Latest Results from the Daya Bay Experiment

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**on behalf of the Daya Bay Collaboration*

NuFact

Uppsala, September 2017

Outline

- The Daya Bay Experiment
- Latest Results
  - nGd oscillation measurement
  - nH oscillation measurement
  - Search for a sterile neutrino
  - Reactor antineutrino absolute rate & shape measurement
  - Fuel evolution measurement*
  - Search for decoherence
  - Search for a seasonal variation of cosmic muon flux *
- Summary & Conclusions

* = released this year

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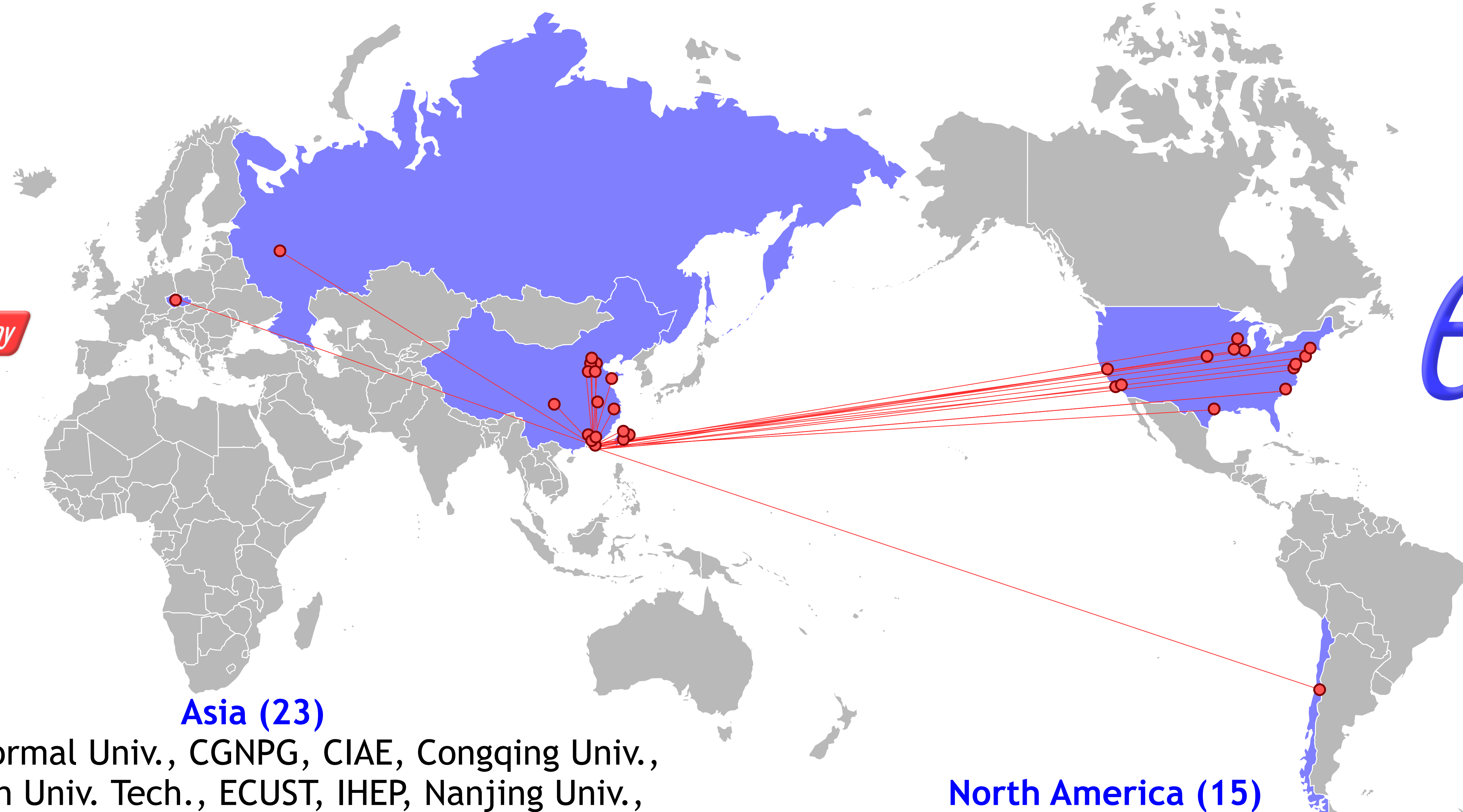
The Daya Bay Collaboration



Asia (23)

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

Europe (2)

Charles University, JINR Dubna

North America (15)

Brookhaven Natl Lab, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Siena College, Temple University, UC Berkeley, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

South America (1)

Catholic University of Chile

~230 Collaborators

Experimental Setup

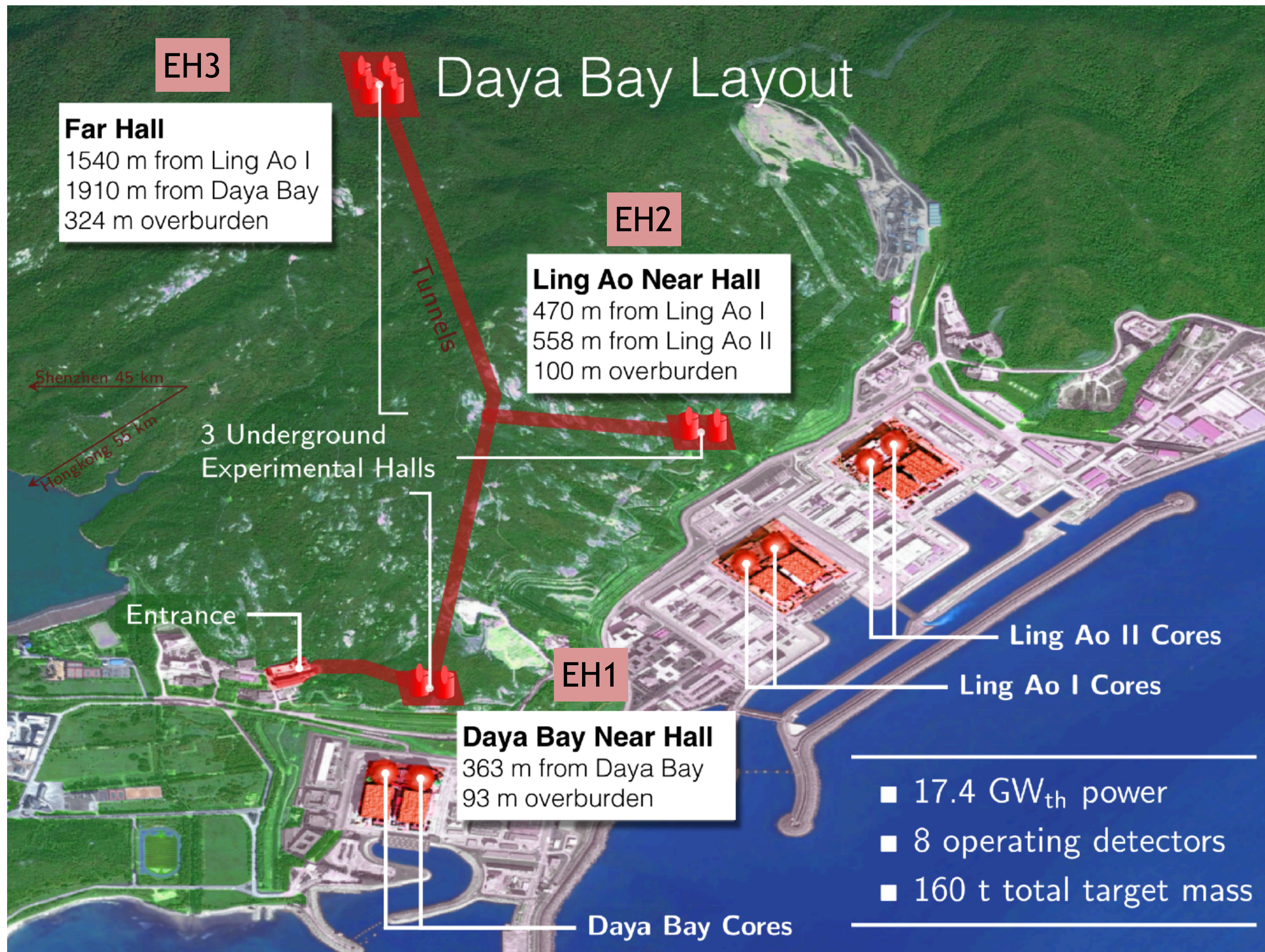
- 8 identically designed detectors positioned beside the Daya Bay Power Plant in China

Among the most powerful reactor complexes in the world!

- Main Principle:

(i) sample the reactor antineutrino flux in the near and far locations, and

(ii) look for evidence of disappearance

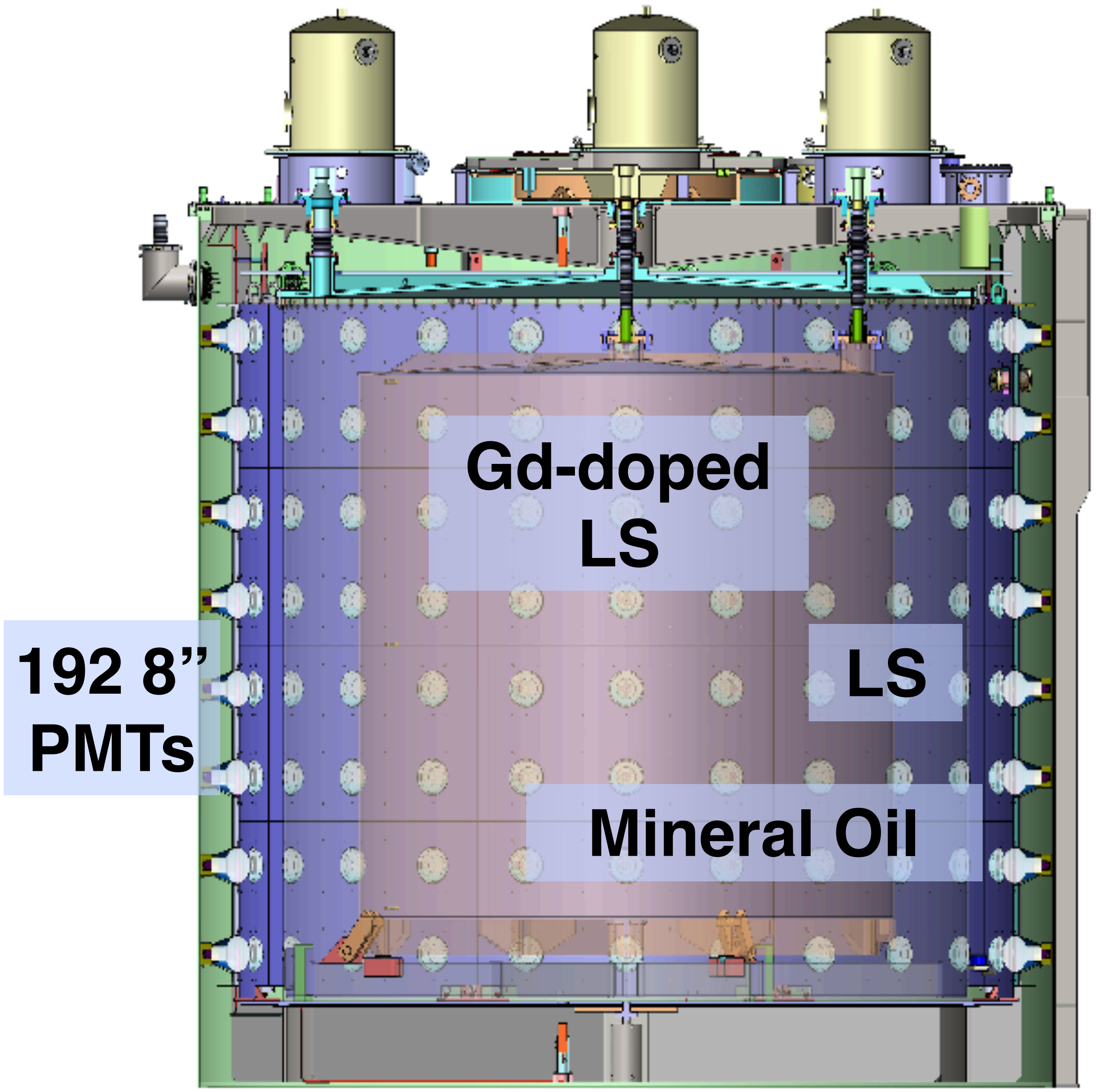


Antineutrino Detectors

- The antineutrino detectors (ADs) are "three-zone" cylindrical modules immersed in water pools:

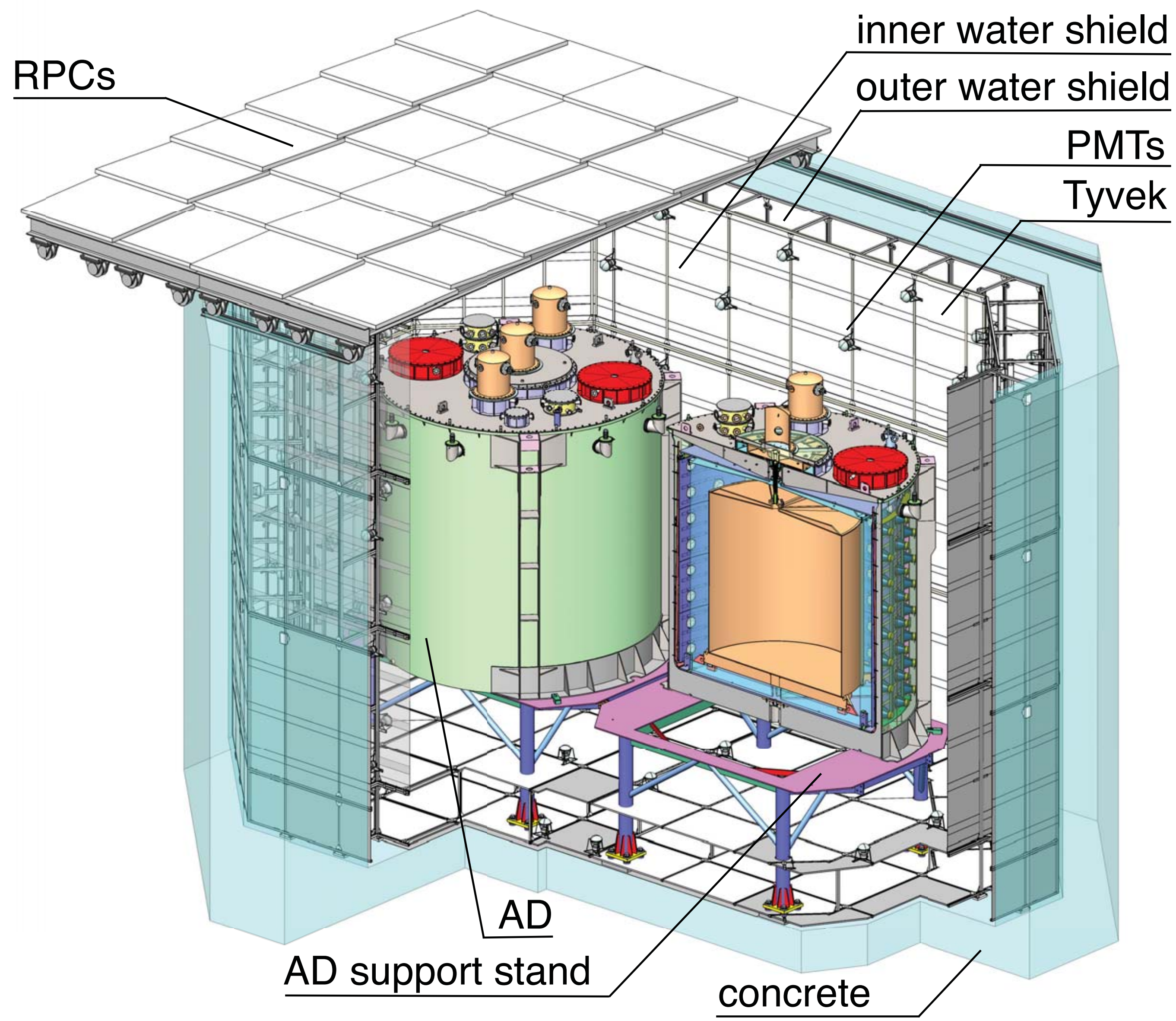
Inverse Beta Decay (IBD):

$\overline{\nu}_e + p \rightarrow e^+ + n$



Energy resolution:
$\sigma_E/E \cong 8.5\%/\sqrt{E}$

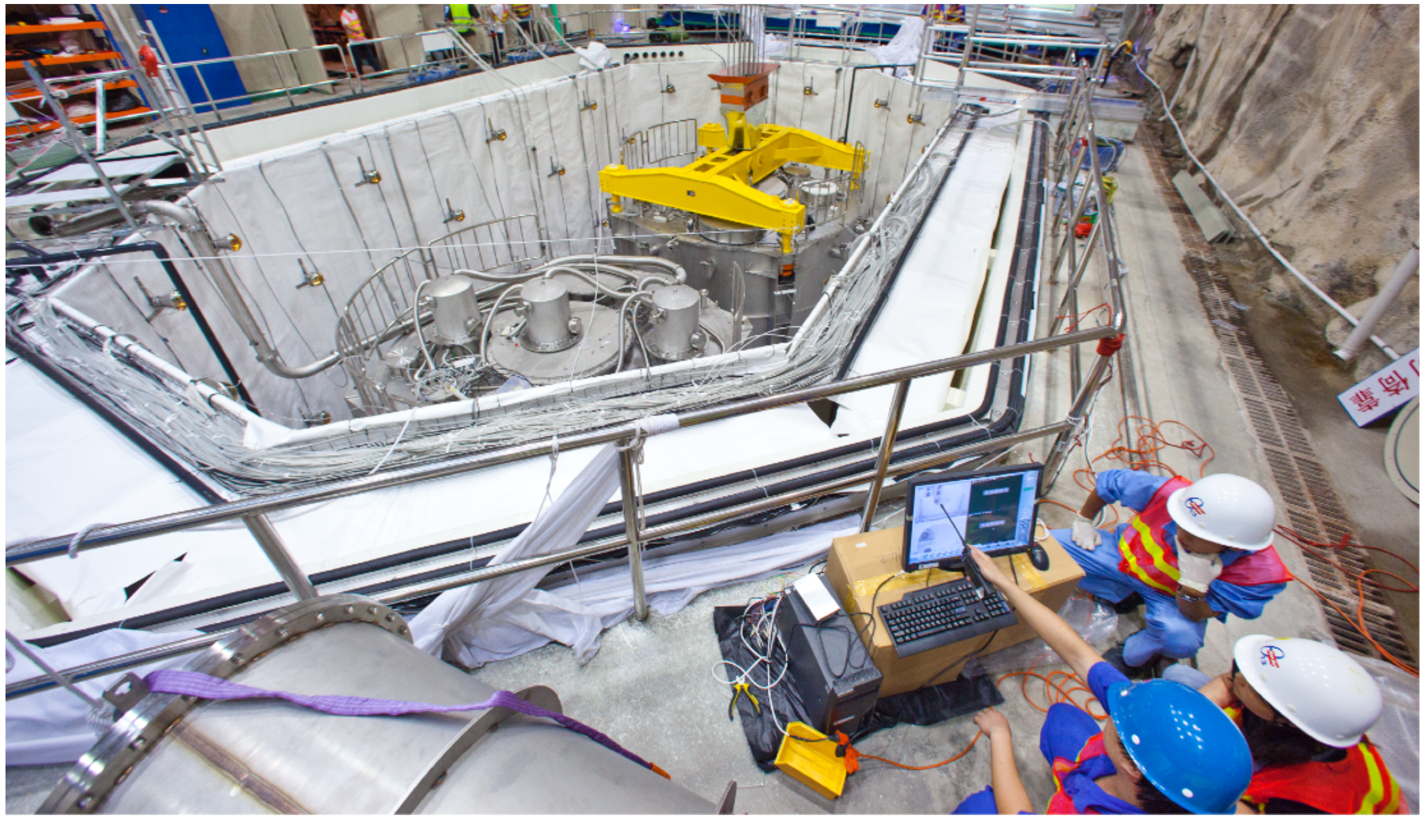
NIM A 811, 133 (2016)



Double purpose: shield the ADs and veto cosmic ray muons

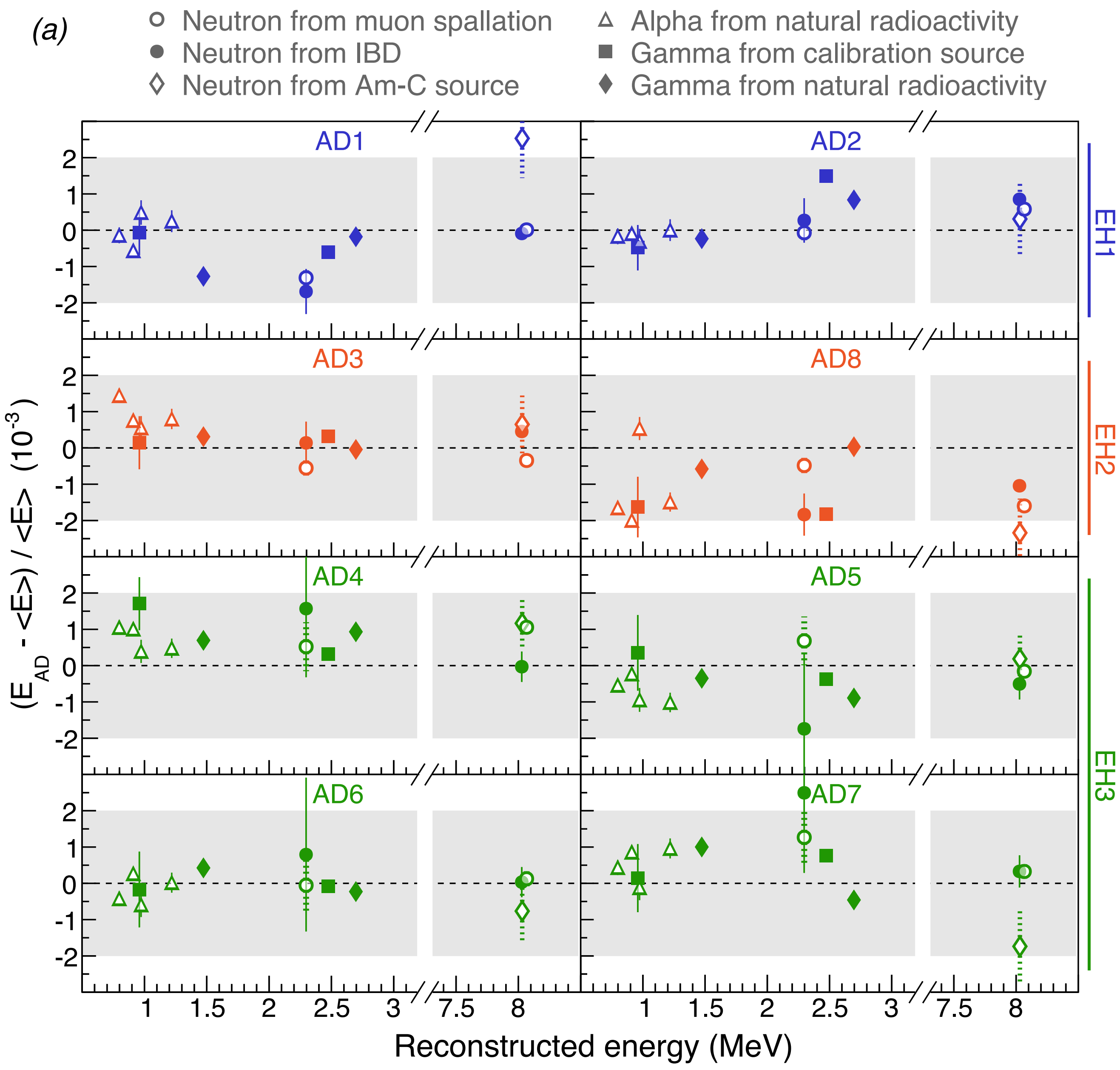
NIM A 773, 8 (2015)

A Selection of Pictures

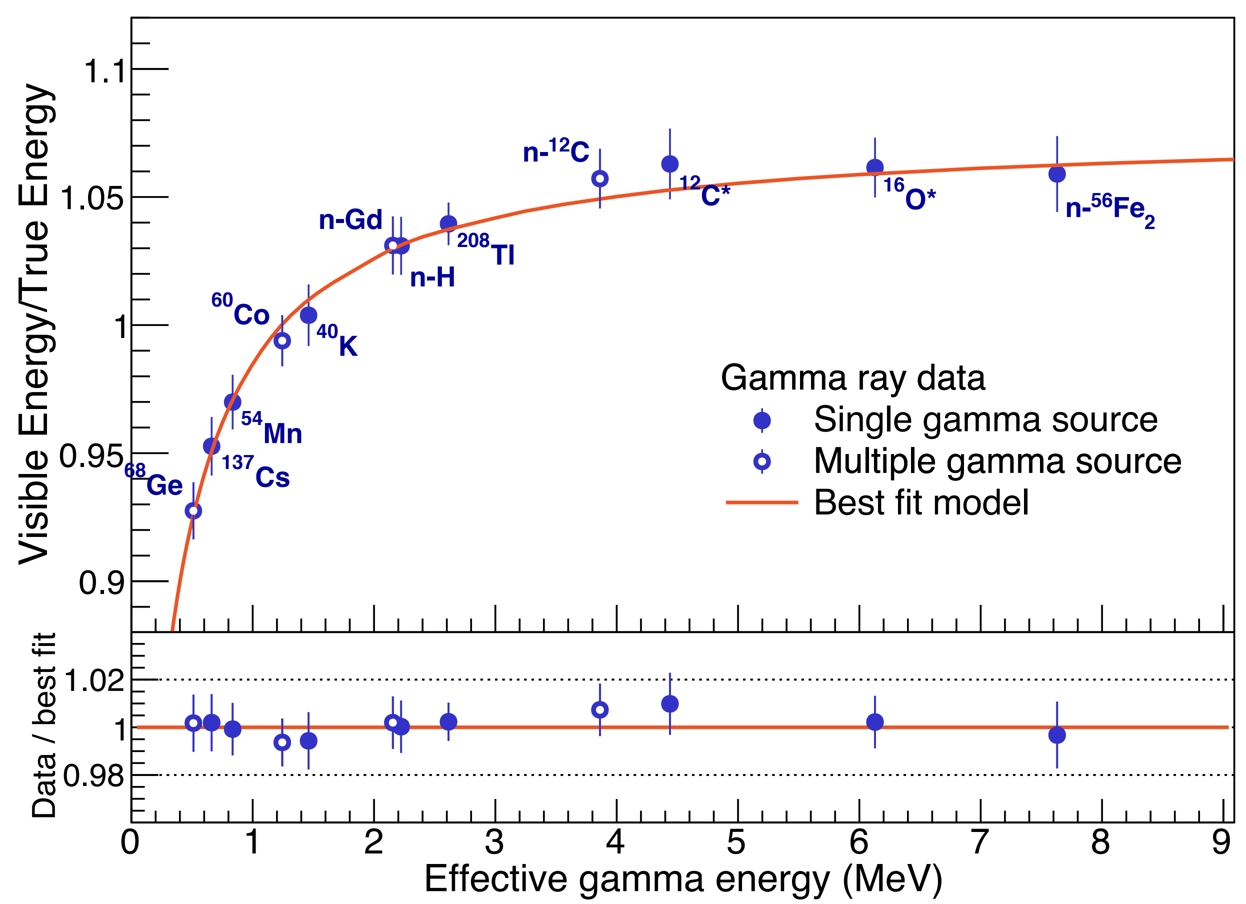


Energy Reconstruction

- Use a variety of natural and artificial sources to perform the relative calibration of the detectors and to construct an energy model:



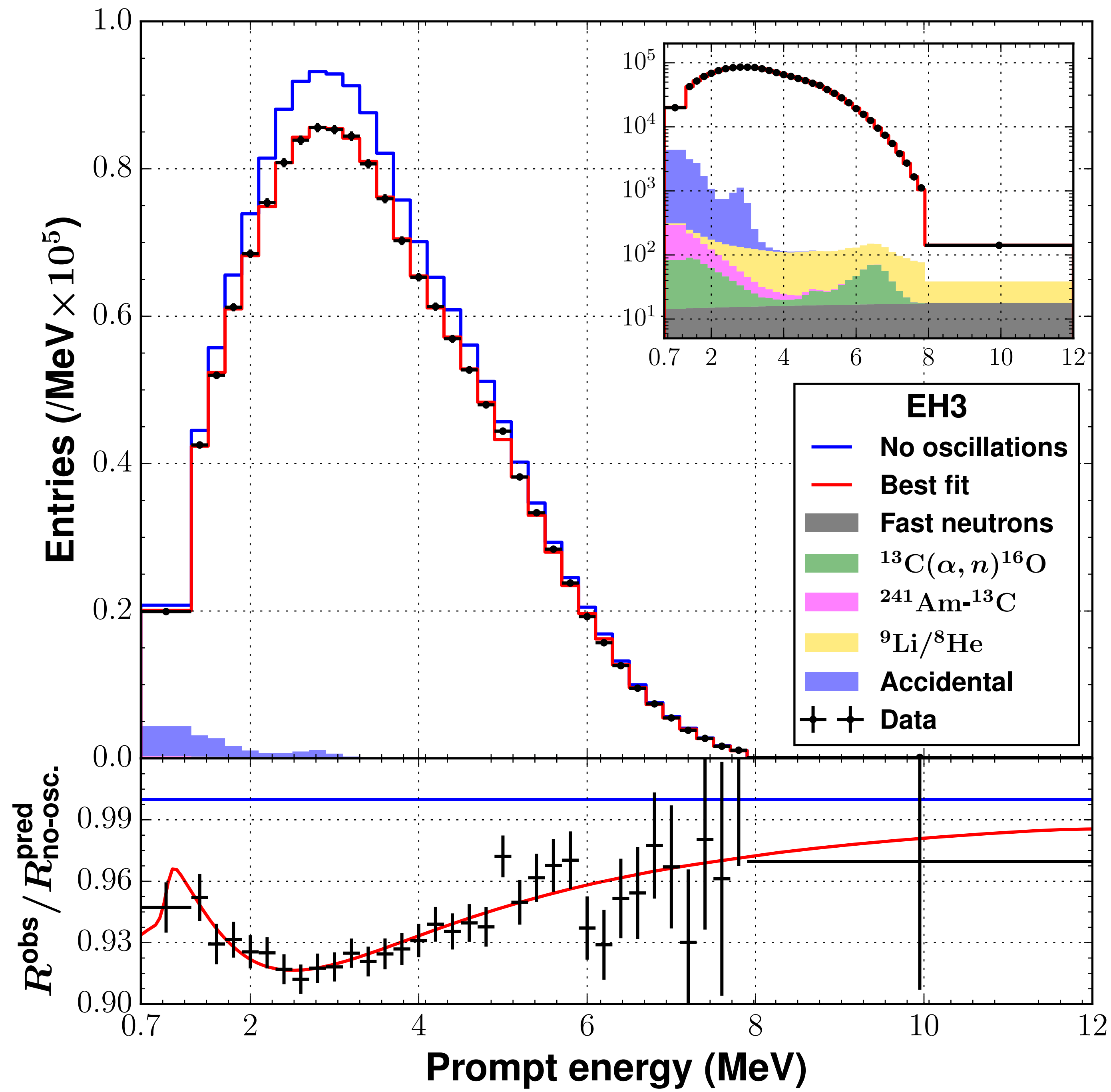
Relative energy scale uncertainty < 0.2%



Absolute antineutrino energy scale uncertainty ~1%

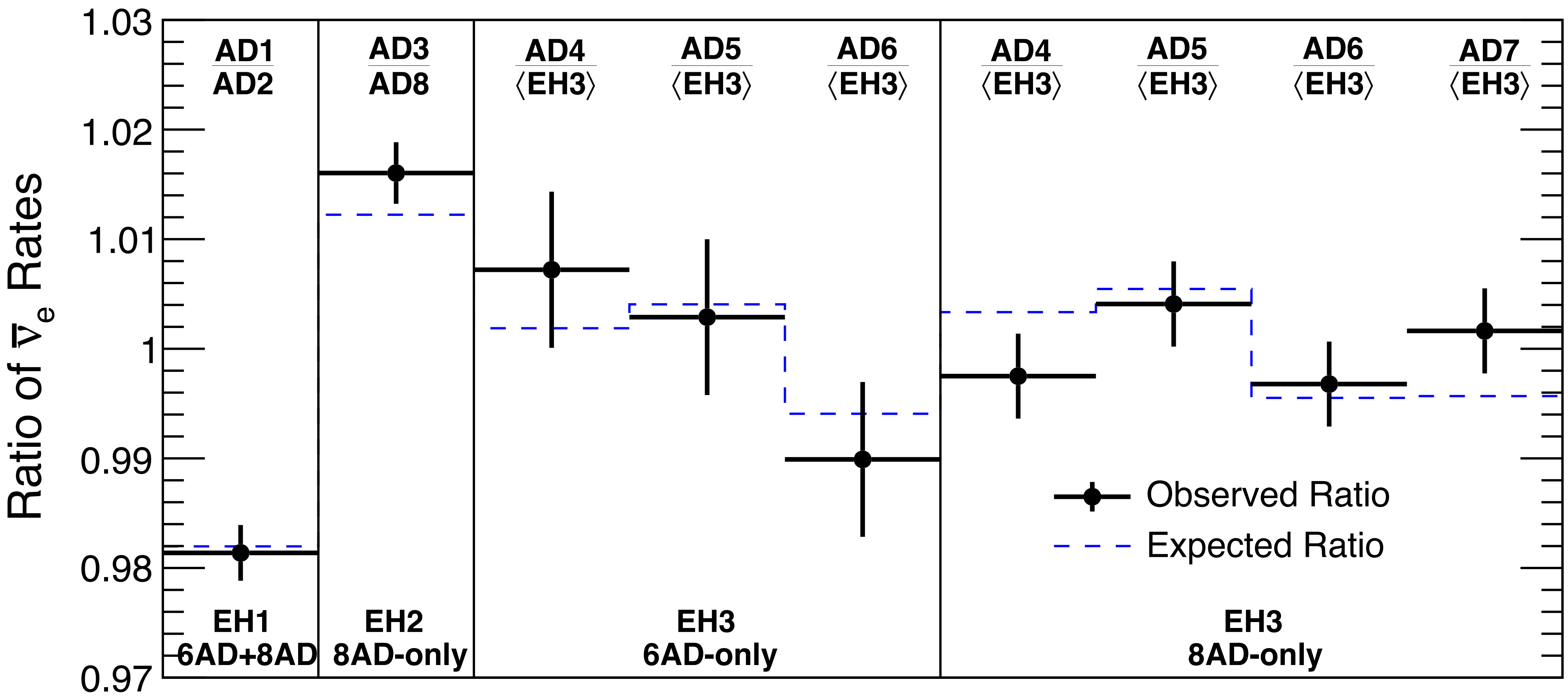
nGd Oscillation Analysis Dataset

- Our latest oscillation result based on neutron capture on Gd uses **1230 days of data**:
  - More than **2.5 million antineutrino interactions** (300K in the far hall)
  - Backgrounds amount to less than 2% in all halls
  - Significant improvements in background reduction and energy calibration with respect to first publications (*see next slide*)



Side-by-side Comparison

- One of the most significant improvements was the reduction of the relative detection efficiency uncertainty down to **0.13%**
- Comparing the rates of detectors in the same hall allows to examine this claim:



Ratios of IBD rates consistent with expectations!

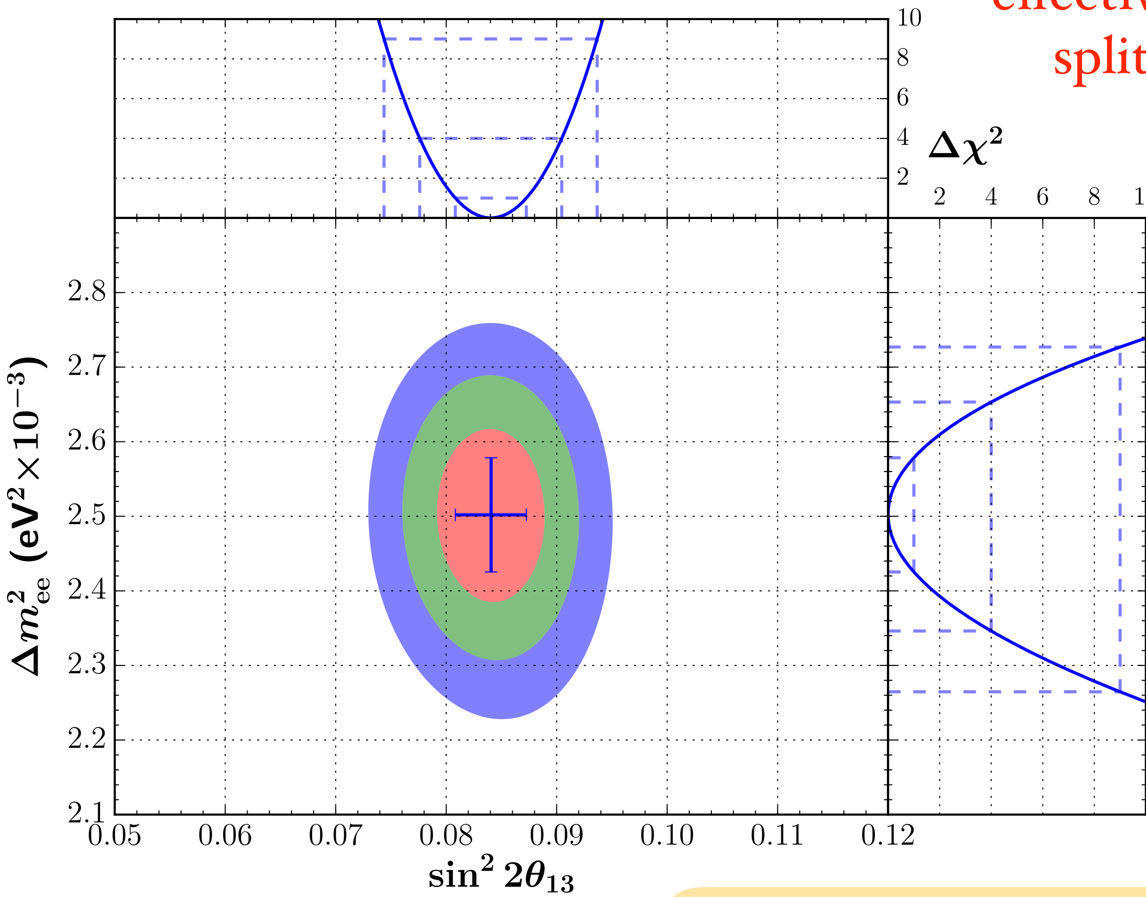
Uncertainty dominated by the statistics and the 0.13% relative error. The background uncertainties mostly cancel in this plot.

nGd Oscillation Analysis Results

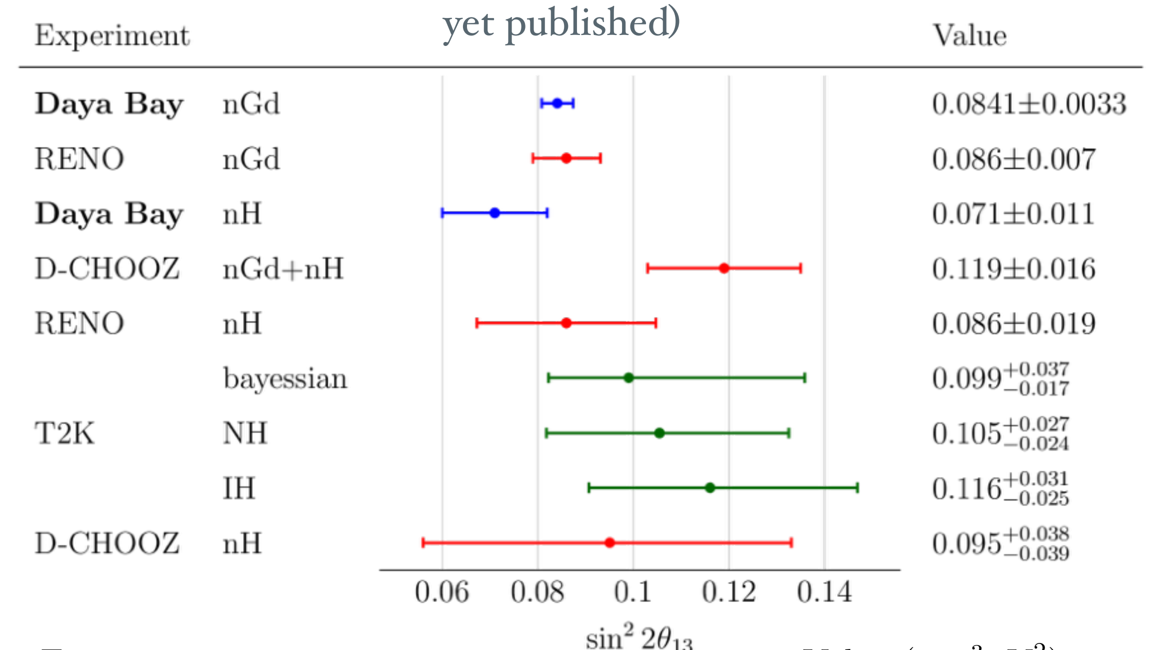
- With a relative rate + shape measurement achieve the **world's most precise determination of θ_{13} and Δm^2_{ee}**:

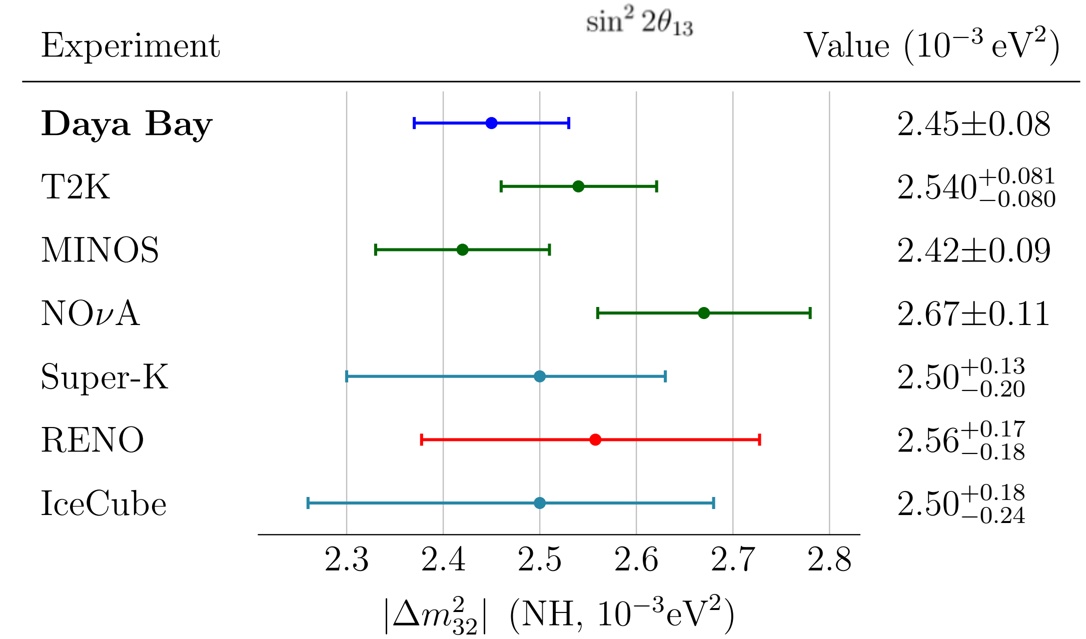
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{1.267\Delta m^2_{21}L}{E} - \sin^2 2\theta_{13}\sin^2\frac{1.267\Delta m^2_{ee}L}{E}$$

effective mass splitting



(some of these results not yet published)





Phys. Rev. D 95, 07006 (2017)

$\sin^2 2\theta_{13}$ = [8.41±0.27(stat.)±0.19(syst.)]x10^{-2}

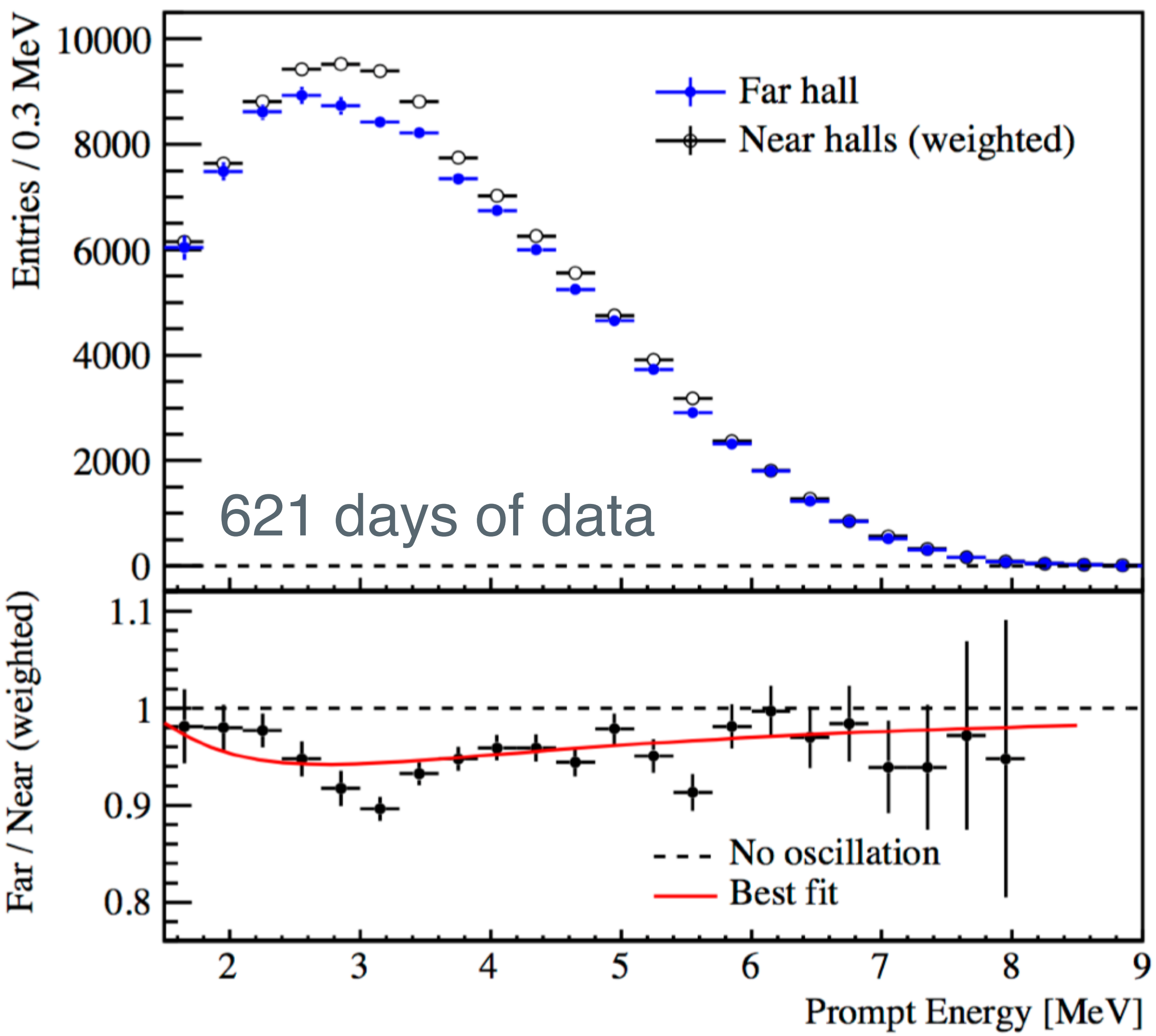
$|\Delta m^2_{ee}|$=[2.50±0.06(stat.)±0.06(syst.)]x10^{-3} eV^2

χ^2/ndf = 234.7/263

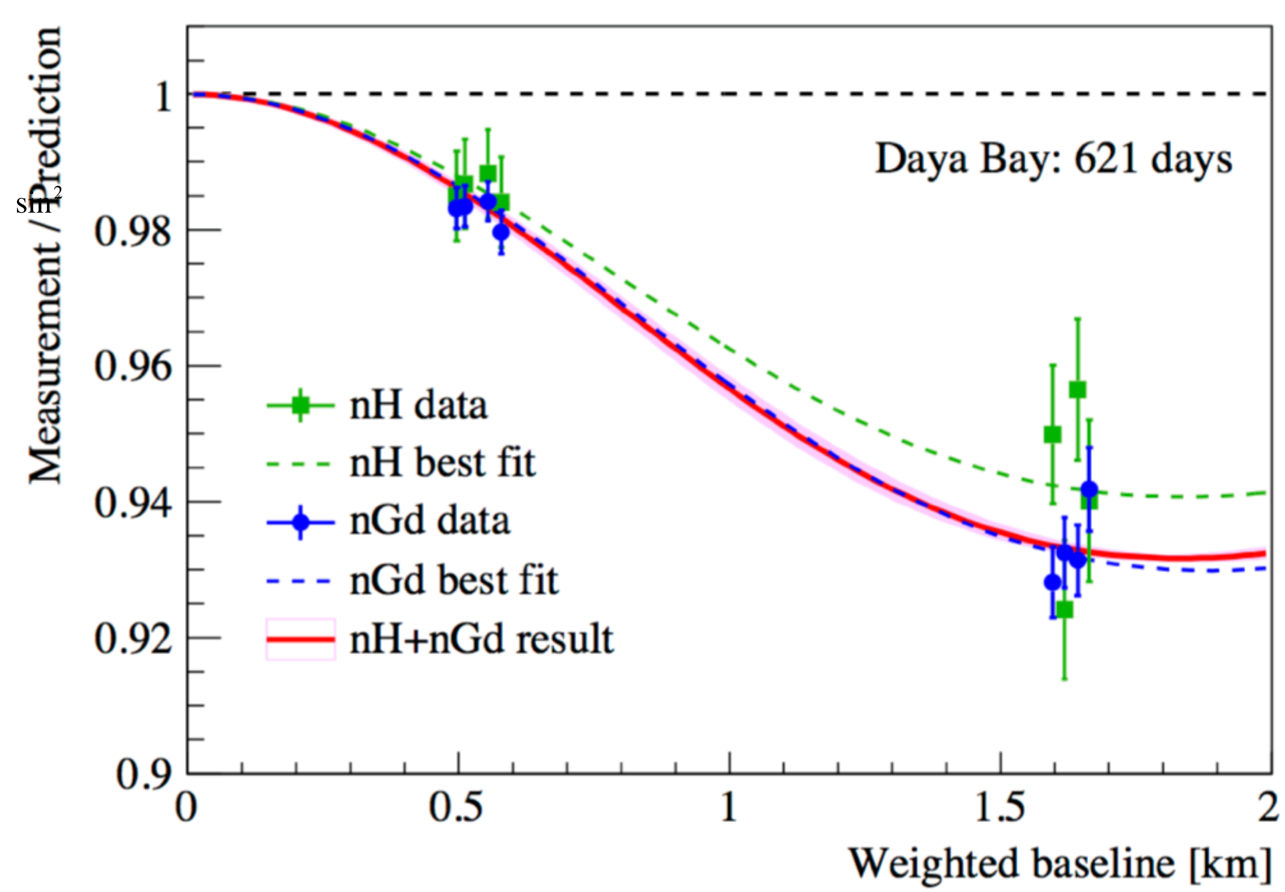
still statistics dominated!

nH Oscillation Analysis Results

- An **independent** measurement is achieved with IBD events where the neutron captures on hydrogen:



One of the challenges is the large accidental background (>50 times larger than for nGd analysis)

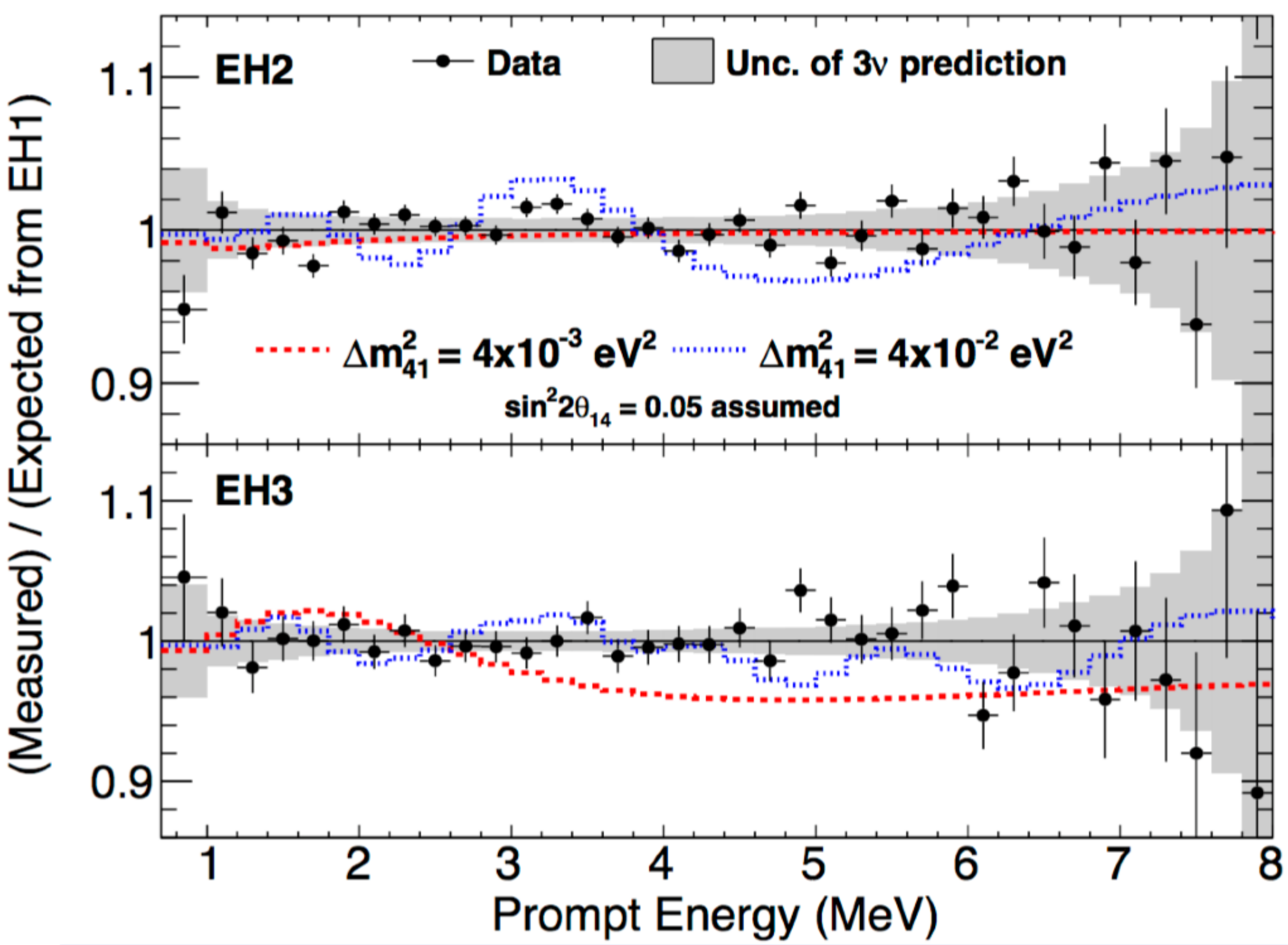


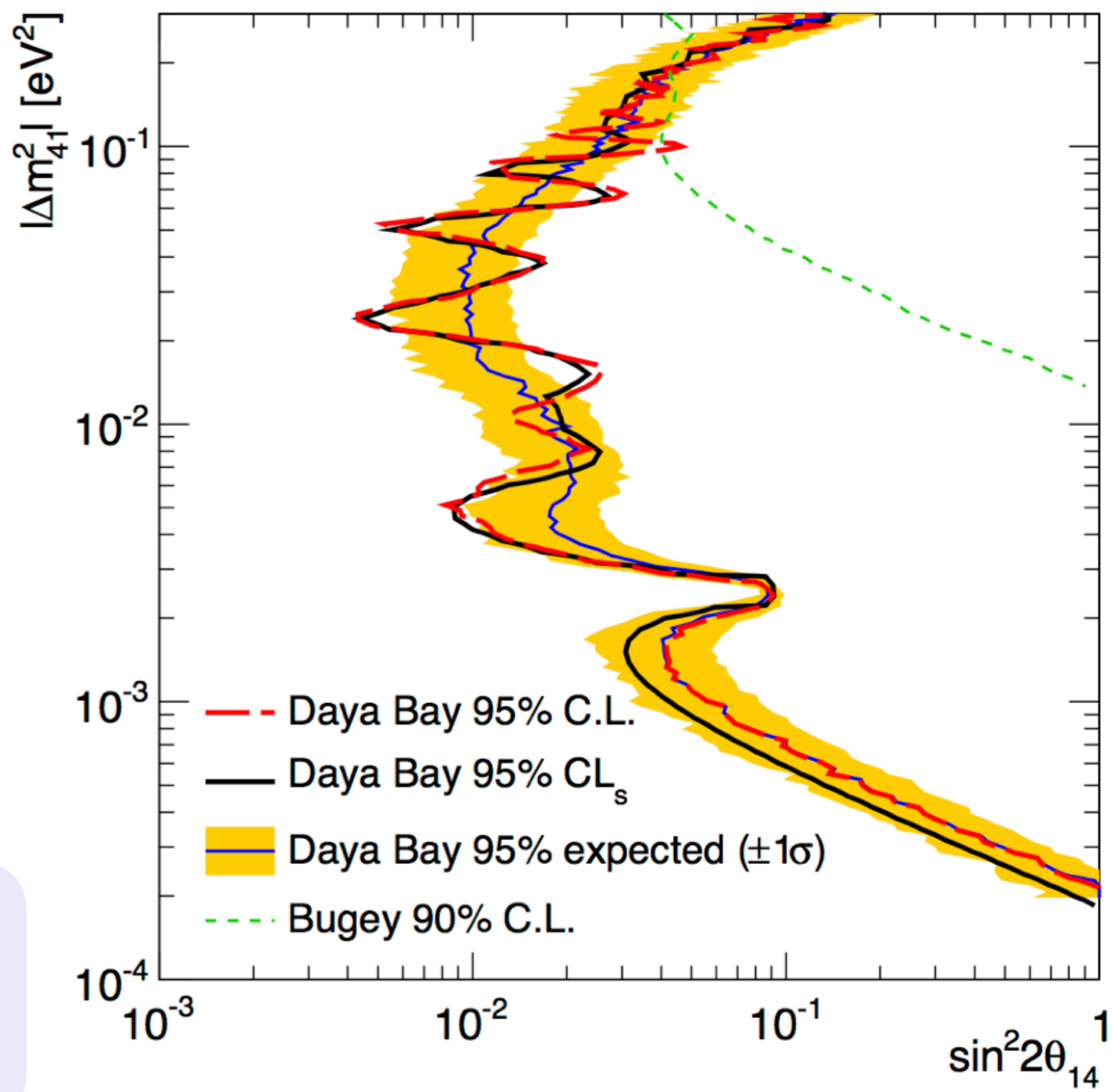
Rate analysis: $\sin^2 2\theta_{13} = 0.071 \pm 0.11$, $\chi^2/\mathrm{ndf} = 6.3/6$

Phys. Rev. D 93, 072011 (2016)

Search for Light Sterile Neutrino Mixing

- A relative comparison of the energy spectra at the three sites allows to search for sterile neutrino mixing:





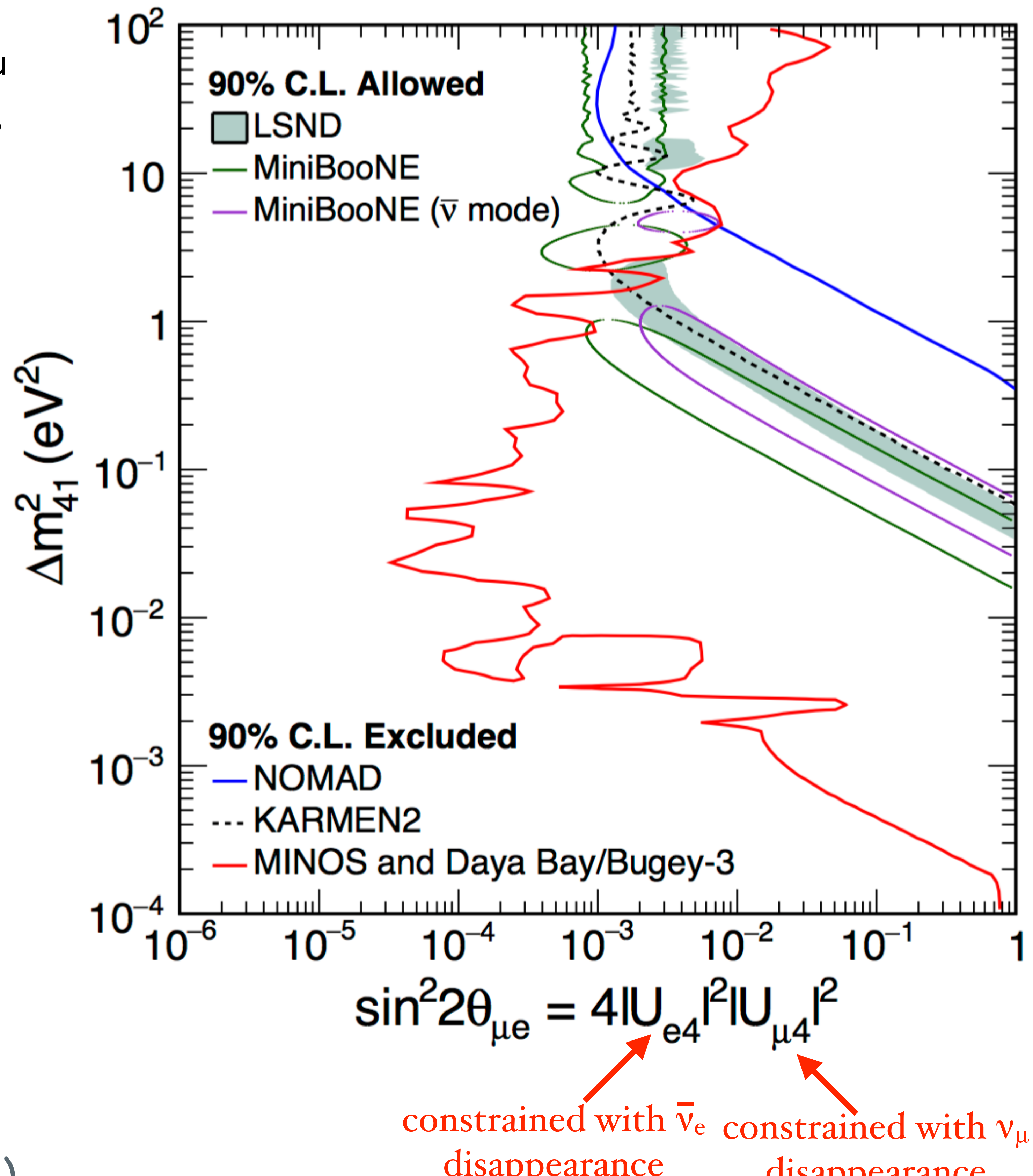
Signal would primarily appear as an additional spectral distortion with a frequency different from standard 3ν oscillations

Obtain the most stringent limits on $\sin^2 2\theta_{14}$ in the 2×10^{-4} eV^2 < $|\Delta m^2_{41}|$ < 0.2 eV^2 region

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

Constraining Appearance Results

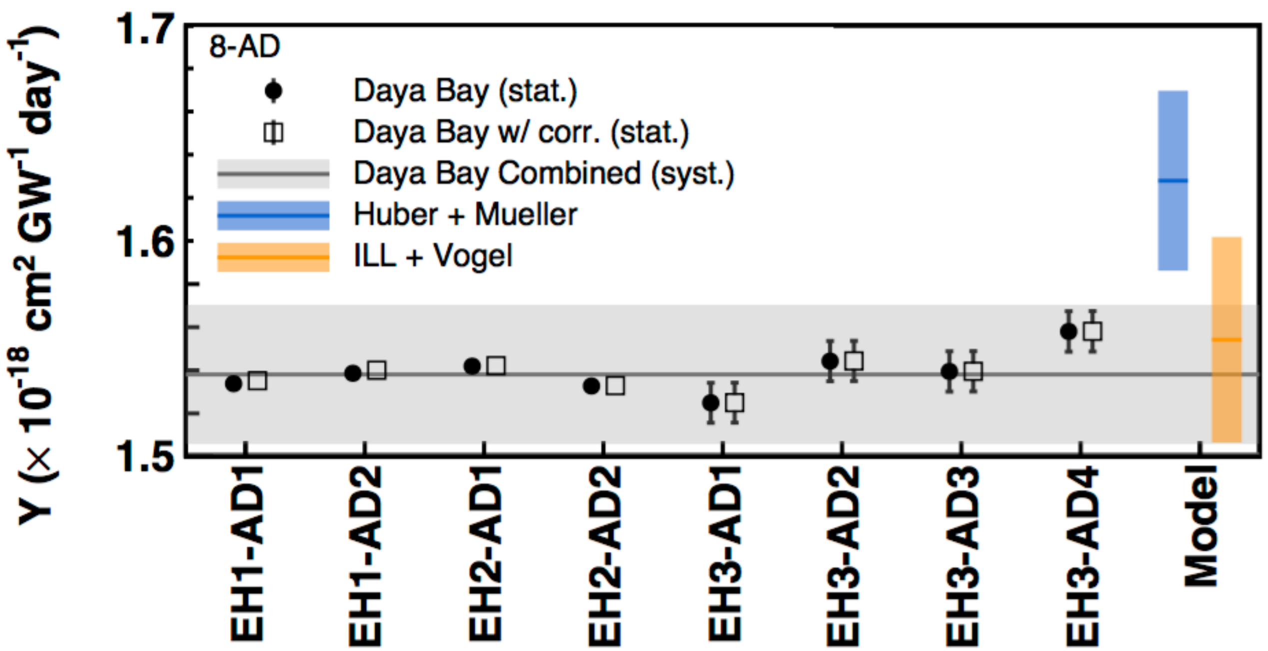
- This result is combined with ν_μ disappearance measurements in order to constrain electron (anti)neutrino appearance results:
    - MINOS & Daya Bay have released a combined result that also includes the updated Bugey-3 $\bar{\nu}_e$ disappearance data
    - **Place stringent limits on $\sin^2\theta_{\mu e}$ over six orders of magnitude in Δm^2_{41}**
    - Exclude parameter space allowed by MiniBoone & LSND for $\Delta m^2_{41} < 0.8$ eV^2

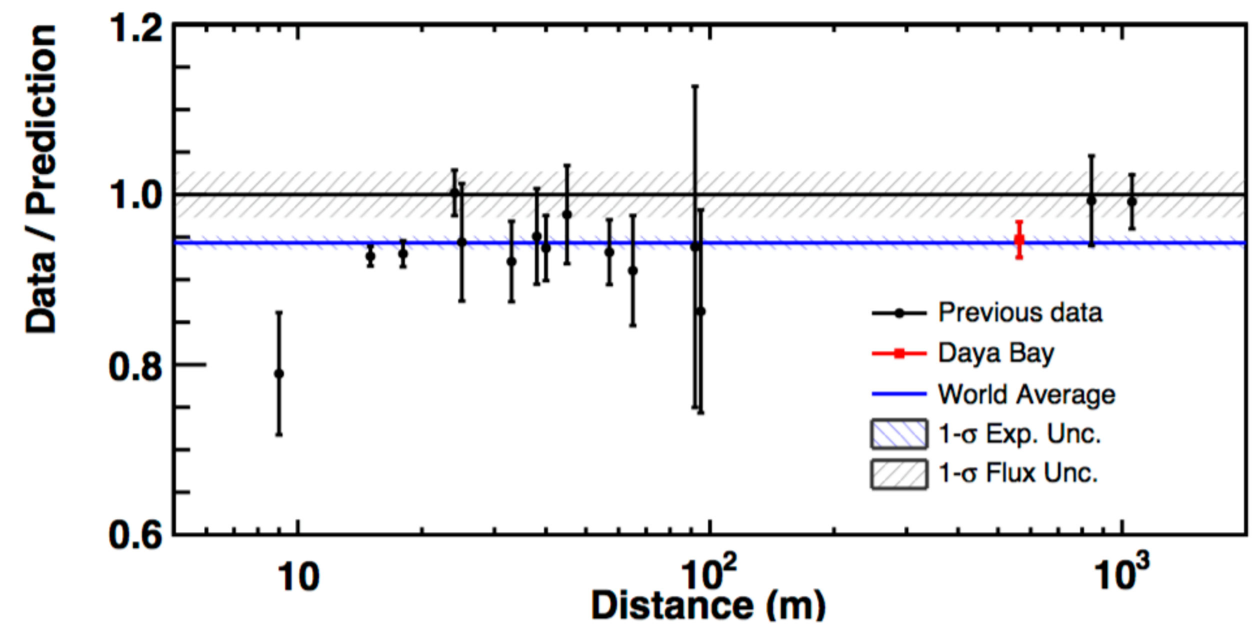


Phys. Rev. Lett. 117, 151801 (2016)

Reactor Antineutrino Flux

- Measurement of IBD yield in the eight detectors is consistent with that from other short baseline reactor experiments:





IBD Yield	
Y (cm^2/GW/day)	$(1.55 \pm 0.03) \times 10^{-18}$
σ_f (cm^2/fission)	$(5.92 \pm 0.12) \times 10^{-43}$
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

R_{global} = 0.942 ± 0.009(exp) ± 0.023(model)

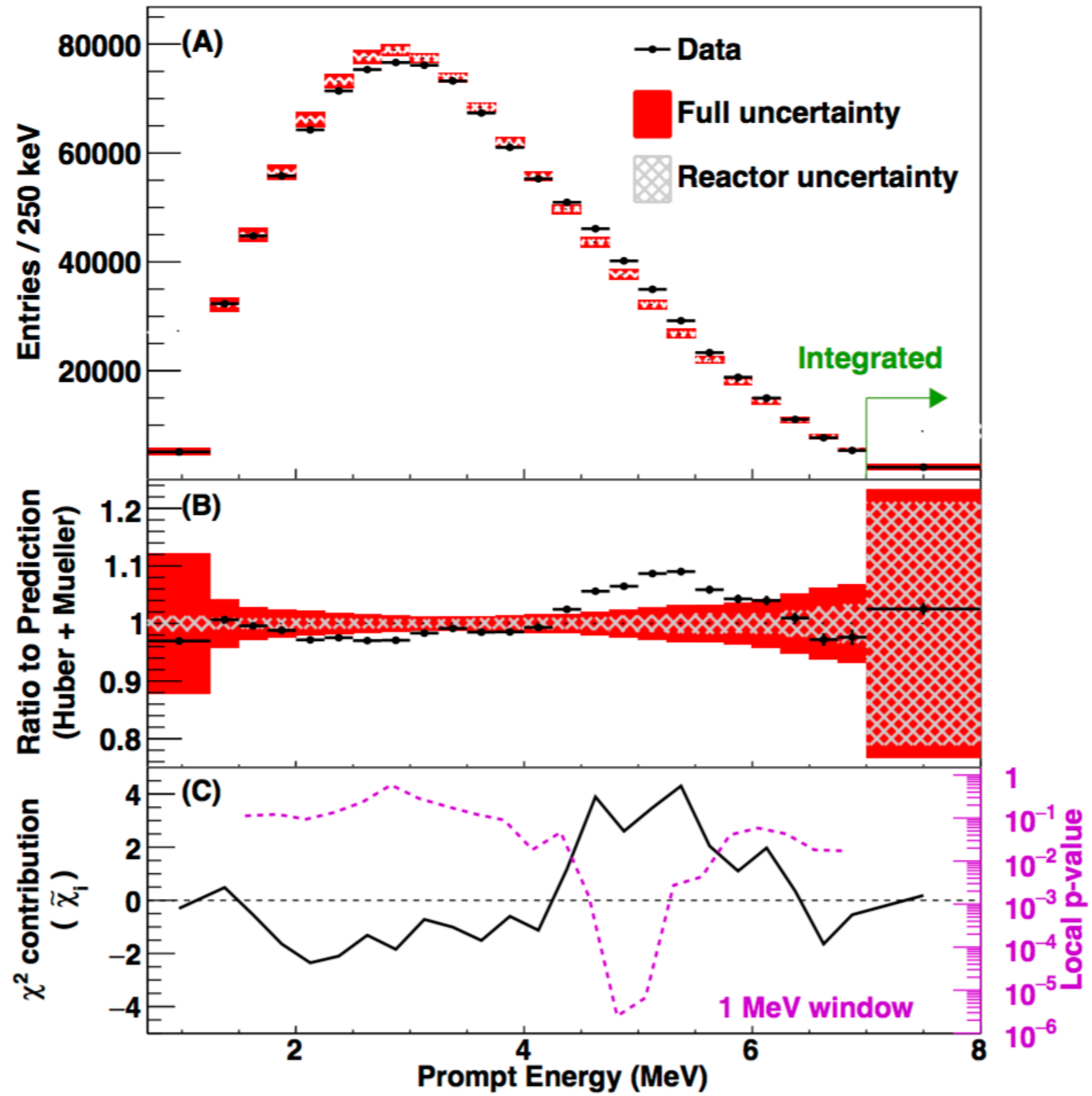
$R_{global+DYB}$ = 0.943 ± 0.008(exp) ± 0.023(model)

Discrepancy with Huber+Mueller model could be due to underestimated uncertainties in the prediction, and/or the existence of a sterile neutrino.

Chin. Phys. C 41, 13002 (2017)

Reactor Antineutrino Spectral Shape

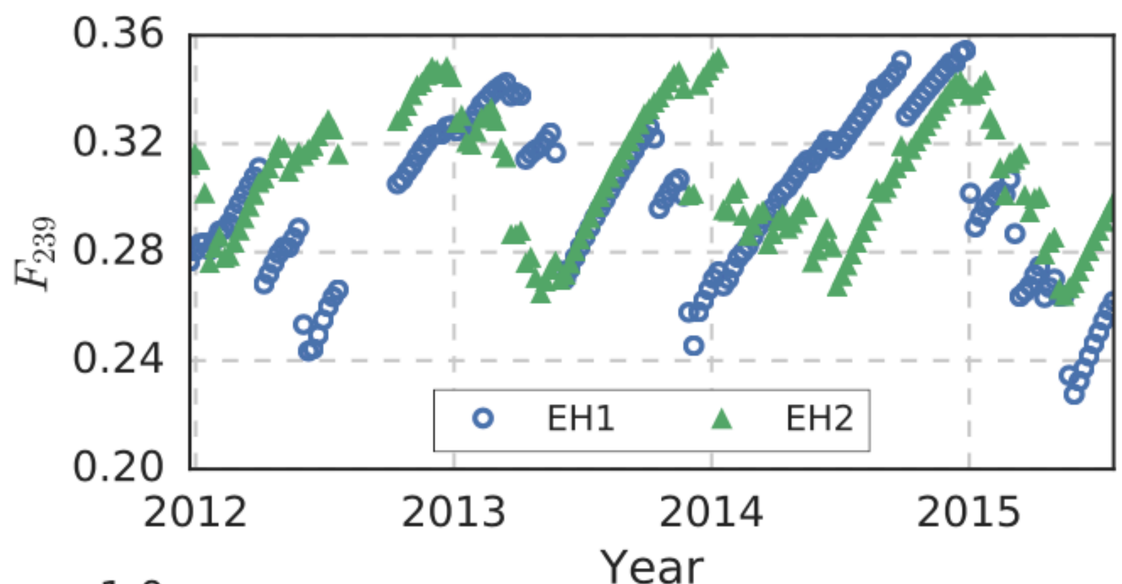
- Have also made a **high-statistics measurement** of the spectral shape of reactor antineutrinos:
  - Comparison with the Huber + Mueller prediction reveals a 2.9σ discrepancy overall (**4.4σ in the 4-6 MeV region**)
  - Excess events have all the IBD characteristics and are reactor power correlated
  - Excess does not appear in ^{12}B spectra (disfavoring detector effects).
- Weakens case for sterile neutrino interpretation of reactor antineutrino anomaly



Chin. Phys. C 41, 13002 (2017)

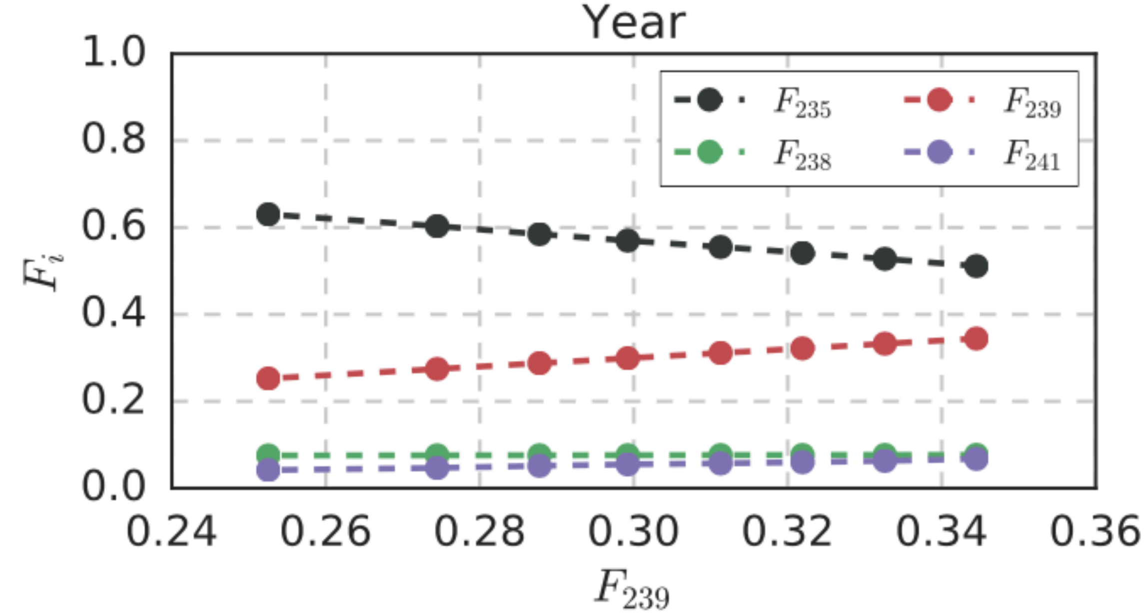
Fuel Evolution

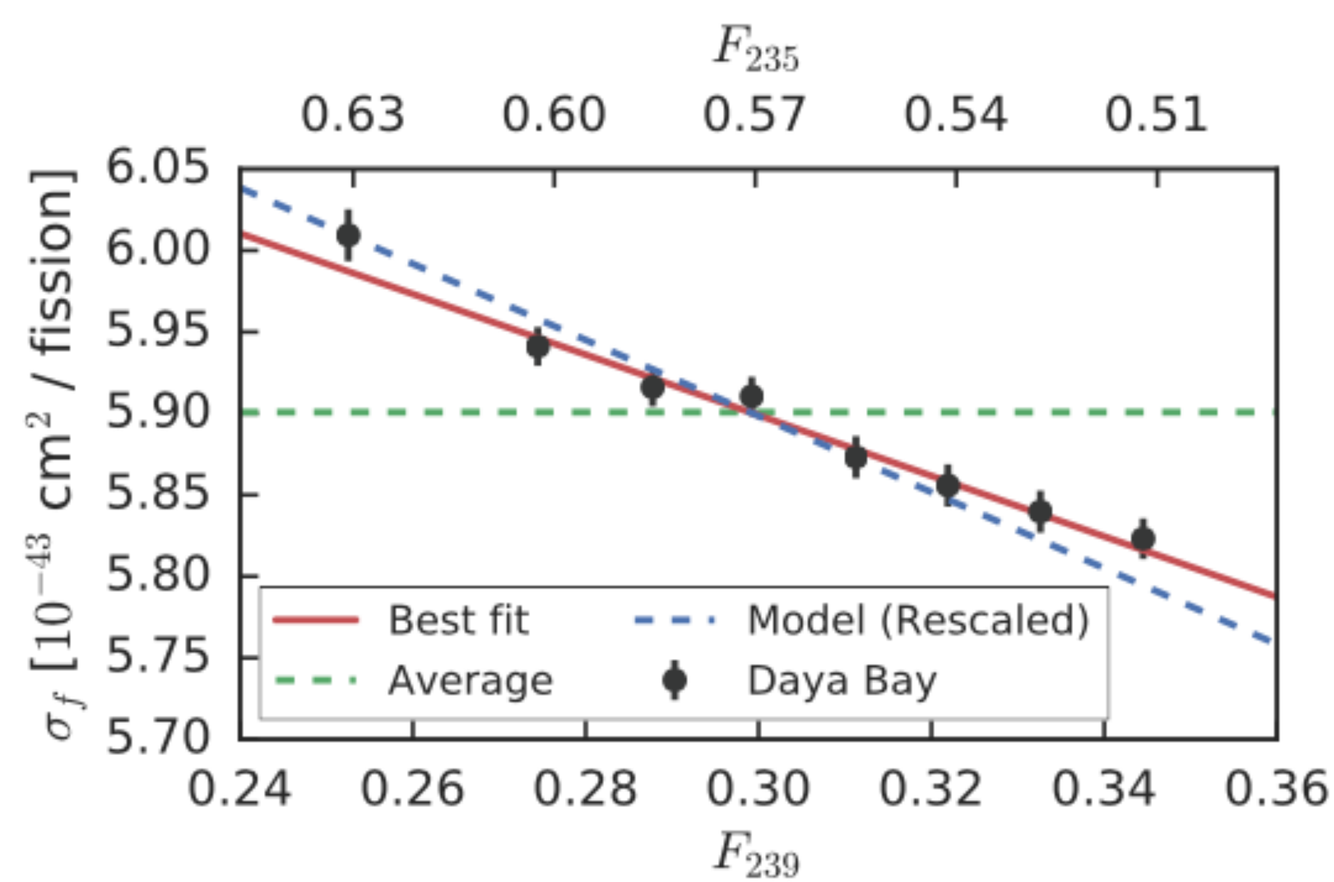
- Daya Bay's high-precision dataset also allows to study how the flux and spectral shape of reactor antineutrinos change with fuel composition:



– See clear changes in flux and shape vs. F239, as expected (>10σ and >5σ respectively)

– Evolution of yield/fission is inconsistent with prediction from Huber + Mueller model at ~3σ



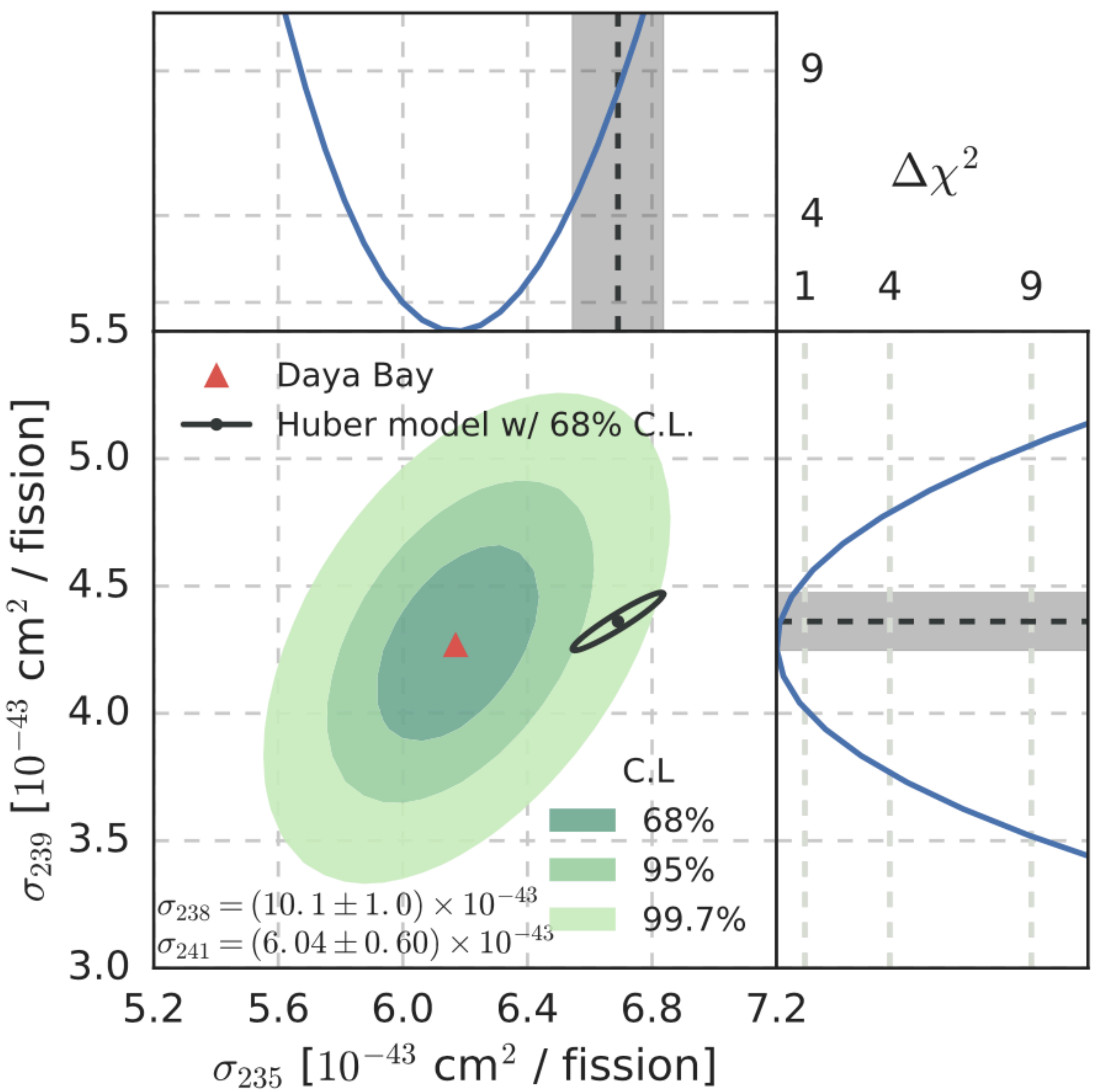


As the nuclear fuel burns, the effective fission fractions (F) change

Phys. Rev. Lett. 118, 251801 (2017)

Fuel Evolution

- Also extract individual yields per fission for the two dominant isotopes (^{235}U and ^{239}Pu) using conservative constraints on the two minor ones (^{241}Pu and ^{238}U):



Phys. Rev. Lett. 118, 251801 (2017)

- ^{235}U identified as the primary source of the reactor antineutrino anomaly
- **Equal deficit of all isotopes** (as required by sterile neutrino interpretation of anomaly) **disfavored at 2.8σ**

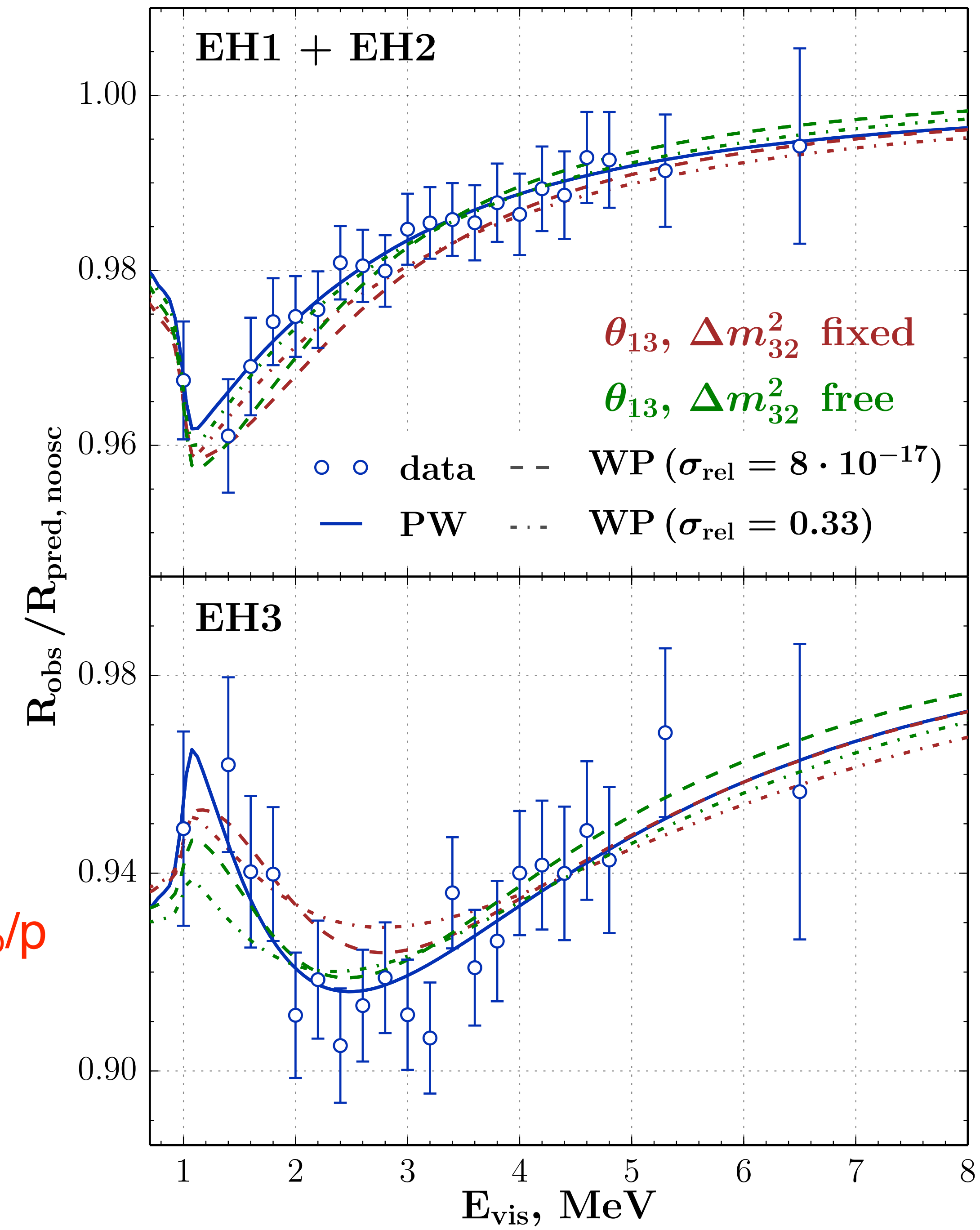
A word of caution: there is a tension between Daya Bay's result and the global reactor flux data, diminishing the significance of this result (see arXiv: 1708.01133 and arXiv:1707.07728)

- Evolution of spectrum is in good agreement with Huber-Mueller model and shows no abnormalities at 4-6 MeV

Search for Neutrino Decoherence

- Daya Bay's rich dataset can also be used to probe neutrino decoherence:
  - The plane-wave approximation has been successful in explaining most experimental results to date, but is not self-consistent
  - We examine the data in a framework where the neutrino momentum is described as a Gaussian wave-packet
  - The resulting modified oscillation probability depends only on one additional parameter: σ_{rel}

= relative wave packet momentum dispersion σ_p/p



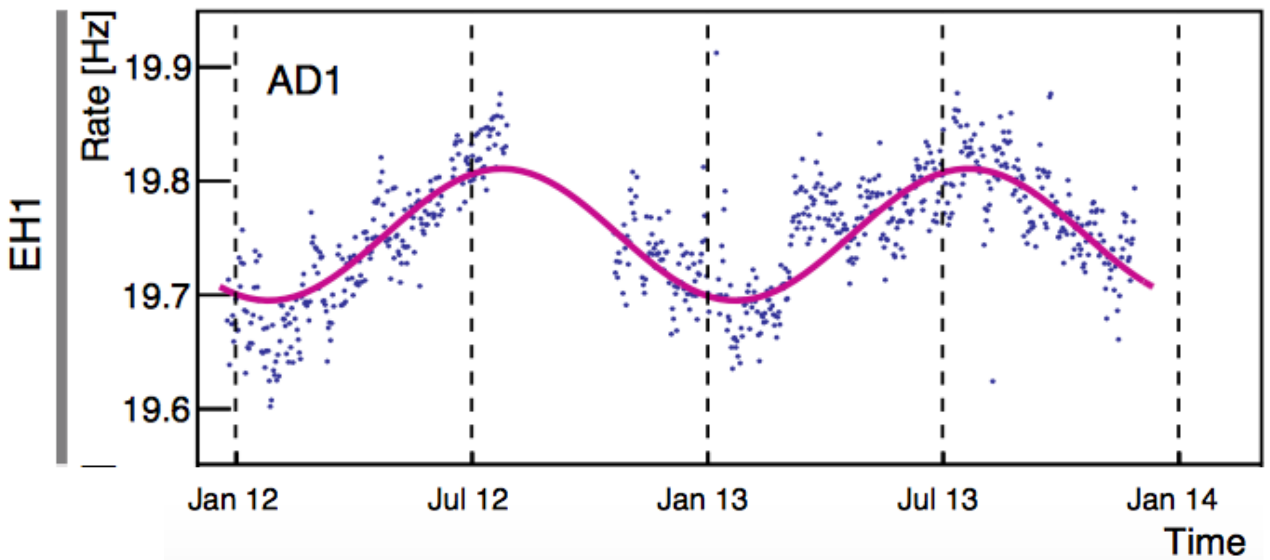
- Provide the first experimental constraints on σ_{rel}:

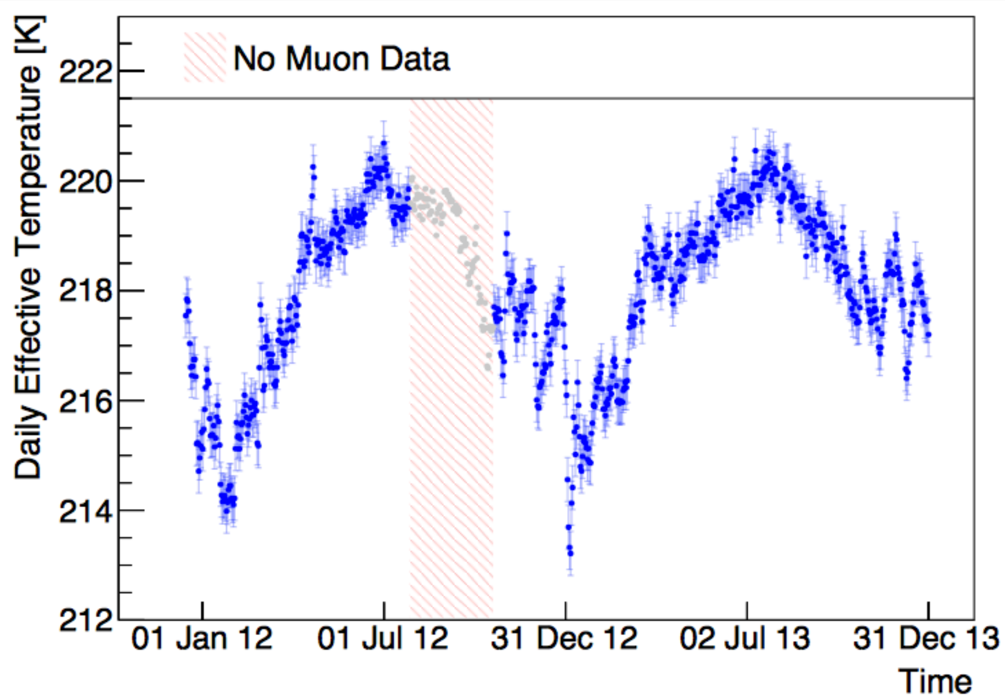
$$10^{-14} \lesssim \sigma_{rel} < 0.23$$

Eur. Phys. C, 77:606 (2017)

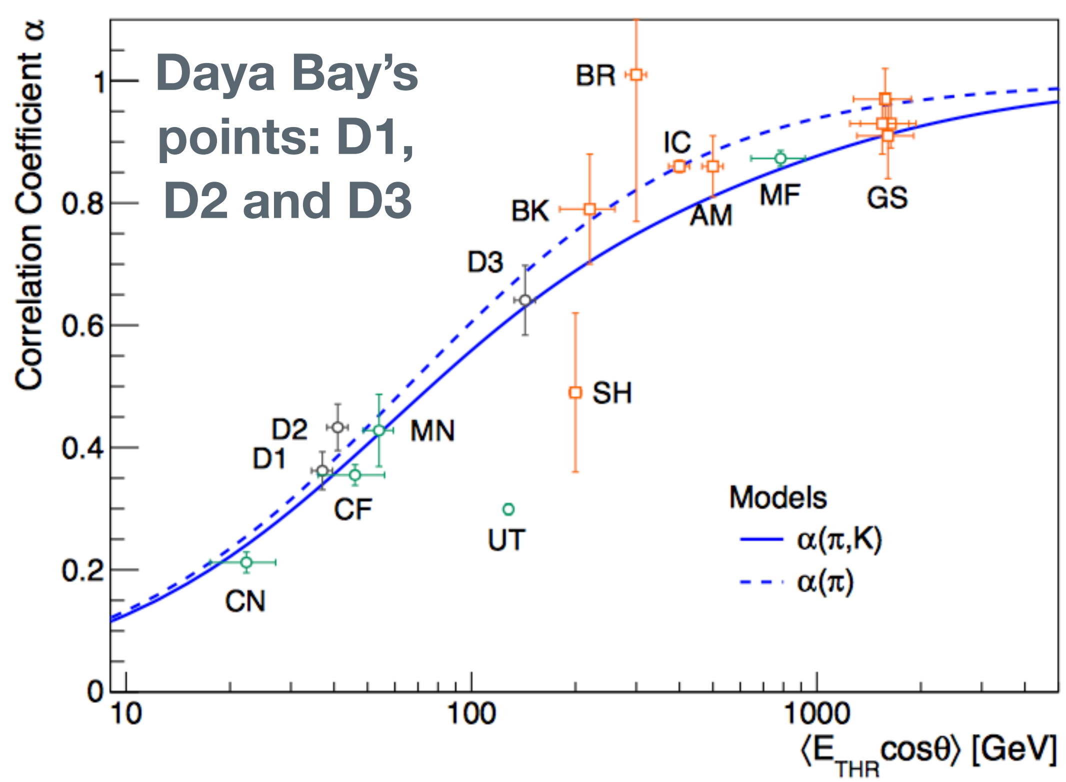
Modulation of Cosmic Muon Flux

- Daya Bay's detectors also allow for a precise measurement of the cosmic muon flux at different overburdens (i.e. average energies).
- Have observed a clear correlation with the stratospheric temperature:





As T increases the atmosphere becomes less dense, reducing mesons' probability of interaction



Measurement of correlation coefficients is consistent with the model.

arXiv:1708.01265

Summary & Outlook

- Have updated many results and released some new ones this summer:

Latest oscillation results →

$$\sin^2 2\theta_{13} = (8.41 \pm 0.33) \times 10^{-2}$$
$$|\Delta m^2_{ee}| = (2.50 \pm 0.08) \times 10^{-3}\ \mathrm{eV}^2$$

+ high-statistics absolute reactor antineutrino flux and shape measurements, fuel evolution, searches for a sterile neutrino, … etc.

- Daya Bay will run until 2020 and produce many other important results:
  - Working to further reduce the systematics through an FADC readout system in EH1-AD1 and a special calibration campaign, among other activities.
  - Goal is to **reduce uncertainties in θ_{13} and Δm^2_{ee} to < 3%.**
  - Other results are also in preparation (CPT violation search, neutron yield…)