Hints for CP violation from upcoming neutrino oscillation experiments

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NuFact 09
July 20-25, 2009
Illinois Institute of Technology, Chicago
What we want to learn

- Size of $\theta_{13}$
- mass hierarchy?
- $\theta_{23} = \pi/4$?
- CP violation in leptons?
# The experiments

<table>
<thead>
<tr>
<th>Setup</th>
<th>$t_\nu$ [yr]</th>
<th>$t_{\bar{\nu}}$ [yr]</th>
<th>$P_{\text{Th}}$ or $P_{\text{Target}}$</th>
<th>$L$ [km]</th>
<th>Detector</th>
<th>$m_{\text{Det}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Chooz</td>
<td>-</td>
<td>3</td>
<td>8.6 GW</td>
<td>1.05</td>
<td>L. scint.</td>
<td>8.3 t</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>-</td>
<td>3</td>
<td>17.4 GW</td>
<td>1.7</td>
<td>L. scint.</td>
<td>80 t</td>
</tr>
<tr>
<td>RENO</td>
<td>-</td>
<td>3</td>
<td>16.4 GW</td>
<td>1.4</td>
<td>L. scint.</td>
<td>15.4 t</td>
</tr>
<tr>
<td>T2K</td>
<td>5</td>
<td>-</td>
<td>0.75 MW</td>
<td>295</td>
<td>Water</td>
<td>22.5 kt</td>
</tr>
<tr>
<td>NO$\nu$A</td>
<td>3</td>
<td>3</td>
<td>0.7 MW</td>
<td>810</td>
<td>TASD</td>
<td>15 kt</td>
</tr>
</tbody>
</table>
CP violation

- inverted true hierarchy
- input values $\sin^2 2\theta_{13} = 0.1$ and $\delta = 90^\circ$
- at most a $2\sigma$ hint for CPV
- w/o reactor data no value of $\delta$ excluded at $3\sigma$
- this is already the best case
CP violation

- inverted true hierarchy
- input values $\sin^2 2\theta_{13} = 0.1$ and $\delta = -90^\circ$
- no result for mass hierarchy
- no result for CPV
From hints to the hunt for $\theta_{13}$

Timeline

- Double Chooz: Start 09/2009, 1.5 yr with FD only, then ND+FD, 5 years total Talk by S. Peeters, NOW 2008
- RENO: Start 06/2010, ND+FD, 5 years Talk by Y. Oh, NOW 2008
- Daya Bay: 7/2011 all modules, Talk by R. McKeown, CIPANP 09
- T2K: 09/2009 - 12/2012: 0 MW - 0.75 MW linear, neutrinos only Talk by H. Kakuno, NOW 2008
- NOvA: 08/2012 - 01/2014: 2.5 kt - 15 kt linear, 1/2 neutrinos & 1/2 antineutrino Talk by M. Messier, ICHEP08
$\sin^2 2\theta_{13}$ discovery potential (NH, 90% CL)

GLoBES 2009

- Double Chooz
- T2K
- RENO
- Daya Bay
- NOνA: $\nu + \bar{\nu}$
- NOνA: $\nu$ only

CHOOZ+

Solar excluded

Year

$\sin^2 2\theta_{13}$ discovery reach

$10^{-2}$

$10^{-1}$

$10^0$
Time evolution of physics reach
Beam upgrades

- **T2K**: 2015 - 2016: 0.75 MW - 1.66 MW linear
  Talk by K. Hasegawa, NNN 2008

- **NOvA**: 03/2018-03/2019: 0.7 MW - 2.33 MW linear, Project X
  Project X: resource loaded schedule

In the following $\sin^2 2\theta_{13} = 0.1$
Single experiment – $\bar{\nu}$ fraction

![Graph showing $f_{\bar{\nu}}$ fraction over years for NO$\nu$A and T2K experiments.](image)
Two experiments – $\bar{\nu}$ fraction
Joint optimization – nominal

- beams nominal
- beams + reactors nominal

fraction of CP

year

2010 2012 2014 2016 2018

2010 2012 2014 2016 2018

P. Huber – p. 12
Joint optimization – upgraded
Optimal sensitivities
Summary

- If current hints for $\theta_{13}$ are true, we should expect exciting results in 1-2 years.
- Very difficult to get CP or mass hierarchy without upgrades, even in the best case!
- With upgrades, good chances at 90% CL ($\sin^2 2\theta_{13} > 0.01$).
- With upgrades, 20-30% chance at 3 $\sigma$ ($\sin^2 2\theta_{13} > 0.02$), no 5 $\sigma$.
- Final sensitivities governed by Daya Bay, T2K and NO\(\nu\)A.
- Coordination between beams crucial for early physics!
Atmospheric Parameters

GLoBES 2009

0.3 0.4 0.5 0.6 0.7

\sin^2 \theta_{23}

\Delta m^2_{31} [eV^2]

T2K

NO\nu A

Combined (no reactors)

Combined

GLoBES 2009

\Delta m^2_{31} [eV^2]

\sin^2 \theta_{23}

\Delta m^2_{31} [eV^2]

\sin^2 \theta_{23}

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GLoBES 2009

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GLoBES 2009

\Delta m^2_{31} [eV^2]

\sin^2 \theta_{23}

GLoBES 2009

\Delta m^2_{31} [eV^2]

\sin^2 \theta_{23}
Maximal Mixing

![Graphs showing mixing angles for T2K, NOvA, Combined (no reactors), and Combined (incl. reactors, large $\theta_{13}$) with fit values of $\sin^2 \theta_{23}$ against true values.](image-url)
Nominal Sensitivities

\[ \sin^2 2\theta_{13} \text{ discovery, } NH \]

\[ \sin^2 2\theta_{13} \text{ discovery, } IH \]

\[ \sin^2 2\theta_{13} \text{ discovery, } NH \]

\[ \sin^2 2\theta_{13} \text{ discovery, } IH \]