New Results of Electron Antineutrino Disappearance From the Daya Bay Experiment

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On behalf of the Daya Bay Collaboration

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Neutrino Mixing

\[ |\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle \]

**PMNS Mixing Matrix**

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

\[ c_{ij} \equiv \cos \theta_{ij} \quad s_{ij} \equiv \sin \theta_{ij} \]

**atmospheric**

\[ \theta_{23} \sim 45^\circ \]

**reactor**

\[ \theta_{13} \sim 9^\circ \]

**solar**

\[ \theta_{12} \sim 34^\circ \]

The gateway for determining neutrino mass hierarchy and CP phase is open.

**PMNS Mixing Matrix**

\[ m^2 \]

- **Normal**
  - \( m_1^2 \)
  - \( m_2^2 \)
  - \( m_3^2 \)

- **Inverted**
  - \( m_1^2 \)
  - \( m_2^2 \)
  - \( m_3^2 \)

**Mixing Angles**

- \( \theta_{23} \sim 45^\circ \)
- \( \theta_{13} \sim 9^\circ \)
- \( \theta_{12} \sim 34^\circ \)
Reactor Neutrinos Oscillation

$\theta_{13}$ can be revealed by a deficit of reactor antineutrinos at $\sim 2\text{km}$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{ee} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

- **Clean Signal**
- **No CP phase term**
- **Negligible matter effect**

$\Delta_{ij} \approx 1.27 \Delta m_{ij}^2 (eV^2) \frac{L(m)}{E(MeV)}$

**Relative Measurement**

$$\frac{N_f}{N_n} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \left( \frac{L_n}{L_f} \right)^2 \left( \frac{\epsilon_f}{\epsilon_n} \right) \left[ \frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)} \right]$$
Daya Bay Collaboration

Asia (21)
Beijing Normal Univ., Chendu Univ. of Sci. and Tech., CGNPG, CIAE, Chinese Univ. of Hong Kong, Dongguan Univ. of Tech., IHEP, Nanjing Univ., Nankai Univ., National Chiao Tung Univ., National Taiwan Univ., National Untied Univ., NCEPU, Shangdong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., Univ. of Hong Kong, USTC, Xi'an Jiao Tong Univ., Zhongshan Univ.

North America (17)
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Europe (2)
Charles University, Czech Republic; JINR, Dubna, Russia

40 institutions
~230 collaborators
Daya Bay Experimental Layout

6 Antineutrino Detectors (ADs) in 3 underground experimental halls (EHs).

6 cores produce 17.4 GW\textsubscript{th} power
\approx 35 \times 10^{20} \text{ neutrinos/sec}

<table>
<thead>
<tr>
<th></th>
<th>Overburden</th>
<th>$R_\mu$</th>
<th>$E_\mu$</th>
<th>D1,2</th>
<th>L1,2</th>
<th>L3,4</th>
</tr>
</thead>
<tbody>
<tr>
<td>EH1</td>
<td>250</td>
<td>1.27</td>
<td>57</td>
<td>364</td>
<td>857</td>
<td>1307</td>
</tr>
<tr>
<td>EH2</td>
<td>265</td>
<td>0.95</td>
<td>58</td>
<td>1348</td>
<td>480</td>
<td>528</td>
</tr>
<tr>
<td>EH3</td>
<td>860</td>
<td>0.056</td>
<td>137</td>
<td>1912</td>
<td>1540</td>
<td>1548</td>
</tr>
</tbody>
</table>

TABLE I. Overburden (m.w.e), muon rate $R_\mu$ (Hz/m\textsuperscript{2}), and average muon energy $E_\mu$ (GeV) of the three EHs, and the distances (m) to the reactor pairs.
Daya Bay Antineutrino Detectors (AD)

6 functionally identical 3-zone detectors

Very well defined target region

Inverse beta decay (IBD)

Prompt Positron:
- Carries antineutrino energy
- \( E_{\text{Prompt}} \approx E_\nu - 0.8 \text{ MeV} \)

Delayed Neutron Capture
- \( \langle \sum E_\gamma \rangle = 8.05 \text{ MeV} \)
- Efficiently tag antineutrino signal
Automatic Calibration Units (ACU)

- 3 sources for each 3 z axis on a turntable
  - $^{68}\text{Ge}$ (2 x 0.511 MeV γ’s)
  - $^{241}\text{Am-}^{13}\text{C}$ neutron source (3.5 MeV n) + $^{60}\text{Co}$ gamma source (1.173+1.332 MeV γ’s)
  - LED diffuser ball for timing and gain

- Temporary special calibration sources:
  - γ: $^{137}\text{Cs}$ (0.662MeV), $^{54}\text{Mn}$ (0.835MeV), $^{40}\text{K}$ (1.461MeV)
  - n: $^{241}\text{Am}^{9}\text{Be}$, $^{239}\text{Pu}^{13}\text{C}$

\[
\frac{\sigma}{E} = \sqrt{(1.48\%)^2 + \frac{8.7\%^2}{E} + \frac{2.71\%^2}{E^2}}
\]

(E in the unit of MeV)
Analysis Data Sets

A. Two-detector data taking:
- Sep 23, 2011 – Dec. 23, 2011 [90 days]
- Side-by-side comparison of 2 detectors
- *NIM A 685, 78-97 (2012)*

B. Six-detector data taking:
[This analysis]
- Full 6AD data set, 4 times more statistics than PRL result
- Previous $\theta_{13}$ measurements:
  - *PRL. 108, 171803 (2012)* [55 days]
  - *CPC 37, 011001 (2013)* [139 days]

C. Eight-detector data taking:
- Start from Oct.28, 2012
Antineutrino (IBD) Selection

**Use IBD Prompt + Delayed correlated signal to select antineutrinos**

**Selection:**
- Reject PMT Flashers
- Prompt Positron: \(0.7 \text{ MeV} < E_p < 12 \text{ MeV}\)
- Delayed Neutron: \(6.0 \text{ MeV} < E_d < 12 \text{ MeV}\)
- Capture time: \(1 \mu\text{s} < \Delta t < 200 \mu\text{s}\)
- Muon Veto for delay neutron:
  - Water Pool Muon (nHit>12): Reject [-2\(\mu\text{s}, 600\mu\text{s}\)]
  - AD Muon (>3000PE): Reject [-2\(\mu\text{s}, 1400\mu\text{s}\)]
  - AD Shower Muon (>\(3 \times 10^5\) PE): Reject [-2\(\mu\text{s}, 0.4s\)]
- Multiplicity:
  No additional prompt-like signal in 400\(\mu\text{s}\) before the delayed signal, and no delayed-like signal in 200\(\mu\text{s}\) after the delayed signal

Reduce ambiguity pairs

![Prompt vs Delayed Energy Diagram](image)
## Data Set Summary

<table>
<thead>
<tr>
<th></th>
<th>AD1</th>
<th>AD2</th>
<th>AD3</th>
<th>AD4</th>
<th>AD5</th>
<th>AD6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antineutrino candidates</td>
<td>101290</td>
<td>102519</td>
<td>92912</td>
<td>13964</td>
<td>13894</td>
<td>13731</td>
</tr>
<tr>
<td>DAQ live time (day)</td>
<td>191.001</td>
<td></td>
<td>189.645</td>
<td></td>
<td>189.779</td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.7957</td>
<td>0.7927</td>
<td>0.8282</td>
<td>0.9577</td>
<td>0.9568</td>
<td>0.9566</td>
</tr>
<tr>
<td>Accidentals (/day/AD)*</td>
<td>9.54±0.03</td>
<td>9.36±0.03</td>
<td>7.44±0.02</td>
<td>2.96±0.01</td>
<td>2.92±0.01</td>
<td>2.87±0.01</td>
</tr>
<tr>
<td>Fast neutron (/day/AD)*</td>
<td>0.92±0.46</td>
<td>0.62±0.31</td>
<td></td>
<td>0.04±0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^8$He/$^9$Li (/day/AD)*</td>
<td>2.40±0.86</td>
<td>1.20±0.63</td>
<td></td>
<td></td>
<td>0.22±0.06</td>
<td></td>
</tr>
<tr>
<td>Am-C corr. (/day/AD)*</td>
<td></td>
<td></td>
<td></td>
<td>0.26±0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{12}$C(α, n)$^{16}$O (/day/AD)*</td>
<td>0.08±0.04</td>
<td>0.07±0.04</td>
<td>0.05±0.03</td>
<td>0.04±0.02</td>
<td>0.04±0.02</td>
<td>0.04±0.02</td>
</tr>
<tr>
<td>Antineutrino rate* (/day/AD)</td>
<td>653.30±2.31</td>
<td>664.15±2.33</td>
<td>581.97±2.07</td>
<td>73.31±0.66</td>
<td>73.03±0.66</td>
<td>72.20±0.66</td>
</tr>
</tbody>
</table>

*rate are muon and multiplicity cut efficiency corrected.

**Over 300,000 antineutrino interactions**

Total Background/Signal ratio is ~5% at Far site, ~2% at Near site
Antineutrino Rate vs. Time

IBD rate is fully correlated with reactor flux expectations

- Predicted rate assumes no oscillation
- *Normalization is determined by fit to data*
- Absolute normalization is within a few percent of expectations
Detector Uncertainty Summary

For near/far oscillation, only uncorrelated uncertainties are used

<table>
<thead>
<tr>
<th>Detector</th>
<th>Efficiency</th>
<th>Correlated</th>
<th>Uncorrelated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Protons</td>
<td>0.47%</td>
<td></td>
<td>0.03%</td>
</tr>
<tr>
<td>Flasher cut</td>
<td>99.98%</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Delayed energy cut</td>
<td>90.9%</td>
<td>0.6%</td>
<td>0.12%</td>
</tr>
<tr>
<td>Prompt energy cut</td>
<td>99.88%</td>
<td>0.10%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Multiplicity cut</td>
<td>0.02%</td>
<td></td>
<td>&lt;0.01%</td>
</tr>
<tr>
<td>Capture time cut</td>
<td>98.6%</td>
<td>0.12%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Gd capture ratio</td>
<td>83.8%</td>
<td>0.8%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Spill-in</td>
<td>105.0%</td>
<td>1.5%</td>
<td>0.02%</td>
</tr>
<tr>
<td>Livetime</td>
<td>100.0%</td>
<td>0.002%</td>
<td>&lt;0.01%</td>
</tr>
<tr>
<td>Combined</td>
<td>78.8%</td>
<td>1.9%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

Largest systematics are smaller than far site statistics (~0.5%)

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Correlated</th>
<th>Uncorrelated</th>
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</thead>
<tbody>
<tr>
<td>Energy/fission</td>
<td>0.2%</td>
<td>Power 0.5%</td>
</tr>
<tr>
<td>$\bar{\nu}_e$/fission</td>
<td>3%</td>
<td>Fission fraction 0.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spent fuel 0.3%</td>
</tr>
<tr>
<td>Combined</td>
<td>3%</td>
<td>Combined 0.8%</td>
</tr>
</tbody>
</table>

Influence of uncorrelated reactor systematics further reduced by far vs. near measurement
Rate Only Analysis

\[ \sin^2 2\theta_{13} = 0.089 \pm 0.009 \]

\[ \chi^2 / NDF = 0.48 / 4 \]

- Rate only analysis
  - Use maximum likelihood method
  - Far vs. near relative measurement [absolute rate is not constrained]
  - Constrain \( |\Delta m^2_{ee}| \) to the MINOS \( |\Delta m^2_{\mu\mu}| = 2.41^{+0.09}_{-0.10} \times 10^{-3} (eV^2) \) \[ PRL. 110, 251801 (2013) \]
  - Consistent results obtained by different reactor flux models

*AD4 and AD6 are artificially displaced by -50m and +50m for visual clarity.

In order to further improve the measurement, we can add the spectrum information.
Spectral Oscillation

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2(1.27 \frac{\Delta m_{ee}^2}{E}) \]

Due to the short baseline, Daya Bay can observe one effective \( |\Delta m_{ee}^2| \), which is a constant shift of \( |\Delta m_{32}^2| \) for two mass hierarchies.

\[ |\Delta m_{ee}^2| \approx |\Delta m_{32}^2| \pm 5 \times 10^{-5} \text{ eV}^2 \]

+(-) for Normal (Inverted) Mass Hierarchy

We can also measure \( |\Delta m_{ee}^2| \) thanks to the “large” \( \theta_{13} \).
Detector energy response model converts particle true kinetic energy to the reconstructed energy

**Energy Response Model**

- **Particle Energy** $E_{true}$
- **Energy Deposition in Scintillator** $E_{dep}$
- **Energy Converted to “Visible” Light** $E_{vis}$
- **Reconstructed Energy** $E_{rec}$

**Energy response parameterization**

$$ f = \frac{E_{true}}{E_{true}} \left( E_{true} \right) = \frac{E_{vis}}{E_{true}} \left( E_\text{true} \right) \cdot \frac{E_{rec}}{E_{vis}} \left( E_{vis} \right) $$

**Scintillator energy response**
- Scintillator quenching effect
- Cerenkov radiation

**Readout electronics response**
- Charge collection efficiency
- PMT signal shaping
- Others
**Electron Energy Response Model**

**Energy Response Parameterization**

\[ f = \frac{E_{\text{rec}}}{E_{\text{true}}} (E_{\text{true}}) = \frac{E_{\text{vis}}}{E_{\text{true}}} (E_{\text{true}}) \times \frac{E_{\text{rec}}}{E_{\text{vis}}} (E_{\text{vis}}) \]

**Scintillator energy response**

- **Electrons**
  - 2 parameterizations to model electron scintillator response

\[ \frac{E_{\text{vis}}}{E_{\text{true}}} (E_{\text{true}}) = \frac{1 + p3 \cdot E_{\text{true}}}{1 + p1 \cdot e^{-p2 \cdot E_{\text{true}}}} \]

\[ \frac{E_{\text{vis}}}{E_{\text{true}}} (E_{\text{true}}) = f_q(E_{\text{true}}; k_B) + k_C \cdot f_C(E_{\text{true}}) \]

- \( k_B \): Birk's constant
- \( k_C \): Cherenkov contribution

**Readout electronics response**

- Empirical parameterization: exponential
Gamma and Positron Energy Response Model

Energy response parameterization

\[ f = \frac{E_{\text{rec}}}{E_{\text{true}}} (E_{\text{true}}) = \frac{E_{\text{vis}}}{E_{\text{true}}} (E_{\text{true}}) \times \frac{E_{\text{rec}}}{E_{\text{vis}}} (E_{\text{vis}}) \]

Scintillator energy response

- **Gamma and Positron Response**
  - Gamma connected electron model through MC
  - Positron assumed to interact with the scintillator in the same way as electrons:
    \[ E_{\text{vis}}^{e^+} = E_{\text{vis}}^{e^-} + 2 \cdot E_{\text{vis}}^{\gamma} (0.511 \text{ MeV}) \]

Readout electronics response

- Same response as electrons
Energy Response Model Constrain

Use calibration gamma sources and continuous $^{12}$B spectrum to constrain the energy model parameters.
Final Positron Energy Response

Multiple models are constructed with different parametrization and data constraints

**Final Positron Energy Model:**
- Conservatively combine 5 minimal correlated energy models
- All remaining models are contained in the 68% confidence interval of the resulting model
- The total positron energy response uncertainty is within 1.5%
Consistent with the MINOS result

Daya Bay (\(\bar{\nu}_e\) disappearance)

Normal \(\Delta m^2_{32} = 2.54^{+0.19}_{-0.20} \times 10^{-3} (eV^2)\)

Inverted \(\Delta m^2_{32} = -2.64^{+0.19}_{-0.20} \times 10^{-3} (eV^2)\)

MINOS (\(\nu_\mu / \bar{\nu}_\mu\) disappearance)

\(\Delta m^2_{32} = 2.37^{+0.09}_{-0.09} \times 10^{-3} (eV^2)\)

\(\Delta m^2_{32} = -2.41^{+0.11}_{-0.09} \times 10^{-3} (eV^2)\)

\[\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}\]

\(|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3} (eV^2)\)

\[\chi^2/NDF = 162.7/153\]
**IBD Prompt Spectra**

**Spectrum distortion consistent with oscillation**

- Both background and predicted no oscillation determined by best fit
- Errors are statistical only
Global $\sin^2 2\theta_{13}$ results

- Best Fit + 68% C.L.
- Normal Hierarchy
- Inverted Hierarchy

*All results assuming: $\delta_{CP} = 0$, $\theta_{23} = 45^\circ$

- Accelerator Experiments
- Reactor Experiments
  - Rate only
  - Rate+Spectral
  - n-Gd
  - n-H

<table>
<thead>
<tr>
<th>Experiment</th>
<th>[Reference]</th>
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<tbody>
<tr>
<td>Solar+KamLand</td>
<td>[1106.6028]</td>
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<tr>
<td>MINOS</td>
<td>[1108.0015]</td>
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<tr>
<td>T2K 6 Events</td>
<td>[1106.2822]</td>
</tr>
<tr>
<td>DC 101 Days</td>
<td>[1112.6353]</td>
</tr>
<tr>
<td>Daya Bay 55 Days</td>
<td>[1203.1669]</td>
</tr>
<tr>
<td>RENO 229 Days</td>
<td>[1204.0626]</td>
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<td>T2K 11 Events</td>
<td>[ICHEP2012]</td>
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<tr>
<td>DC 228 Days</td>
<td>[1207.6632]</td>
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<tr>
<td>Daya Bay 139 Days</td>
<td>[1210.6327]</td>
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<tr>
<td>DC n-H Analysis</td>
<td>[1301.2948]</td>
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<tr>
<td>RENO 416 Days</td>
<td>[NuTel2013]</td>
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<tr>
<td>T2K 11 Events</td>
<td>[1304.0841]</td>
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<td>DC RRM Analysis</td>
<td>[1305.2734]</td>
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<td>T2K 28 Events</td>
<td>[EPS2013]</td>
</tr>
<tr>
<td>Daya Bay 217 Days</td>
<td>[NuFact2013]</td>
</tr>
</tbody>
</table>
Completion of 8-AD Installation

Two more ADs are installed in EH2 and EH3 in the fall of 2012.
$\sin^2 2\theta_{13}$ and $\Delta m^2_{ee}$ Sensitivity Projection

- Current error is dominated by the statistical uncertainty
- Daya Bay $\sin^2 2\theta_{13}$ final precision $\sim 4\%$
- Daya Bay $|\Delta m^2_{ee}|$ final precision $<0.1 \times 10^{-3}$ eV$^2$, comparable to the results from $\nu_\mu$ disappearance channel

Data collected up to now

$|\Delta m^2_{\mu\mu}| = 2.41^{+0.09}_{-0.10} \times 10^{-3} (\text{eV}^2)$

PRL. 110, 251801 (2013)
Summary

We report currently the most precise measurement of

$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

We report the first measurement of

$$|\Delta m_{ee}^2| = 2.59^{+0.19}_{-0.20} \times 10^{-3} \text{(eV}^2)$$

from the electron antineutrino disappearance channel.

Neutrino physics enters the precision era.

Stay tuned for more exciting results from Daya Bay.
backup
Spectra Only Analysis

- **Spectra only analysis**
  - For each AD, total event prediction fixed to the observed data
    - $\chi^2/\text{NDF} = 161.2/148$ (Float $\sin^2 2\theta_{13}$)
    - $\chi^2/\text{NDF} = 178.5/146$ (Fix $\sin^2 2\theta_{13}$ = 0)
    - $\Delta \chi^2/\text{NDF} = 17.3/2$, corresponding to $P=1.75\times10^{-4}$.
      - Rule out $\sin^2 2\theta_{13} = 0$ at $>3\sigma$ from spectra only information

\[ \sin^2 2\theta_{13} = 0.108 \pm 0.028 \]

\[ |\Delta m^2_{ee}| = 2.55^{+0.21}_{-0.18} \times 10^{-3} \text{ (eV}^2) \]

\[ \chi^2/\text{NDF} = 161.2/148 \]

**Strong Confirmation of oscillation hypothesis**
Flux Model Comparison

- **ILL + Petr**
  - **Rate Only:**
    - $\chi^2 / \text{ndf} : 0.475584 / 4$
    - $\sin^2 2\theta_{13} : 0.0890$
  - **Rate + Shape:**
    - $\chi^2 / \text{ndf} : 162.131 / 153$
    - $\sin^2 2\theta_{13} : 0.0909$
    - $\Delta m^2_{32} : 2.48 \times 10^{-3} \text{eV}^2$

- **ILL + Mueller**
  - **Rate Only**
    - $\chi^2 / \text{ndf} : 0.479858 / 4$
    - $\sin^2 2\theta_{13} : 0.0889$
  - **Rate + shape**
    - $\chi^2 / \text{ndf} : 163.444 / 153$
    - $\sin^2 2\theta_{13} : 0.0904$
    - $\Delta m^2_{32} : 2.51 \times 10^{-3} \text{eV}^2$
Neutrino Flux Prediction

\[ S(E_\nu) = \frac{W_{th}}{\sum f_i e_i} \sum f_i S_i(E_\nu) \]

Reactor operator provide:
- Daily thermal power \(W_{th}\)
- Relative isotope fission fraction: \(f_i\)

Energy release per fission: \(e_i\)

Antineutrino spectra per fission: \(S_i(E_\nu)\)
- P. Huber, Phys. Rev. C84, 024617 (2011)

New reactor neutrino flux model gives 6-8% more neutrinos than the old calculation (Reactor Anomaly)
\( \chi^2 \) Definition

\[
\chi^2 = \sum_i \left[ N_i^{\text{pred}}(\theta_{13}, \Delta m^2_{ee}, \vec{f}, \vec{\eta}, \vec{\epsilon}, \vec{b}), -N_i^{\text{data}} + N_i^{\text{data}} \log \frac{N_i^{\text{data}}}{N_i^{\text{pred}}(\theta_{13}, \Delta m^2_{ee}, \vec{f}, \vec{\eta}, \vec{\epsilon}, \vec{b})} \right]
\]

- Binned maximum likelihood method
- Constrain with the uncertainty from reactor flux model, background and relative detection efficiency.
  - Using covariance matrix to reduce number of the nuisance parameters for the reactor flux model.

Far vs. near relative measurement [No constraint on the absolute rate]
Daya Bay Future

Improved precision on oscillation parameters
- Constrains non-standard oscillation models
- Improves reach of future neutrino experiments

Measure absolute reactor neutrino flux
- Explore the ‘reactor antineutrino anomaly’
- Precise spectrum probes reactor models

Cosmogenic Backgrounds
- Measurement of cosmogenic production vs. depth

Supernova Neutrinos

Approximate Daya Bay near-site precision

PRD 83, 073006
arXiv:1303.0900
Calibration: Performance

Obtain a stable and consistent Energy Response

After calibration, achieve energy response that is stable to \( \sim 0.1\% \) in all detectors, with a total relative uncertainty of 0.35% between detectors.

Spallation \( n\text{Gd} \) capture peak vs. time
(after all calibration)

Relative energy peaks in all detectors (after calibration)

8/20/13
Spectral Measurement of Antineutrino Oscillation at Daya Bay
**Manual Calibration System (MCS)**

- MCS installed on AD1 during the summer of 2012.
- $^{239}\text{Pu}^{13}\text{C} + ^{60}\text{Co}$ composite source 4π source calibration, ~1700 locations
Delayed Energy Cut

Some $n$Gd gammas escape scintillator region, visible as tail of $n$Gd energy peak

*Use variations in energy peaks to constrain relative efficiency*

$$\text{Asym} = \frac{(E_{AD1} - E_{ADn})}{<E>}$$

- Energy peak variation: $<0.35\%$

0.35% relative energy uncertainty between detectors can cause $\sim0.12\%$ efficiency variation
H/Gd Capture Ratio

Neutron capture time in each detector constrains Gd capture ratio.

Measurement of neutron capture time from Am-C source constrains uncertainty in relative H/Gd capture efficiency to <0.1% among detectors.