Sensitivity of the NO$\nu$A $\nu_e$ appearance analysis

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Christopher Backhouse
Caltech

for the NO$\nu$A Collaboration
Introduction

- NO$\nu$A and neutrino oscillations
- Selecting $\nu_e$ events
- Updated sensitivity
  - Hierarchy
  - CP-violation
  - Octant
- Conclusion
Neutrino oscillations – $\theta_{13}$

- Non-zero $\theta_{13}$ established by reactor experiments (via $\bar{\nu}_e$ disappearance)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sin^2 2\theta_{13}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daya Bay</td>
<td>$0.089 \pm 0.010 \pm 0.005^a$</td>
</tr>
<tr>
<td>RENO</td>
<td>$0.113 \pm 0.013 \pm 0.019^b$</td>
</tr>
<tr>
<td>Double Chooz</td>
<td>$0.086 \pm 0.041 \pm 0.030^c$</td>
</tr>
</tbody>
</table>

- $\sin^2 2\theta_{13} \approx 0.1$

- Long-baseline expts observe $\nu_\mu \rightarrow \nu_e$

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$^a$ Chin. Phys. C37, 011001 (2013)
$\nu_e$ physics goals

- To first order, NO$\nu$A measures $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ evaluated at 2GeV

$\nu_\mu \rightarrow \nu_e$

- Measure $\theta_{13}$ via $\nu_e$ appearance
- Determine the $\theta_{23}$ octant
$\nu_e$ physics goals

- To first order, NOνA measures $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ evaluated at 2GeV

$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- Measure $\theta_{13}$ via $\nu_e$ appearance
- Determine the $\theta_{23}$ octant
- Determine the mass hierarchy
- Search for $\delta_{CP} \neq 0, \pi$
Event topologies

- Very good granularity, especially considering scale
- Radiation length 38cm (6 cell depths, 10 cell widths)
Several $\nu_e$ PIDs under development

**ANN** Likelihood ratios for particle hypotheses

**LEM** Matching to Monte Carlo library events

**BDT** MVA on simple reconstructed quantities

Good separation of $\nu_e$ signal from backgrounds

See poster by Himansu Sahoo (session K2)

Approximate expected event counts

<table>
<thead>
<tr>
<th></th>
<th>$\nu$</th>
<th>$\bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 x $10^{20}$ POT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutral current</td>
<td>19</td>
<td>10</td>
</tr>
<tr>
<td>$\nu_{\mu}$ charged current</td>
<td>5</td>
<td>$&lt;1$</td>
</tr>
<tr>
<td>Intrinsic $\nu_e$ CC</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Total background</td>
<td>32</td>
<td>15</td>
</tr>
<tr>
<td>$\nu_{\mu} \rightarrow \nu_e$ signal</td>
<td>68</td>
<td>32</td>
</tr>
</tbody>
</table>
Sensitivities

- Assuming 3 years $\nu$-mode + 3 years $\bar{\nu}$-mode @ $6 \times 10^{20}$ POT/yr
- Start in neutrino mode
- Switching to/from antineutrino running is technically easy

- $\Delta m_{32}^2 = 2.40 \times 10^{-3} \text{eV}^2$ (MINOS best-fit)
- $\sin^2 2\theta_{23} = 1.00$ (SK best-fit, except where otherwise stated)
- $\sin^2 2\theta_{13} = 0.095$ (Reactor average, assumed well-known)

- Results from full simulation, reconstruction, selection, and analysis framework
  - FD only. Extrapolation methods from ND in progress
Exposure assumptions and early reach

- 2.5kton when beam returns
- Ramp up to full 700kW (dependent on Booster improvements)
- 14kton in Aug 2014
Exposure assumptions and early reach

NOvA early reach

\[ \sin^2 2\theta_{13} = 0.095, \sin^2 2\theta_{23} = 1.00, \delta = 0 \]

Mar 2013 version

- **5σ** observation of \( \nu_e \) appearance within first year (for NH, \( \delta = 0 \))
- With detector still under construction and beam commissioning
Assuming tight measurement of $\theta_{13}$ from reactors

Combine with NO$\nu$A $\nu_\mu$ analysis for $\theta_{23}$ constraints

In this favourable case we distinguish hierarchy and octant at $> 2\sigma$

Rule out half of $\delta_{CP}$ space ($2\sigma$)
Assuming tight measurement of $\theta_{13}$ from reactors

Combine with NO$\nu$A $\nu_\mu$ analysis for $\theta_{23}$ constraints

In a degenerate case hierarchy and $\delta$ information are coupled

Octant information mostly independent
Significance to resolve hierarchy/discover CPV

For favourable values of $\delta$ we can measure the hierarchy at high significance.

There also exist degenerate scenarios.
Significance to resolve hierarchy/discover CPV

For favourable values of $\delta$ we can measure the hierarchy at high significance.

There also exist degenerate scenarios.

In addition provide input on $\delta_{CP}$.
Significance to resolve hierarchy/discover CPV

> Matter effects have a much smaller impact on T2K
> Help to break hierarchy degeneracies but not CPV
> Small improvement in best-case scenarios
Octant sensitivity

Octant sensitivity less dependent on $\delta$ and hierarchy

In this case ($\sin^2 2\theta_{23} = 0.95, \theta_{23} > \pi/4$) determine octant at better than $2\sigma$ for any $\delta$ and hierarchy
Conclusion

▸ First Far Detector beam data coming soon
▸ Substantial analysis components already in place

▸ Longest baseline of any current accelerator experiment
▸ Will be first to have significant mass hierarchy sensitivity

▸ Will run in both neutrino and antineutrino modes
▸ Provide first information on CP-violation

▸ Can determine $\theta_{23}$ octant in combination with $\nu_\mu$ analysis

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Backup
Neutrino oscillations – 3 flavours

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

= \begin{bmatrix}
c_{12}c_{13} & s_{12}s_{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_{23}c_{13} \\
 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{bmatrix}

“atmospheric” × “reactor” × “solar”

Effect of \( \delta \) changes sign under CP

Need all three angles nonzero for CPV effect

\( \delta \) has no effect on survival probabilities
  - Only transition (appearance) probabilities

Is \( \delta \neq 0^\circ, 180^\circ \)?
Neutrino oscillations – matter effects

- Apparent source of CP violation (Earth is made of matter)
- CC interactions change effective mass of neutrinos
- Effect depends on hierarchy
  - Is the most-$\nu_e$ state the lightest, or one of the heaviest?

\[
\Delta m^2_M = \sqrt{(\Delta m^2 \cos 2\theta \mp 2\sqrt{2} E G_F N_e)^2 + (\Delta m^2 \sin 2\theta)^2}
\]

\[
\tan 2\theta_M = \frac{\tan 2\theta}{1 \mp \frac{2\sqrt{2} E G_F N_e}{\Delta m^2 \cos 2\theta}}
\]