

\[
3 \sigma \text{ Sensitivity to } \sin^2(2\theta_{13}) = 0
\]

- Once NOvA finds best-fit (\( \theta_{13}, \delta \)), how big will the uncertainties be?

1, 2, and 3 \( \sigma \) Contours for Starred Point

[1]
For what \((\theta_{13}, \delta)\) range will the hierarchy be resolved?
Usefulness of NOvA results for atmospheric parameters: how big will the uncertainties be?

- Simultaneous best-fit to \{ |\Delta m^2_{23}|, \sin^2(\theta_{23}) \}
- \sin^2(\theta_{23}) as a function of \delta

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[1] Sensitivity Contours (15 kt*36E20 POT)

- \Delta m^2 (10^{-3} \text{eV}^2)
- \sin^2(2\theta_{23})
- 1\sigma CL
- 2\sigma CL
- input parameter
- best fit

[3] Example NOvA 1\sigma and 2\sigma contours, 3+3 yr (v+\bar{v})
- \sin^2(2\theta_{23})=0.095, \sin^2(2\theta_{23})=0.95

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[1]
Take existing best-fit $|\Delta m^2_{23}|$, $\sin^2(\theta_{13})$

Determine sign of $\cos(2\theta_{23})$, i.e. whether $\nu_e$ oscillates more strongly to $\nu_\mu$ or $\nu_\tau$

- Requires comparing NOvA to reactor results

For what $(\theta_{13}, \theta_{23})$ range will NOvA resolve sign?

95% CL Resolution of the $\theta_{23}$ Ambiguity

- NOvA (15kT) + Reactor
  - $\Delta m^2_{32} = 2.4 \times 10^{-3} \text{ eV}^2$

- 3 years for each $\nu$ and $\bar{\nu}$
  - NOvA at 700kW, 1.2 MW, and 2.3 MW
  - + a reactor with $\sigma = 0.005$
ATMOSPHERIC $\nu$ MEASUREMENT PROGRAM

$\theta_{23}$, $|\Delta m^2_{23}|$

- Possibility $|\Delta m^2_{23}|$ and/or $\theta_{23}$ different for neutrinos vs anti-neutrinos
- How accurately could NOvA pin down such an asymmetry?

[2]
BSM: STERILE $\nu$ SEARCH

- BSM possibility: 4$^{th}$ light neutrino state, $\nu_s$
  - “Sterile” (no coupling to Z or W)
- Have $\nu_\mu \to \nu_? \ (\text{with } \nu_? = \text{admixture of } \nu_\tau, \nu_s)$?
  - Consequence: fewer than expected NC events in NOvA Far-detector

Current 90%CL bounds on $\nu_? :$
< 20% $\nu_s$

Expected NOvA sensitivity:
~10% $\nu_s$
EXPERIMENTAL DESIGN: OVERALL LAYOUT

- Mainly detect leptonic showers from CC interactions
- Optimize for 2 GeV $\nu$'s ($\nu_\mu \to \nu_e$ oscillation max)
- “Baseline exposure”: 6 yrs of running

Near-detector: 330 metric-ton @Fermilab

Far-detector: 14000 metric-ton @Ash River
EXPERIMENTAL DESIGN: BACKGROUNDS

- Non-signal $\nu$ events (~0.5%)
  - Energy cuts, requiring good energy resolution
- Mistaking NC for $\nu_e$ CC (~0.1%)
  - Highly-segmented detector
  - Careful choice and understanding of detector materials
- “Wrong-sign” $\nu$ beam component (~1%)
- Precise estimates made for unavoidable bg
- Dominant uncertainties will be statistical
EXPERIMENTAL DESIGN: SENSITIVITY

- Signal $\sim \sqrt{\text{exposure time}}$ until systematics-limited
- High signal efficiency + good bg rejection requires tracking + calorimetry: frequent sampling in low-Z material
- $>100:1$ bg rejection
- $\nu$ event detection efficiency $\approx 0.4$

<table>
<thead>
<tr>
<th>Candidate events expected in Far-detector</th>
<th>$\nu$</th>
<th>$\bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>19</td>
<td>10</td>
</tr>
<tr>
<td>$\nu_\mu$ CC</td>
<td>5</td>
<td>&lt;1</td>
</tr>
<tr>
<td>$\nu_e$ CC</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>total bg.</td>
<td>32</td>
<td>15</td>
</tr>
</tbody>
</table>

Event rate in anti-neutrino mode: $\sim 30\%$ lower

Event rate in anti-neutrino mode: $\sim 30\%$ lower
3 “beam tunes” (low-, medium-, high- energy)
EXPERIMENTAL DESIGN: BEAM

I stood in the beam (nothing happened) and took these photos!

Underground tunnel @Near-detector: \( \nu \) beam comes out here
In-flight pion decay: $\nu$ flux peaks in forward direction

But, lab-frame $E_\pi$ vs $E_\nu$ relationship changes with $\theta$

$$F = \left(\frac{2\gamma}{1 + \gamma^2\theta^2}\right)^2 \frac{A}{4\pi z^2}, \quad E_\nu = \frac{0.43E_\pi}{1 + \gamma^2\theta^2}$$

See nearly mono-energetic $\nu_\mu$ beam by placing detector slightly off-axis

- Total $\nu$ flux lower than on-axis
- But, much higher $\nu$ fraction in target energy range
EXPERIMENTAL DESIGN: DETECTOR CONSTRUCTION

- Acts as tracker and total absorption calorimeter
- 80% detector mass is active scintillator

(My photo of Near-detector)
EXPERIMENTAL DESIGN: DETECTOR CONSTRUCTION

Highly segmented:

[Diagram of detector construction with labels for vertical and horizontal planes, module, cell, and dimensions.]
EXPERIMENTAL DESIGN : PROTOTYPE DETECTOR

- Near Detector on the Surface (NDOS) : installation completed May 2011
- Full-scale detector assembly & integration tests, electronics & DAQ development, calibration R&D, simulation tuning, early analysis R&D, etc.

Has recorded hundreds of ψ interactions from NuMI, millions from cosmic rays
NOvA uses $\nu_\mu (\bar{\nu}_\mu)$ beam, Near-detector, and Far-detector to measure $\nu_\mu \rightarrow \nu_e (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

- 700 kW beam from Fermilab
- Off-axis, highly-segmented liquid scintillator detectors separated by ~800 km
- Optimized for neutrino energies at the oscillation max (~2 GeV)
- Capable of tracking + calorimetry, to meet demanding signal-to-background requirements

Main measurement program: $\theta_{13}$, $\delta$, hierarchy determination

Will also contribute to $\theta_{23}$, $|\Delta m^2_{23}|$, $\nu_s$ measurements

Prototype detector operational since mid-2011, full setup running since mid-October

~6 yrs running time expected to greatly enhance our understanding of the neutrino sector’s unsolved mysteries
REFERENCES


Ghostbuster team finds ghostly neutrinos in Batavia

On a hunch that short- and long-baseline experiments might not be adequate for finding ghostly neutrinos, Fermilab management went retro earlier this year and hired the original Ghostbuster team to carry out its own independent, unimpeded search for the elusive particles.

The gamble paid off. At a pre-Halloween press conference earlier this week, members of Fermilab management and the Ghostbusters team announced finding neutrinos along the neutrino beamline in complex 80sGB, a special undisclosed Fermilab facility built just for the New York-based team.

"We got slimed, as we knew we would," said senior ghostbuster Peter Venkman. "But we found them, and we are not telling how. It was so &%#@& scary!"

In addition to bagging the neutrinos, Venkman's team also reviewed earlier Fermilab neutrino experiment protocols. Venkman said there were major flaws in the way the experiments were conducted and the data made public.

"The problem with one of the older experiments was that the team gave too much away," Venkman said. "They were too loose and mouthed off to other scientists. That is not the way do science, let alone go after neutrinos."

Despite his team's refusal to disclose details and data, Venkman said his team's experiment will be both reproducible and disprovable.

"That smarty pants Karl Popper would be a-ok with our research. It is Karl Popper, right?" he publicly surmised. "Or was it Carl Yaz who came up with the test?"

Fermilab confirms that the Ghostbuster experiment's results will be published in a January issue of Nature and its antiresults in Science that same month.

Venkman said being down "in the neutrino beam area with all that gooey stuff and then seeing the ghostly neutrinos was scary beyond words."

He added that he is very proud of his team's good work.
BACKUP
EXPERIMENTAL DESIGN: DETECTOR CONSTRUCTION

- Each cell has
  - Titanium dioxide-loaded PVC shell
  - Liquid scintillator: mineral oil + 4.1% pseudocumene [1,2,4-Trimethybenzene]
  - Wavelength-shifting fiber loop
- Charged particles produce scintillator light
- Fiber carries captured scintillator light to pixel on Avalanche Photodiode Array → electronic pulse
- Charged-particle energy of event = sum of all cell pulse heights
EXPERIMENTAL DESIGN: DETECTOR POSITIONING
EXPERIMENTAL DESIGN: EVENT RECONSTRUCTION

- $\mu$: long, straight path
- $\pi$ decay: gap between $\nu$ interaction and $\gamma$ conversion
- Proton: distinct $dE/dx$ profile
- EM showers: high detector granularity allows easy identification