Lastest Results from Daya Bay

Wei Wang / 王為 (on behalf of Daya Bay), SYSU
DISCRETE, Vienna, Nov 29, 2018

• The Daya Bay Experiment and Recent Improvements
• Latest Oscillation Results
• Reactor Antineutrino Flux Measurements
• New Physics Searches
• Summary
Years between KamLAND and DYB+RENO+DC

Sometimes, we just need to push it a bit further, or a bit more……

Reactor Neutrino Experiments: 1956 - 2001
Reactor Neutrino Experiment: 2001 - 2002

We almost found it!
Reactor $\nu_e$ Disappearance Depends on $\theta_{13}$ (~km)
This is what happens after working harder for 15 years ……

http://irfu.cea.fr/Spp/Phocea/Vie_des_labos/Ast/ast_visu.php?id_ast=3045
The Daya Bay International Collaboration

Asia (21)
IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Univ. of Tech., Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xi’an Jiaotong Univ., Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

North America (17)
BNL, LBNL, Iowa State Univ., RPI, Illinois Inst. Tech., Princeton, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin, William & Mary, Virginia Tech., Univ. of Illinois-Urbana-Champaign, Siena, Temple Univ., Yale

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

South America (1)
Catholic Univ. of Chile
Daya Bay: A Powerful Neutrino Source at an Ideal Location

Mountains shield detectors from cosmic ray background

Daya Bay NPP
2 × 2.9 GW_{th}

Ling Ao I NPP
2 × 2.9 GW_{th}

Ling Ao II NPP
2 × 2.9 GW_{th}

Among the top 5 most powerful reactor complexes in the world, 6 cores produce 17.4 GW_{th} power, $35 \times 10^{20}$ neutrinos per second
4 x 20 tons target mass at far site

Far site (Hall 3)
1615 m from Ling Ao
1985 m from Daya
Overburden: 350 m

Ling Ao Near site (Hall 2)
481 m from Ling Ao
526 m from Ling Ao II
Overburden: 112 m

Daya Bay Near site (Hall 1)
363 m from Daya Bay
Overburden: 98 m

Total Tunnel length
~ 3000 m
Daya Bay Detectors

- The antineutrino detectors (ADs) are of a “3-zone” design
- Doped (Gd) LS as the target for inversed beta decays (IBDs)

Energy Resolution: \(\sigma_E/E \approx 8.5\%/\sqrt{E}\,[\text{MeV}]\)
Daya Bay Detector System

- ~100m-350m overburdens for 3 sites
- RPC + Water Cherenkov = inner (IWS) in water & outer (OWS) Water Cherenkov
  → 2.5 m thick water in each direction
From Assembly to Installation
A Small Big Science Project: Far Site
Daily IBD Event Rates per Detector per Day

- Since Christmas Eve of 2011, 1958 days of data made official

- 1230 days of data have been used for reactor antineutrino flux
The Latest Daya Bay Reactor Neutrino Data Set

• Summary of the 1958 days data sample:

<table>
<thead>
<tr>
<th></th>
<th>EH1</th>
<th></th>
<th>EH2</th>
<th></th>
<th>EH3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AD1</td>
<td>AD2</td>
<td>AD3</td>
<td>AD8</td>
<td>AD4</td>
<td>AD5</td>
</tr>
<tr>
<td>$\bar{\nu}_e$ candidates</td>
<td>830036</td>
<td>964381</td>
<td>889171</td>
<td>784736</td>
<td>127107</td>
<td>127726</td>
</tr>
<tr>
<td>DAQ live time (days)</td>
<td>1536.621</td>
<td>1737.616</td>
<td>1741.235</td>
<td>1554.044</td>
<td>1739.611</td>
<td>1739.611</td>
</tr>
<tr>
<td>$\varepsilon_\mu$</td>
<td>0.8261</td>
<td>0.8221</td>
<td>0.8576</td>
<td>0.8568</td>
<td>0.9831</td>
<td>0.9831</td>
</tr>
<tr>
<td>$\varepsilon_m$</td>
<td>0.9744</td>
<td>0.9748</td>
<td>0.9758</td>
<td>0.9757</td>
<td>0.9761</td>
<td>0.9760</td>
</tr>
<tr>
<td>Accidentals (day$^{-1}$)</td>
<td>8.27 ± 0.08</td>
<td>8.12 ± 0.08</td>
<td>6.00 ± 0.06</td>
<td>5.86 ± 0.06</td>
<td>1.06 ± 0.01</td>
<td>1.00 ± 0.01</td>
</tr>
<tr>
<td>Fast neutron (AD$^{-1}$ day$^{-1}$)</td>
<td>0.79 ± 0.10</td>
<td>0.57 ± 0.07</td>
<td>0.05 ± 0.01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^9$Li/$^8$He (AD$^{-1}$ day$^{-1}$)</td>
<td>2.38 ± 0.66</td>
<td>1.59 ± 0.49</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Am-C correlated 6-AD (day$^{-1}$)</td>
<td>0.29 ± 0.13</td>
<td>0.27 ± 0.12</td>
<td>0.30 ± 0.14</td>
<td>0.24 ± 0.11</td>
<td>0.23 ± 0.10</td>
<td>0.23 ± 0.10</td>
</tr>
<tr>
<td>Am-C correlated 8-AD (day$^{-1}$)</td>
<td>0.15 ± 0.07</td>
<td>0.14 ± 0.06</td>
<td>0.12 ± 0.05</td>
<td>0.13 ± 0.06</td>
<td>0.04 ± 0.02</td>
<td>0.03 ± 0.02</td>
</tr>
<tr>
<td>$^{13}$C($\alpha$,n)$^{16}$O (day$^{-1}$)</td>
<td>0.08 ± 0.04</td>
<td>0.06 ± 0.03</td>
<td>0.04 ± 0.02</td>
<td>0.06 ± 0.03</td>
<td>0.04 ± 0.02</td>
<td>0.04 ± 0.02</td>
</tr>
<tr>
<td>$\bar{\nu}_e$ rate (day$^{-1}$)</td>
<td>659.36 ± 1.00</td>
<td>681.09 ± 0.98</td>
<td>601.83 ± 0.82</td>
<td>595.82 ± 0.85</td>
<td>74.75 ± 0.23</td>
<td>75.19 ± 0.23</td>
</tr>
</tbody>
</table>

TABLE I. Summary of signal and backgrounds. Rates are corrected for the muon veto and multiplicity selection efficiencies $\varepsilon_\mu \cdot \varepsilon_m$. The measured ratio of IBD rates in AD1 and AD2 in the 6+8 AD period (AD3 and AD8 in the 8+7 AD period) is $0.981±0.002$ ($1.014±0.002$) while the expected ratio is $0.982$ ($1.013$).

• Largest Reactor Neutrino Data Ever:
  - More than 3.9 million IBDs (0.5 million at far site)
  - Statistical error in $\bar{\nu}_e$ rates: ~0.11% (near ADs), ~0.29% (far ADs)
  - Background uncertainty in $\bar{\nu}_e$ rates: ~0.12% (all ADs)
Nonlinearity in Energy Scale

- Scintillator’s energy scale suffers from nonlinearity --- **Common**
- Additional electronics nonlinearity for Daya Bay

- Nonlinearity is primarily due to imperfect charge integration
- Loss of late hits (150 ns timing component in LS) also contributes
- More calibration
A Landmark Achievement for LS Detectors

- **0.5% uncertainty achieved!**

Two 10-bit FADC systems are installed side-by-side for AD1&2 (Jan 2016)

Calibration source effects studied *in-situ* (Jan 2017)
Improved $^9$Li/$^8$He and Spent Fuel Backgrounds

- Cosmogenic $^9$Li/$^8$He $\beta$-n decays are indistinguishable from IBD events
- Taking advantage of very large statistics:

Apply a large $E_{\text{prompt}}$ cut to enhance the $^9$Li/$^8$He fraction:

$^9$Li/$^8$He uncertainty in near ADs reduced from 50% to 30%

A more careful accounting of the spent nuclear fuel history reduced its uncertainty from 100% to 30% (SNF=0.3% of total rate)

The calculated antineutrino spectra from SNF after a typical 1 GW reactor
Relative Detection Efficiency

- The relative detection efficiency uncertainty and the relative energy scale uncertainty are the dominant systematics for $\theta_{13}$ and $|\Delta m^2_{ee}|$:

- Achieve a relative detection efficiency uncertainty of 0.13%.
- Relative energy scale uncertainty < 0.2%.
- Relative Gd capture fraction uncertainty < 0.10%.

Achieve a relative detection efficiency uncertainty of 0.13%.
Oscillation Results of 1958 Days

Rate-only
$\chi^2/\text{ndf}=8.8/6$ (p-value=0.19)  

Rate + Shape
$\chi^2/\text{ndf}=148.0/154$

Old news: data fits in the 3-neutrino oscillation paradigm nicely
Oscillation Results of 1958 Days

- Measure $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ to 3.4% and 2.8% respectively

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.267 \Delta m^2_{ee} L}{E}$$

- The statistical uncertainty contributes about 60% (50%) of the total $\theta_{13}$ ($\Delta m^2_{ee}$) uncertainty.

$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3} \text{ eV}^2$$
• Dominated systematic is the neutron detection efficiency
• New neutron calibration data
  – $^{241}\text{Am-}^{13}\text{C}$ and $^{241}\text{Am-}^{9}\text{Be}$ sources
  – Deployed along 3 axes

<table>
<thead>
<tr>
<th>Source</th>
<th>Previous value rel. err.</th>
<th>This work value rel. err.</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistic</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>oscillation</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>target proton</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>reactor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>power</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>energy/fission</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IBD cross section</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>fission fraction</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>spent fuel</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>non-equilibrium</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\varepsilon_{\text{IBD}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_n$</td>
<td>81.83% 1.69%</td>
<td>81.48% 0.74%</td>
</tr>
<tr>
<td>$\varepsilon_{\text{other}}$</td>
<td>98.49% 0.16%</td>
<td>98.49% 0.16%</td>
</tr>
<tr>
<td>total</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- Was: $\varepsilon_n = (81.83 \pm 1.38)\%$
- Now: $\varepsilon_n = (81.48 \pm 0.60)\%$
Flux Measurement (RAA) Updates

- Reactor antineutrino yield: $f = (5.91 \pm 0.09) \times 10^{-43}$ cm$^2$/fission

<table>
<thead>
<tr>
<th>Distance [m]</th>
<th>Data/prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Previous data</td>
</tr>
<tr>
<td>100</td>
<td>Daya Bay</td>
</tr>
<tr>
<td>1000</td>
<td>World average</td>
</tr>
<tr>
<td></td>
<td>1-σ Exp. Unc.</td>
</tr>
<tr>
<td></td>
<td>1-σ Flux Unc.</td>
</tr>
</tbody>
</table>

ILL+Vogel
$R = 1.001 \pm 0.015 \pm 0.0026$
(exp) (model)

Huber+Mueller
$R = 0.952 \pm 0.014 \pm 0.023$
(exp) (model)
Search for Time-Varying Antineutrino Signal

*Phys. Rev. D98 (2018) no.9, 092013*

- We performed a search for a time-varying $\bar{\nu}_e$ signal over 704 calendar days
  - Motivated by models with ultralight dark matter coupling to neutrinos, as well as Lorentz and CPT violation.

- Search for any periodicity with a Lomb-Scargle (LS) periodogram:

Highest LS powers in each hall

<table>
<thead>
<tr>
<th>Hall</th>
<th>Frequency [hr$^{-1}$]</th>
<th>Period [hr]</th>
<th>Confidence Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>EH1</td>
<td>0.15</td>
<td>6.6</td>
<td>69.8%</td>
</tr>
<tr>
<td>EH2</td>
<td>0.10</td>
<td>10.4</td>
<td>5.1%</td>
</tr>
<tr>
<td>EH3</td>
<td>0.11</td>
<td>8.9</td>
<td>33.9%</td>
</tr>
</tbody>
</table>

No signal was found

- Also search for a sidereal modulation in the context of the Standard Model Extension (SME):
  - The multiple directions and high-statistics can disentangle the complex relationship between sidereal amplitudes and individual SME coefficients
Other Recent Results

- Two cosmic-ray results from Daya Bay were released recently:

  **Seasonal Variation of the Underground Cosmic Muon Flux**

  Observe a clear correlation between atmospheric temperature and variations in muon flux

  *JCAP 1801 no1 (2018)*

  ![Graph showing correlation coefficient vs. muon energy](image)

  **Cosmogenic neutron production at Daya Bay**

  Measurement of neutron yield in LS. Important input for underground experiments.

  *Phys. Rev. D97, 052009 (2018)*

  ![Graph showing neutron yield vs. average muon energy](image)
Outlook & News

- Daya Bay will run until 2020: achieve < 3% precision in $\sin^22\theta_{13}$

- After the special calibration campaign in early 2017, EH1-AD1 was taken down permanently and its Gd-LS replaced with JUNO LS
  - Loss of this detector will only impact $\sin^22\theta_{13}$ precision by < 0.05%
  - Carrying out measurements on LS R&D in conjunction with subset of JUNO collaboration
    - Evaluating performance of purification methods and of different LS recipes, among others

- Also working on improving our other results:
  - A single-channel non-linearity correction derived from the FADC data will improve our absolute reactor antineutrino shape measurement
  - New sterile neutrino, nH and fuel evolution results are already well advanced
Summary

• With the increased statistics (1958 days) and improved systematics, Daya Bay delivers the most precise $\theta_{13}$ measurement and the 2$^{nd}$ best $\Delta m^2_{atm}$
  – The value of theta13 has enabled the possibility of resolving neutrino mass hierarchy in medium-baseline reactor neutrino experiments

• “RAA” and the “bump” stay (1230 days)

➢ Daya Bay will keep taking data till 2020, while improving statistics and updating all analyses; Helping other experiments like JUNO; Joint analysis with VSBL experiment…
Global Measurements of $\theta_{13}$ and $\Delta m^2_{\text{atm}}$

- The most precise $\sin^22\theta_{13}$
- Once most precise now the 2nd place $\Delta m^2_{\text{atm}}$

Painting a better and better global picture
Take home message: \( \sim 6 \nu's \) / fission
e-Flavor and $\mu$-Flavor Feels MH Effect Differently

\[
P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}
\]
\[
= 1 - 2s_{13}^2 c_{13} - 4c_{13}^4 s_{12}^2 c_{12}^2 \sin^2 \Delta_{21} + 2s_{13}^2 c_{13}^2 \sqrt{1 - 4s_{12}^2 c_{12}^2 \sin^2 \Delta_{21} \cos(2\Delta_{32} \pm \phi)}
\]

\[
P_{\nu_\mu \rightarrow \nu_\mu} = 1 - P_{21}^\mu - \cos^2 \theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{32}^2 \pm \phi}{4E}
\]

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**Qian et al, PRD87(2013)3, 033005**

**Minakata and Parke et al PRD74(2006), 053008**

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**FIG. 6:** The dependence of effective mass-squared difference $\Delta m_{ee}^2$ (solid line) and $\Delta m_{\mu\mu}^2$ (dotted line) w.r.t. the value of $\delta_{CP}$ for $\bar{\nu}_e$ and $\nu_\mu$ disappearance measurements, respectively.
Known $\theta_{13}$ Enables Neutrino Mass Hierarchy at Reactors

- How to resolve neutrino mass hierarchy using reactor neutrinos
  - KamLAND (long-baseline) measures the solar sector parameters
  - Short-baseline reactor neutrino experiments designed to utilize the oscillation of atmospheric scale
  ✓ Both scales can be studied by observing the spectrum of reactor neutrino flux

\[ P_{\nu_e \rightarrow \bar{\nu}_e} = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} \]

\[ -\sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}) \]

✓ Mass hierarchy is reflected in the spectrum
✓ Signal independent of the unknown CP phase

\[ \sim \sin^2 2\theta_{13} \]

Realization&Plausibility: L. Zhan et al, PRD.78.111103; J. Learned et al PRD.78.071302
Three Cities, Five Campuses

The 5-Campus system of SYSU is attracting, training and keeping top-level talents for the Greater Bay Area (Guangdong - Hong Kong - Macao); SYSU in return enjoys resources and opportunities for developments and talent cultivation.

<table>
<thead>
<tr>
<th>Campuses</th>
<th>Schools/Departments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guangzhou Campuses</td>
<td></td>
</tr>
<tr>
<td>East Campus</td>
<td>33</td>
</tr>
<tr>
<td>North Campus</td>
<td></td>
</tr>
<tr>
<td>Shenzhen Campus</td>
<td>16</td>
</tr>
<tr>
<td>Zhuhai Campus</td>
<td>8</td>
</tr>
<tr>
<td>In total</td>
<td>57</td>
</tr>
</tbody>
</table>

广州校区 Guangzhou Campuses
文、理、医传统优势学科
Liberal arts, Sciences and Medical Sciences

北校园 Guangzhou North Campus
南校园 Guangzhou South Campus
东校园 Guangzhou East Campus

珠海 Zhuhai
深海、深空、深地
Medical Sciences and New Engineering

深圳校区 Shenzhen Campus

珠海上校区 Zhuhai Campus

香港 Kong

澳门 Macao

东校园 Guangzhou East Campus
School of Physics: Facts and Vision

Currently: ~85 Faculties

*ESI Top 1%; Top 10 in China*

Goal: ~150 Faculties

*First Class in the World*

Traditionally Established
- Theoretical Physics
- Condensed Matter
- Optics

Newly Developed
- Energy Physics
- Soft Condensed Matter

New Research Platforms
- Neutron Science Center
- Ultrafast Laser Platform
- Center for Particle Physics