Latest Results from Daya Bay

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Outline

- The Daya Bay Experiment
- New Results*
  - New oscillation measurement
  - Improved measurement of reactor antineutrino flux
  - Search for a time-varying electron antineutrino signal
- Brief review of other results
- Outlook & Summary

* = shown here for the first time. Articles in preparation
Daya Bay Basics

- Daya Bay was designed to measure the $\theta_{13}$ mixing angle:

$$P_{\bar{\nu}_e \rightarrow \nu_e} = 1 - \sin^2 2\theta_{13} \left( \cos^2 \theta_{12} \sin^2 \frac{\Delta m_{31}^2 L}{4E} + \sin^2 \theta_{12} \sin^2 \frac{\Delta m_{32}^2 L}{4E} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$

- Keys to a precise measurement:
  - High-statistics
  - Suppressing backgrounds
  - Keeping systematics under control
    - Relative near/far measurement
    - Make detectors as similar as possible (design, construction & calibration)

With > 5 years of data, controlling systematic uncertainties becomes increasingly important
Experimental Setup

- 8 identically designed detectors distributed in three underground experimental halls (EHs) beside the Daya Bay Power Plant in China

Six 2.9 GWth reactors distributed in 3 Nuclear Power Plants (NPPs)

Among the most powerful nuclear power complexes in the world!
Antineutrino Detection

- Antineutrinos are detected via the Inverse Beta Decay (IBD) reaction:
  \[ \overline{\nu}_e + p \rightarrow e^+ + n \]

- Coincidence between positron and neutron signals allows for powerful background rejection

- Energy of positron preserves information about energy of incoming \( \overline{\nu}_e \)
The antineutrino detectors (ADs) are “three-zone” cylindrical modules immersed in water pools:

- **Daya Bay Detectors**
- **Energy resolution:** $\sigma_E/E \cong 8.5%/\sqrt{E}[\text{MeV}]
- **Double purpose:** shield the ADs and veto cosmic ray muons

**Images:**
- 192 8” PMTs
- Gd-doped Liquid Scintillator (LS)
- Mineral Oil
- Data from:
  - NIM A 811, 133 (2016)
  - NIM A 773, 8 (2015)
A Selection of Pictures
We have new oscillation results with **1958 days of data**

Select unambiguous prompt-delayed pairs with right energies and time separation, not in coincidence with a muon

- $1 \, \mu s < \Delta t < 200 \, \mu s$
- $0.7 \, \text{MeV} < E_{\text{prompt}} < 12 \, \text{MeV}$
- $6 \, \text{MeV} < E_{\text{delayed}} < 12 \, \text{MeV}$

- **< 2% background** in all halls
- Roughly 60% increase in statistics with respect to previous result
- Other important improvements (see next slides)
## Improved Energy Response Model

- A model is needed to convert reconstructed positron energy to antineutrino energy.

- Energy response is non-linear mainly due to two reasons:
  - Normal quenching + Cerenkov light in liquid scintillator
  - Response of the electronics

- Carried out two key measurements:
  - End of 2015: installation of a full FADC readout system in EH1-AD1, taking data simultaneously with standard electronics.
  - Early 2017: deployment of $^{60}\text{Co}$ calibration sources with different encapsulating materials, to constrain optical shadowing effects.

### Graph

![Graph showing energy response and non-linearity](image)

- **Gamma data**
- **FADC data**
- **Best fit model**

**Note:** Both in the order of 10%!
• The model is built based on various gamma peaks and the continuous $^{12}$B spectrum
  - Validated with low energy $\beta+\gamma$ spectra from $^{212}$Bi and $^{214}$Bi
  - Halved uncertainty of absolute energy scale to $\sim0.5\%$
Improved $^{9}\text{Li}/^{8}\text{He}$ and SNF Estimations

- $\beta$-n decays of cosmogenically produced $^{9}\text{Li}/^{8}\text{He}$ are indistinguishable from $\bar{\nu}_{e}$ signal
- Now can take advantage of very large statistics:

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

  Fit the time-since-last-muon distribution

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

- Also, a review of the spent nuclear fuel history with power plant reduced its uncertainty from 100% to 30% (SNF=0.3% of total rate)
Relative Detection Efficiency

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

- Relative Gd capture fraction uncertainty < 0.10%
- Relative energy scale uncertainty < 0.2%

Achieve a relative detection efficiency uncertainty of 0.13%
Data Set

• Summary of the 1958 days data sample:

|                  | EH1 AD1  | EH1 AD2  | EH2 AD3  | EH2 AD8  | EH3 AD4  | EH3 AD5  | EH3 AD6  | EH3 AD7  |
|------------------|----------|----------|----------|----------|----------|----------|----------|----------|
| $\bar{\nu}_e$ candidates | 830036   | 964381   | 889171   | 784736   | 127107   | 127726   | 126666   | 113922   |
| DAQ live time (days) | 1536.621 | 1737.616 | 1741.235 | 1554.044 | 1739.611 | 1739.611 | 1739.611 | 1551.945 |
| $\varepsilon_\mu$     | 0.8261   | 0.8221   | 0.8576   | 0.8568   | 0.9831   | 0.9831   | 0.9829   | 0.9833   |
| $\varepsilon_m$       | 0.9744   | 0.9748   | 0.9758   | 0.9757   | 0.9761   | 0.9760   | 0.9758   | 0.9758   |
| Accidentally (day$^{-1}$) | 8.27 ± 0.08 | 8.12 ± 0.08 | 6.00 ± 0.06 | 5.86 ± 0.06 | 1.06 ± 0.01 | 1.00 ± 0.01 | 1.03 ± 0.01 | 0.86 ± 0.01 |
| Fast neutron (AD$^{-1}$ day$^{-1}$) | 0.79 ± 0.10 | 0.57 ± 0.07 | 0.05 ± 0.01 | 0.05 ± 0.01 | 0.05 ± 0.01 | 0.05 ± 0.01 | 0.05 ± 0.01 | 0.05 ± 0.01 |
| $^9$Li/$^8$He (AD$^{-1}$ day$^{-1}$) | 2.38 ± 0.66 | 1.59 ± 0.49 | 0.19 ± 0.08 | 0.19 ± 0.08 | 0.19 ± 0.08 | 0.19 ± 0.08 | 0.19 ± 0.08 | 0.19 ± 0.08 |
| Am-C correlated 6-AD (day$^{-1}$) | 0.29 ± 0.13 | 0.27 ± 0.12 | 0.30 ± 0.14 | 0.24 ± 0.11 | 0.23 ± 0.10 | 0.23 ± 0.10 | 0.23 ± 0.10 | 0.23 ± 0.10 |
| Am-C correlated 8-AD (day$^{-1}$) | 0.15 ± 0.07 | 0.14 ± 0.06 | 0.12 ± 0.05 | 0.13 ± 0.06 | 0.04 ± 0.02 | 0.03 ± 0.02 | 0.03 ± 0.02 | 0.04 ± 0.02 |
| $^{13}$C$(\alpha,n)^{16}$O (day$^{-1}$) | 0.08 ± 0.04 | 0.06 ± 0.03 | 0.04 ± 0.02 | 0.06 ± 0.03 | 0.04 ± 0.02 | 0.04 ± 0.02 | 0.04 ± 0.02 | 0.04 ± 0.02 |
| $\bar{\nu}_e$ rate (day$^{-1}$) | 659.36 ± 1.00 | 681.09 ± 0.98 | 601.83 ± 0.82 | 595.82 ± 0.85 | 74.75 ± 0.23 | 75.19 ± 0.23 | 74.56 ± 0.23 | 75.33 ± 0.24 |

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).

• Some highlights:
  - More than 3.9 million antineutrino interactions (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)
  - Relative efficiency uncertainty: 0.13% (all ADs)
Oscillation Results with 1958 Days

- See a clear rate and shape distortion that fits well to the 3-neutrino hypothesis:

\[ \chi^2/\text{ndf} = 8.8/6 \] (p-value = 0.19)

Nothing abnormal found with two far ADs whose rates deviate from best-fit
Oscillation Results with 1958 Days

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

\[
P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.267 \Delta m^2_{ee} L}{E} - \text{solar term}
\]

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

\[
|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3} \text{ eV}^2
\]

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

Results are cross-checked by a few independent analyses.
Absolute Antineutrino Flux

- Previous measurement of the absolute reactor $\bar{\nu}_e$ flux compared to the Huber+Mueller expectation:
  \[ R_{\text{data/pred}} = 0.946 \pm 0.020 \text{ (exp.)} \]
  - systematics-dominated from absolute detection efficiency

- New strategy: take new neutron calibration data and use it to constrain the “neutron detection efficiency” $\varepsilon_n$

| Source                  | $\varepsilon$ | $\delta \varepsilon / \varepsilon$ |
|-------------------------|--------------|-----------------------------------|
| Target protons          |              | 0.92%                             |
| Flasher cut             | 99.98%       | 0.01%                             |
| Capture time cut        | 98.70%       | 0.12%                             |
| Prompt energy cut       | 99.81%       | 0.10%                             |
| Gd capture fraction     | 84.17%       | 0.95%                             |
| nGd detection efficiency| 92.7%        | 0.97%                             |
| Spill-in correction     | 104.9%       | 1.00%                             |
| Combined                | 80.6%        | 1.93%                             |

Carried out an extensive calibration campaign in late 2016 / early 2017

Deployed two neutron sources ($^{241}\text{Am-}^{13}\text{C}$ and $^{241}\text{Am-}^{9}\text{Be}$) along three vertical calibration axes

ACU=Automated Calibration Unit
Absolute Antineutrino Flux

- For each calibration point define a proxy for $\varepsilon_n$:
  
  *benchmark for detector geometry, nonlinearity, neutron and gamma models*

  $$F = \frac{N([6,12] \text{ MeV})}{N([1.5,12] \text{ MeV})}$$

- Compare with 20 different simulation models (5 neutron scattering x 4 Gd capture gamma emission models)
  - Extract a correction on $\varepsilon_n$ from the measured data-MC differences in $F$ via linear regression
  - Uncertainty conservatively estimated with spread from “reasonable” models

  $$\varepsilon_n = (81.48 \pm 0.60)\%$$

  Results with 1230 days

  $$R_{\text{data/pred}} = 0.952 \pm 0.014(\exp.) \pm 0.023(\text{model})$$

  $$\sigma_f = (5.91 \pm 0.09) \times 10^{-43} \text{ cm}^2 / \text{fission}$$
Search for Time-Varying Antineutrino Signal

- 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:
  
  | Hall | Frequency | Period | Confidence Level |
  |------|-----------|--------|-----------------|
  | EH1  | 0.15 hr$^{-1}$ | 6.6 hr | 69.8% |
  | EH2  | 0.10 hr$^{-1}$ | 10.4 hr | 5.1% |
  | EH3  | 0.11 hr$^{-1}$ | 8.9 hr | 33.9% |

  No signal was found

- Also search for a sidereal modulation in the context of the Standard Model Extension (SME):
  - Thanks to its multiple directions and high-statistics, Daya Bay is able to 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 n°1 (2018)*
  - **Cosmogenic neutron production at Daya Bay**
    - Measurement of neutron yield in LS. Important input for underground experiments.
    - *Phys. Rev. D97, 052009 (2018)*
Other Results

- Finally, there are also other older results:

  - **Evolution of the Reactor Antineutrino Flux and Spectrum**
    
    Physics Rev. Lett. 182, 251801 (2017)

  - **Independent measurement of $\theta_{13}$ via neutron capture on hydrogen**
    
    Physics Rev. D93, 072011 (2016)

  - **Improved search for a sterile neutrino (with Bugey-3 + MINOS)**
    
    Physics Rev. Lett. 117, 151802 (2016)  
    Physics Rev. Lett. 117, 151801 (2016)

  - **Search for neutrino decoherence**
    
    Eur. Phys. J. C77, 606 (2017)
Outlook & News

• Daya Bay will run until 2020
  - Will 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

• Daya Bay is releasing three new results this summer:

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

\[
|\Delta m_{ee}^2| = (2.52 \pm 0.07) \times 10^{-3} \text{ eV}^2
\]

\[
\Delta m_{32}^2 = (2.47 \pm 0.07) \times 10^{-3} \text{ eV}^2 \text{ (NH)}
\]

Articles in preparation

• Also a search for a time-varying electron antineutrino signal.

• We also have many other recent results in other areas

We encourage you to look at the 9 posters from Daya Bay in this conference

• Much work is going into better understanding and improving our systematics, given the statistical precision we have achieved with a > 5 year data set

• Future looks bright ahead with ~2.5 more years of data taking, as well as many new and improved results in the works
Thank you for your attention!