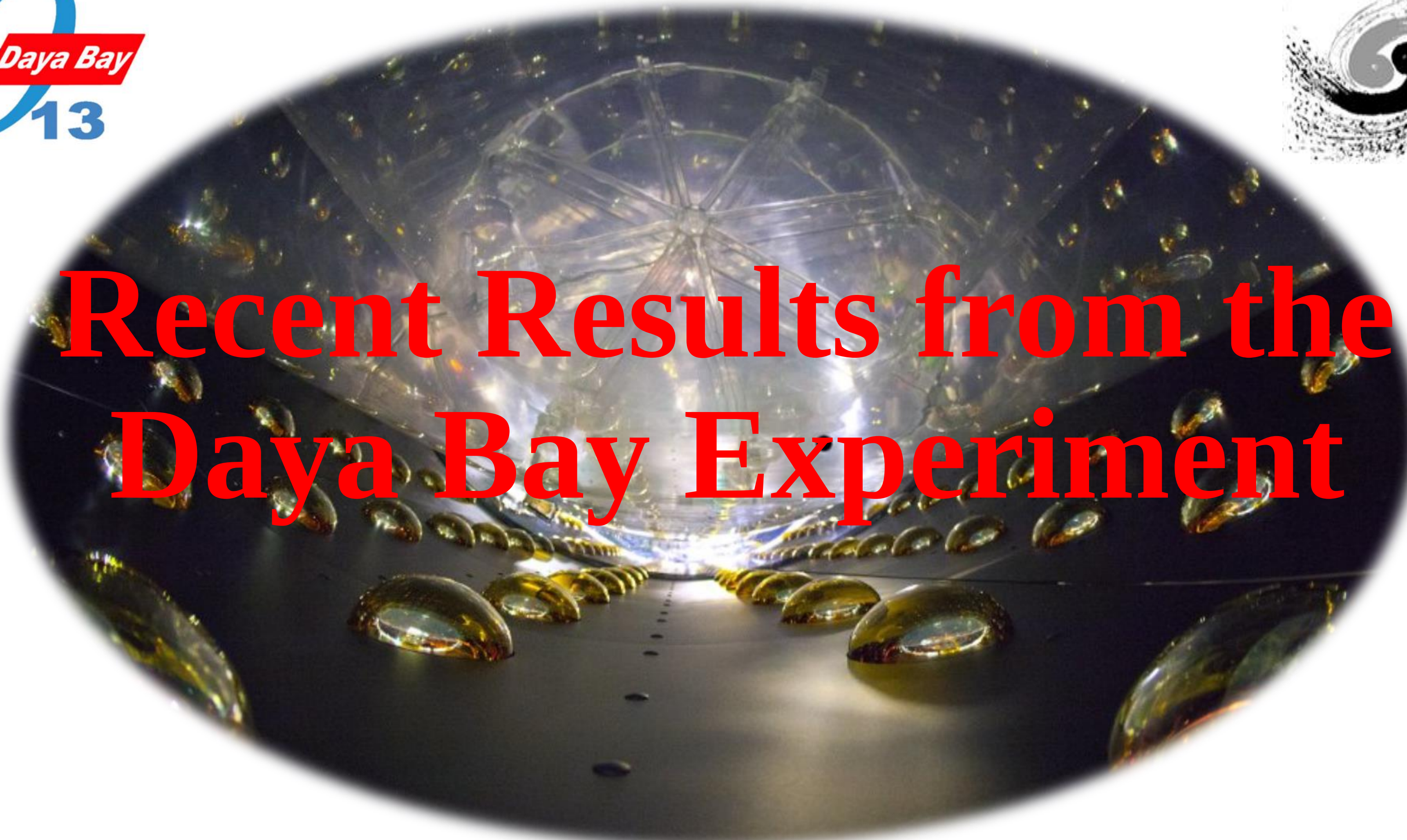
Recent Results from the Daya Bay Experiment



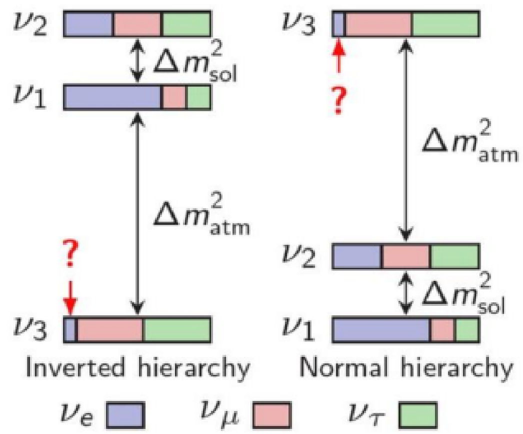
Zeyuan Yu
Institute of High Energy Physics, China
On behalf of the Daya Bay collaboration

PANIC 2017, Sep.1 to Sep.5, Beijing

Neutrino oscillation

flavor eigenstate — **neutrino mixing** — ***mass eigenstate***

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$$\mathrm{NH}: |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|, \quad |\Delta m^2_{31}| > |\Delta m^2_{32}|$$

$$\mathrm{IH}: |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|, \quad |\Delta m^2_{31}| < |\Delta m^2_{32}|$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

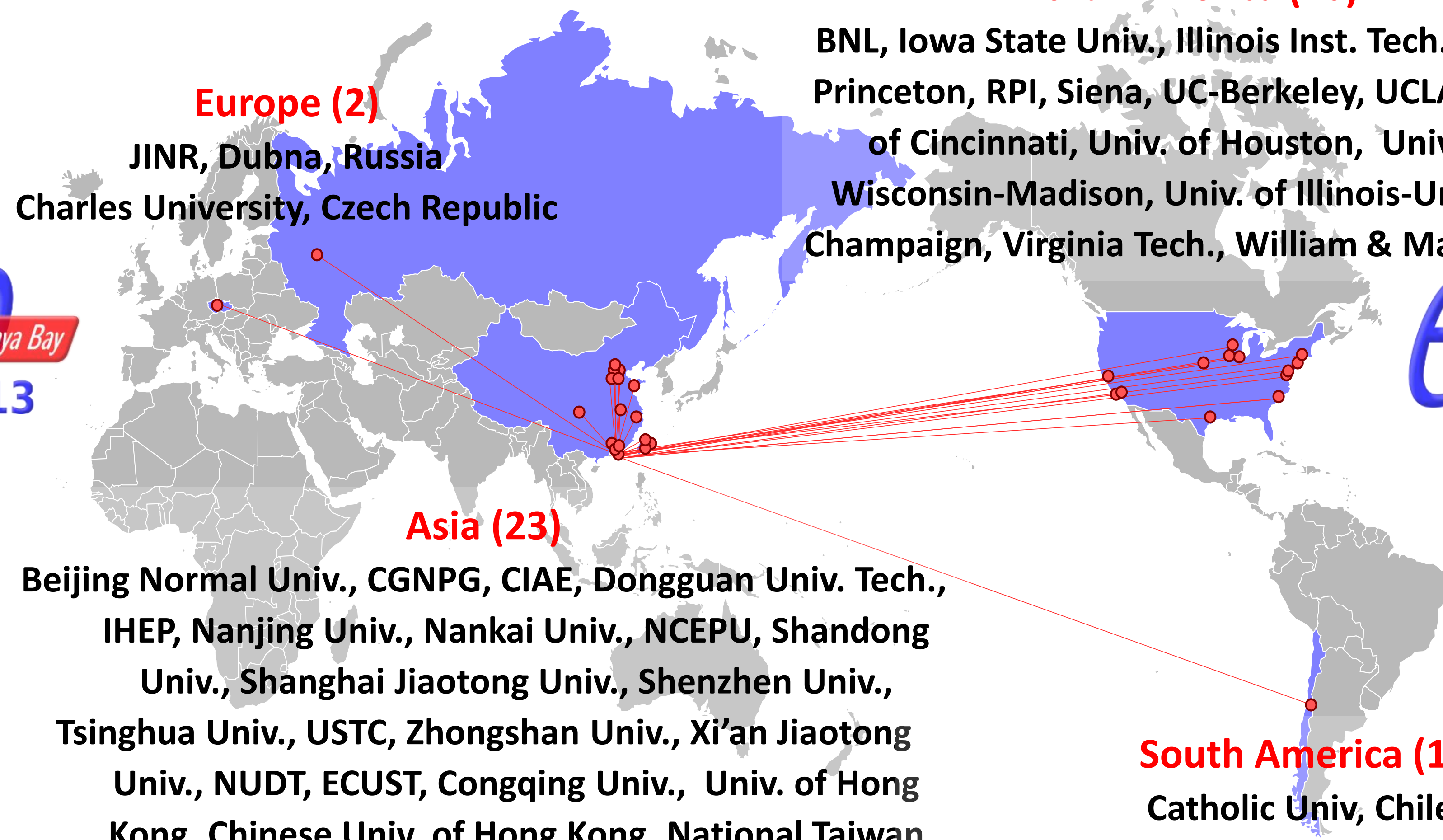
$\theta_{23} \sim 45°$
Atmospheric
Accelerator

θ_{13} :The smallest and the last one to be determined
Reactor
Accelerator

$\theta_{12} \sim 34°$
Solar
Reactor

The collaboration

203 collaborators from 42 institutions:



Europe (2)

JINR, Dubna, Russia
Charles University, Czech Republic

North America (16)

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

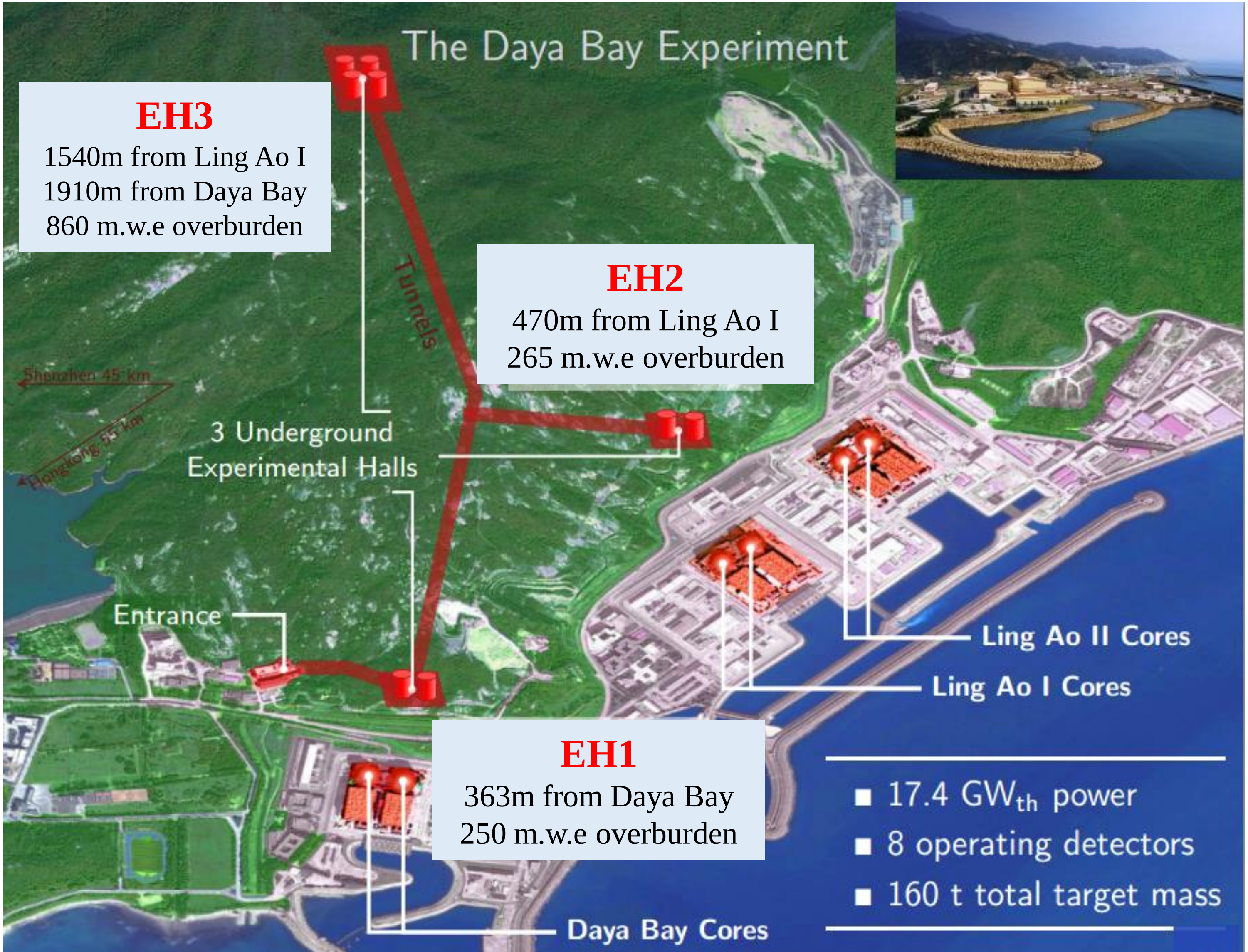
Asia (23)

Beijing Normal Univ., CGNPG, CIAE, Dongguan Univ. Tech., IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiaotong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Xi'an Jiaotong Univ., NUDT, ECUST, Congqing Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

South America (1)

Catholic Univ, Chile

Experimental site



EH3
1540m from Ling Ao I
1910m from Daya Bay
860 m.w.e overburden

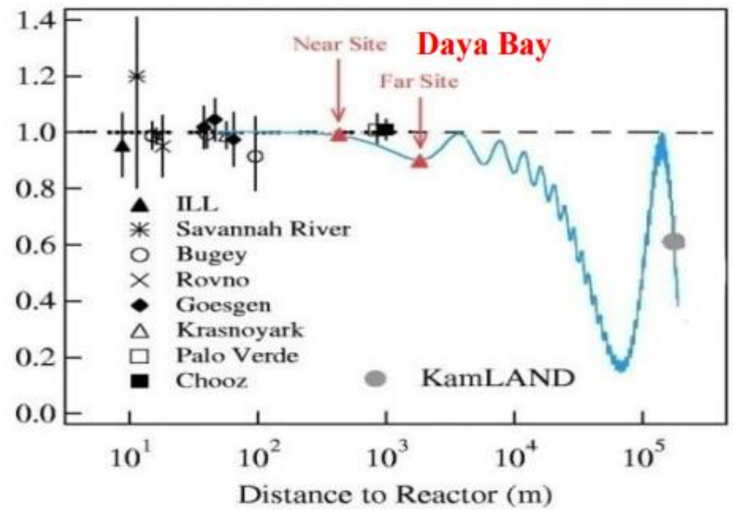
EH2
470m from Ling Ao I
265 m.w.e overburden

EH1
363m from Daya Bay
250 m.w.e overburden

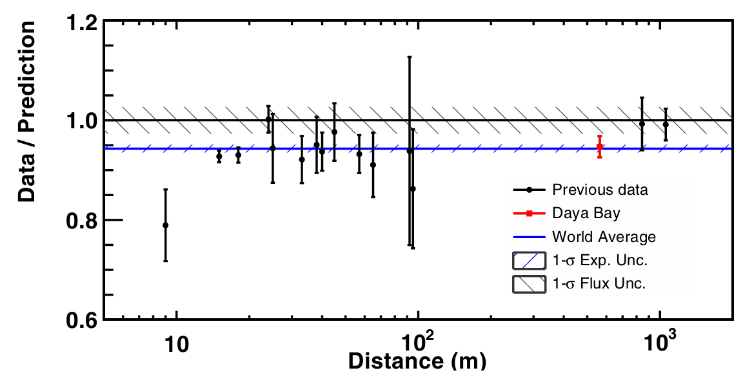
Two types of measurements

$$\frac{N_{\text{Far}}}{N_{\text{Near}}} = \left(\frac{N_{\text{target,Far}}}{N_{\text{target,Near}}}\right)\left(\frac{L_{\text{Near}}}{L_{\text{Far}}}\right)^2\left(\frac{\varepsilon_{\text{Far}}}{\varepsilon_{\text{Near}}}\right)\left[\frac{P_{\text{survival}}(E, L_{\text{Far}})}{P_{\text{survival}}(E, L_{\text{Near}})}\right]$$

- **Relative measurement**
  - Standard ν oscillation, sterile ν search, etc.
  - **Compare the rate and spectrum between near and far detectors**
  - Cancellation of detector and reactor systematics



- **Absolute measurement**
  - Reactor ν flux and spectrum, fuel evolution
  - **Compare the measurement to model predictions**

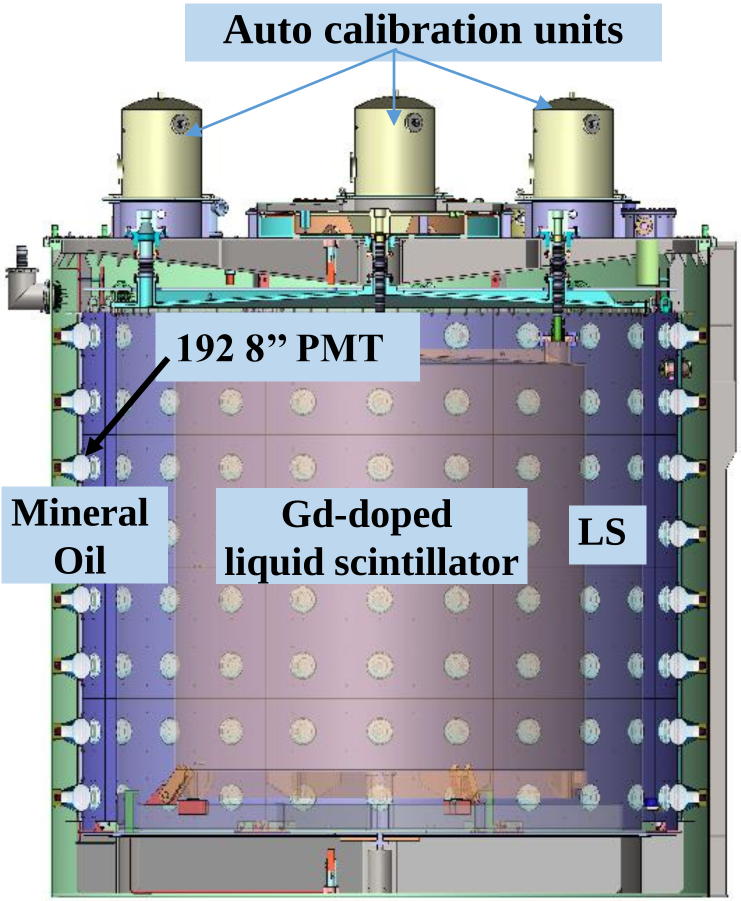


Detector

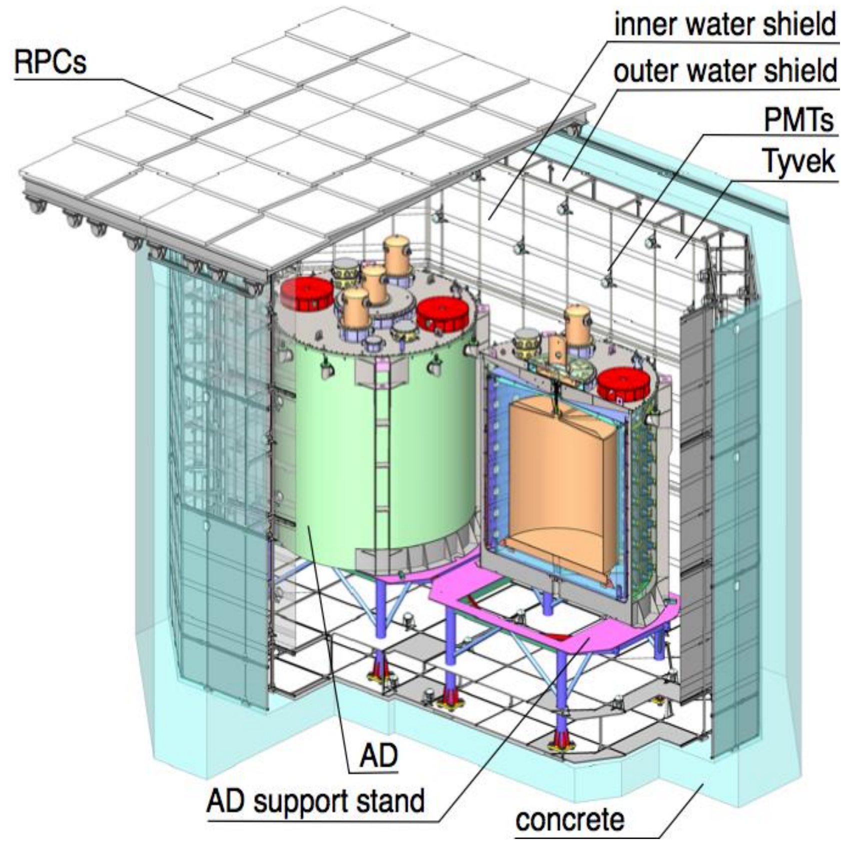
Eight functionally identical detectors

- **Study the near/far ratio and spectrum distortion**

$$\frac{N_{Far}}{N_{Near}} = \left(\frac{N_{target,Far}}{N_{target,Near}}\right)\left(\frac{L_{Near}}{L_{Far}}\right)^2\left(\frac{\varepsilon_{Far}}{\varepsilon_{Near}}\right)\left[\frac{P_{survival}(E, L_{Far})}{P_{survival}(E, L_{Near})}\right]$$



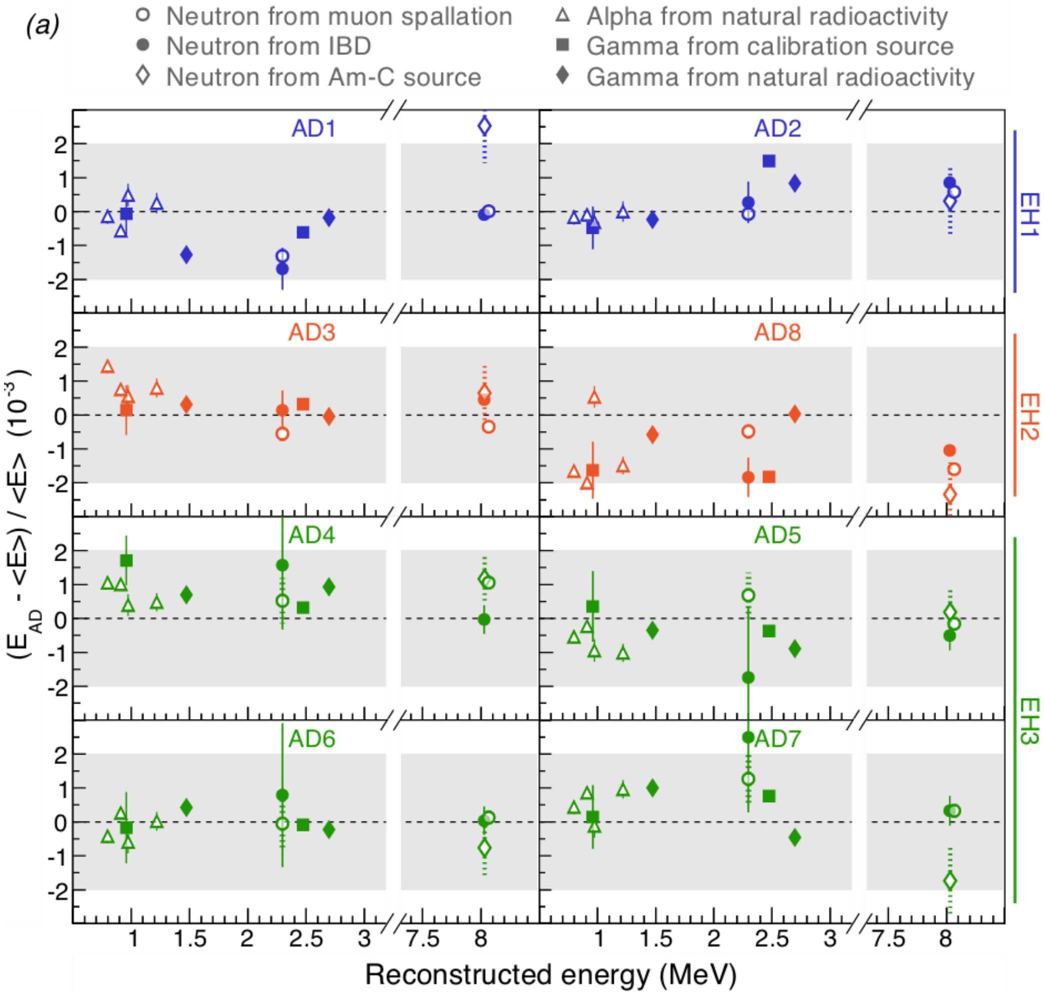
Nucl. Instrum. Meth. A 811, 133 (2016)



Nucl. Instrum. Meth. A 773, 8 (2015)

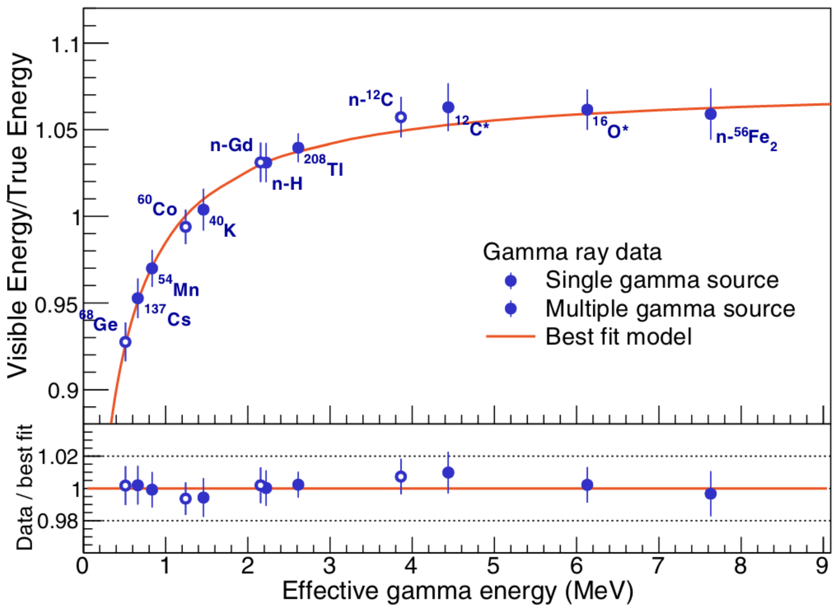
Energy reconstruction

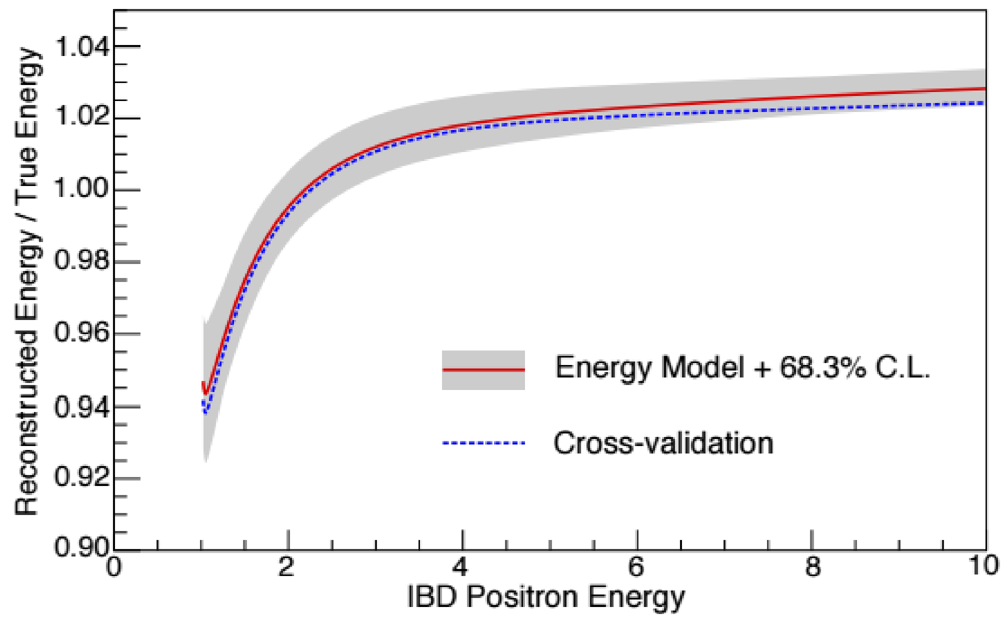
- **PMT gain calibration**
  - Single p.e. from PMT dark noise
  - Weekly deployment of LED
- **Energy reconstruction**
  - Calibration sources
  - Spallation neutrons
- **Relative energy scale**
  - ^{68}Ge, ^{60}Co, ^{241}Am-^{13}C
  - Spallation neutrons
  - Natural radioactivity



The relative energy scale uncertainty is less than 0.2%.

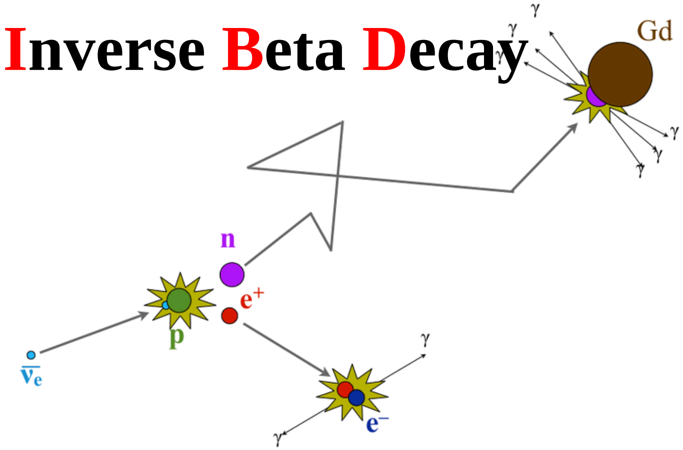
Energy model



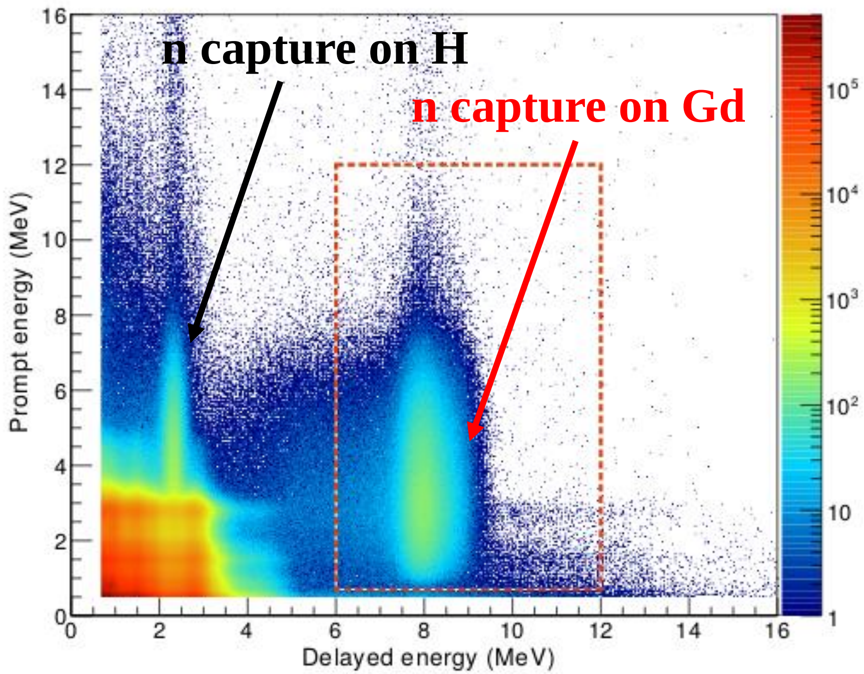


- **Energy model:**
  - **The relationship between true energy and its reconstructed energy**
  - **Built based on various γ peaks and continuous ^{12}B β spectrum**
- **Validated with**
  - **Michel electron; β+γ continuous spectra from $^{212/214}Bi$ and ^{208}Tl**
  - **Bench tests of Compton scattering electrons in LS**

$\bar{\nu}_e$ selection



- **Reject PMT flashers**
- **Muon veto**
- **Prompt and delayed energy cuts**
- **Neutron capture time cut**
- **Multiplicity cut**



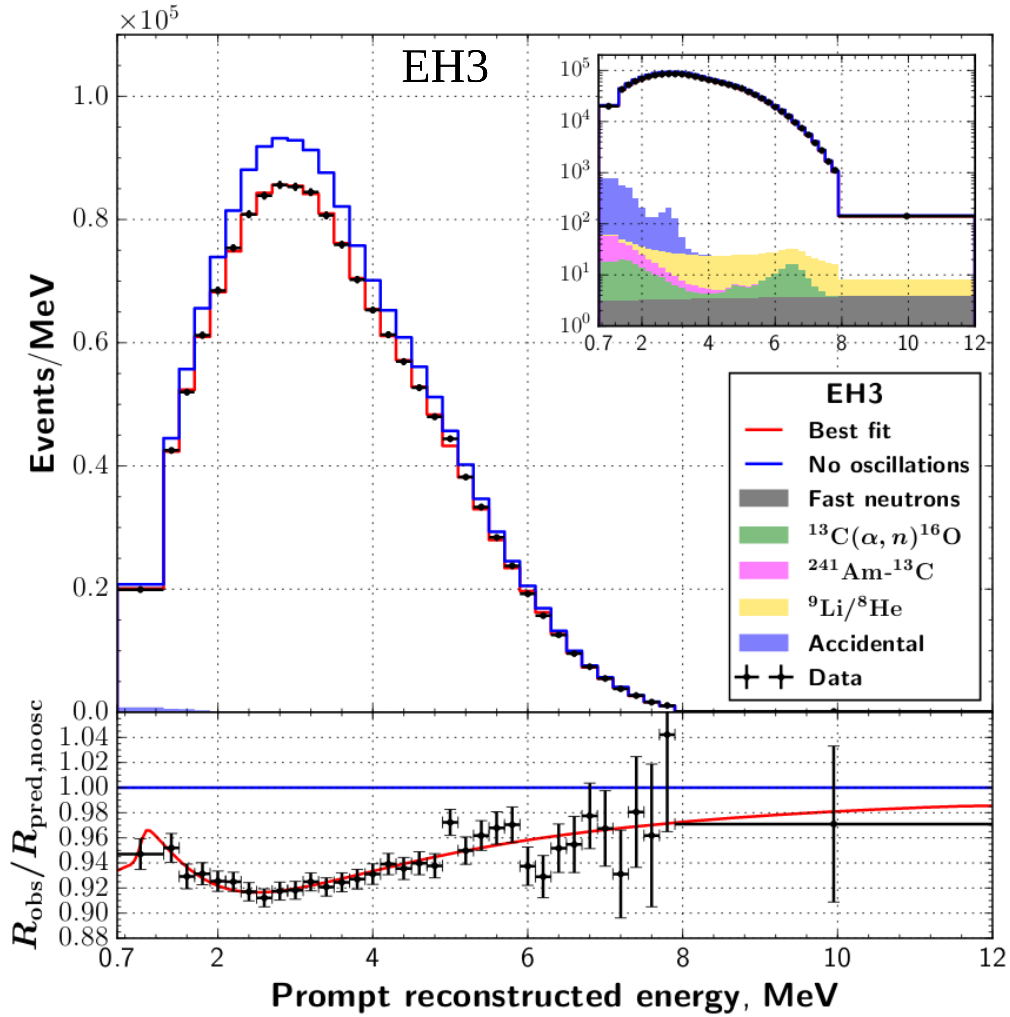
Detection efficiencies

	Efficiency	Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.08%
Prompt energy cut	99.8%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Gd capture fraction	84.2%	0.95%	0.10%
Spill-in	104.9%	1.00%	0.02%
Livetime	-	0.002%	0.01%
Combined	80.6%	1.93%	0.13%
Previous	80.6%	2.1%	0.2%

Backgrounds

- **Accidentals:**
  - Uncertainty less than 0.02%
- **Fast neutron**
  - Uncertainty less than 0.05%
- **$^{9}Li/^{8}He$**
  - Uncertainty 0.1%~0.15%
- **From the ^{241}Am-^{13}C source**
  - Uncertainty 0.05%~0.1%
- **$^{13}C(\alpha,n)^{16}O$**
  - Uncertainty less than 0.05%

Sites	B/S ratio	Background uncertainty
Daya Bay	1.8%	0.2%
Ling Ao	1.5%	0.15%
Far	2.0%	0.2%

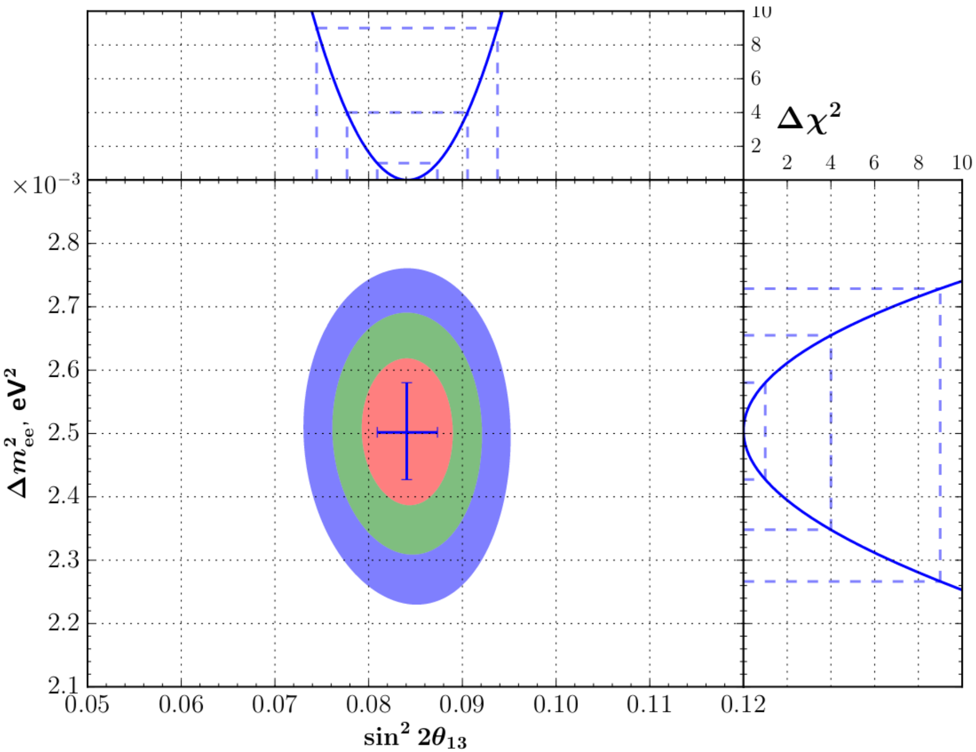


Two types of measurements

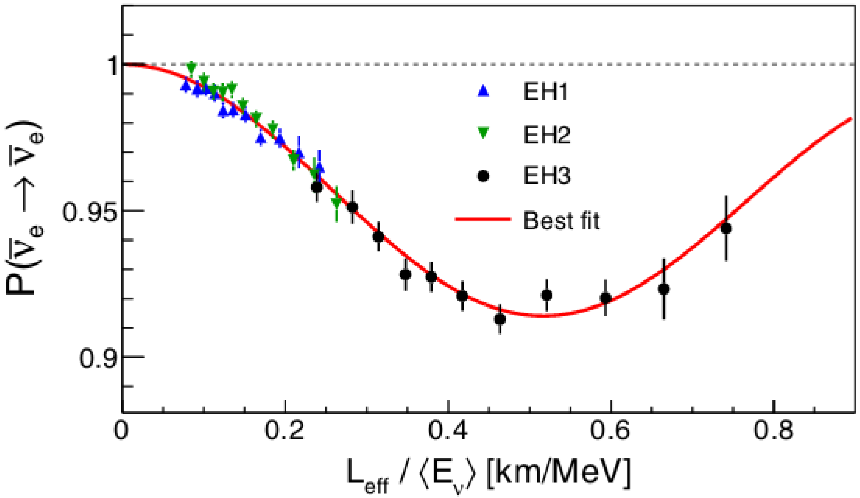
- **Relative measurement**
  - Standard ν oscillation, sterile ν search, etc.
  - **Compare the rate and spectrum between near and far detectors**
  - Cancellation of detector and reactor systematics

- **Absolute measurement**
  - Reactor ν flux and spectrum, fuel evolution
  - Compare the measurement to model predictions
  - Understanding the reactor and detector systematic uncertainties

Oscillation results



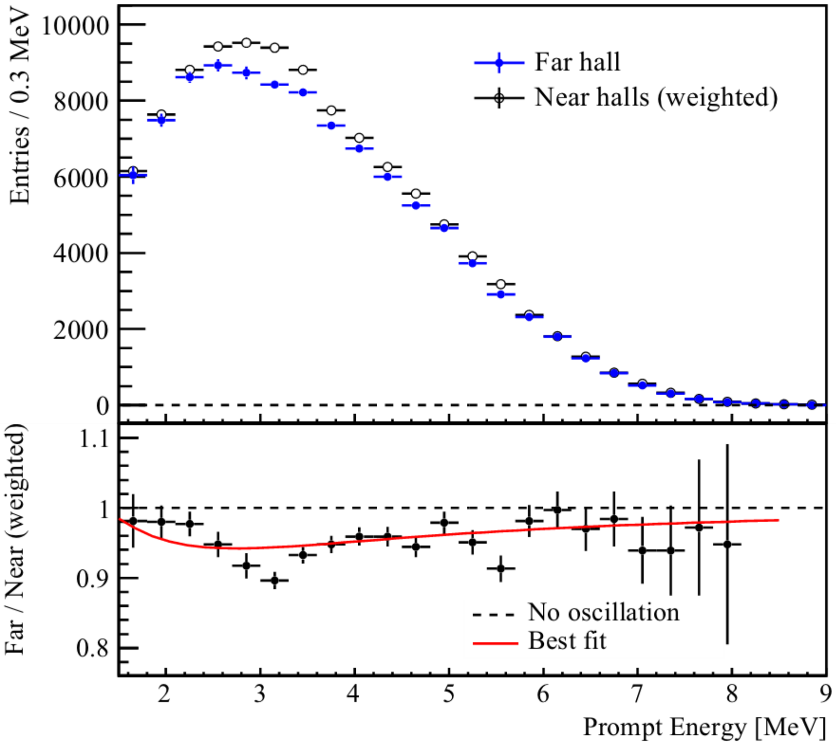
$$P = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{1.267\Delta m^2_{21}L}{E} - \sin^2 2\theta_{13}\sin^2\frac{1.267\Delta m^2_{ee}L}{E}.$$

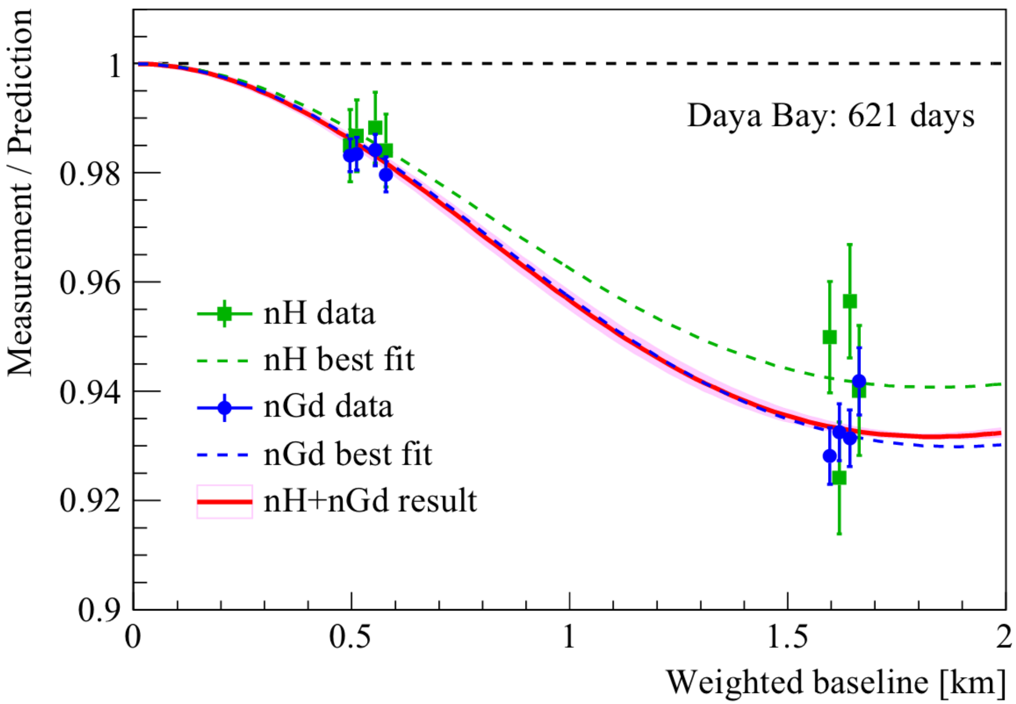


$\sin^2 2\theta_{13}$ = [8.41 ± 0.27(stat.) ± 0.19(syst.)] × 10^{-2}
$|\Delta m^2_{ee}|$ = [2.50 ± 0.06(stat.) ± 0.06(syst.)] × 10^{-3} eV^2
χ^2/NDF = 234.7/263

Phys. Rev. D 95, 072006 (2017)

$\sin^2 2\theta_{13}$ through n-H





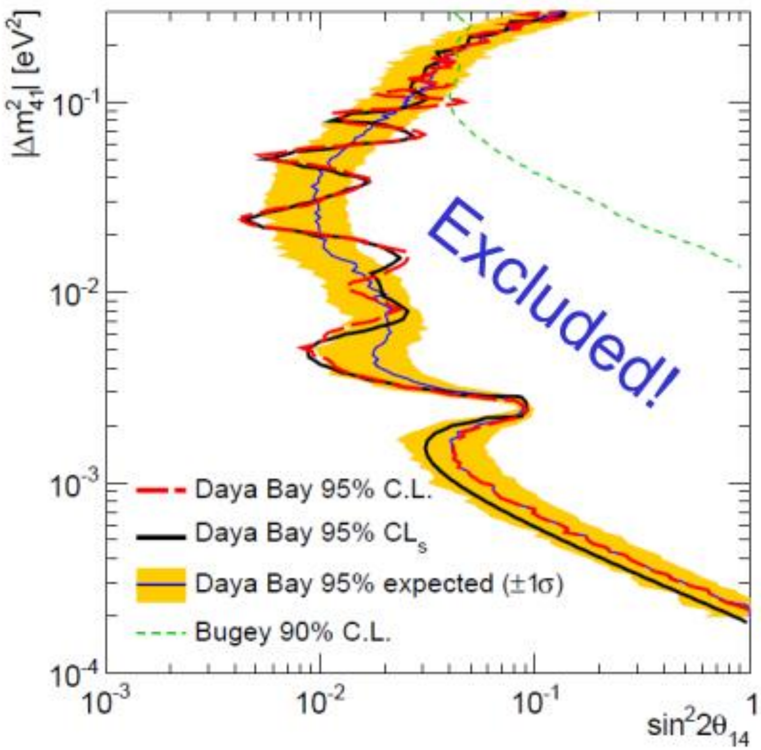
- **Rate analysis: $\sin^2 2\theta_{13} = 0.071 \pm 0.011$ $\chi^2/NDF = 6.3/6$**
- Consistent results with those of the n-Gd analysis
- Spectrum distortion consistent with the oscillation hypothesis

Phys. Rev. D 93, 072011 (2016)

Light sterile ν search

- **Sterile neutrino(3+1)**

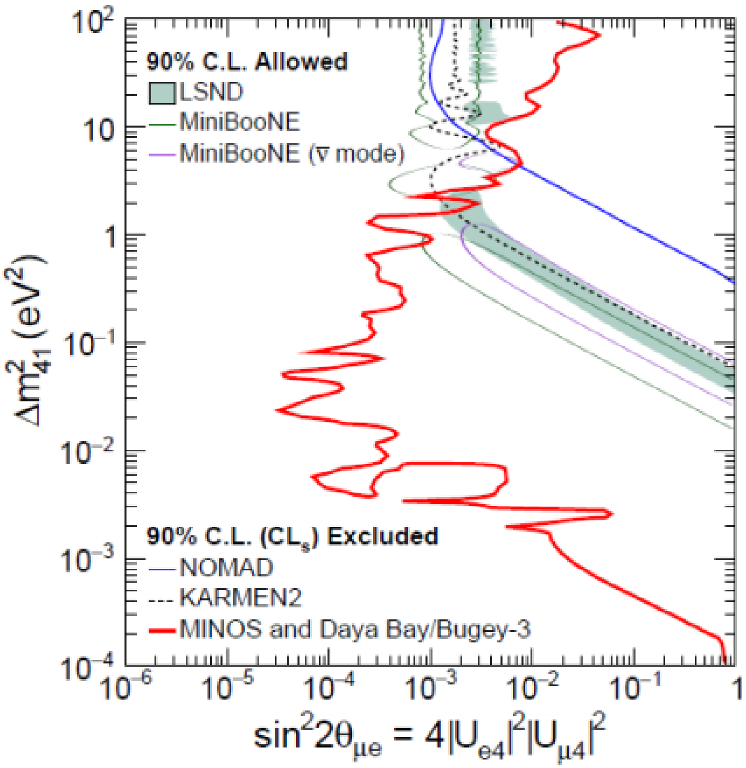
Phys. Rev. Lett. 117 ,151802(2016)



- **No hint for light sterile neutrino observed**
- **Most stringent limit for $|\Delta m_{41}^2| < 0.2\ eV^2$**

DayaBay + MINOS + Bugey-3

Phys. Rev. Lett. 117, 151801 (2016)



- **Exclude parameter space allowed by LSND and MiniBooNE for $\Delta m_{41}^2 < 0.8\ eV^2$**

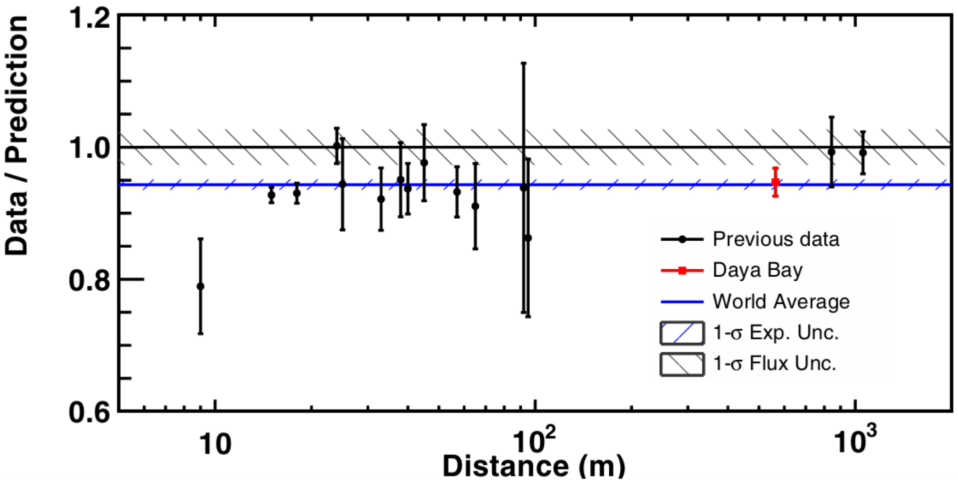
Two types of measurements

- **Relative measurement**
  - Standard ν oscillation, sterile ν search, etc.
  - Comparison of rate and spectrum between near and far detectors
  - Cancellation of detector and reactor systematics
- **Absolute measurement**
  - Reactor ν flux and spectrum, fuel evolution
  - **Compare the measurement to model predictions**
  - Understanding the reactor and detector systematic uncertainties

Absolute reactor $\bar{\nu}_e$ flux

- **Daya Bay's blind analysis of reactor neutrino flux agrees with previous experiments**
- **Discrepancies to the Huber+Mueller model indicate:**
  - Over estimated flux and/or underestimated flux uncertainty
  - Or the existence of a sterile neutrino

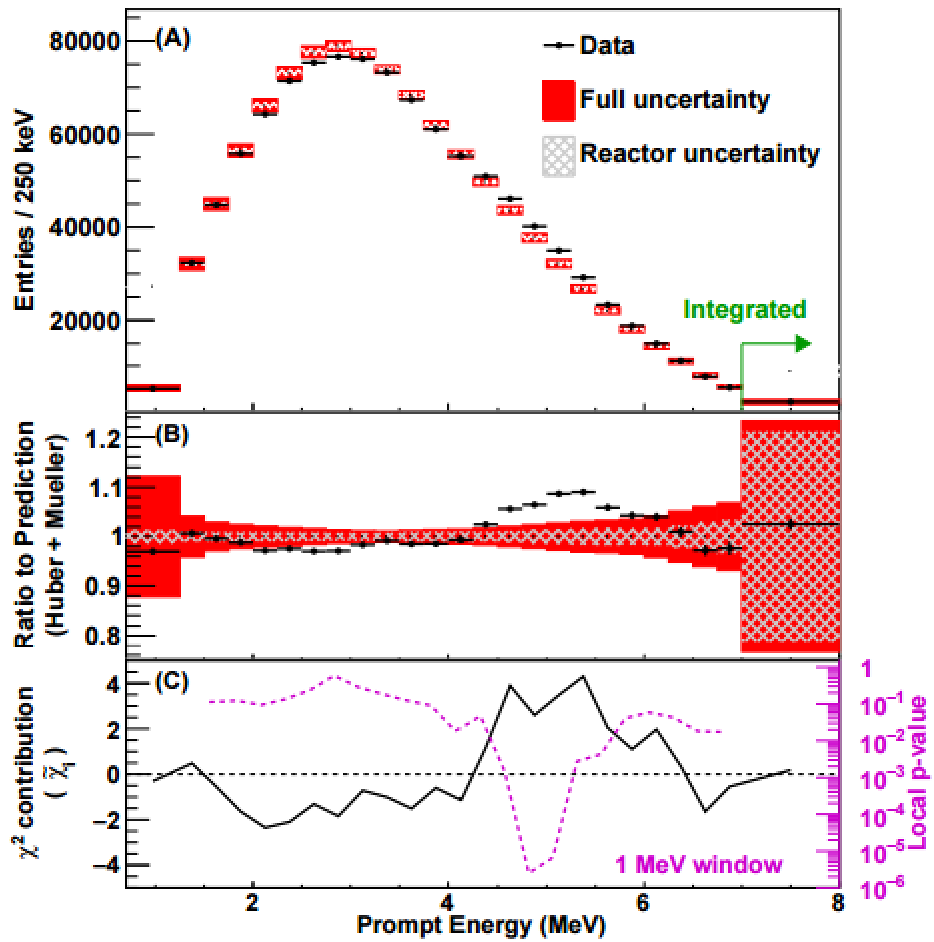
IBD Yield	
Y (cm^2/GW/day)	$(1.53 \pm 0.03) \times 10^{-18}$
σ_f (cm^2/fission)	$(5.91 \pm 0.12) \times 10^{-43}$
Data / Prediction	
R (Huber+Mueller)	0.946 ± 0.020 (exp.)
R (ILL+Vogel)	0.992 ± 0.021 (exp.)
^{235}U : ^{238}U : ^{239}Pu : ^{241}Pu	0.561 : 0.076 : 0.307 : 0.056



Chin. Phys. C 41(1) (2017)

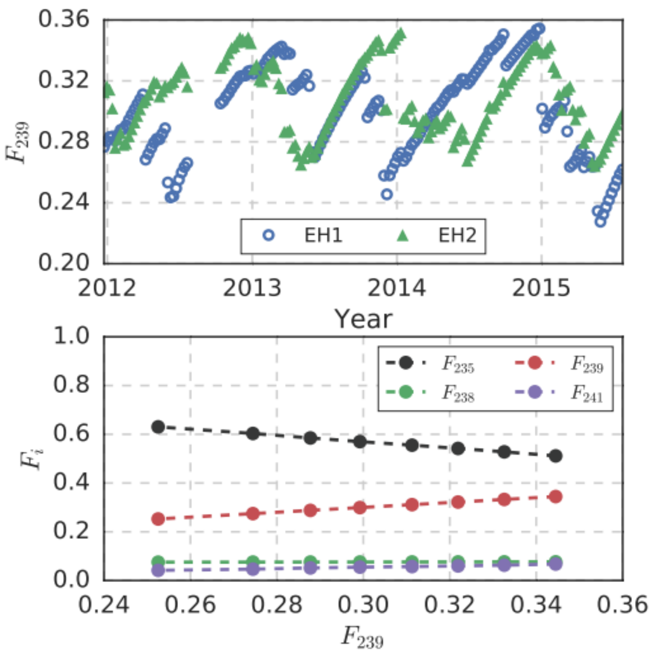
Absolute $\bar{\nu}_e$ spectrum

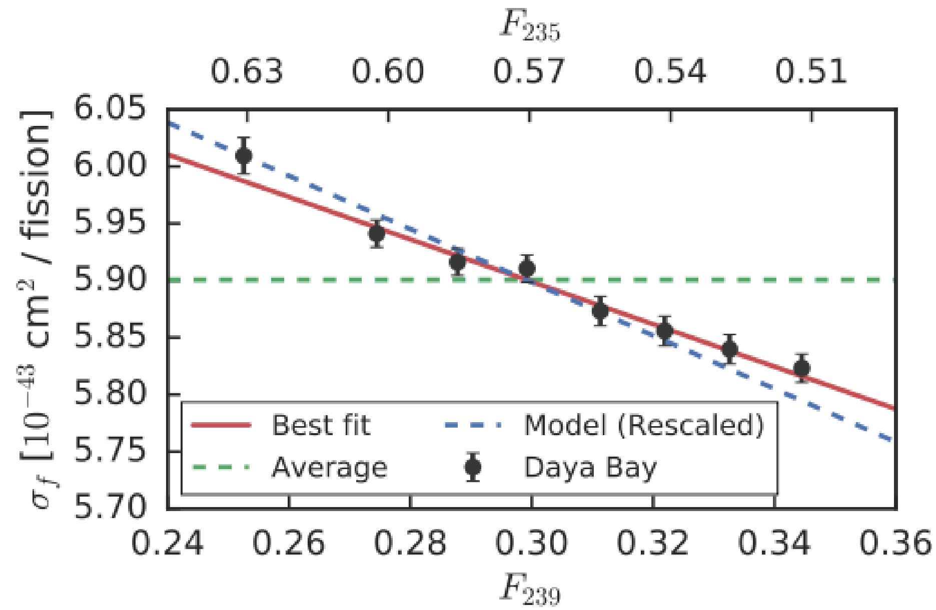
- **Compare the prompt energy spectrum to the Huber+Mueller model**
  - 2.9 σ discrepancy at the full energy range
  - 4.4 σ local significance at 4 to 6 MeV
- **Excess events have all characteristics of IBD**
  - Correlated to reactor power
  - Could not be explained by detector response



Chin. Phys. C 41(1) (2017)

Fuel evolution analysis



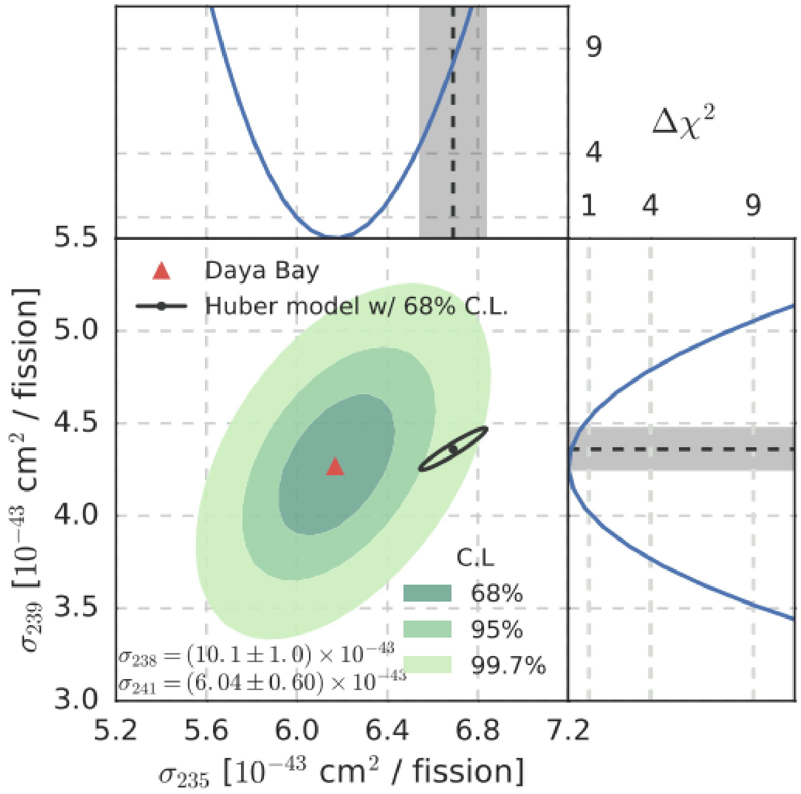


- **With the nuclear fuel burning, the fission fraction of ^{235}U is decreasing while ^{239}Pu is increasing**
- **Clear linear evolution between the neutrino yield and the ^{239}Pu fission fraction**
  - However, the slopes of data and model prediction disagree

Phys. Rev. Lett. 118, 251801

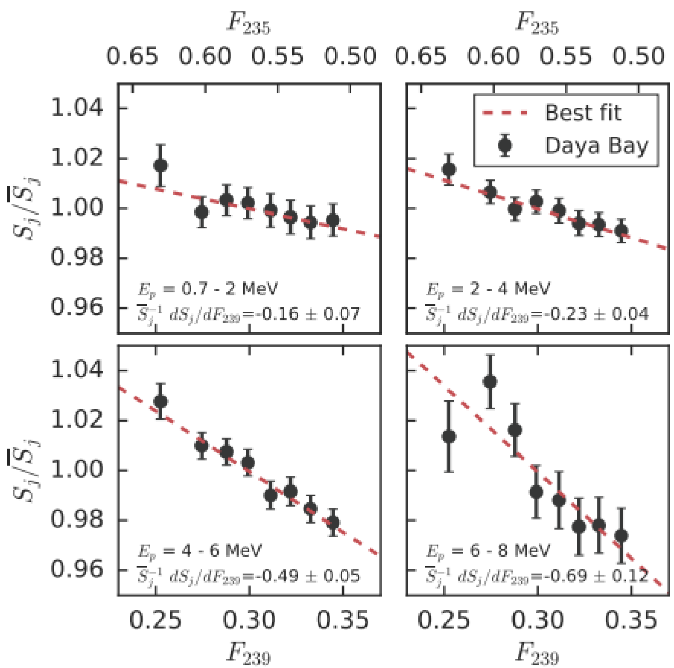
^{235}U and ^{239}Pu yield

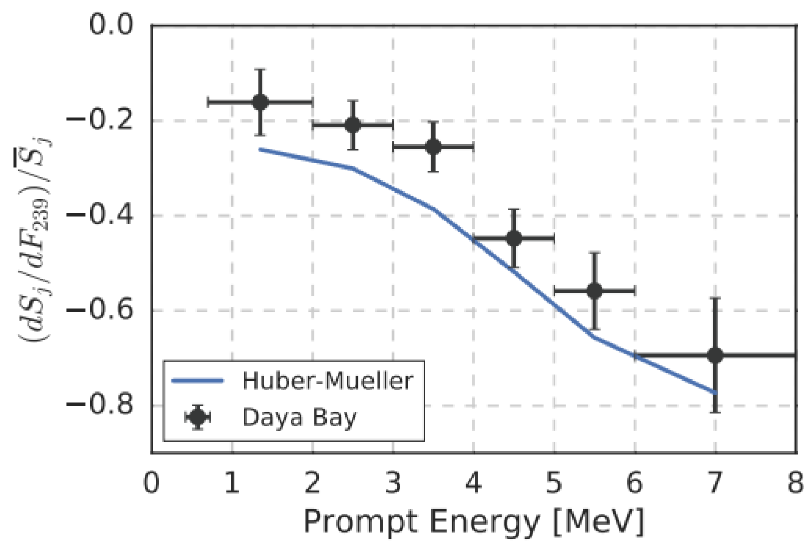
- **Combined fit to the major fission isotopes ^{235}U and ^{239}Pu**
  - Assume yields of the minor fission isotopes ^{238}U and ^{241}Pu from model with an enlarged uncertainty 10%
- **Results suggest ^{235}U being the main contributor to the Reactor Antineutrino Anomaly (RAA)**
  - ^{235}U is 7.8% lower than H-M model (2.7% meas. uncertainty)
  - ^{239}Pu is consistent with H-M model (6% meas. uncertainty)
- **Sterile neutrino as the sole cause of RAA is disfavored by 2.8σ**



Spectrum evolution

- **The evolution slopes are different at different energy ranges**
  - Neutrino spectrum do change with ^{239}Pu fission fraction, in agreement with most models' predictions
  - No strange behavior at 4 to 6 MeV region
  - Larger statistics and better detection efficiency estimates would improve the fuel evolution results

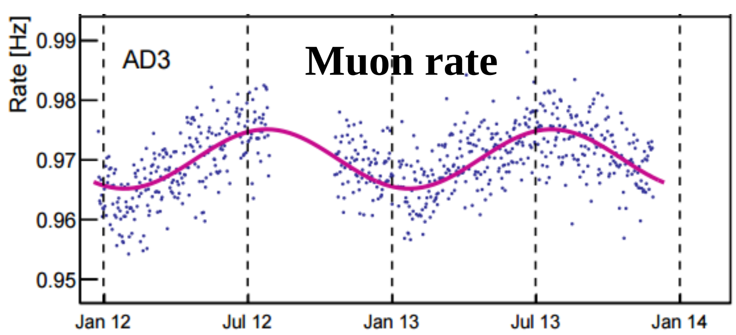


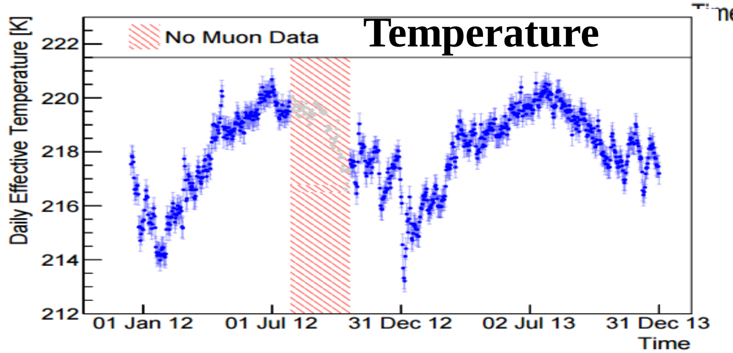


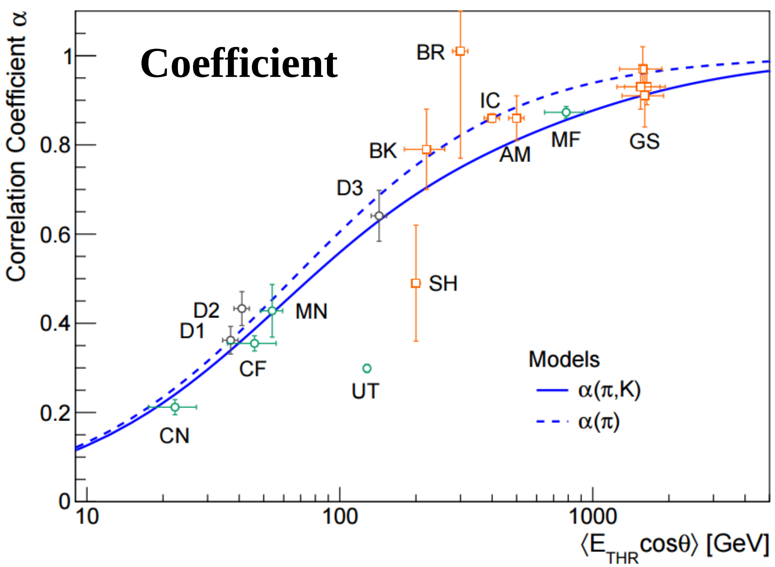
Muon flux modulation

arXiv:1708.01265

- **The underground muon flux was known to be positively correlated with the atmospheric temperature**
- **Daya Bay measures the correlation coefficient which is consistent to model prediction**
  - The only experiment measuring the coefficient with functionally identical detectors at different overburdens







Summary

- **Daya Bay gives the most precise measurements to $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$.**
  - Together with the updated measurement to reactor neutrino flux and spectrum, new limit on the light sterile neutrino
- **A reactor fuel evolution analysis is performed.**
  - Suggesting the Reactor Antineutrino Anomaly is mainly contributed by the overestimated ^{235}U flux in H-M model
- **Plan to run till 2020: uncertainties of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ below 3%.**
  - A neutron calibration campaign was done at Jan. 2017, aiming to reduce the absolute detection efficiency uncertainty
  - One AD in the Daya Bay Near Hall was used for liquid scintillator study since Feb. 2017, including light yield, radio-purity, etc.