Improved Oscillation Measurements from Daya Bay

Outline

• Standard 3-flavor oscillation:
  PRD 95, 072006 (2017)

• Improved search for a light sterile neutrino:
  PRL 117, 151802 (2016)

• Combination with MINOS and Bugey-3:
  PRL 117, 151801 (2016)

• Reactor flux/spectrum/evolution

Also see:
Poster 772, Dr. Ming-chung Chu
for details in standard oscillation analysis
The Daya Bay Experiment

- Daya Bay is the largest, deepest, and most precise $\theta_{13}$ experiment in town.

Optimized reactor and detector locations leads to \(~95\%\) cancellation of reactor-related uncertainties for oscillation analysis.

- Daya Bay Near site: 363 m from Daya Bay, Overburden: 98 m
- Ling Ao Near site: ~500 m from Ling Ao, Overburden: 112 m
- Mid site: 873 m from Ling Ao, 1156 m from Daya, Overburden: 208 m
- Far site: 1615 m from Ling Ao, 1985 m from Daya, Overburden: 350 m

4 x 20 tons target mass at far site

Daya Bay: Powerful reactor by mountains
Reactor Neutrino Detection

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

• Coincidence signal from Inverse Beta Decay:
  – Prompt: \( e^+ \) & annihilation \( \rightarrow \)
    \[ E_{\text{prompt}} \approx E_\nu - E_n - 0.78 \text{MeV} \]
  – Delayed: \( n + \text{Gd} \rightarrow \) 8 MeV with 30 us capture time
Comprehensive Calibration of Detector Response

- Excellent control of both relative and absolute detector response!

Also precise determination of electronics response with new FADC data
Standard 3-flavor Oscillation Results

• Consistent results from multiple independent “blind” analyses
• World’s most precise measurement of $\theta_{13}$ and $\Delta m^2_{32}$

$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027$ (stat.) $\pm 0.0019$ (syst.)

$|\Delta m^2_{ee}| = 2.50 \pm 0.06$ (stat.) $\pm 0.06$ (syst.)
Light sterile neutrino oscillation

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \cos^4 \theta_{14} \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m^2_{ee} L}{4E_\nu} \right) - \sin^2 2\theta_{14} \sin^2 \left( \frac{\Delta m^2_{41} L}{4E_\nu} \right)$$

- Search for a higher frequency oscillation pattern besides $|\Delta m^2_{ee}|$

Illustration of Sensitivity with Daya Bay's unique multiple baseline

Daya Bay: Full 6 AD data

$\Delta m^2_{41} = m^2_{4} - m^2_{1}$
Sterile Neutrino Oscillation Results

- No evidence of Sterile Neutrino in the search region
- Most stringent constraints to date in $\Delta m^2_{41} < 0.2$ eV$^2$

CL$_s$ Method*

For each ($\theta_{14}, \Delta m^2_{41}$) compare two hypotheses: 3v and 4v.

Define $\Delta \chi^2 = \chi^2_{4v} - \chi^2_{3v}$
then $CL_s = \frac{1 - p_1}{1 - p_0}$

For Gaussian CL$_s$†,

data
$\Delta \chi^2_{3v}$ — 3v Asimov data
$\Delta \chi^2_{4v}$ — 4v Asimov data

$CL_s = \frac{1 + Erf\left(\frac{\Delta \chi^2_{3v} - \Delta \chi^2_{data}}{\sqrt{8|\Delta \chi^2_{4v}|}}\right)}{1 + Erf\left(\frac{\Delta \chi^2_{4v} - \Delta \chi^2_{3v}}{\sqrt{8|\Delta \chi^2_{4v}|}}\right)}$

* A. L. Read J. Phys. G28, 2693
† T. Junk NIMA 434, 435
‡ X. Qian et al. NIMA 827, 63 (2016)

- Feldman-Cousins method was used to derive confidence interval
- CLs method was used to combine results with Bugey-3 and MINOS (see Leigh Whitehead’s talk)
Combined Oscillation Results with (Gaussian) CLs

Daya Bay + Bugey-3

Daya Bay + Bugey-3 + MINOS
Daya Bay’s result is consistent with previous world measurement

- World average including Daya Bay is $0.9430 \pm 0.008$ (exp.)$\pm 0.023$ (model)
  - About **1.5% higher** than the previously claimed reactor antineutrino anomaly world fits which include a **tricky statistical mistake**

\[
\chi^2 (R_{g \text{ past}}) = (R_{g \text{ past}} - R_i) \cdot V_{ij}^{-1} (R_{g \text{ past}} - R_j)
\]

\[
V = V^{\text{exp}} + V^{\text{theory}}
\]

\[
V^{\text{theory}} = R_i^{\text{obs}} \cdot R_j^{\text{obs}} \cdot (\sigma^{\text{theory}})^2
\]

should be

\[
V^{\text{theory}} = R_i^{\text{theory}} \cdot R_j^{\text{theory}} \cdot (\sigma^{\text{theory}})^2
\]

See G. D’Agostini NIMA 346, 306 (1994),
V. Blobel, SLAC-R-0703, p101,
B. Roe arXiv:1506.09077
• Incompatible with Huber+Mueller model at $3\sigma$ ($4.4\sigma$) at the full (4-6 MeV) energy range $\rightarrow$ uncertainty of reactor flux model is underestimated

• Weaken the foundation of reactor antineutrino anomaly (RAA), but enlarged the allowed parameter space for a light sterile neutrino
Reactor Flux Evolution

• See Dr. Patrick Tsang’s talk for details

\[ \sigma_f \left[10^{-48} \text{ cm}^2 / \text{fission}\right] \]

\[ F_{239} \]

\[ F_{235} \]

\[ 0.63 \quad 0.60 \quad 0.57 \quad 0.54 \quad 0.51 \]

PRL 118, 251801 (2017)

• Measured evolution of reactor flux is about 2.8 \( \sigma \) incompatible with the prediction of Huber-Mueller model + sterile neutrino for RAA
Summary

• Daya Bay is leading the precise measurements of $\theta_{13}$ and $\Delta m^2_{32}$

• Null results in searching for a light sterile neutrino.
  – Combined results with Bugey-3 and MINOS narrowed the allowed phase space for a light sterile neutrino explaining LSND/MiniBooNE anomalies

• Measurements of reactor spectrum and absolute flux evolution indicate that uncertainties of model calculation are underestimated