Latest Results from the Daya Bay Reactor Neutrino Experiment

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****on behalf of the Daya Bay Collaboration***

NuFact

Quy Nhon, August 2016

Outline

- Daya Bay
- Latest Results
  - nGd oscillation measurement*
  - nH oscillation measurement
  - Reactor antineutrino absolute rate & shape measurement*
  - Sterile neutrino search*
  - Decoherence search*
- Summary & Conclusions

* = just released this summer

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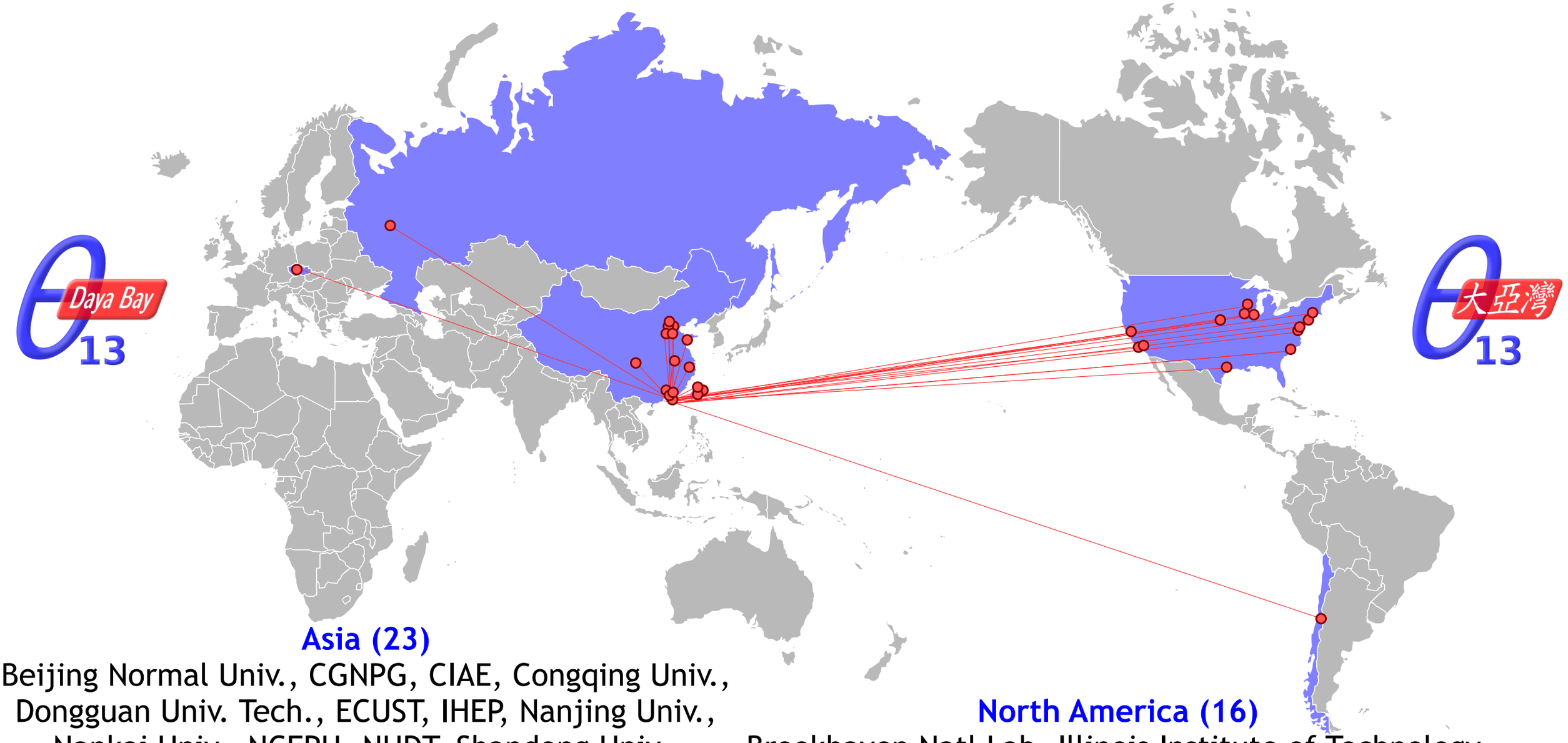
The Daya Bay Collaboration



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

~230 Collaborators

North America (16)
Brookhaven Natl Lab, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Siena College, Temple University, UC Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

South America (1)
Catholic University of Chile

Experimental Setup

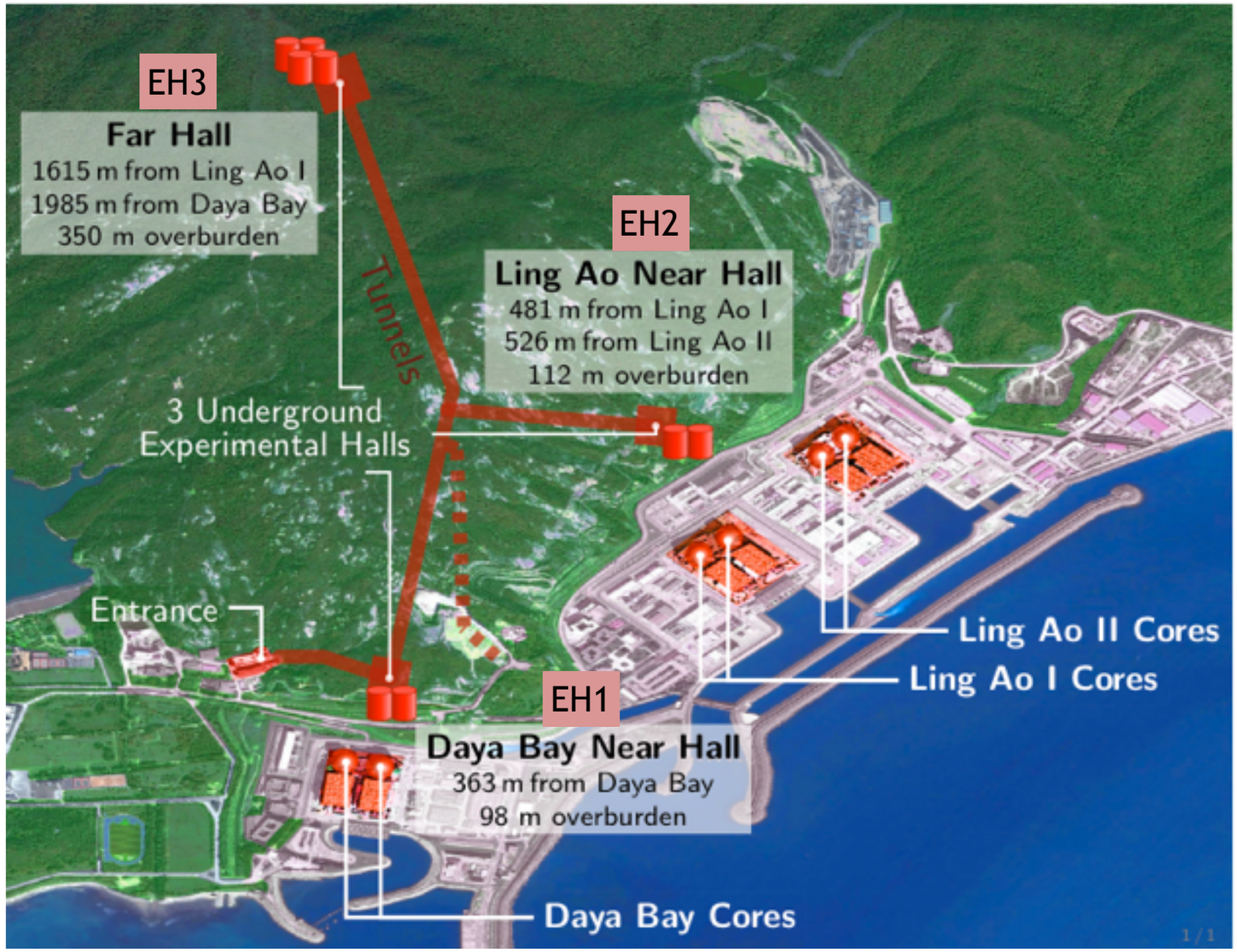
- 8 identically designed detectors positioned beside the Daya Bay Power Plant in China

Among the most powerful reactor complexes in the world!

- Main Principle:

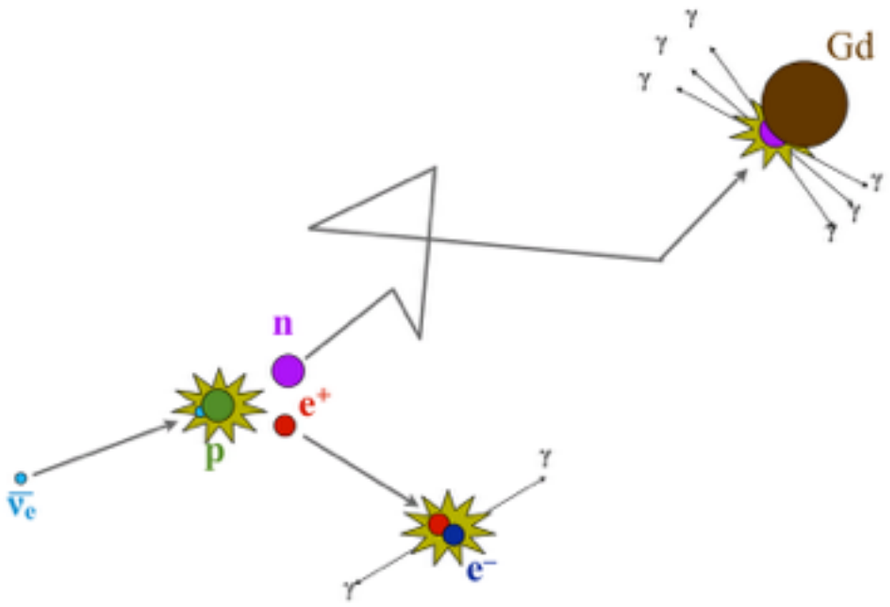
(i) sample the reactor antineutrino flux in the near and far locations, and

(ii) look for evidence of disappearance



Antineutrino Detection

- Antineutrinos are detected via the Inverse Beta Decay (IBD) reaction:



- ✔ Powerful background rejection
- ✔ Positron preserves most information about antineutrino energy

$\bar{\nu}_e + p \rightarrow e^+ + n$ (prompt signal)

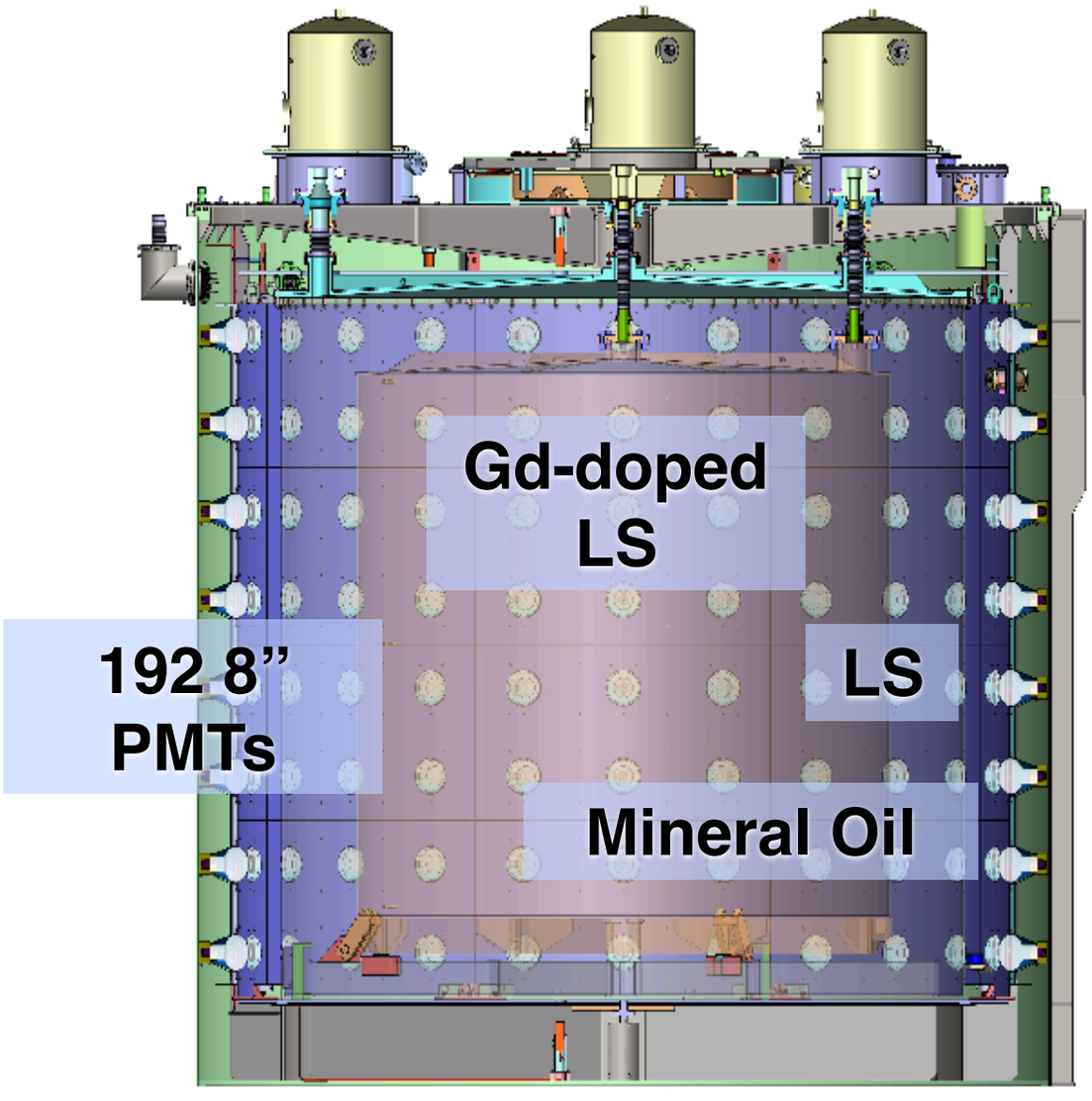
~200μs → $+ p \rightarrow D + \gamma$ (2.2 MeV) (delayed signal)

~30μs → $+ Gd \rightarrow Gd^*$ (for 0.1% Gd)

$Gd \rightarrow Gd + \gamma$'s (8 MeV) (delayed signal)

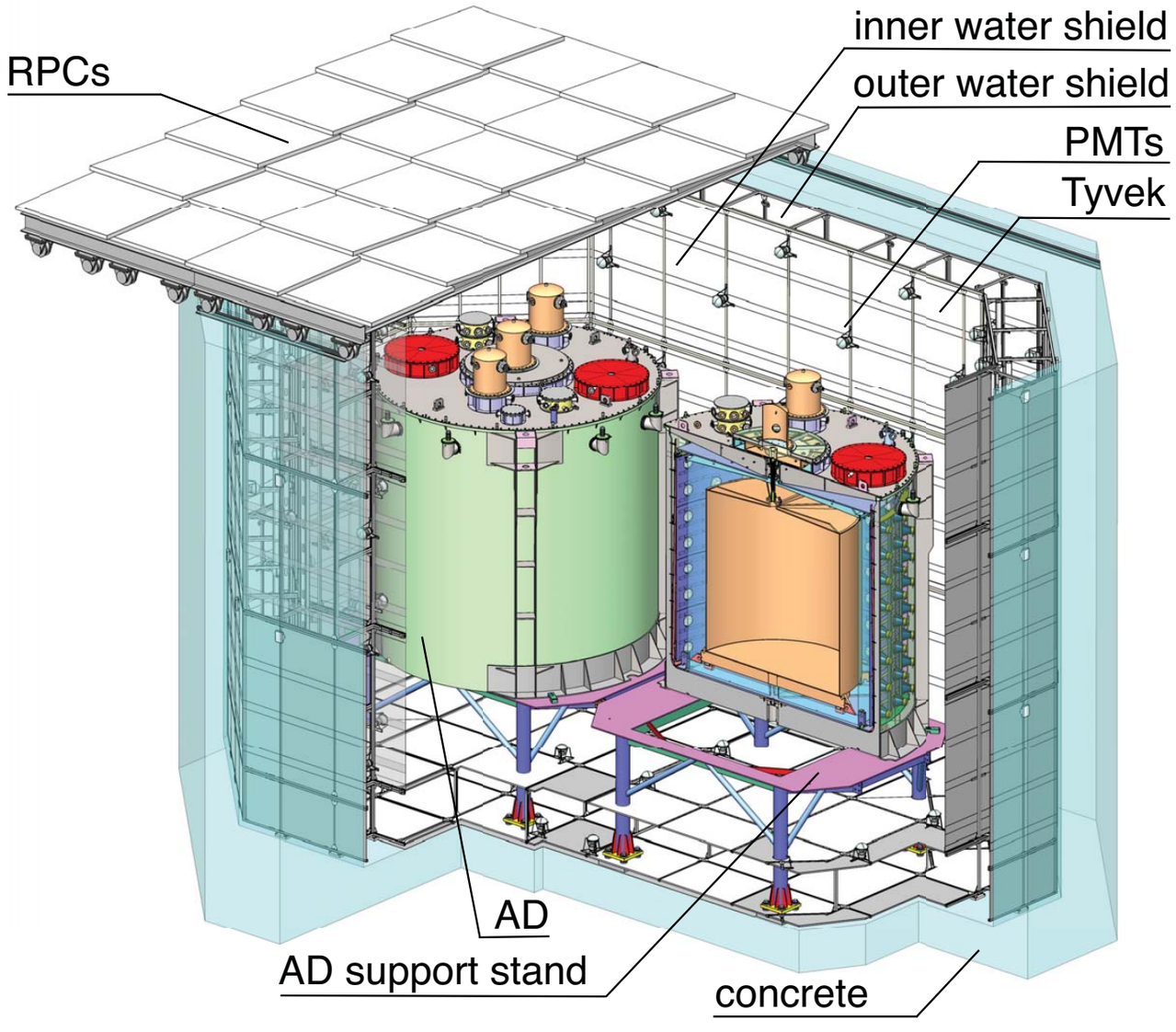
Antineutrino Detectors

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



Energy resolution:
$\sigma_E/E = 7.5\%/\sqrt{E}$

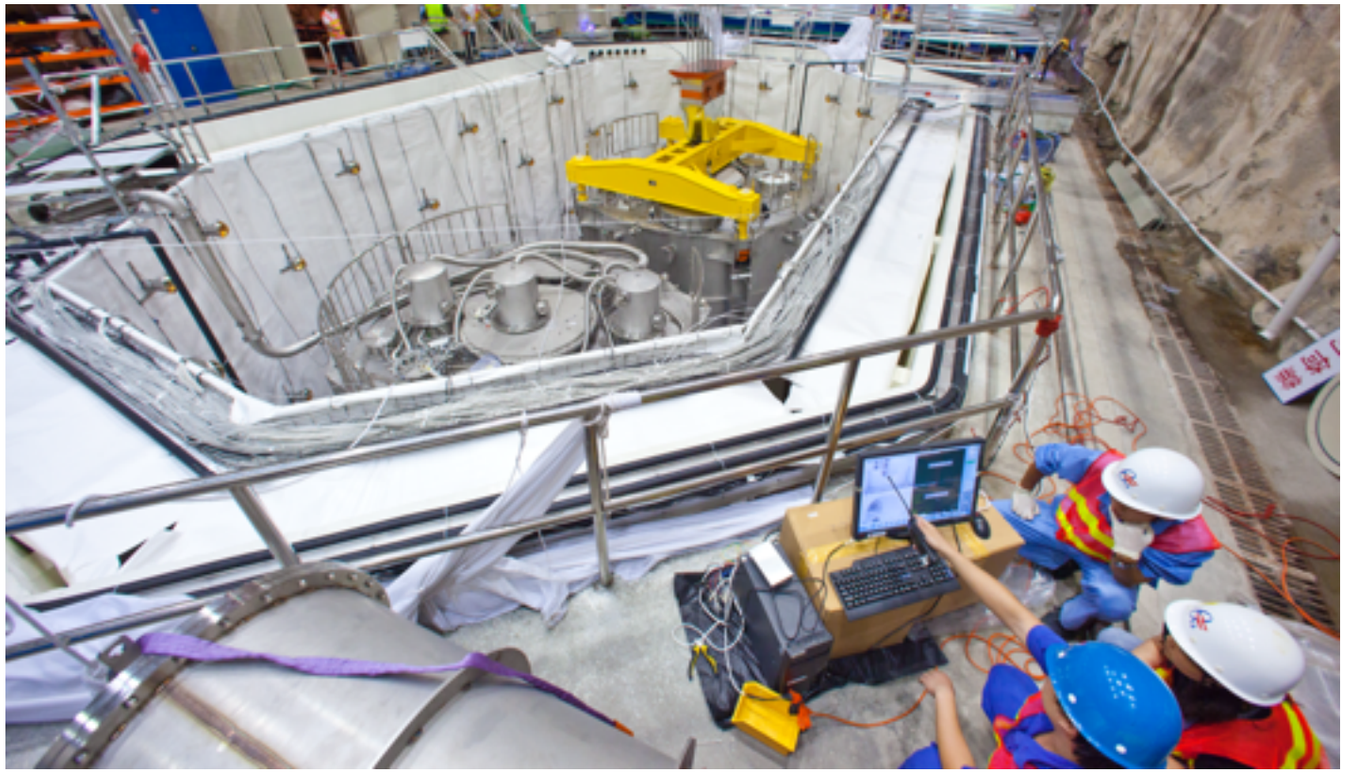
NIM A 811, 133 (2016)



Double purpose: shield the ADs and veto cosmic-rays

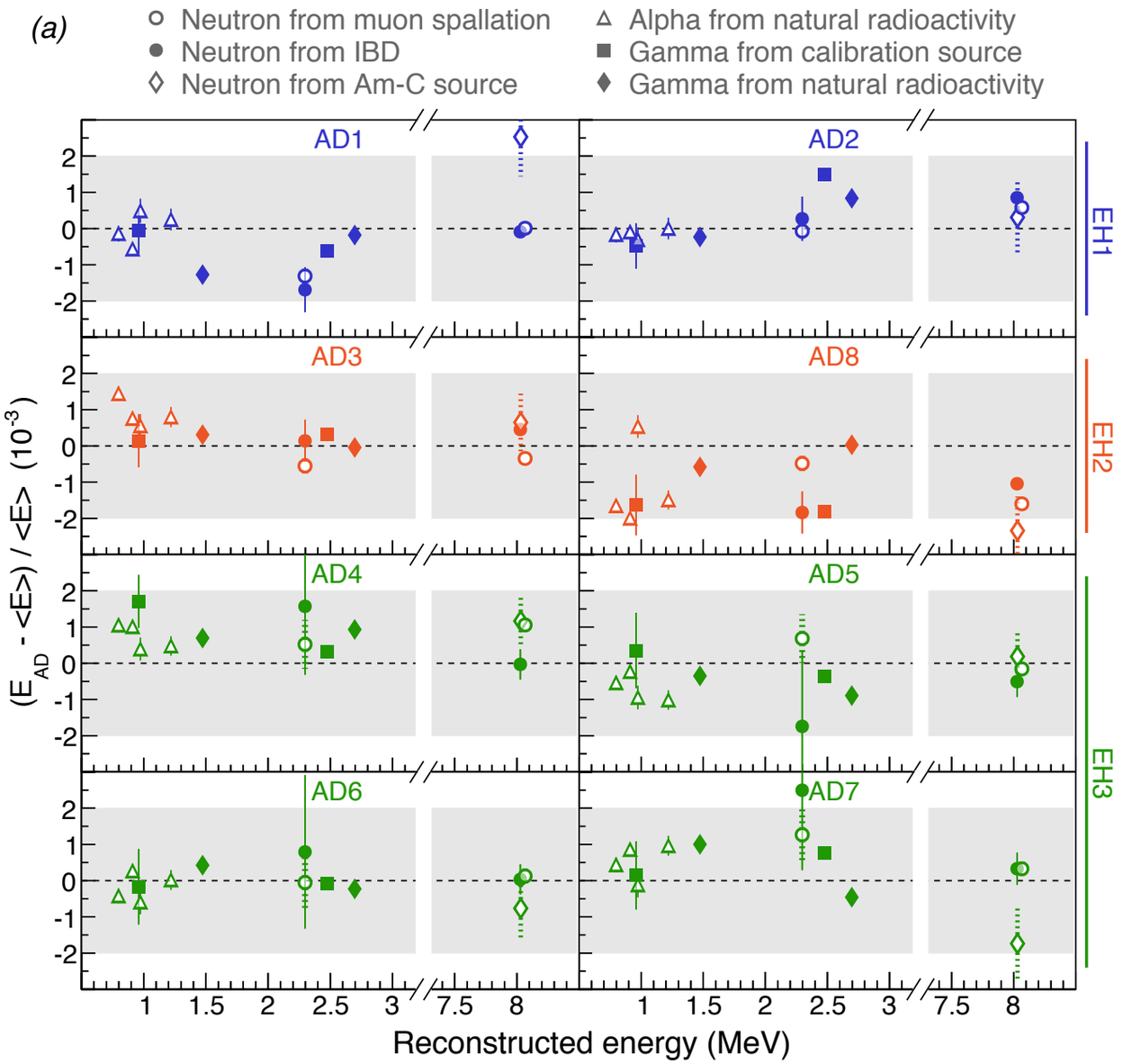
NIM A 773, 8 (2015)

Some Pictures

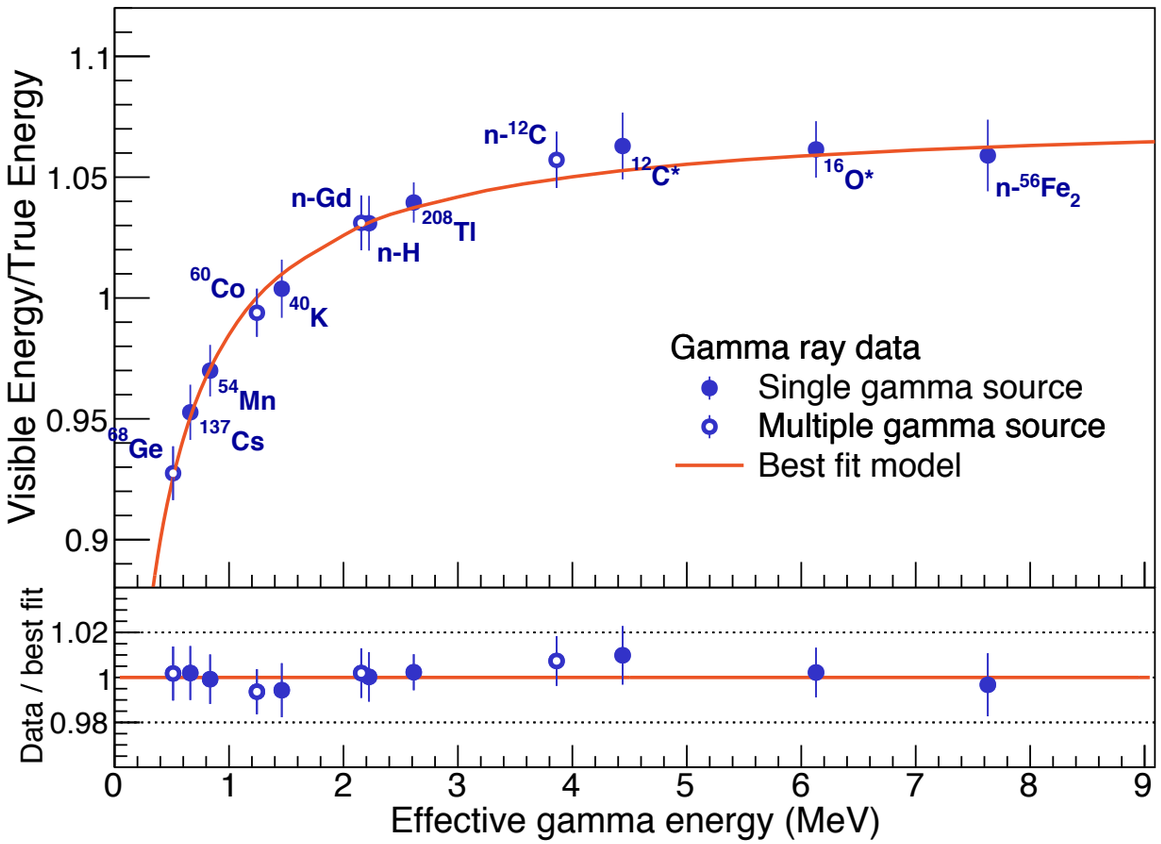


Energy Reconstruction

- 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 neutrino energy scale uncertainty ~1%

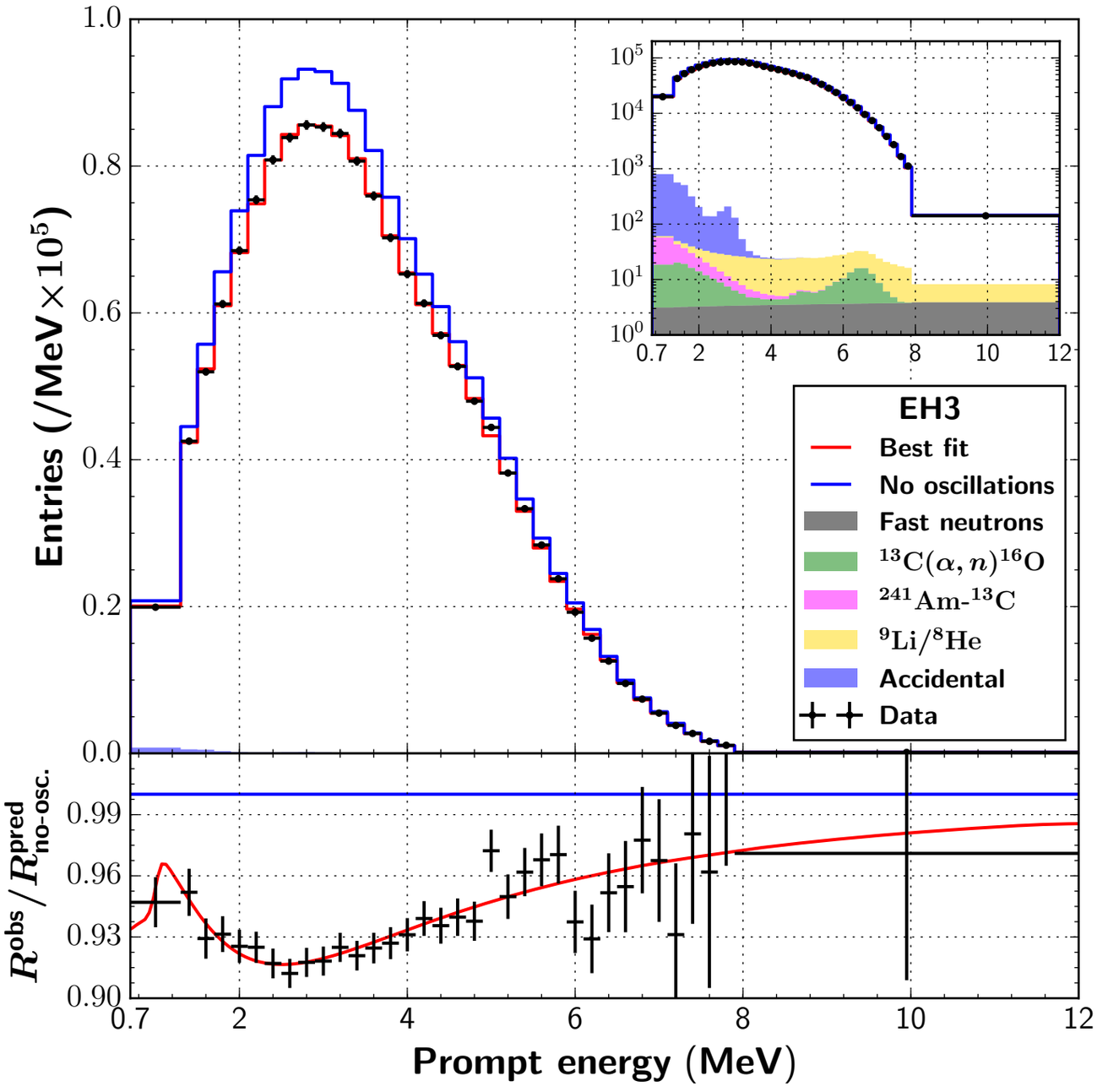
nGd Oscillation Analysis Dataset

- A new oscillation result based on neutron capture on Gd using **1230 days of data** has just been released :

  - More than **2.5 million antineutrino interactions** (300K in the far hall)

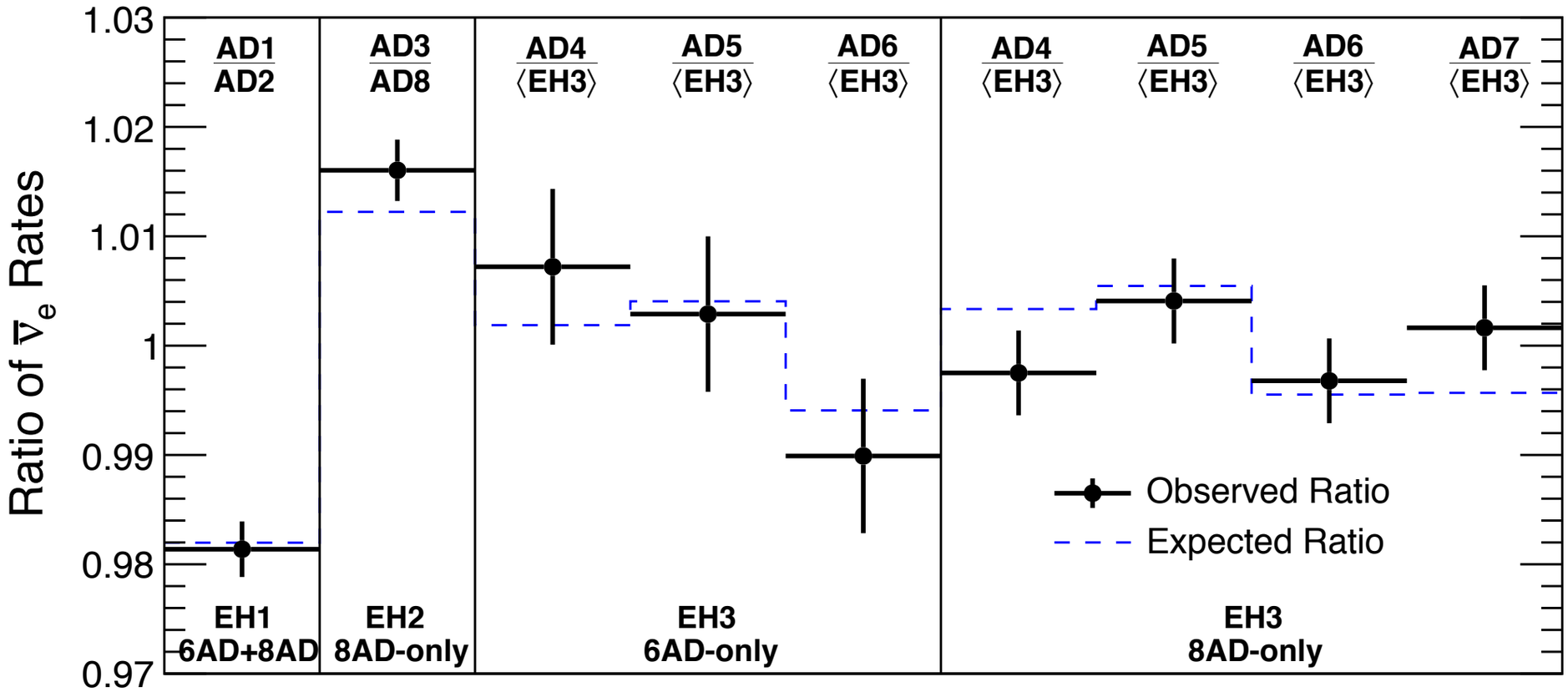
  - Backgrounds amount to less than 2% in all halls

  - 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!

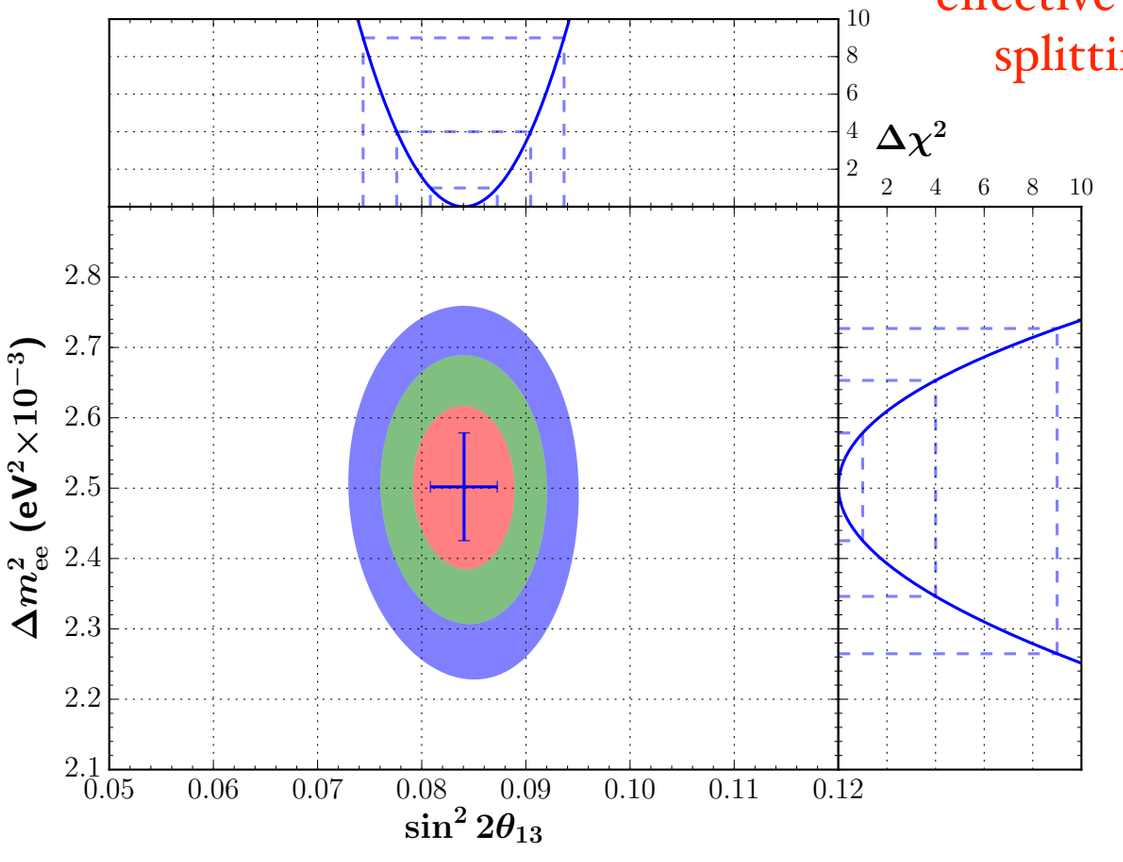
Uncertainty dominated by the statistics and the 0.13% relative error. The background uncertainties mostly cancel in this plot.

nGd Oscillation Analysis Results

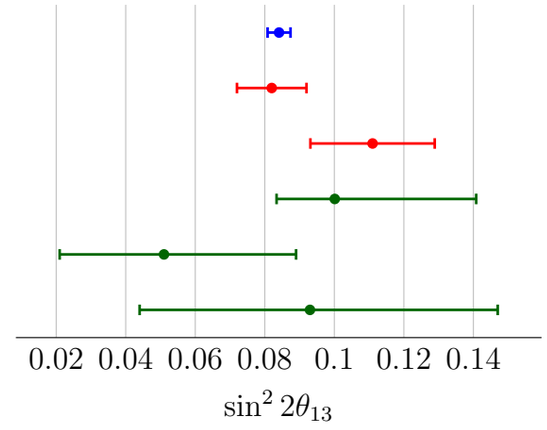
- With a relative rate + shape measurement achieve the **world's most precise determination of θ_{13} and Δm^2_{ee}**:

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

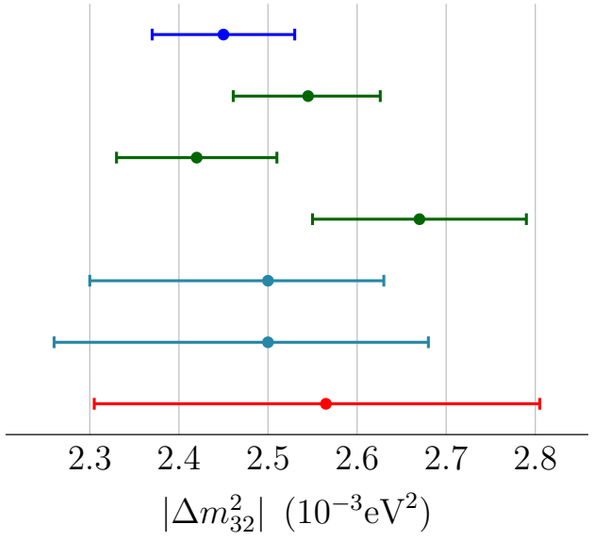
effective mass splitting



Experiment		Value
Daya Bay		0.0841 ± 0.0033
RENO		0.082 ± 0.010
D-CHOOZ		0.111 ± 0.018
T2K		$0.100^{+0.041}_{-0.017}$
MINOS	NH	$0.051^{+0.038}_{-0.030}$
	IH	$0.093^{+0.054}_{-0.049}$



Experiment	Value (10^{-3} eV^2)
Daya Bay	2.45 ± 0.08
T2K	$2.545^{+0.081}_{-0.084}$
MINOS	2.42 ± 0.09
NOνA	2.67 ± 0.12
Super-K	$2.50^{+0.13}_{-0.20}$
IceCube	$2.50^{+0.18}_{-0.24}$
RENO	$2.57^{+0.24}_{-0.26}$



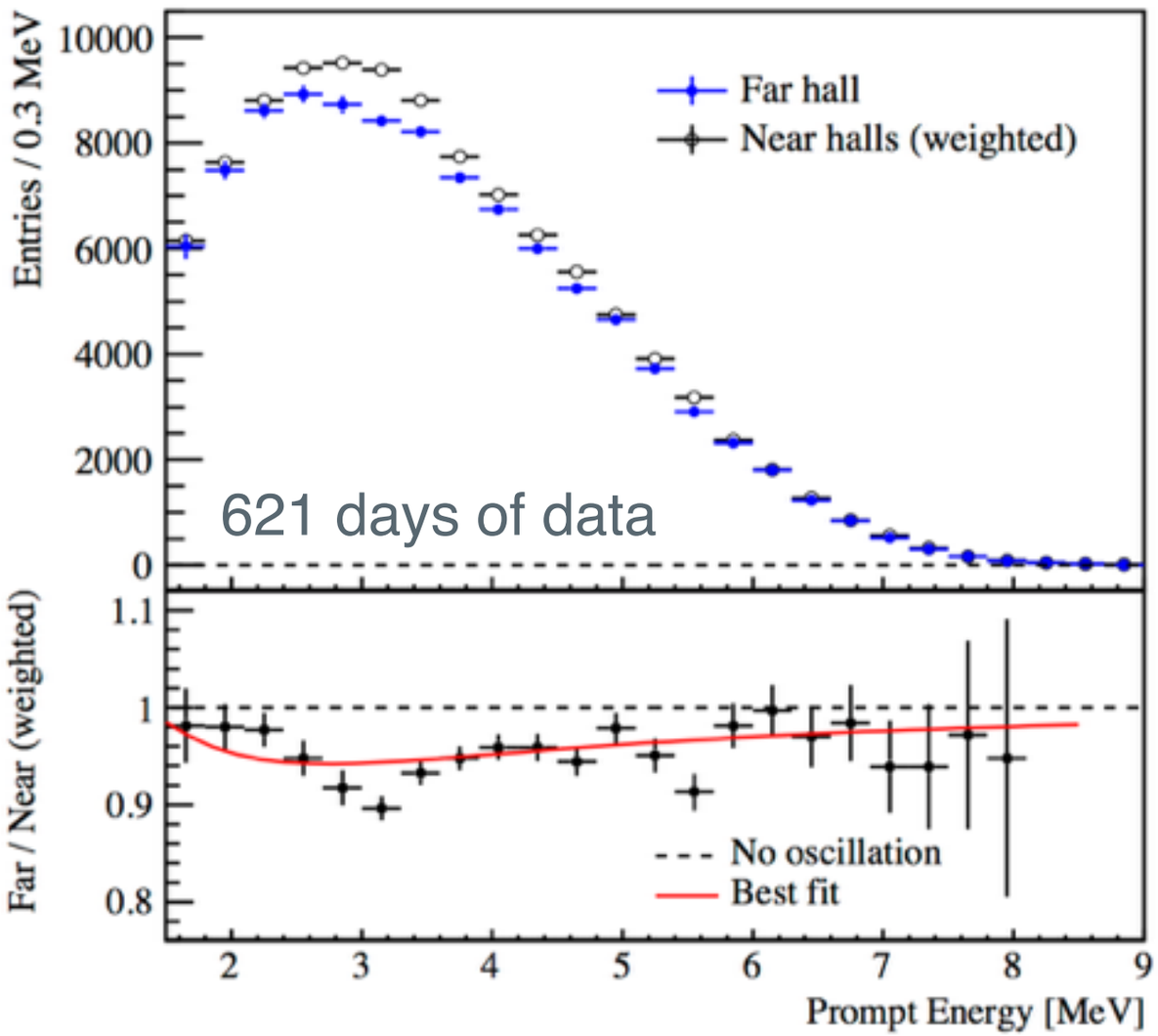
To appear in arXiv very soon!

$$\sin^2 2\theta_{13} = [8.41 \pm 0.27(\text{stat.}) \pm 0.19(\text{syst.})] \times 10^{-2}$$
$$|\Delta m^2_{ee}| = [2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})] \times 10^{-3}\text{eV}^2$$
$$\chi^2/\text{NDF} = 232.6/263$$

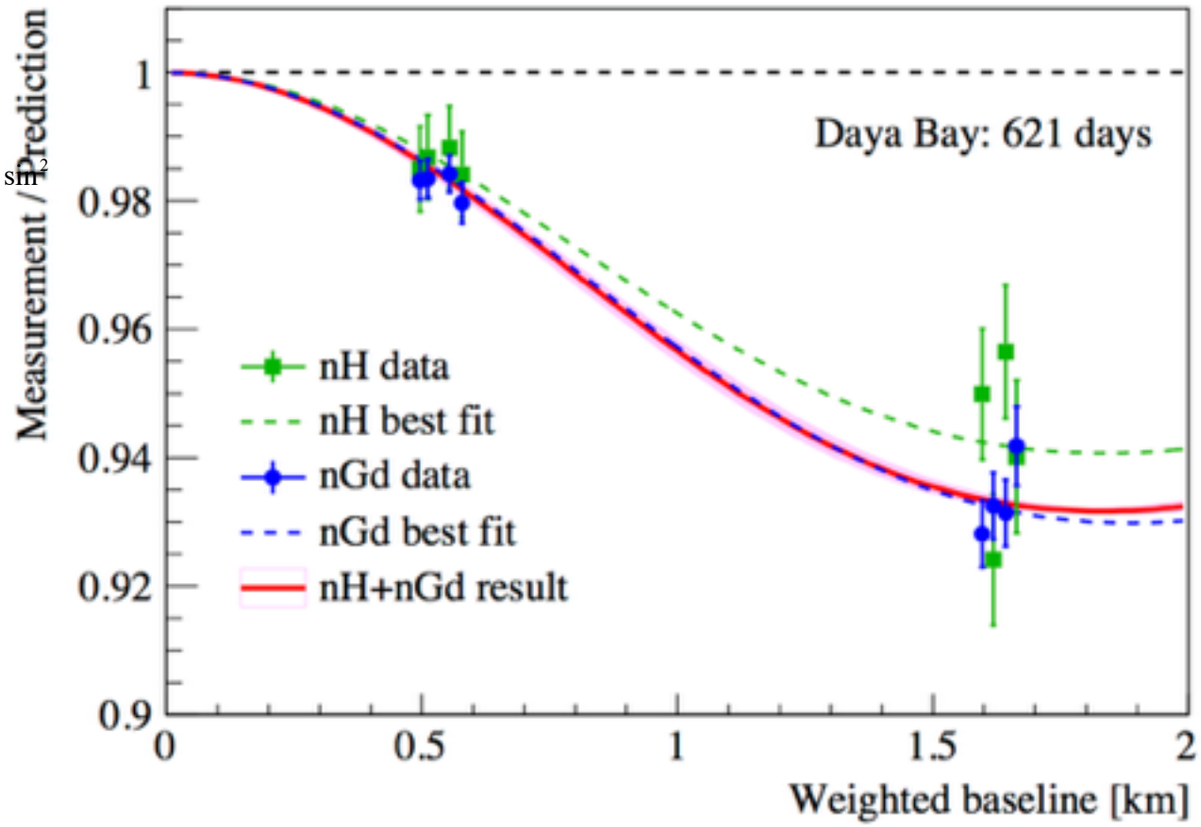
still statistics dominated!

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)

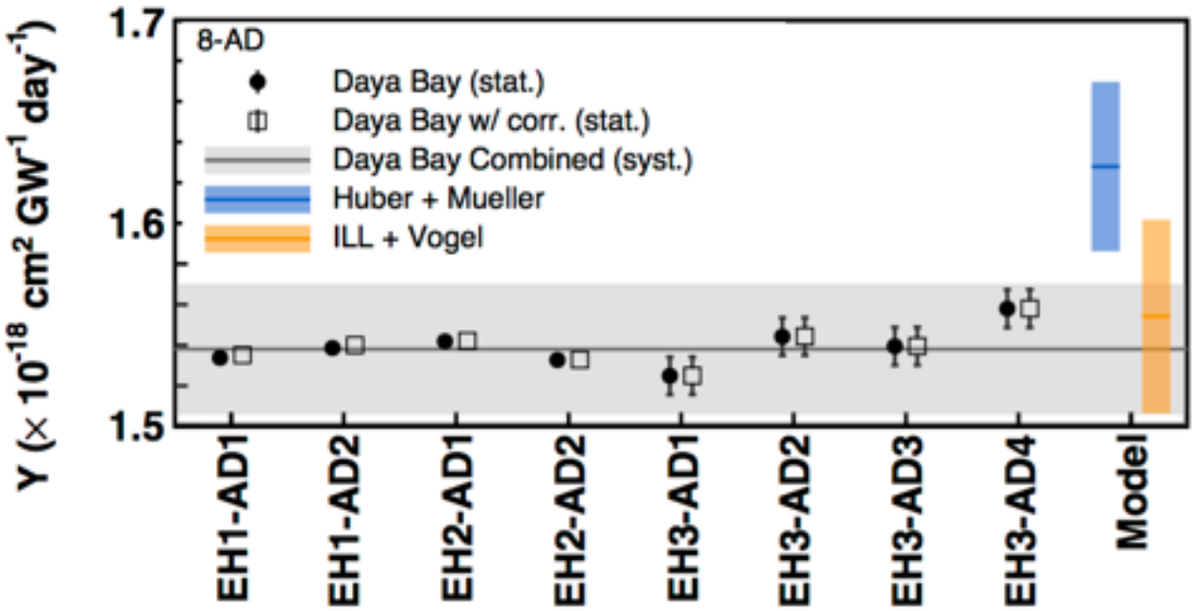


Rate analysis: $\sin^2 2\theta_{13} = 0.071 \pm 0.11$, $\chi^2/ndf = 6.3/6$

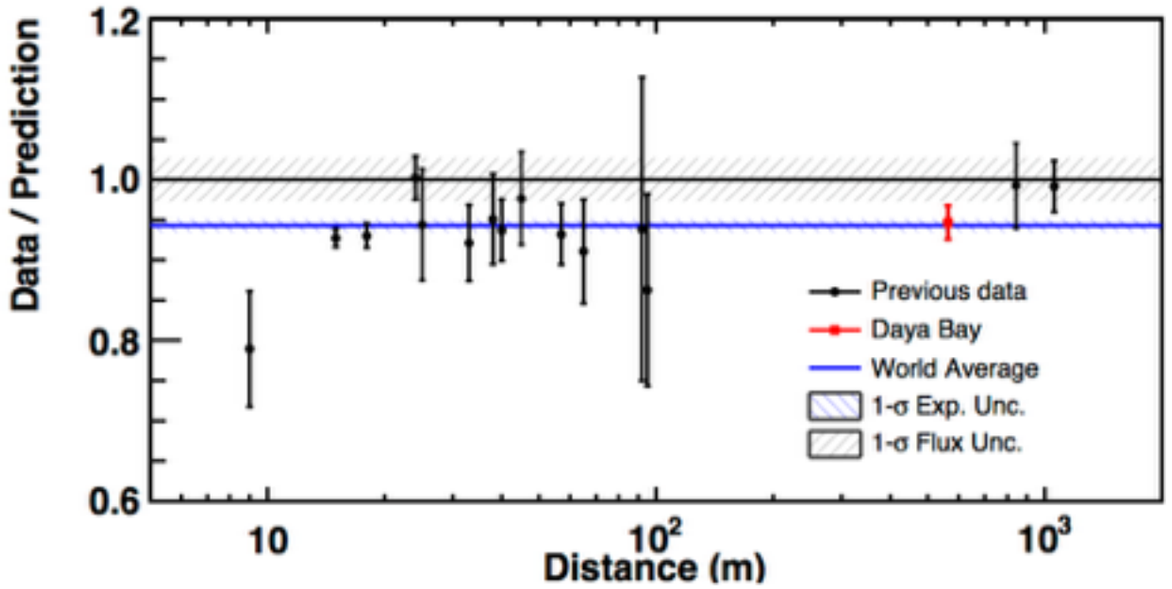
Phys. Rev. D 93, 072011 (2016)

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



$R_{global} = 0.942 \pm 0.009(exp) \pm 0.023(model)$

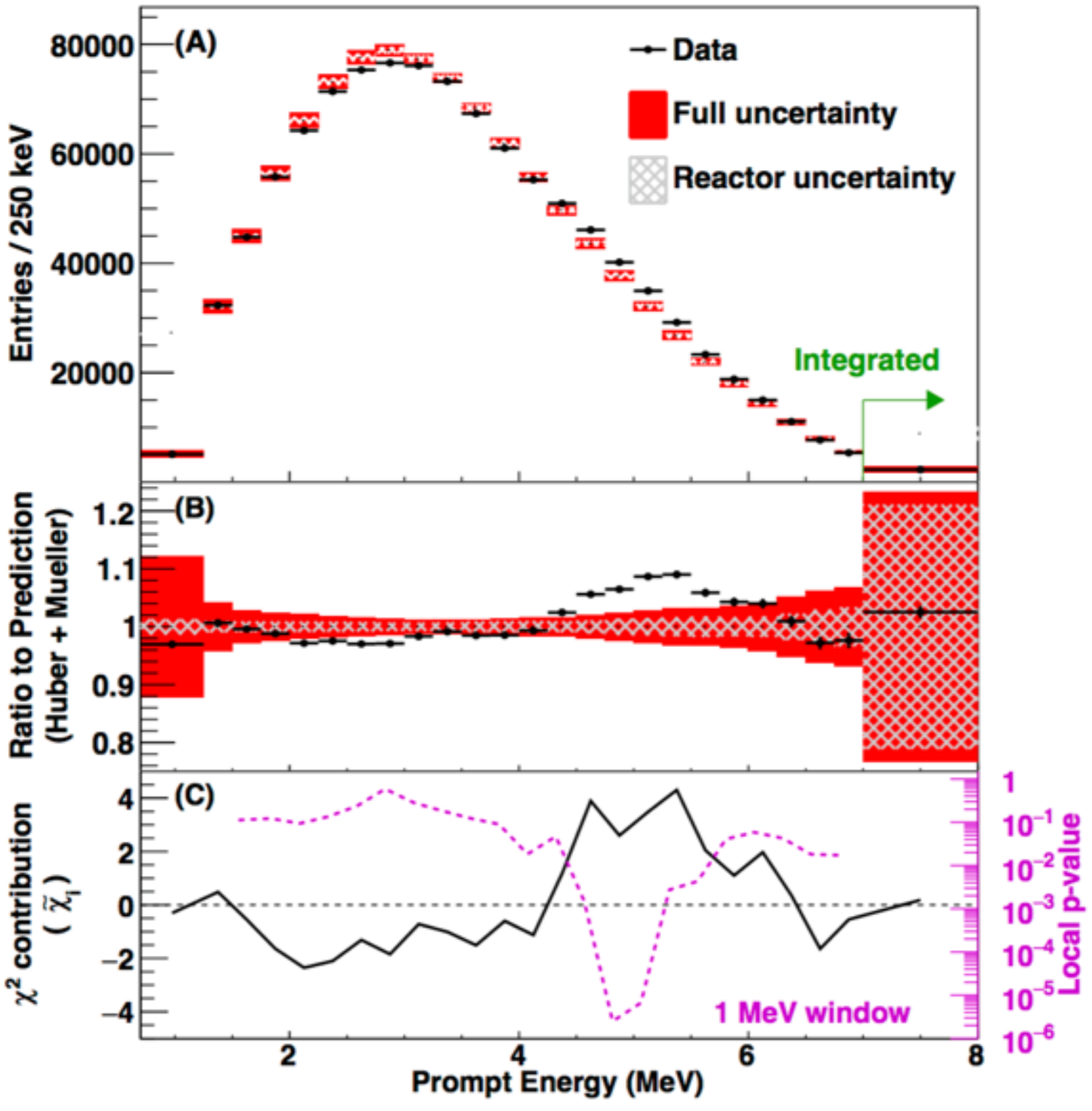
$R_{global+DYB} = 0.943 \pm 0.008(exp) \pm 0.023(model)$

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

arXiv:1607.05378

Reactor Antineutrino Spectral Shape

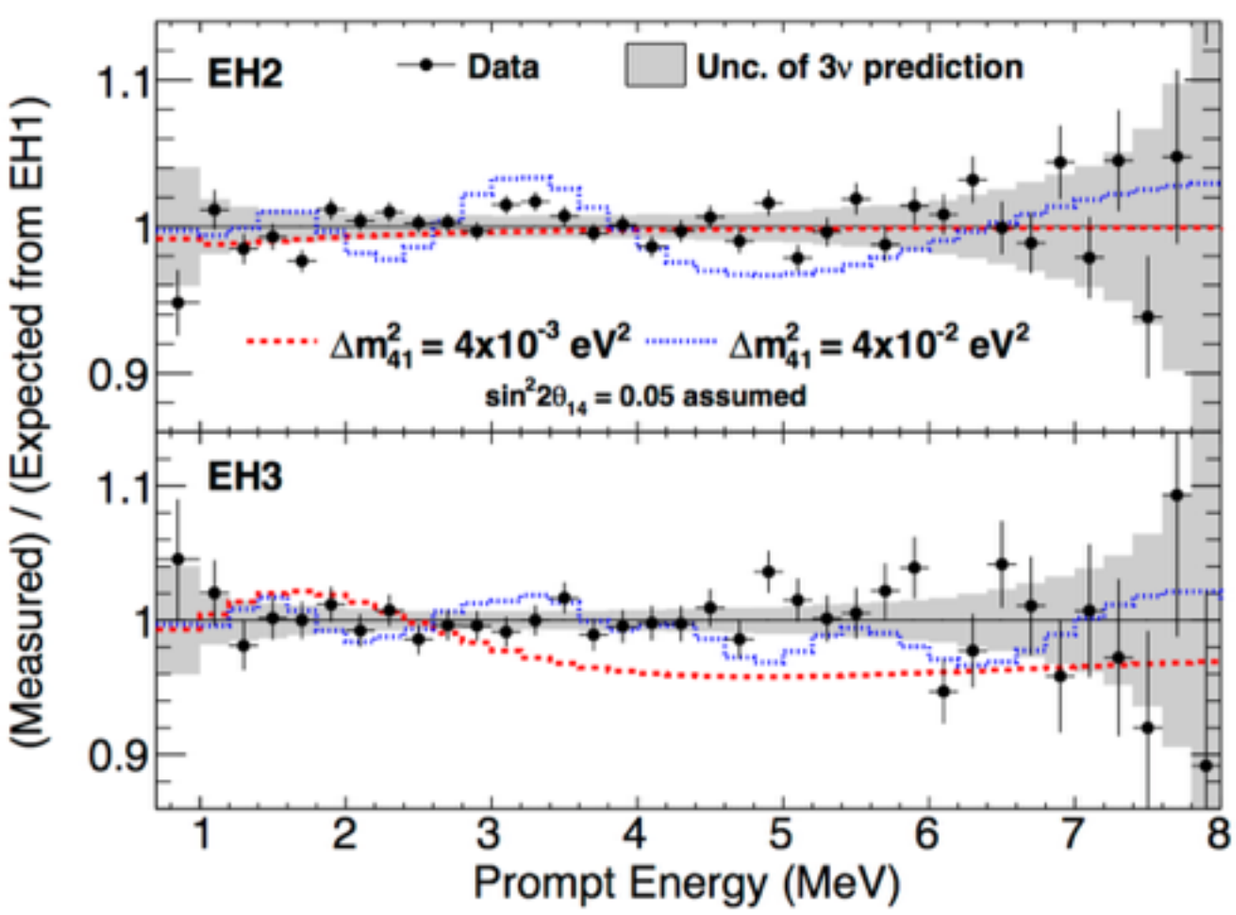
- Have also made a **high-statistics measurement** of the spectral shape of reactor antineutrinos:
  - Comparison with the Huber + Mueller prediction reveals a 2.9σ discrepancy overall (**4.4σ in the 4-6 MeV region**)
  - Excess events have all the IBD characteristics and are power correlated and time independent
  - Excess does not appear in ^{12}B spectra (disfavoring detector effects), and cannot be reproduced by a single β-decay branch or mono-energetic line

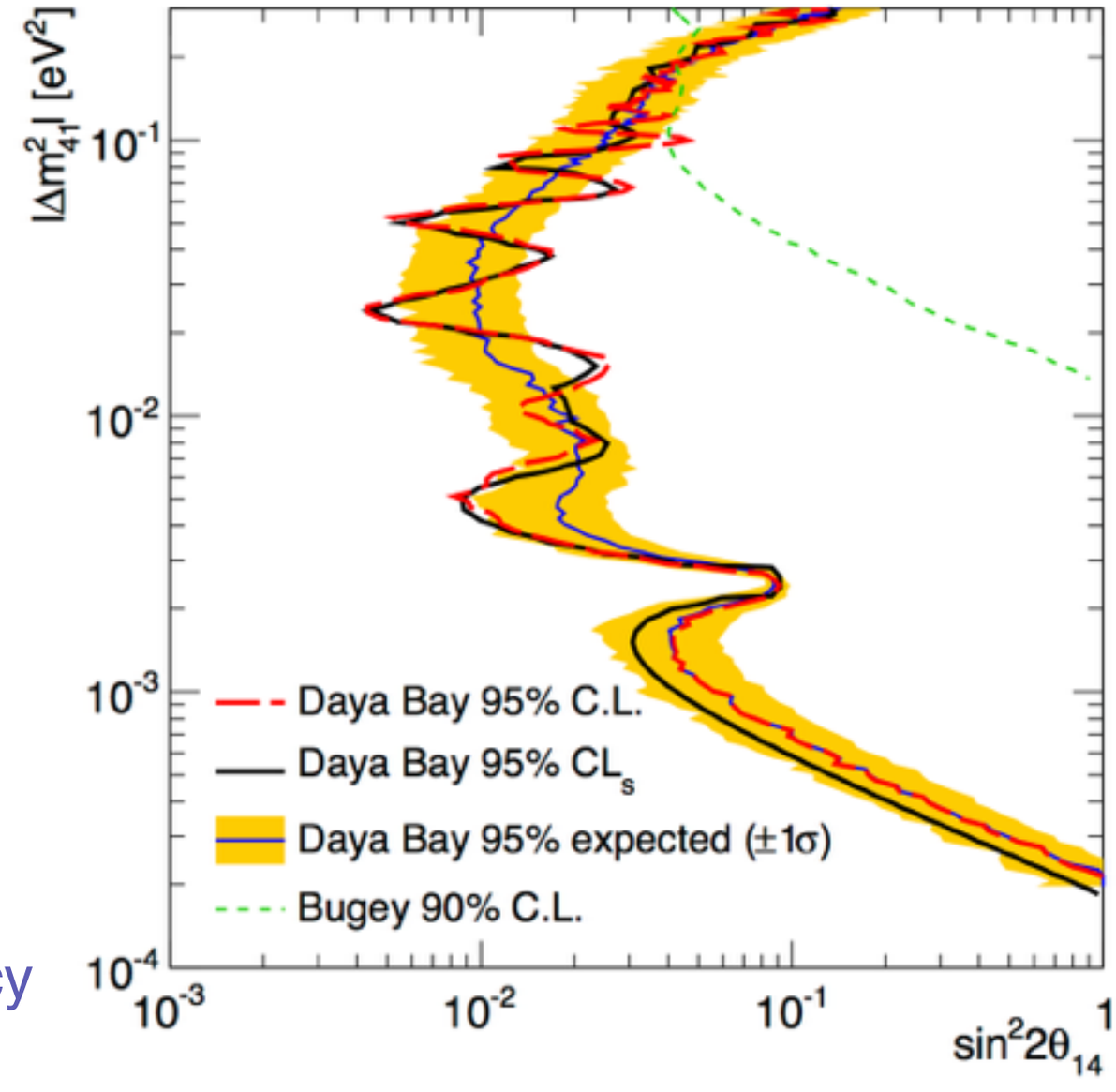


arXiv:1607.05378

Search for Light Sterile Neutrino Mixing

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





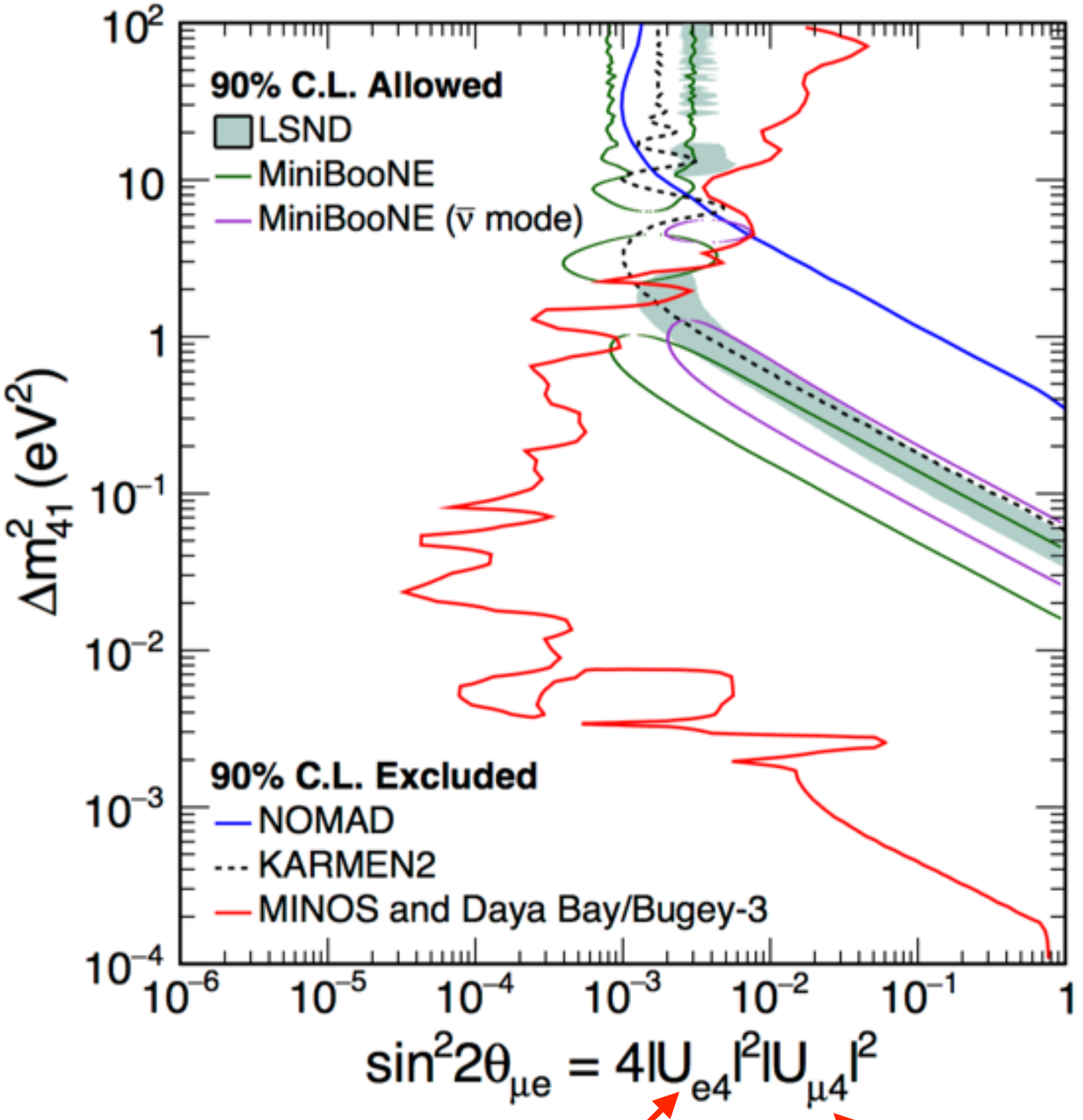
Signal would primarily appear as an additional spectral distortion with a frequency different from standard 3ν oscillations

Obtain the most stringent limits on $\sin^2 2\theta_{14}$ in the $2x10^{-4}$ eV^2 < Δm^2_{41} < 0.2 eV^2 region

arXiv:1607.01174

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 phase-space allowed by MiniBoone & LSND for $\Delta m^2_{41} < 0.8\ eV^2$



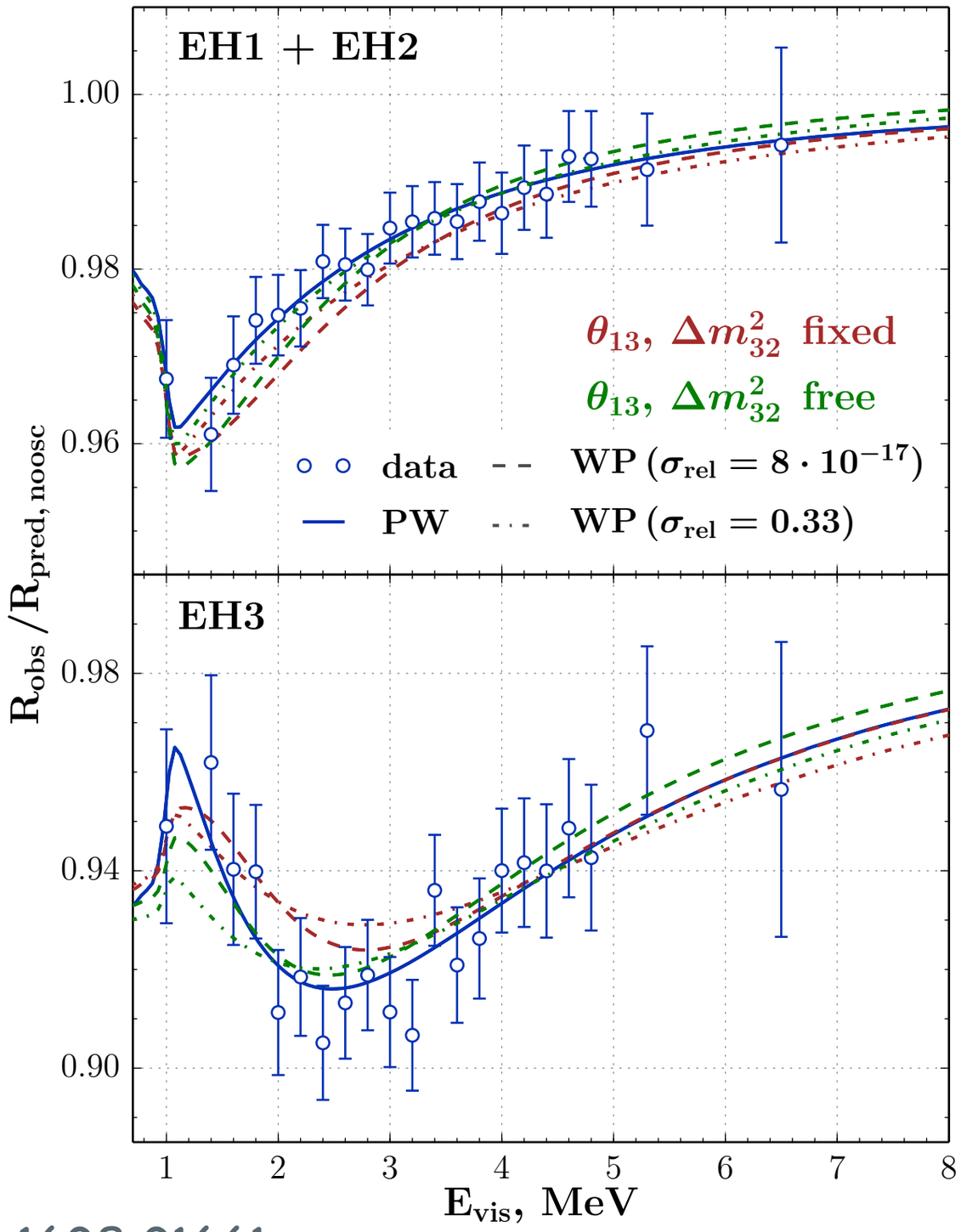
arXiv:1607.01177 and arXiv:1607.01176

Search for Neutrino Decoherence

- Daya Bay's high-statistics 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
  - This analysis examines the data in the framework of a model 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



arXiv:1608.01661

Search for Neutrino Decoherence

- This analysis provides the **first experimental limits on σ_{rel}**:

$2.38 \times 10^{-17} < \sigma_{rel} < 0.23$

- Treating the dimensions of the reactor cores and the detectors as constraints (< 2m), the limits can be improved:

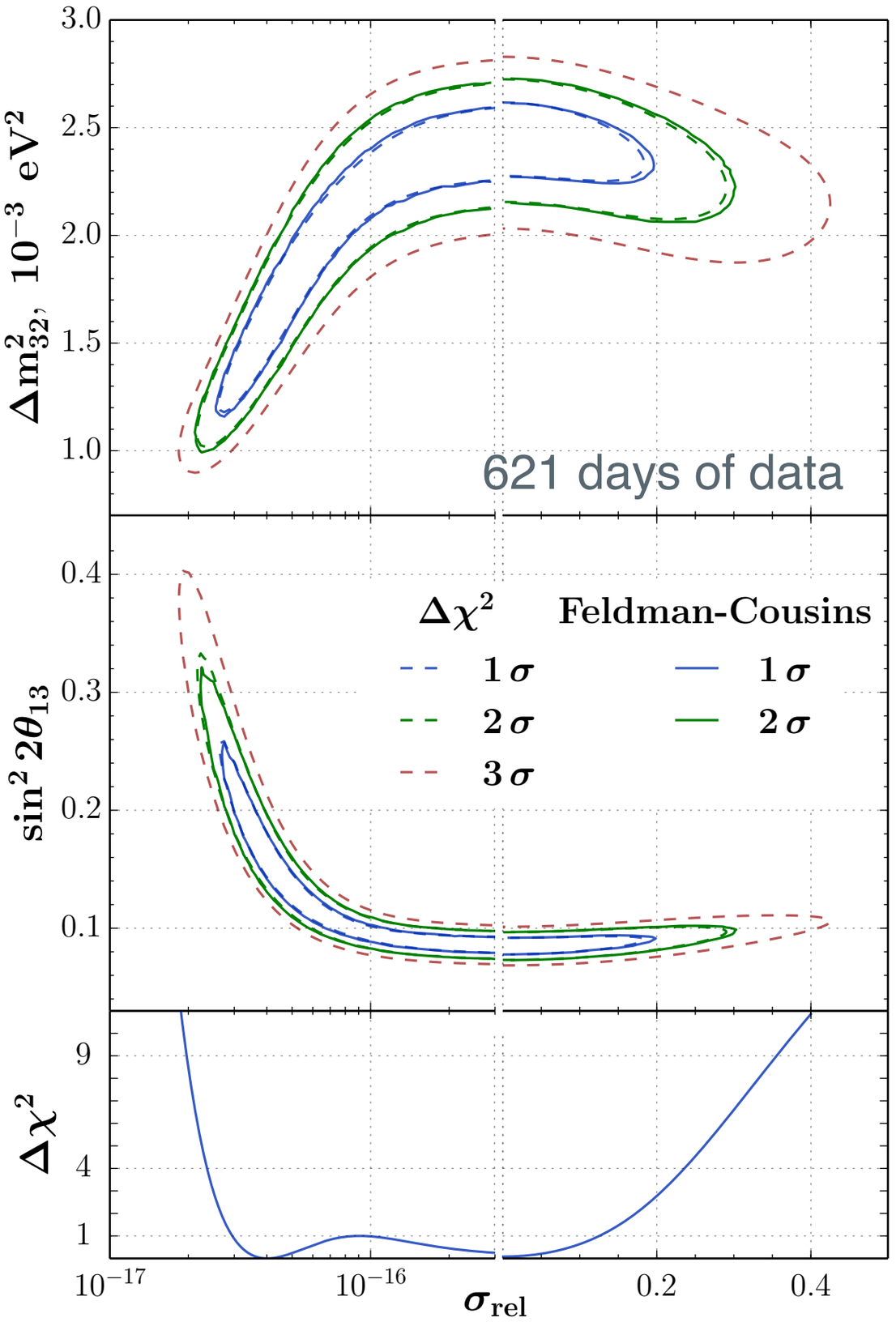
$10^{-14} < \sigma_{rel} < 0.23$

which can be read as:

10^{-11} cm $< \sigma_x <$ 2m

= spatial width of wave packet ($1/2\sigma_p$)

arXiv:1608.01661



Summary & Outlook

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

Latest oscillation results →

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

+ high-statistics absolute reactor antineutrino flux and shape measurements, as well as searches for a sterile neutrino and neutrino decoherence, among others

- Daya Bay will run until 2020 and produce many other groundbreaking results:
  - Working to further reduce the systematics through the installation of a 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…)