Improved Oscillation Measurements from Daya Bay

Outline

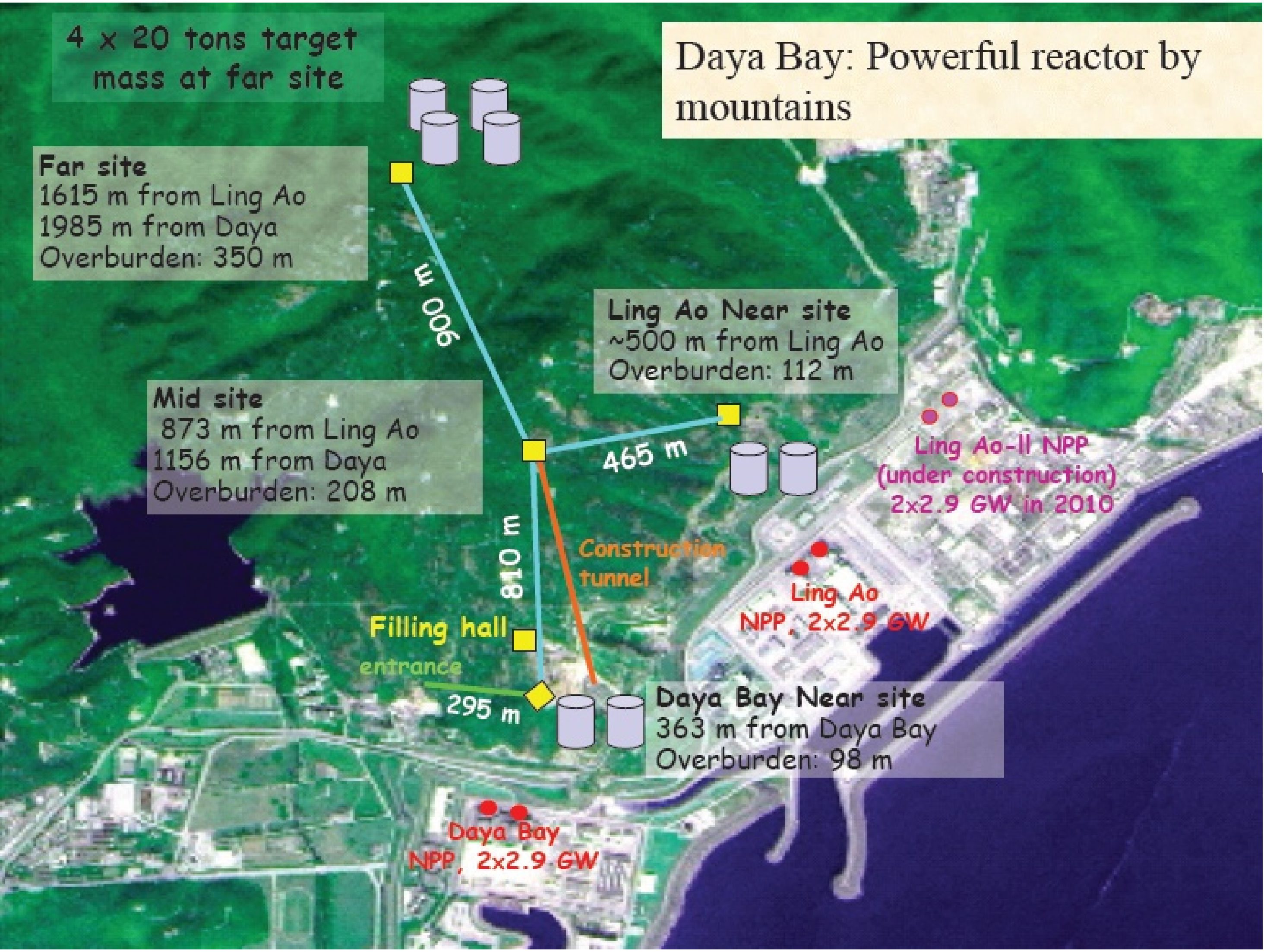
- Standard 3-flavor oscillation:
  PRD 95, 072006 (2017)
- Improved search for a light sterile neutrino:
  PRL 117, 151802 (2016)
- Combination with MINOS and Bugey-3:
  PRL 117, 151801 (2016)
- Reactor flux/spectrum/evolution

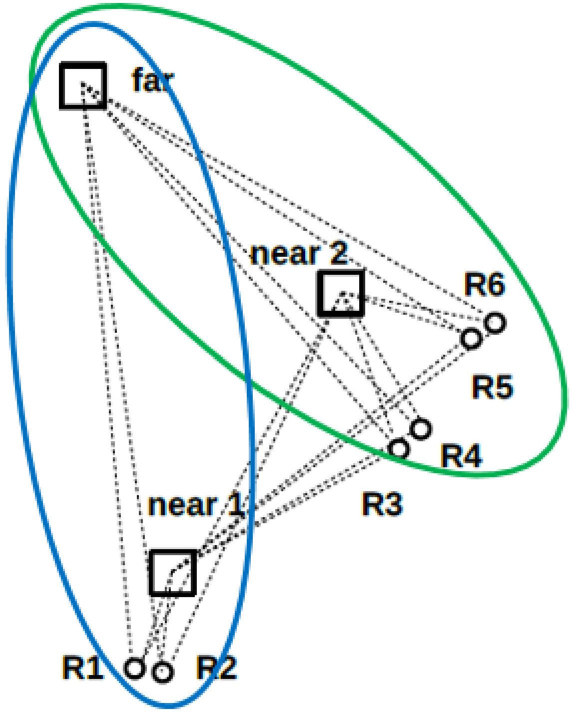
Xin Qian

BNL

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

The Daya Bay Experiment



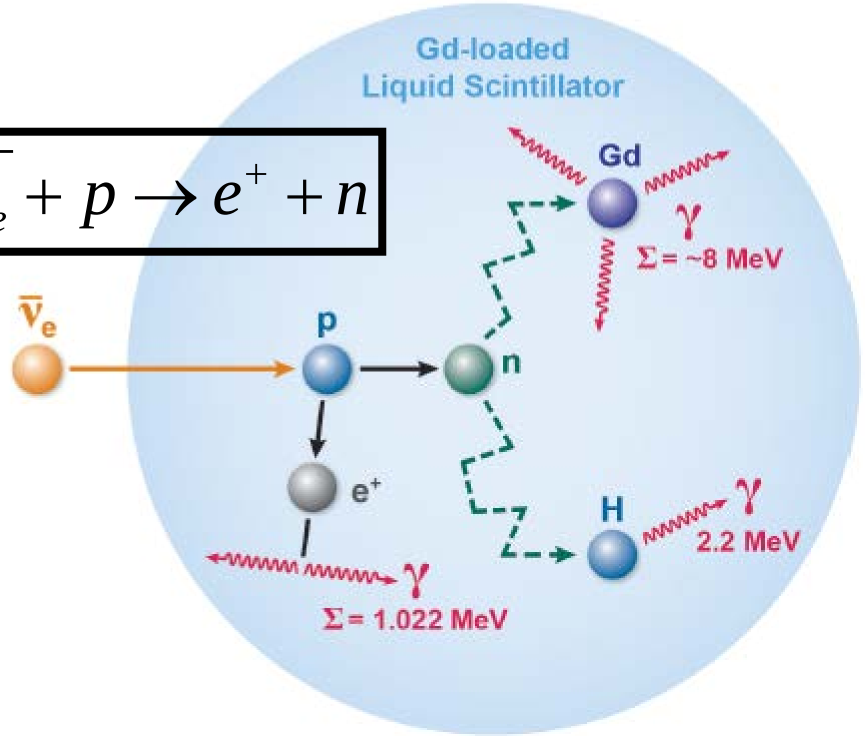


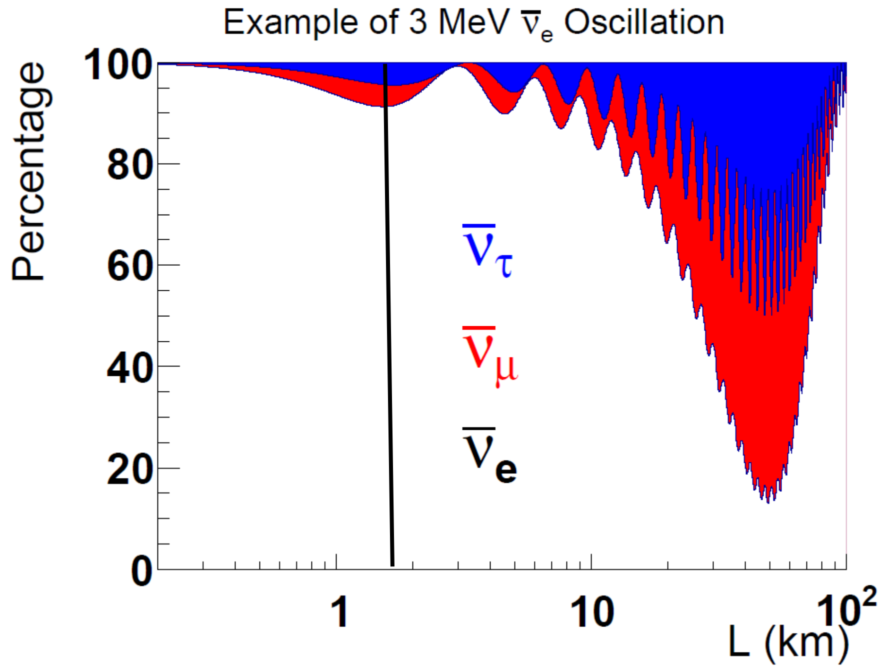
Optimized reactor and detector locations leads to **~95%** cancellation of reactor-related uncertainties for oscillation analysis

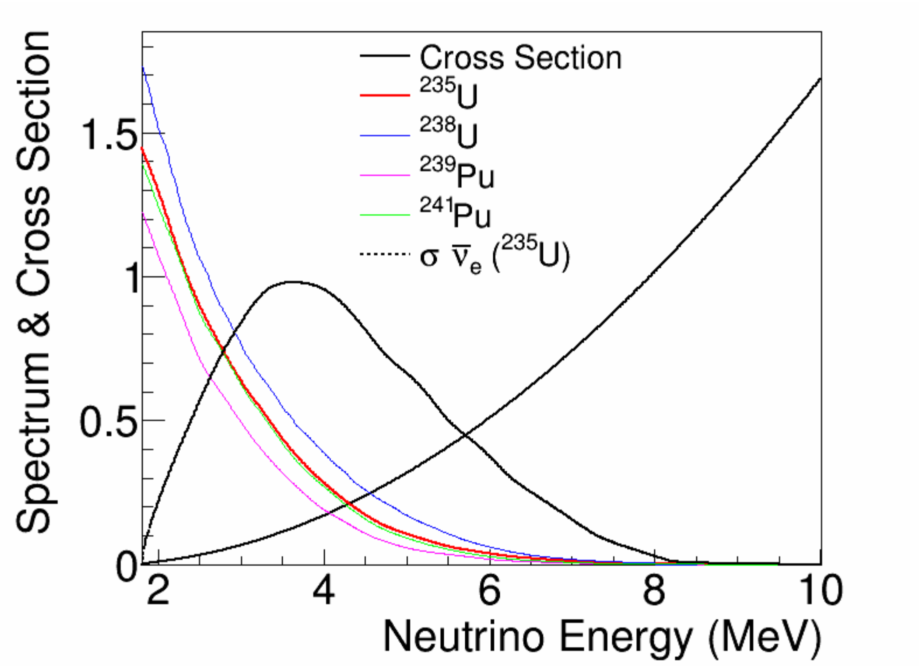
- Daya Bay is the largest, deepest, and most precise θ_{13} experiment in town

Reactor Neutrino Detection

$$\overline{\nu_e} + p \rightarrow e^+ + n$$





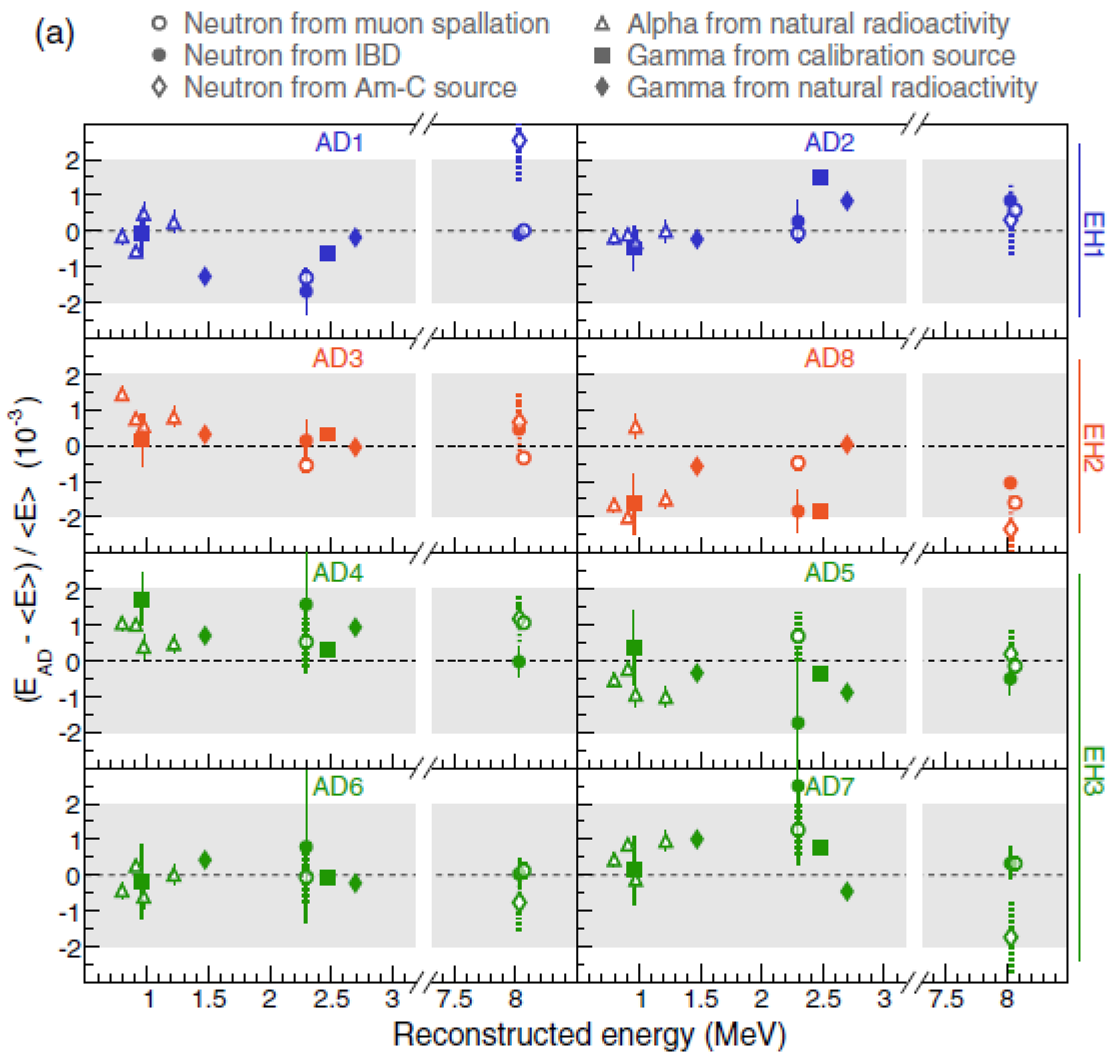


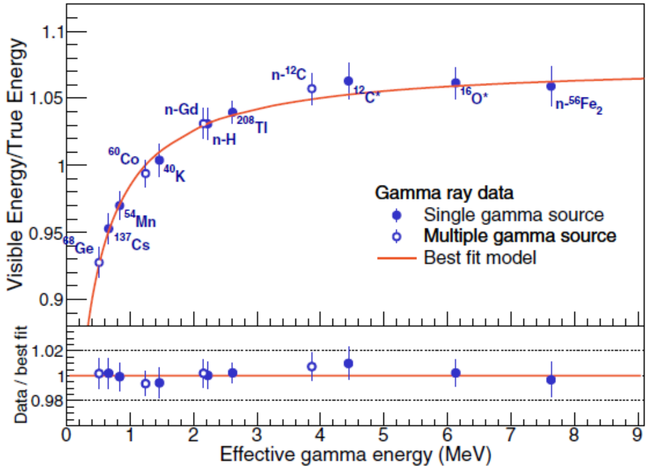
- Coincidence signal from Inverse Beta Decay:
  - Prompt: e^+ & annihilation →

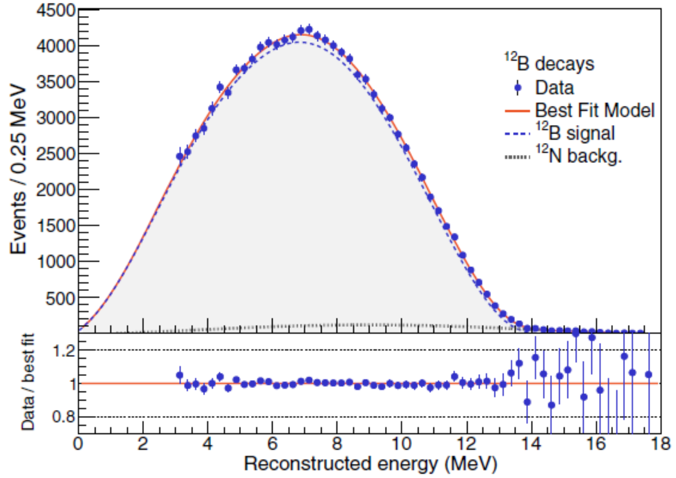
$$E_{prompt} \approx E_\nu - E_n - 0.78MeV$$

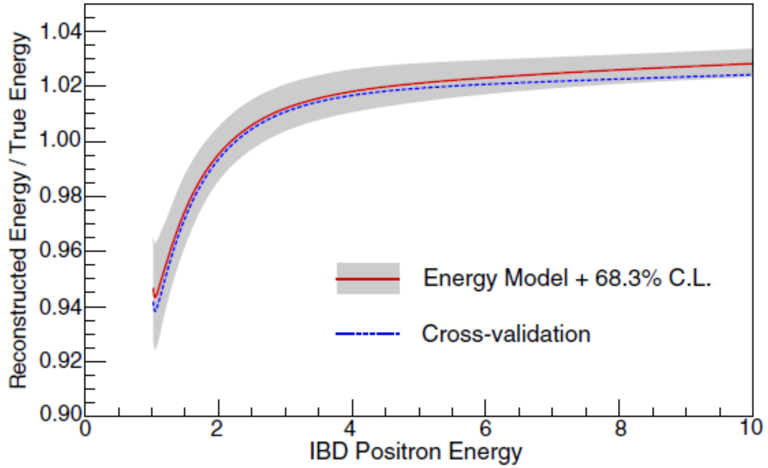
  - Delayed: n + Gd → 8 MeV with 30 us capture time

Comprehensive Calibration of Detector Response





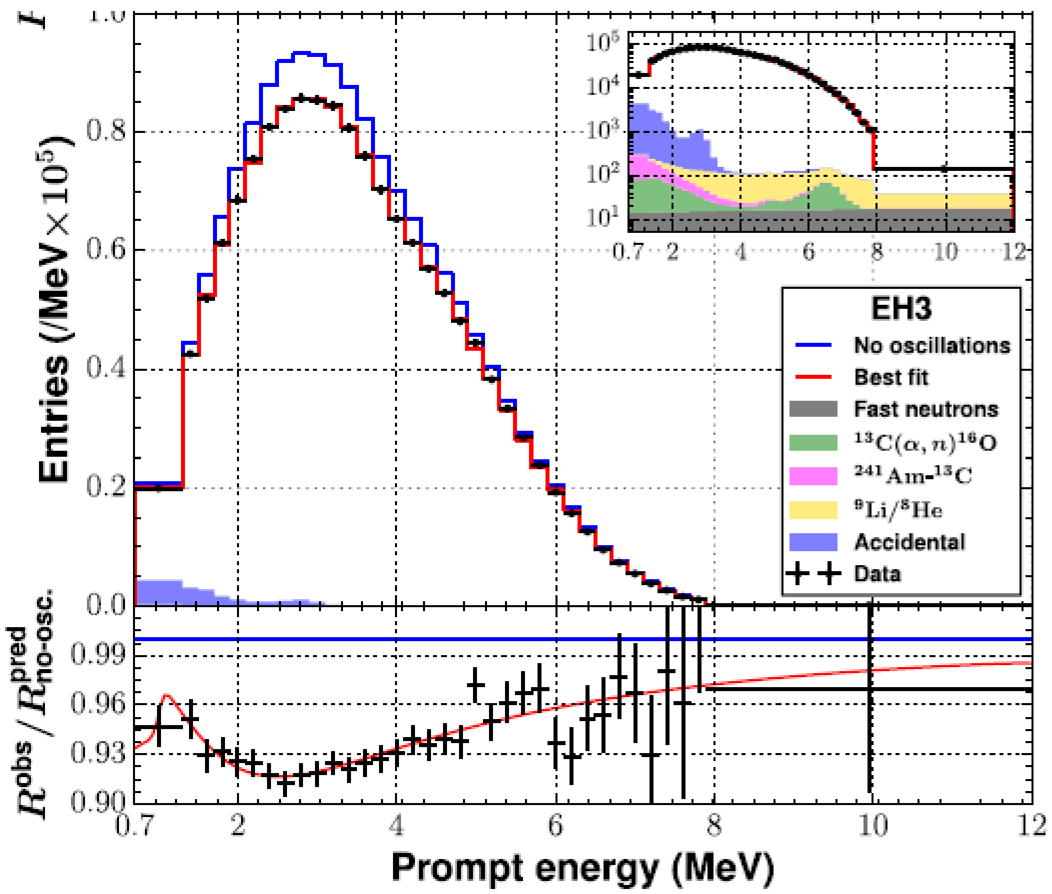


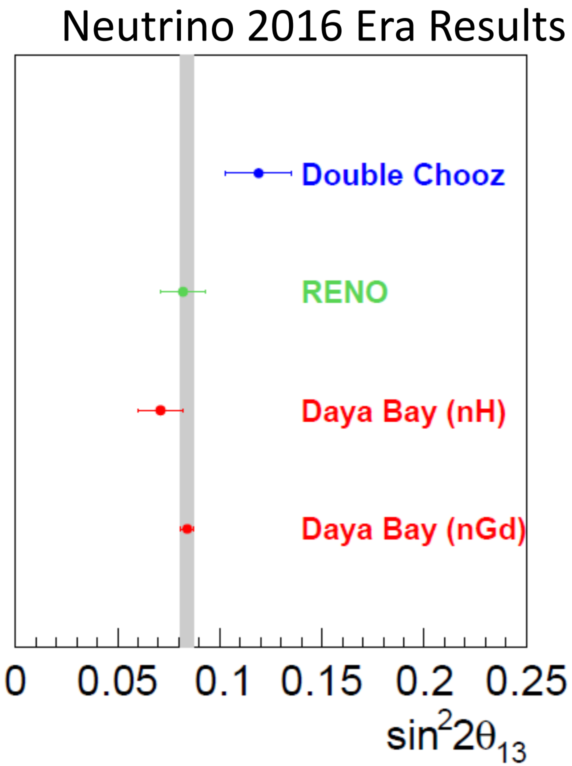


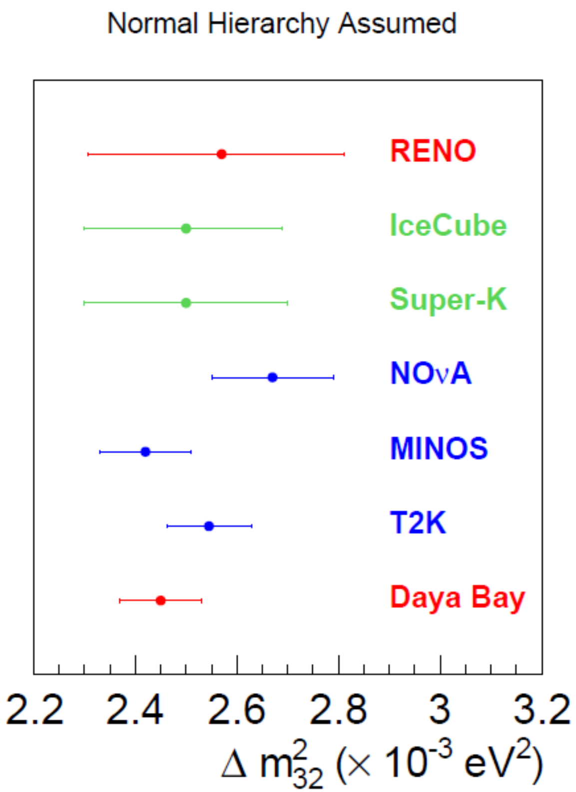
Also precise determination of electronics response with new FADC data

- Excellent control of both relative and absolute detector response!

Standard 3-flavor Oscillation Results





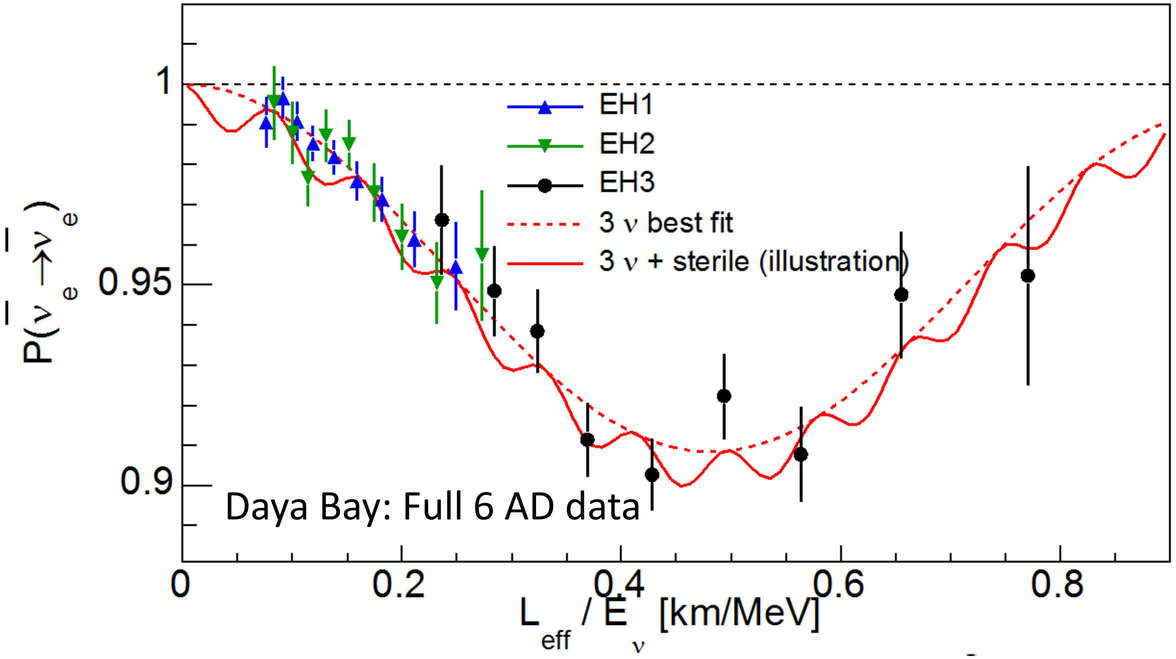


$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027\ (\text{stat.}) \pm 0.0019\ (\text{syst.})$$

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

- Consistent results from multiple independent “blind” analyses
- World’s most precise measurement of θ_{13} and Δm^2_{32}

Light sterile neutrino oscillation



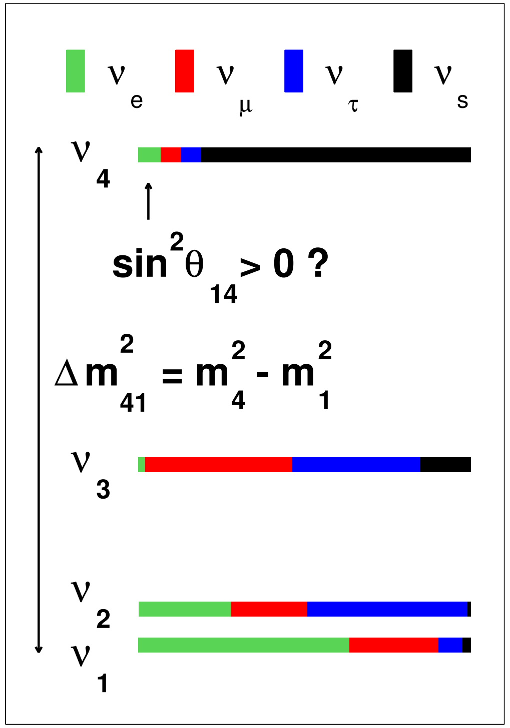
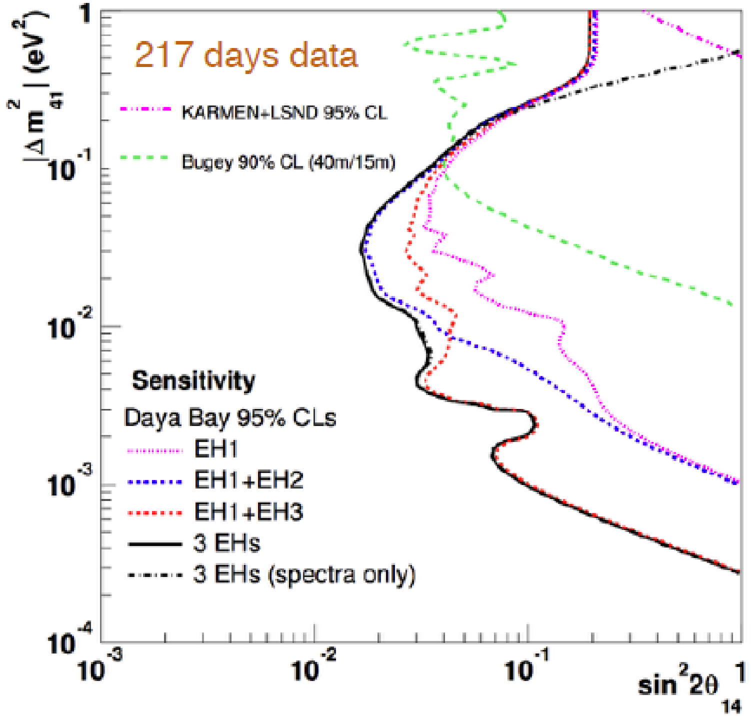


Illustration of Sensitivity with Daya Bay's unique multiple baseline

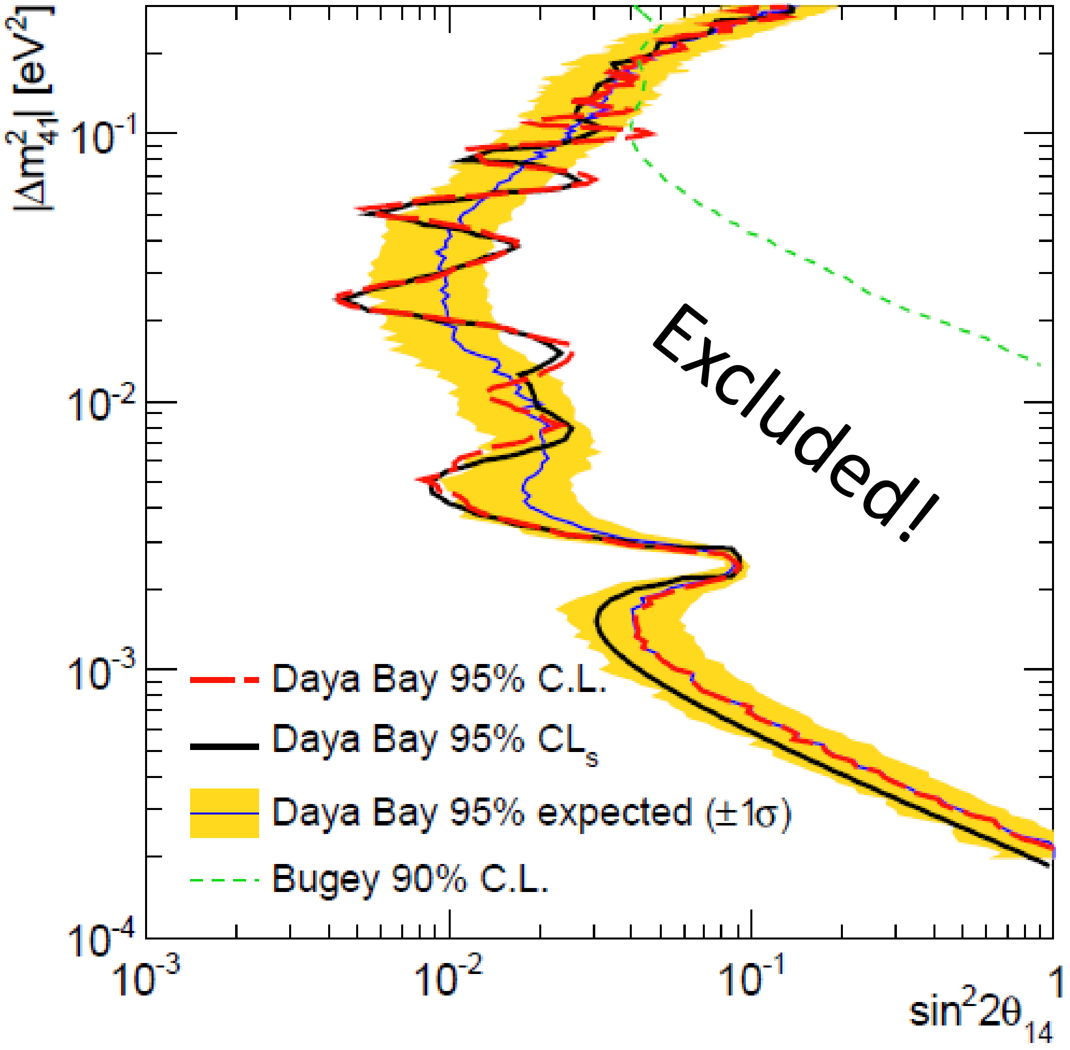


Phys.Rev. Lett.113,141802 (2014)

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

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

Sterile Neutrino Oscillation Results



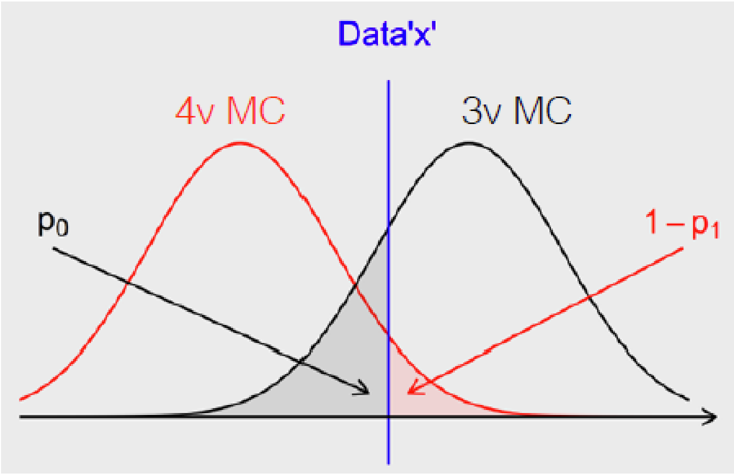
- No evidence of Sterile Neutrino in the search region
- Most stringent constraints to date in $\Delta m^2_{41} < 0.2$ eV^2

CLs Method*

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

Define $\Delta\chi^2 = \chi^2_{4\nu} - \chi^2_{3\nu}$

then $CL_s = \frac{1-p_1}{1-p_0}$



For Gaussian CLs†, calculate

$\Delta\chi^2_{data}$ – data

$\Delta\chi^2_{3\nu}$ – 3ν Asimov data

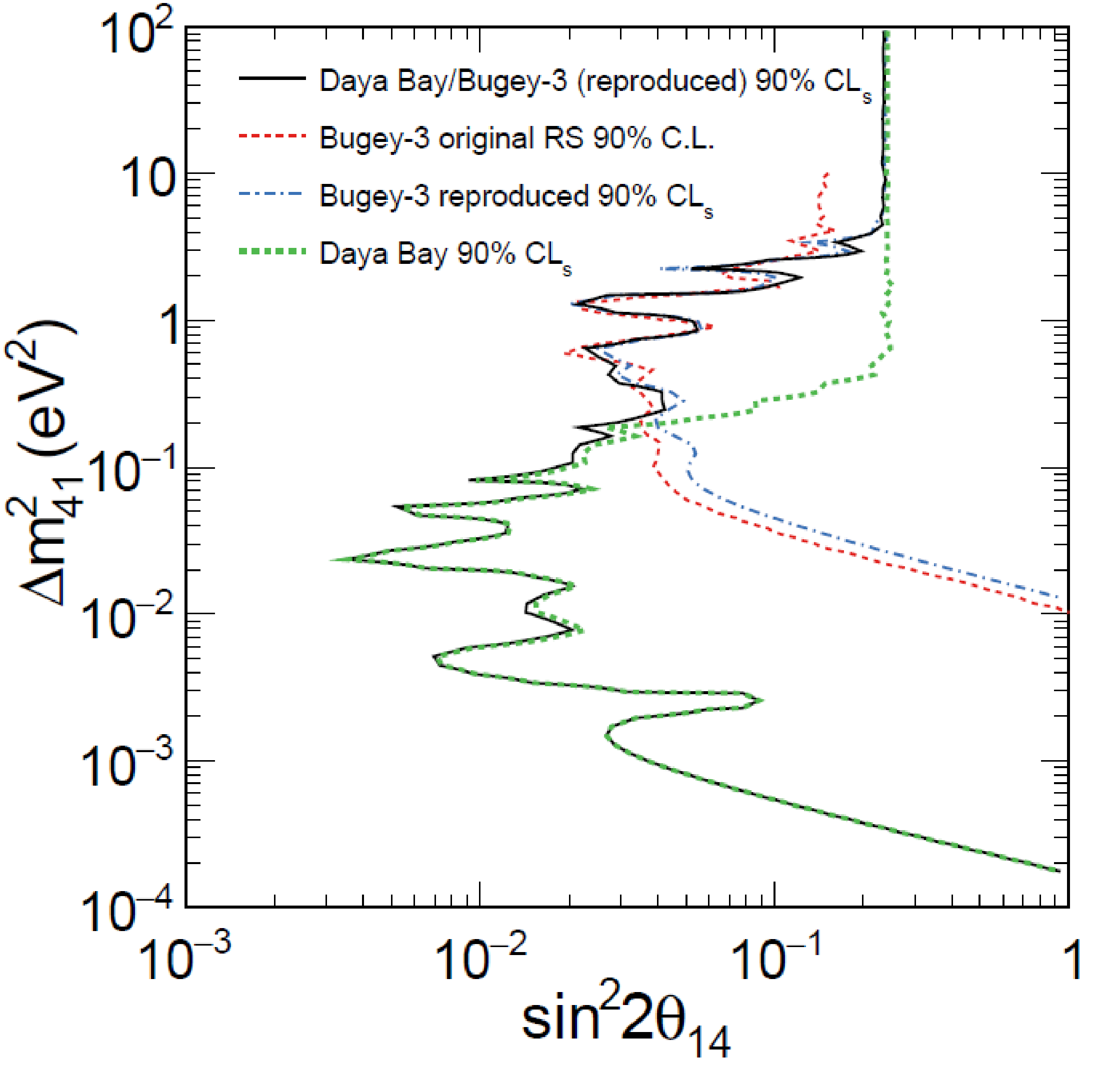
$\Delta\chi^2_{4\nu}$ – 4ν Asimov data

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

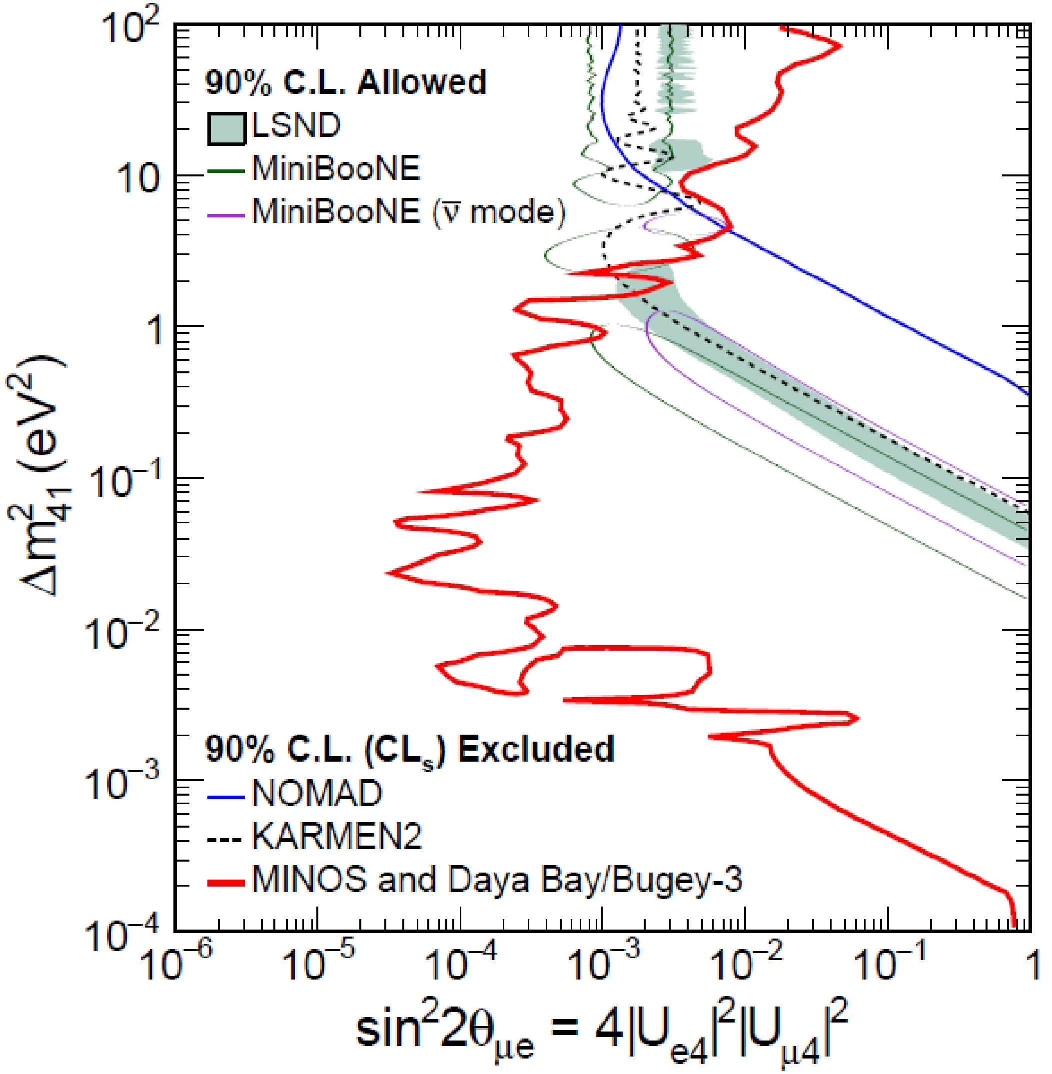
* A.L. Read J. Phys. G28, 2693
* T. Junk NIMA 434, 435
† X. Qian et al. NIMA 827, 63 (2016)

- 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

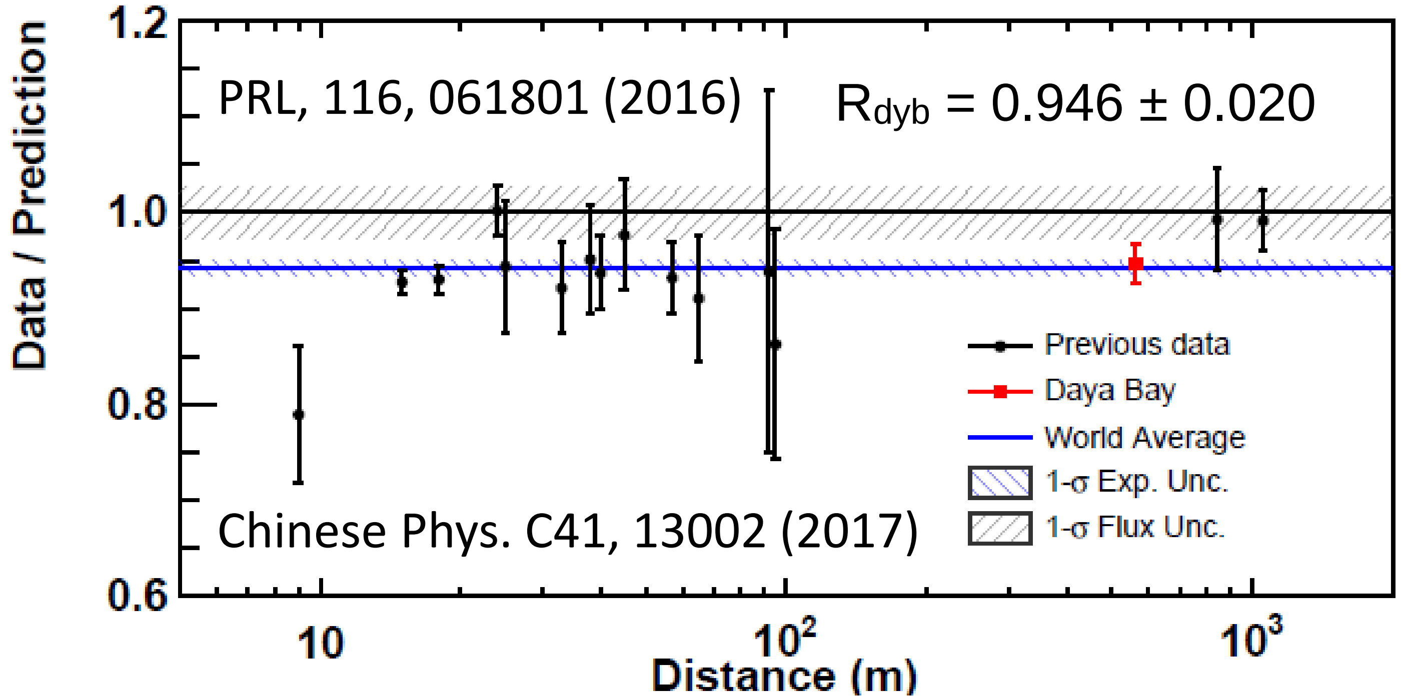


Daya Bay + Bugey-3



Daya Bay + Bugey-3 + MINOS

Absolute Flux Measurements



$$\chi^2(R_g^{past}) = (R_g^{past} - R_i)\cdot V_{ij}^{-1}\left(R_g^{past} - R_j\right)$$

$$V = V^{\exp} + V^{theory}$$

$$V^{theory} = R_i^{obs} R_j^{obs} (\sigma^{theory})^2$$

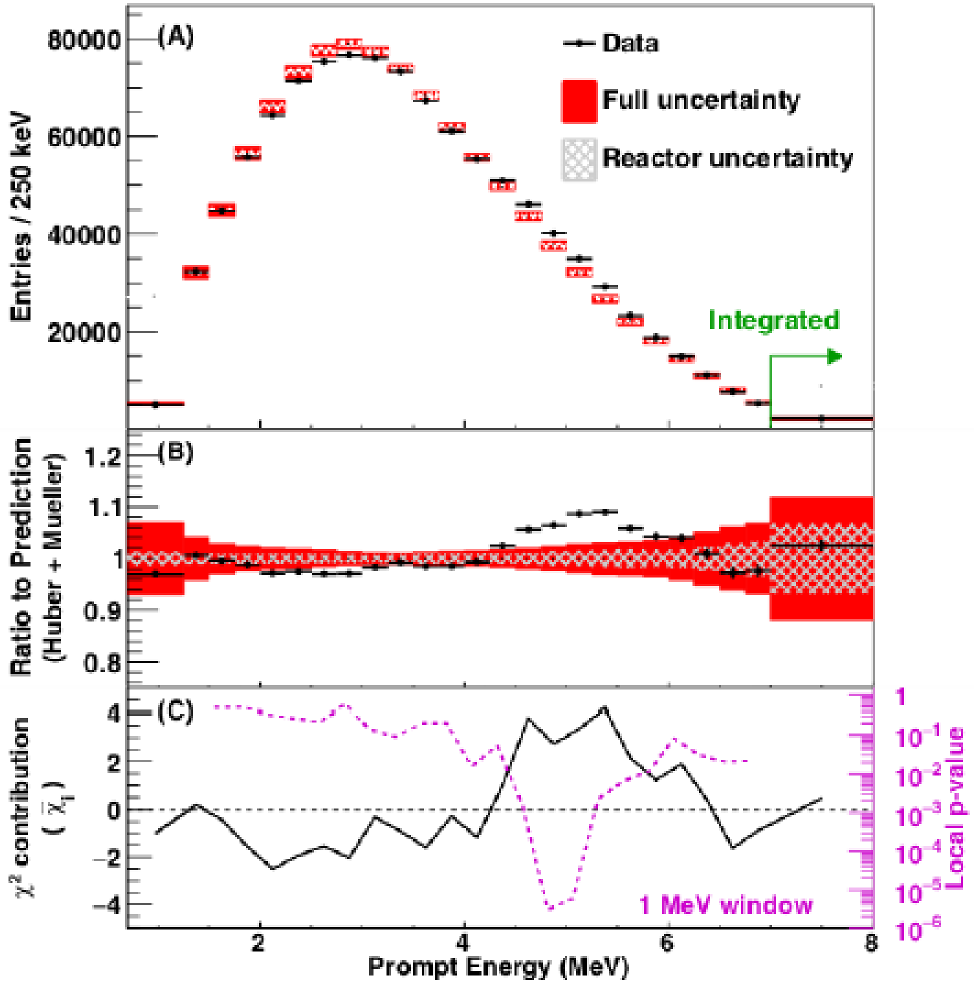
should be $V^{theory} = R_i^{theory} R_j^{theory} (\sigma^{theory})^2$

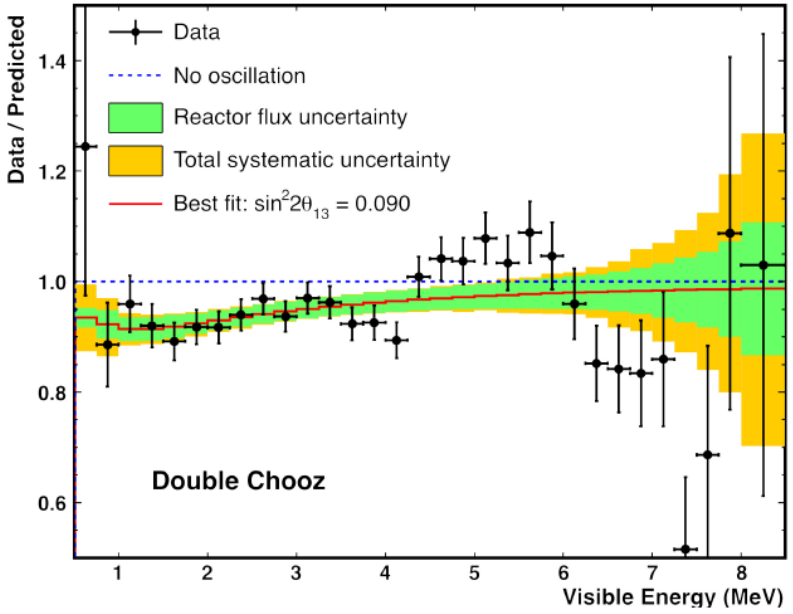
See G. D'Agostini NIMA 346, 306 (1994),
V. Blobel, SLAC-R-0703, p101,
B. Roe arXiv:1506.09077

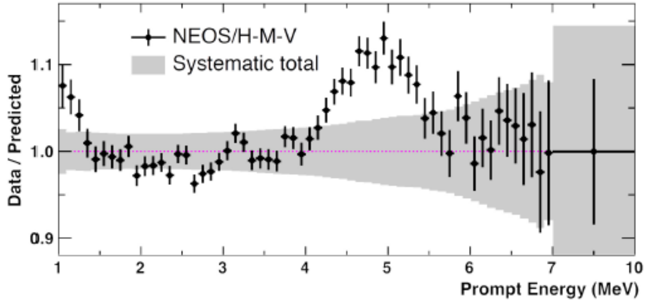
- Daya Bay's result is consistent with previous world measurement
- World average including Daya Bay is 0.9430+-008 (exp.)+-0.023 (model)
  - About **1.5% higher** than the previously claimed reactor antineutrino anomaly world fits which include **a tricky statistical mistake**

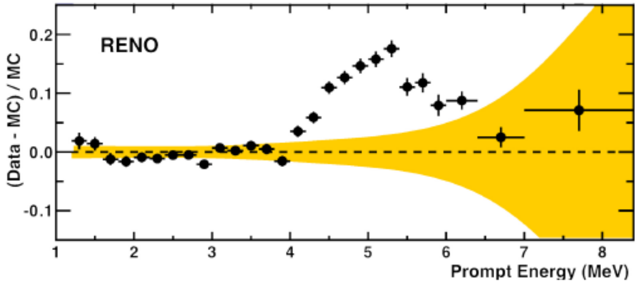
Chinese Phys. C41, 13002 (2017)

Absolute Neutrino Spectrum Measurements







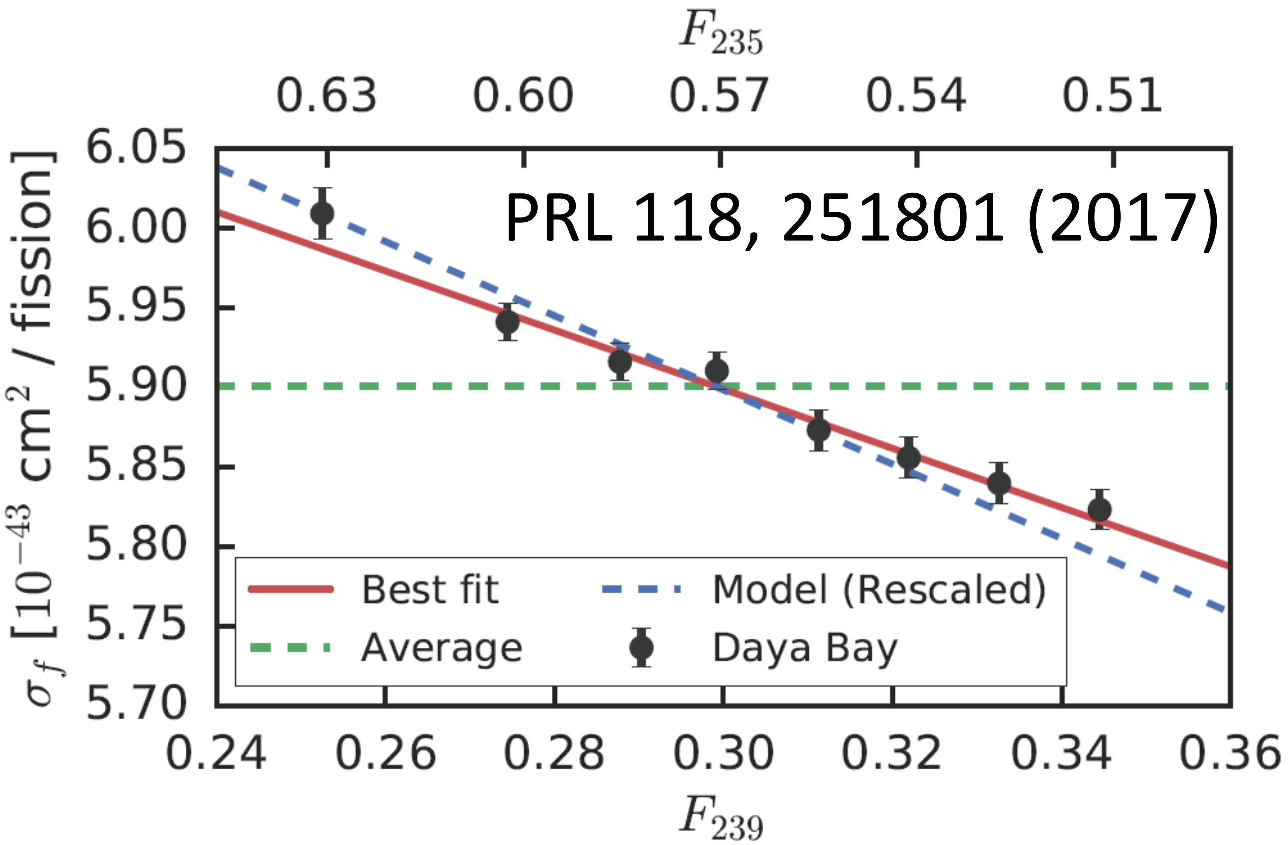


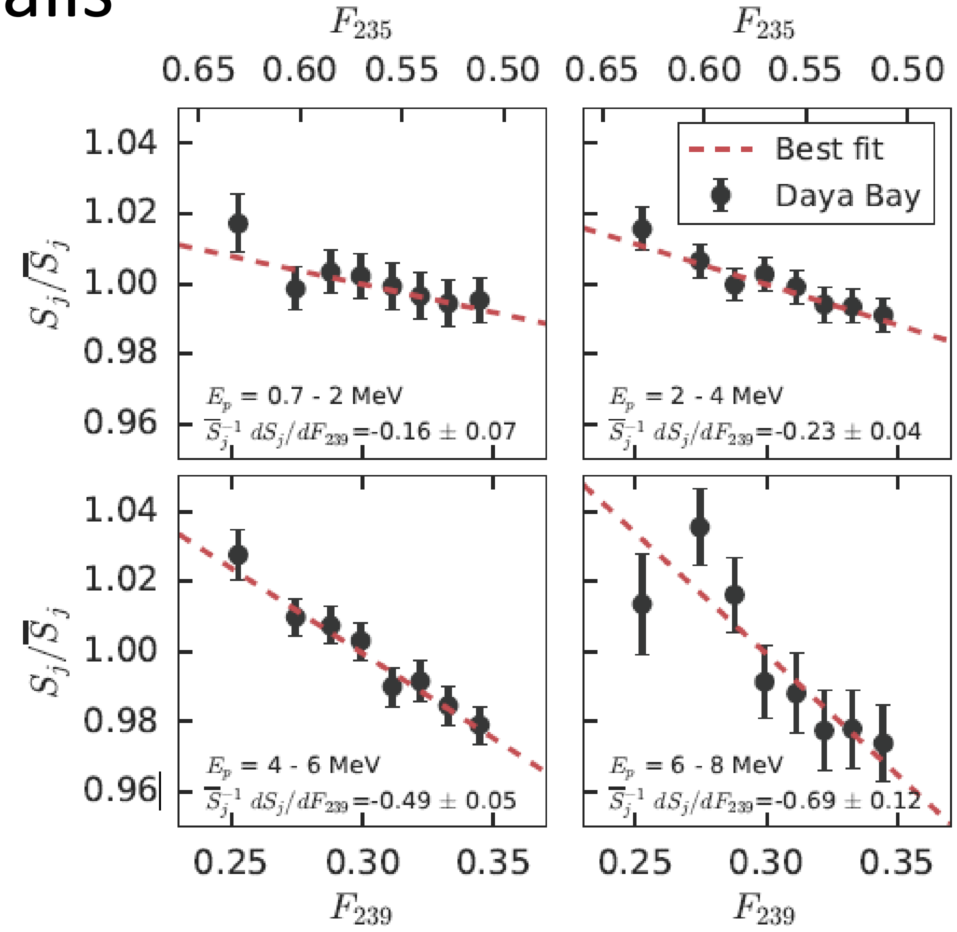
Structure also seen in RENO, Double Chooz and NEOS

- Incompatible with Huber+Mueller model at 3σ (4.4σ) at the full (4-6 MeV) energy range → 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





- Measured evolution of reactor flux is about 2.8 σ incompatible with the prediction of Huber-Mueller model + sterile neutrino for RAA

Summary

- Daya Bay is leading the precise measurements of θ_{13} and Δm^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