$\theta_{13}$ Quest at Daya Bay

Measurement of $\theta_{13}$ Mixing Parameter

Viktor Pěč

on behalf of Daya Bay Experiment Collaboration

Charles University in Prague

Nu HoRlZons III, February 8-10, 2010, Allahabad, India
Outline

1. Motivation
2. Location and Onsite Layout
3. Detection Method
4. Systematic Uncertainties
5. Backgrounds
6. Sensitivity
7. Status and Plans
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Motivation

PMNS Matrix

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

\[\theta_{23} \approx 45^\circ \]
Atmospheric \( \nu \)
Accelerator \( \nu \)

\[\theta_{13} < 10^\circ \]
Short-baseline Reactor \( \nu \)
Future accelerator \( \nu \)

\[\theta_{12} \approx 35^\circ \]
Solar \( \nu \)
Long-baseline Reactor \( \nu \)

- Measure \( \theta_{13} \) with sensitivity of \( \sin^2 2\theta_{13} < 0.01 \) at 90% C.L.
- Currently known to be \( \sin^2 2\theta_{13} < 0.19 \) at 90% C.L. from the Chooz Reactor Neutrino Experiment in France

\( \sin^2 \theta_{13} < 0.0025 \) and \( \theta_{13} < 3^\circ \)
Motivation

Importance

- Step to complete basic model of $\nu$ oscillations
- Open gate to go further
- Is it possible to measure CP violation from neutrino oscillations:
  \[ P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin(2\theta_{12}) \sin(2\theta_{23}) \cos^2(\theta_{13}) \sin(2\theta_{13}) \sin \delta \]
- Mass hierarchy: $m_2 < m_3$ or $m_2 > m_3$

Help discriminate among theoretical models of mixing matrix
Neutrino Oscillations

Expected Count Rate in Detector

\[ P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m^2_{13} L}{4E_{\nu}} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m^2_{21} L}{4E_{\nu}} \right) \]
Neutrino Oscillations
Expected Count Rate in Detector

\[ P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m^2_{13} L}{4E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m^2_{21} L}{4E_\nu} \right) \]

Integrated over $\bar{\nu}_e$ energy $E_\nu \in [1.8, 8] \text{ MeV}$
$\sin^2 2\theta_{13} = 0.1$
$\theta_{12} = 34^\circ$
$\Delta m^2_{13} = 2.5 \times 10^{-3} \text{ eV}^2$
$\Delta m^2_{21} = 7.9 \times 10^{-5} \text{ eV}^2$
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Daya Bay Nuclear Powerplant
~ 50 km from Hong Kong
On Site Layout

- 3 sites at different distances — 2x Near (2x2 detectors), 1x Far (4 detectors)

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<table>
<thead>
<tr>
<th>Reactors</th>
<th>Experimental site</th>
</tr>
</thead>
<tbody>
<tr>
<td>DyB</td>
<td>LA</td>
</tr>
<tr>
<td>DayaBay</td>
<td>363</td>
</tr>
<tr>
<td>LingAo I</td>
<td>857</td>
</tr>
<tr>
<td>LingAo II</td>
<td>1307</td>
</tr>
<tr>
<td>Overburden</td>
<td>98</td>
</tr>
</tbody>
</table>

Distance from detectors to reactor cores in meters

Reactor Thermal Output:
11.6 GW now, 17.4 GW in 2011
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Detection Method

- Inverse $\beta$-decay:
  $$\bar{\nu}_e + p \rightarrow e^+ + n$$
- Trigger on 2-fold coincidence:
  - Prompt signal from $e^+$
  - Delayed signal from $n$ capture on Gadolinium $\approx 30\mu s$
- Detector with Gd doped Liquid Scintillator (LS)

Prompt signal

![Reconstructed Positron Energy Spectrum]

Delayed signal

![Reconstructed Neutron (Delayed) Capture Energy Spectrum]
Detector

- Cylindrical 3-Zone Structure separated by acrylic vessels
  - **Target**: Inner 20t GdLS (0.1% of Gd, d=3m)
  - **γ-catcher**: Mid 20t LS (d=4m, ≈42cm thick)
  - **Oil Buffer**: Outer 40t mineral oil (d=5m, ≈49cm thick)

- 192 8-inch PMTs
- $12\% / \sqrt{E(\text{MeV})}$ energy resolution
- Reflectors on top and bottom
Signals

<table>
<thead>
<tr>
<th>Site</th>
<th>Signal/day/module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daya Bay</td>
<td>840</td>
</tr>
<tr>
<td>Ling Ao</td>
<td>760</td>
</tr>
<tr>
<td>Far Site</td>
<td>90</td>
</tr>
</tbody>
</table>

- Positron energy cuts at 1 – 8 MeV
- Neutron capture energy cut at 6 MeV
- Time cut 0.3 – 200μs
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Relative Measurements

\[
\frac{N_f}{N_n} (E) = \frac{N_{p,f}}{N_{p,n}} \left( \frac{L_n}{L_f} \right)^2 \frac{\epsilon_f}{\epsilon_n} \frac{P(E, L_f)}{P(E, L_n)}
\]

- Expected ratio of measured events for particular energy at Near and Far site
- Number of protons in target – careful measurements during filling
- Neutrino flux at distance \( L \propto 1/L^2 \)
- Detector detection efficiencies – intensive calibration program
- Survival probabilities – sign of oscillation
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Detector Systematic Uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conservative</td>
</tr>
<tr>
<td># protons</td>
<td>0.3</td>
</tr>
<tr>
<td>Detector Efficiency</td>
<td></td>
</tr>
<tr>
<td>Energy cuts</td>
<td>0.2</td>
</tr>
<tr>
<td>Time cuts</td>
<td>0.1</td>
</tr>
<tr>
<td>H/Gd ratio</td>
<td>0.1</td>
</tr>
<tr>
<td>n multiplicity</td>
<td>0.05</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.01</td>
</tr>
<tr>
<td>Live time</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Total</td>
<td>0.38%</td>
</tr>
</tbody>
</table>

### Reactor related uncertainty

<table>
<thead>
<tr>
<th>Number of cores</th>
<th>Power</th>
<th>Location</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.035%</td>
<td>0.08%</td>
<td>0.087%</td>
</tr>
<tr>
<td>6</td>
<td>0.097%</td>
<td>0.08%</td>
<td>0.126%</td>
</tr>
</tbody>
</table>
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Backgrounds

- **Accidental** coincidence of uncorrelated signals — natural radioactivity
- Correlated signals from **fast neutrons** — spallation processes of muons in surrounding rock
- $\beta$–delayed neutron decays of $^9$Li and $^8$He — products of muonic showers

### Background subtraction uncertainties

<table>
<thead>
<tr>
<th></th>
<th>DYB</th>
<th>LA</th>
<th>Far</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast n/signal</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>$^9$Li, $^8$He/signal</td>
<td>0.3%</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Accidentals/signal</td>
<td>&lt;0.2%</td>
<td>&lt;0.2%</td>
<td>&lt;0.1%</td>
</tr>
</tbody>
</table>
Muon veto system

- Multiple muon veto detectors
- Water Čerenkov
  - ADs submerged in water, provide $\geq 2.5\text{m}$ shielding against radioactivity
  - Inner/Outer regions optically separated
  - 8-inch PMTs on frames (289/near, 384/far site)
- RPC—Resistive Plate Chamber
  - 4 layers in modules
  - Layer of modules covers water pool
  - Provides independent veto system
- Combined efficiency of both systems $> 99.5\%$
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Sensitivity

- 90% C.L. after 3 years of data taking assuming baseline systematics, compared to Chooz results

- Green band is 90% C.L. limits from atmospheric neutrino experiments

- Best fit and 1σ errors from MINOS


\[ \Delta m^2 = 0.0025 \text{ eV}^2 \]
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Excavation continues, more than 3,000 m of tunnels excavated
Status

2 experimental halls excavated
Status

First AD being assembled
Schedule

- **October 2007**: Ground breaking
- **March 2009**: Surface assembly building occupancy
- **Upcoming months**: Commissioning first AD - Dry run
- **2010**: Daya Bay Near Hall ready for data
- **2011**: Far Hall ready for data
Collaboration

<table>
<thead>
<tr>
<th>Region</th>
<th>Institutions</th>
<th>Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>14</td>
<td>109</td>
</tr>
<tr>
<td>Czech</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>Russia</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Taiwan</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>USA</td>
<td>16</td>
<td>96</td>
</tr>
<tr>
<td>Sum</td>
<td>38</td>
<td>243</td>
</tr>
</tbody>
</table>
Detector Dry Run

**Purpose**
- PMT readout and system integration
- Coordination of calibration and DAQ
- PMT measurements
  - Timing
  - Gain
  - Peak-to-valley ratio
  - Relative efficiency

**Implementation**
- Assembled detector without filling (no scintillator, no mineral oil)
- Use LED sources
3σ Discovery

GLoBES models

Data Taking Time (year)

- Discovery at 3σ (DYB)
- Discovery at 3σ (DC)
- Discovery at 3σ (RENO)
- Best fit 1σ (SNO+KamLAND)
- Best fit 1σ (Fogli et al)
- Best fit value (Fogli et al, SNO)
- Best fit value (Balantekin et al)
- Upper limit (95% C.L., SNO)
- Upper limit (90% C.L., Schwetz et al)

Assumptions

- Daya Bay: standard near-far configuration, 6 reactor cores
- Double Chooz: far detector first, then near-far
- Double Chooz results are corrected based on their official 90% C.L. curve
- Experimental start dates from Huber et al (arXive: 0907.1896)

Analysis by C. Lewis, B. Littlejohn, M. McFarlane, W. Wang, K. Heeger from University of Wisconsin

Models for RENO and Double Chooz from GLoBES website

Starting dates from Huber et al (arXive: 0907.1896)
### Overburden

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<thead>
<tr>
<th></th>
<th>DYB site</th>
<th>LA site</th>
<th>Far site</th>
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<tbody>
<tr>
<td>Vertical overburden (m)</td>
<td>98</td>
<td>112</td>
<td>355</td>
</tr>
<tr>
<td>Vertical overburden (m.w.e.)</td>
<td>255</td>
<td>291</td>
<td>910</td>
</tr>
<tr>
<td>Muon Flux (Hz/m²)</td>
<td>1.16</td>
<td>0.73</td>
<td>0.041</td>
</tr>
<tr>
<td>Muon Mean Energy (GeV)</td>
<td>55</td>
<td>60</td>
<td>138</td>
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<tr>
<td>Energy cuts</td>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Position cuts</td>
<td>0.32</td>
<td>0.0</td>
</tr>
<tr>
<td>Time cuts</td>
<td>0.4</td>
<td>0.1</td>
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Viktor Pˇeˇc (Charles Uni) The Daya Bay Experiment Nu HoRlzones III
Gd Liquid Scintillator Stability

Absorption of IHEP prototype Gd-LS

1 = 10μm (QCL)
Weekly deployment of radioactive sources
- $\beta^+ - ^{68}\text{Ge}$
- neutrons – Am/Pu-C
- $\gamma - ^{60}\text{Co}, ^{137}\text{Cs}$

LED diffuser balls
- monitor optical properties of materials
- PMT gains and timing
- Electronics performance
AD Filling and Target Mass Measurement

ISO Gd-LS weighing tank

filling platform with clean room

pump stations

detector

load cell accuracy < 0.02%

load cell stands and calibration weights

Coriolis mass flowmeters < 0.1%
Table 1: Summary of the standard setups at their nominal luminosities.
MINOS $\nu_e$ appearance observation

MINOS Projected 90% Exclusion Region

- CHOOZ 90% CL
- $3.25 \times 10^{20}$ POT $\Delta m^2_{32} > 0$ (2008, 10%)
- $3.25 \times 10^{20}$ POT $\Delta m^2_{32} < 0$ (2008, 10%)
- $6.5 \times 10^{20}$ POT $\Delta m^2_{32} > 0$ (+ ~1 year, 5%)
- $9.5 \times 10^{20}$ POT $\Delta m^2_{32} > 0$ (+ ~2 years, 5%)

$|\Delta m^2_{32}| = 2.4 \times 10^{-3} \text{ eV}^2$

$\sin^2(2\theta_{23}) = 1.0$

From MINOS web page.