Recent Results from the Daya Bay Reactor Neutrino Experiment

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Prague v15

Outline

- Neutrino Oscillation
- Daya Bay Experiment
- Latest Results
  - Precise measurement of θ_{13} and $|\Delta m^2_{ee}|$
  - Hydrogen capture
  - Sterile neutrino
  - Measured spectrum and rate

Neutrino Oscillation

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

atmospheric — reactor — solar

- **Around 2010, θ_{23} and θ_{12} were determined as**

$$\sin^2 2\theta_{12} = 0.87 \pm 0.03$$

$$\sin^2 2\theta_{23} > 0.92$$

- **However, $\sin^2 2\theta_{13}$ was constrained to be**

$$\sin^2 2\theta_{13} < 0.15$$

- **Daya Bay was designed to measure $\sin^2 2\theta_{13}$ with sensitivity of 0.01**

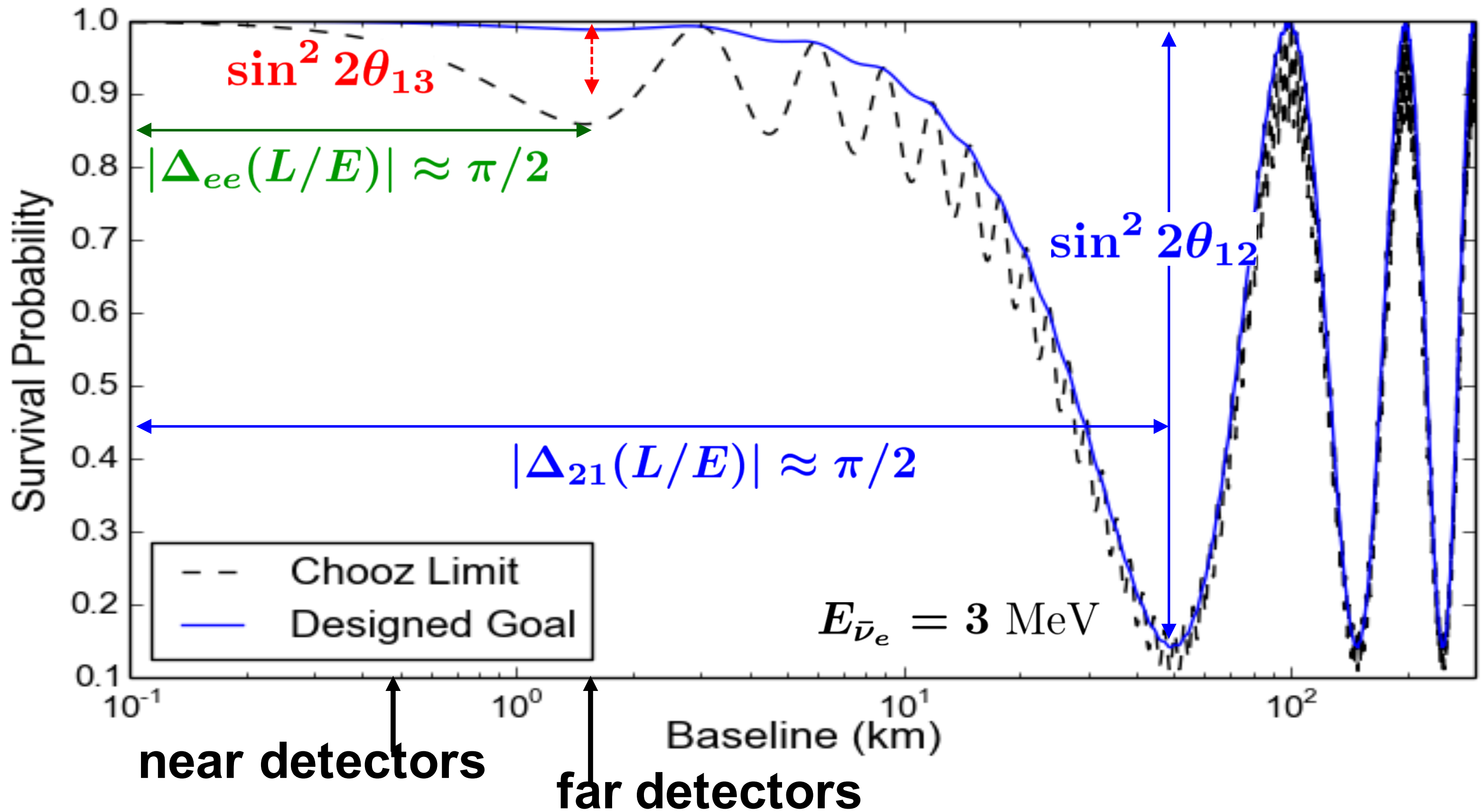
Design of Daya Bay

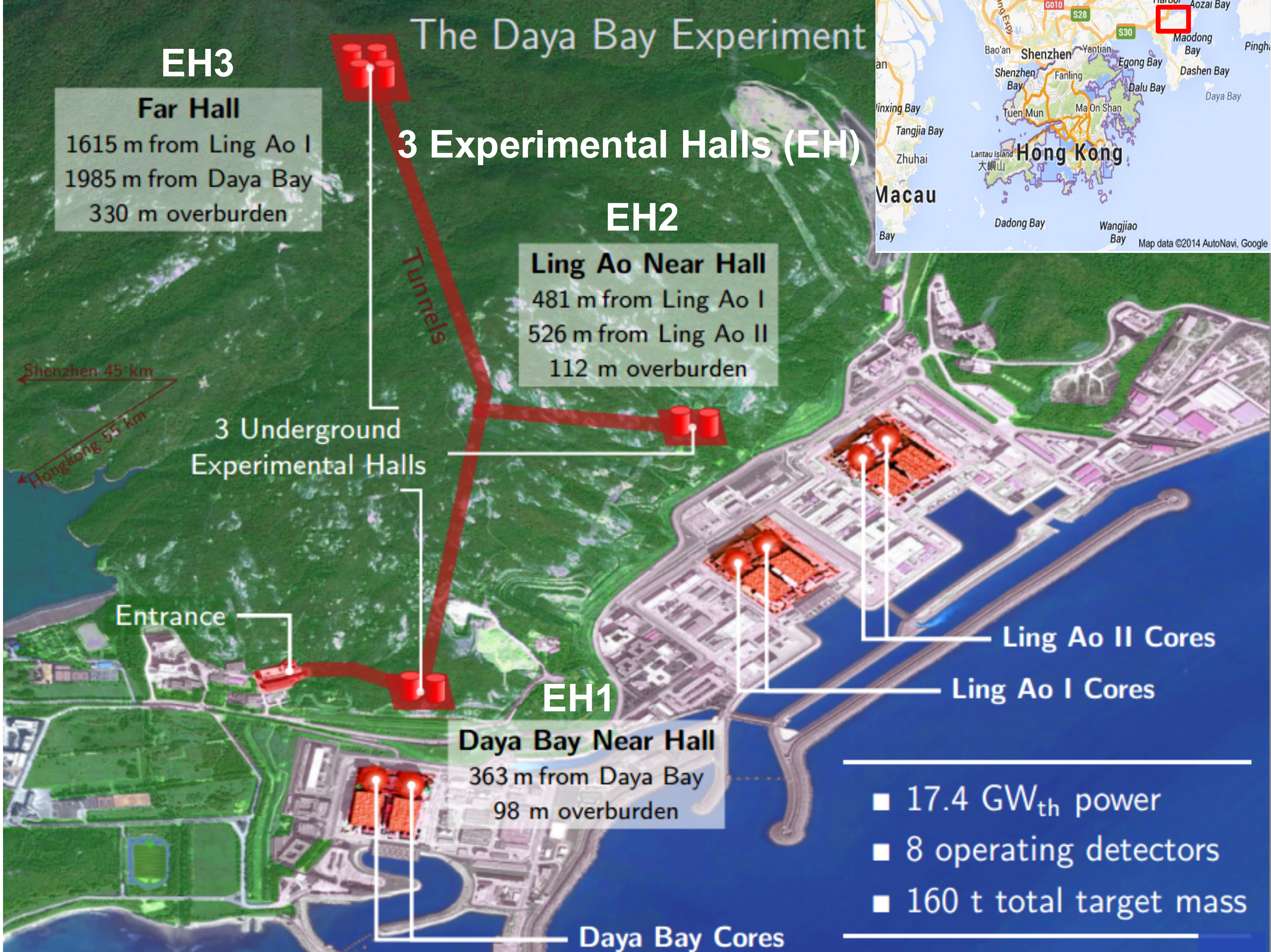
- **Relative Measurement**
  - **Near and far detectors:**
    minimize reactor related uncertainties
  - **Identical modules:**
    minimize detector related uncertainties
- **Low Backgrounds**
  - **Large overburden at far site(860 m.w.e.)**
- **Large statistics**
  - **Large target mass**: 8x20-ton detectors
  - **Large neutrino flux:** 6x2.9 GWth reactors

Distance of the Detectors

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\underbrace{\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right)}_{\approx \sin^2\Delta_{ee}}$$

$$\Delta_{ij}(L/E) \equiv 1.267\Delta m^2_{ij}\,[\mathrm{eV}^2]\frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}$$





The Daya Bay Experiment
EH3
Far Hall
1615 m from Ling Ao I
1985 m from Daya Bay
330 m overburden
3 Experimental Halls (EH)
EH2
Ling Ao Near Hall
481 m from Ling Ao I
526 m from Ling Ao II
112 m overburden
Tunnels
Shenzhen 45 km
Hongkong 55 km
3 Underground
Experimental Halls
Entrance
EH1
Daya Bay Near Hall
363 m from Daya Bay
98 m overburden
Ling Ao II Cores
Ling Ao I Cores
Daya Bay Cores
17.4 GW$_{th}$ power
8 operating detectors
160 t total target mass
Shenzhen
Hong Kong
Macau
Zhuhai
Bao'an
Yantian
Shenzhen Bay
Fanling
Tuen Mun
Ma On Shan
Egong Bay
Dalu Bay
Dashen Bay
Daya Bay
Maodong Bay
Aozai Bay
Tangjia Bay
Dadong Bay
Wangjiao Bay
Map data ©2014 AutoNavi, Google

Detection Method

- **Inverse beta decay (IBD) reaction**

Prompt signal

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

Delayed Signal

$n + {}^{x}\mathrm{Gd} \rightarrow {}^{x+1}\mathrm{Gd} + \gamma's$	~30 μs	8MeV
$n + \mathrm{H} \rightarrow \mathrm{D} + \gamma$	~200 μs	2.2MeV

- **Prompt signal:**

$$E_{prompt} \approx E_{\bar{\nu}_e} - 0.8\ \mathrm{MeV}$$

Obtain neutrino spectrum information

- **Delayed signal comes from neutron capture on both Gd and H:**

Independent check on the measured parameters

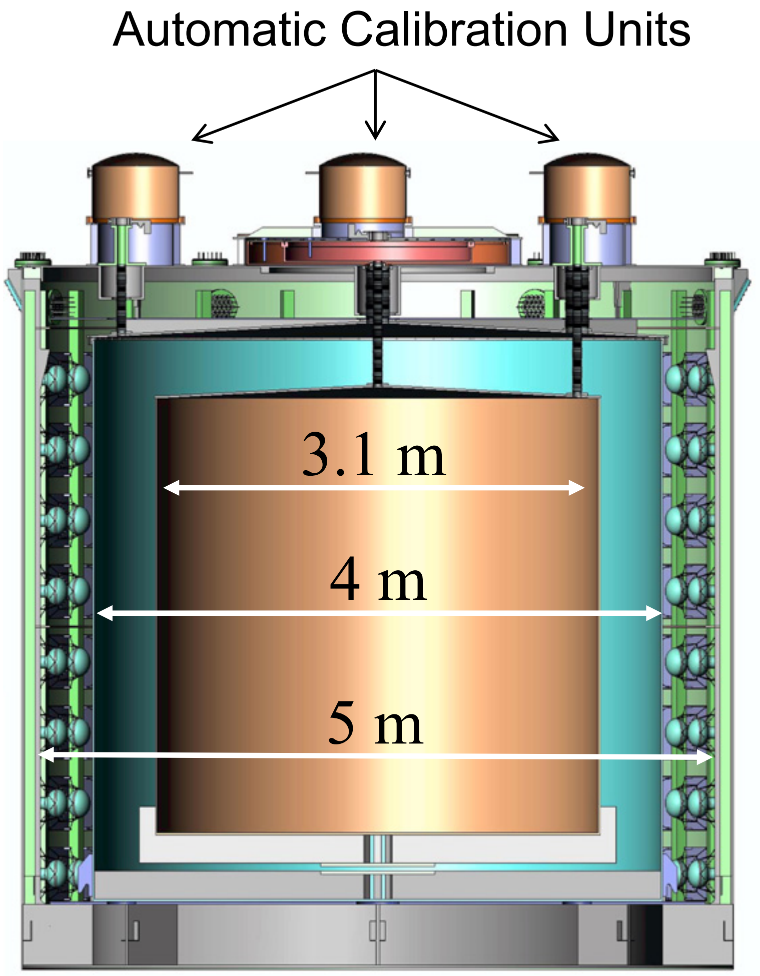
Antineutrino Detector (AD)

- **3-zone structure**

Size	Zone	Liquid	Function
3m 20 ton	Inner Acrylic	Gd-LS	Anti-neutrino target
4m 22 ton	Outer Acrylic	LS	Gamma catcher
5m 37 ton	Stainless Steel	MO	Radiation Shield

LS = Liquid Scintillator, MO= Mineral Oil

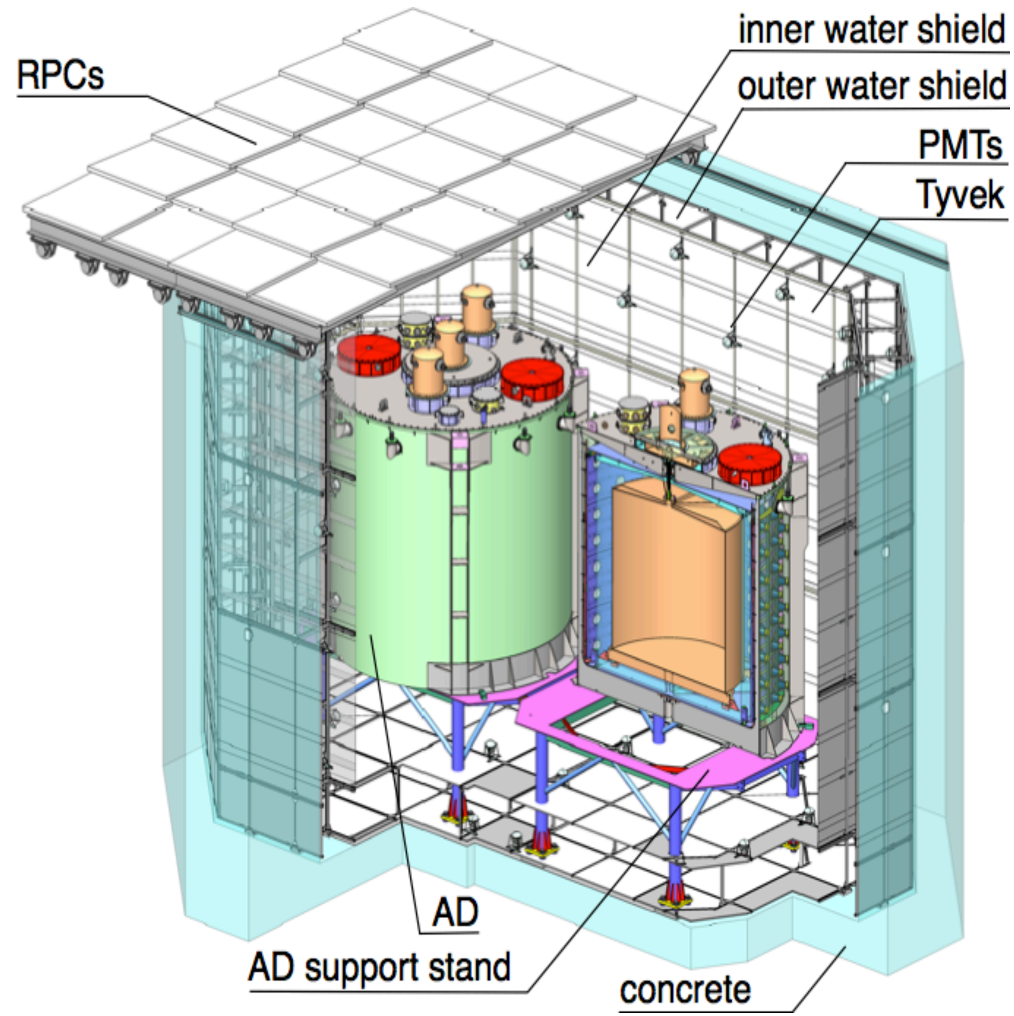
- **192 PMT**
- **Top and bottom reflectors**
- **3 Automatic Calibration Units (ACUs) sit on top**



arXiv:1508.03943

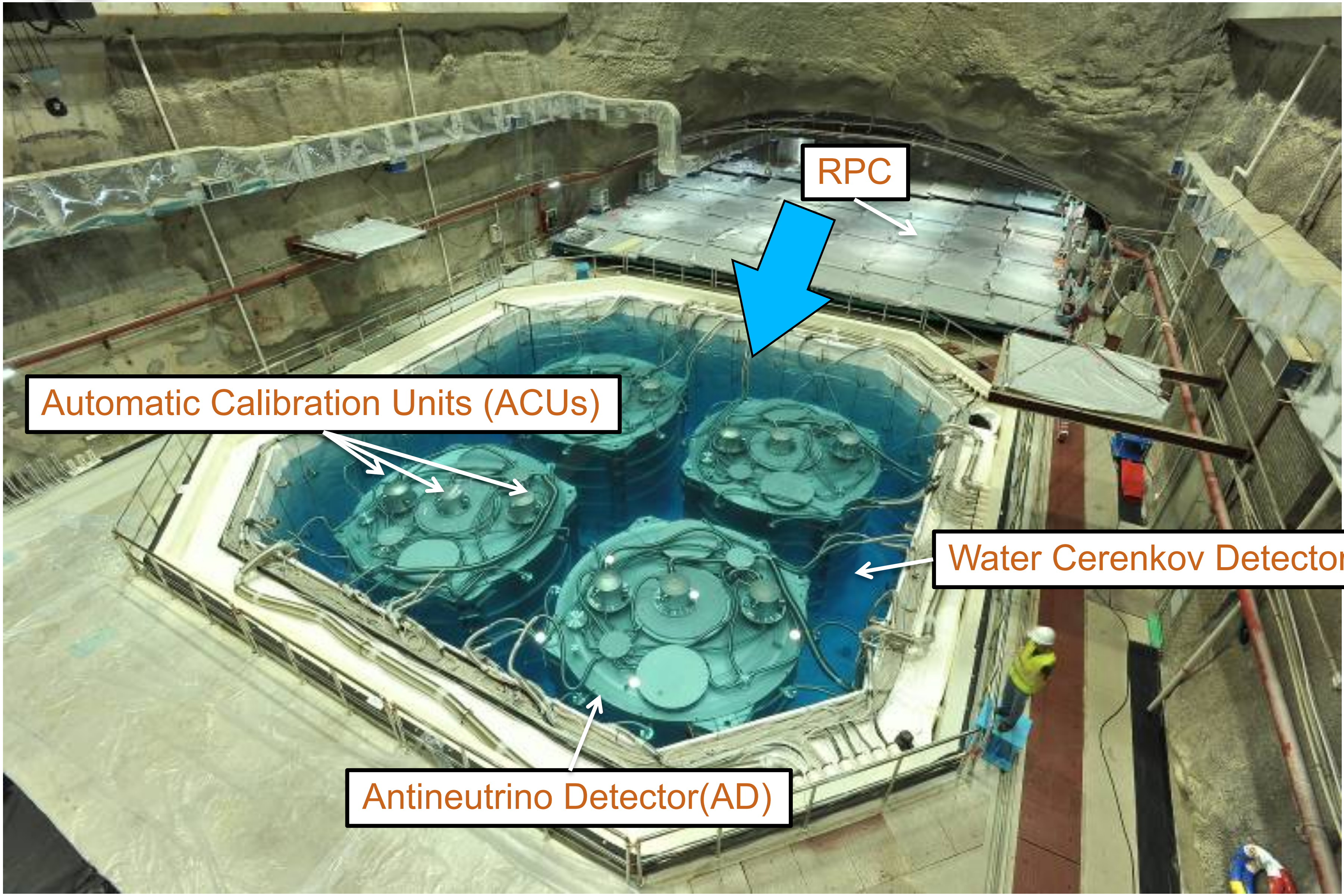
Muon Veto System

- **Water Cerenkov Detectors**
  - **2.5 m of water from any direction**
  - **Two optically-isolated detectors at each hall**
  - **Tags cosmic muons**
  - **Shields against low energy radiation from surrounding material**
- **Resistive plate chambers (RPCs)**
  - **Covers water pool for further muon tagging**



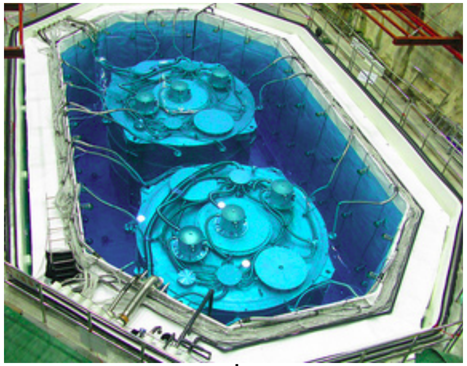
Nucl. Instrum. Meth. A 773, 8 (2015)

Far Hall (EH3)

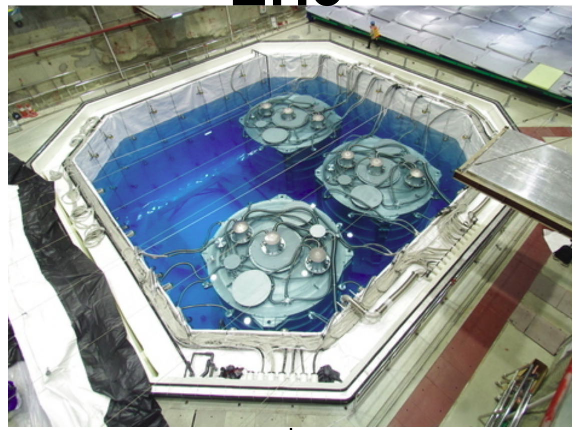

RPC
Automatic Calibration Units (ACUs)
Water Cerenkov Detector
Antineutrino Detector(AD)

Installation of ADs

Experimental Hall 1 (EH1)



EH3



EH3

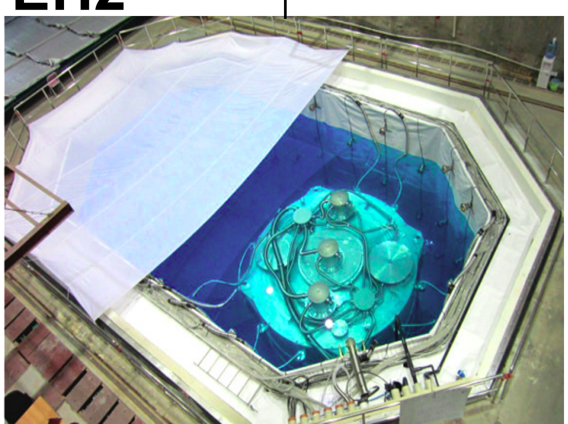
6-AD | 8-AD Data Taking

2012 | 2013 | 2014 | 2015

AD = Antineutrino Detector

Data processed

EH2



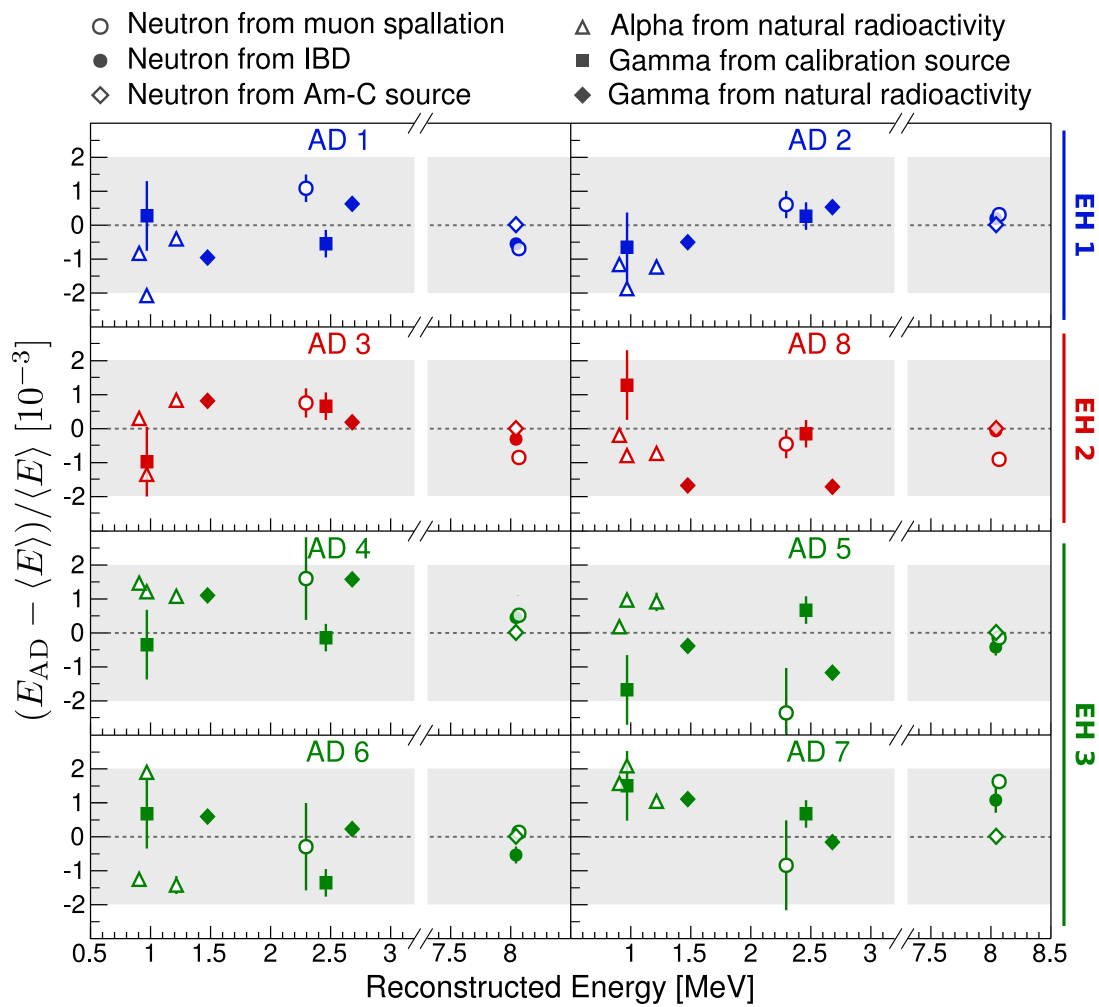
6 AD : Oscillation results and sterile neutrino search published

This talk will present the results from both the 6 and 6+8 AD period.

EH2

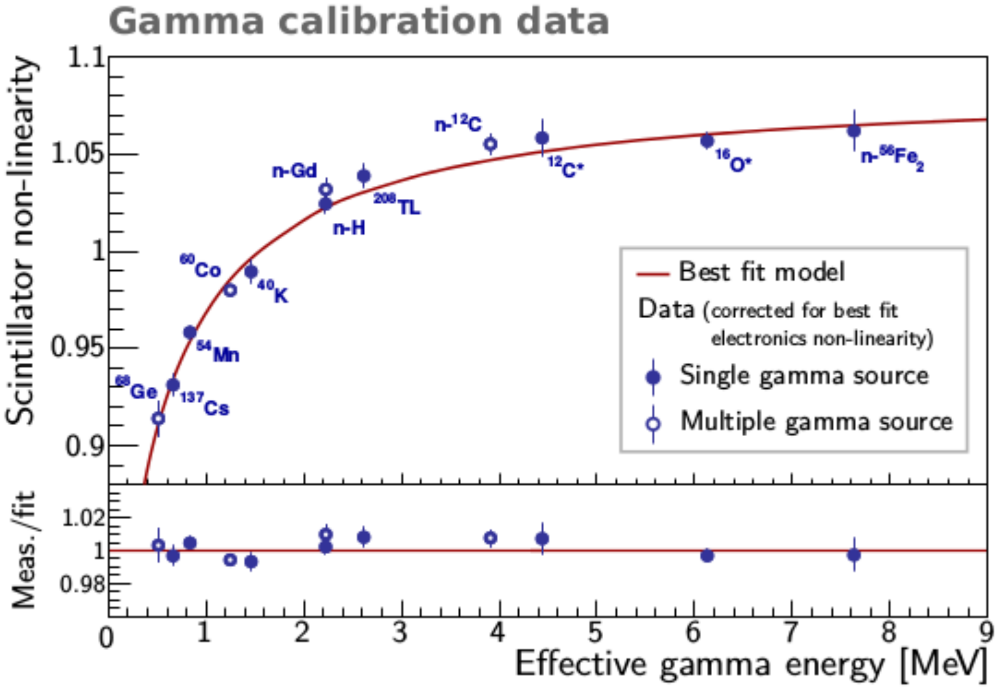
Calibrataion

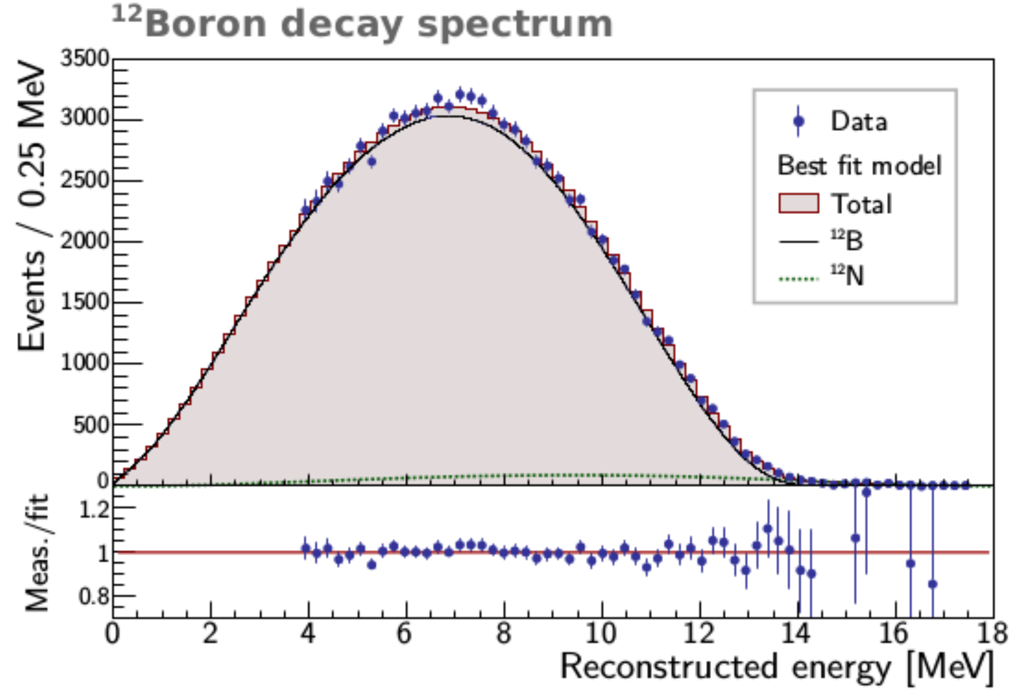
- **PMT Gain:**
  - **Weekly deployment of LED from ACU**
  - **Single photoelectron from dark noise (every ~6 hours)**
- **Energy scale & Non-uniformity**
  - **^{60}Co from ACU**
  - **Spallation neutrons captured by Gd**
- **Relative energy scale:**
  - **ACU: ^{60}Co, ^{68}Ge, AmC**
  - **Spallation: nGd, nH**
  - **Gamma: ^{40}K, ^{208}Tl**
  - **Alpha: ^{212}Po, ^{214}Po, ^{215}Po**



The uncertainty of relative energy scale is < 0.2%

Energy Nonlinearity





- **Sources of energy non-linearity**
  - Scintillator response
  - Readout electronics
- **Constrained by**
  - Radioactive calibration sources
  - Spectra from physics runs, e.g., ^{40}K and nH capture
  - Continuous spectrum from muon-induced ^{12}B

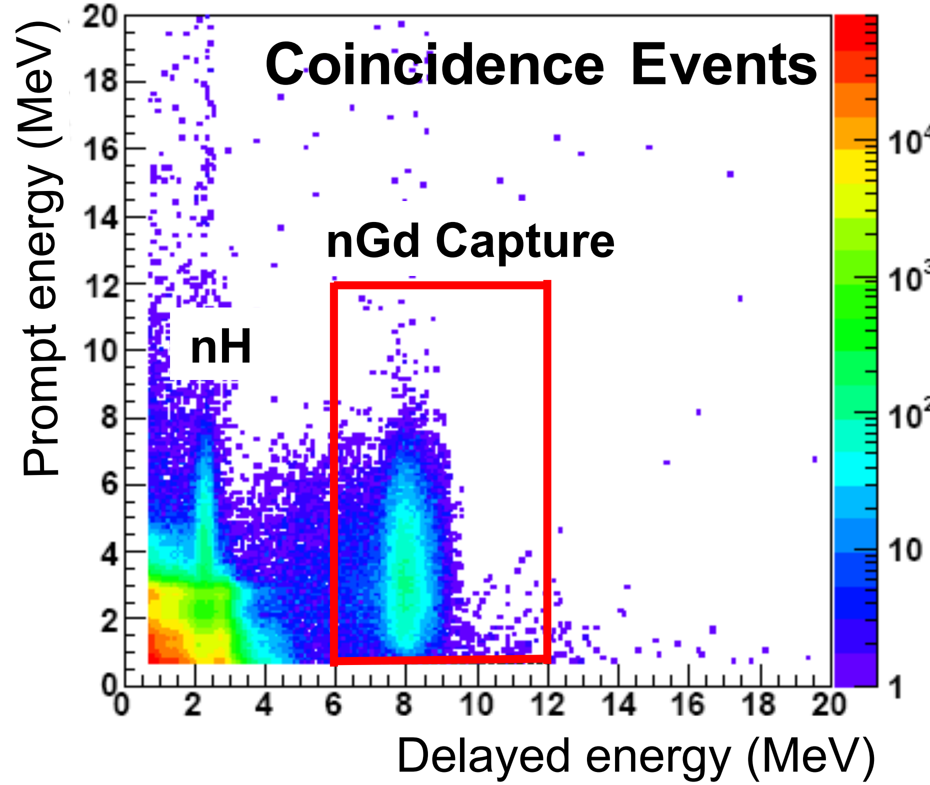
Antineutrino Selection

Select IBD Events if

$0.7\ \text{MeV} < E_{prompt} < 12.0\ \text{MeV}$

$6.0\ \text{MeV} < E_{delayed} < 12.0\ \text{MeV}$

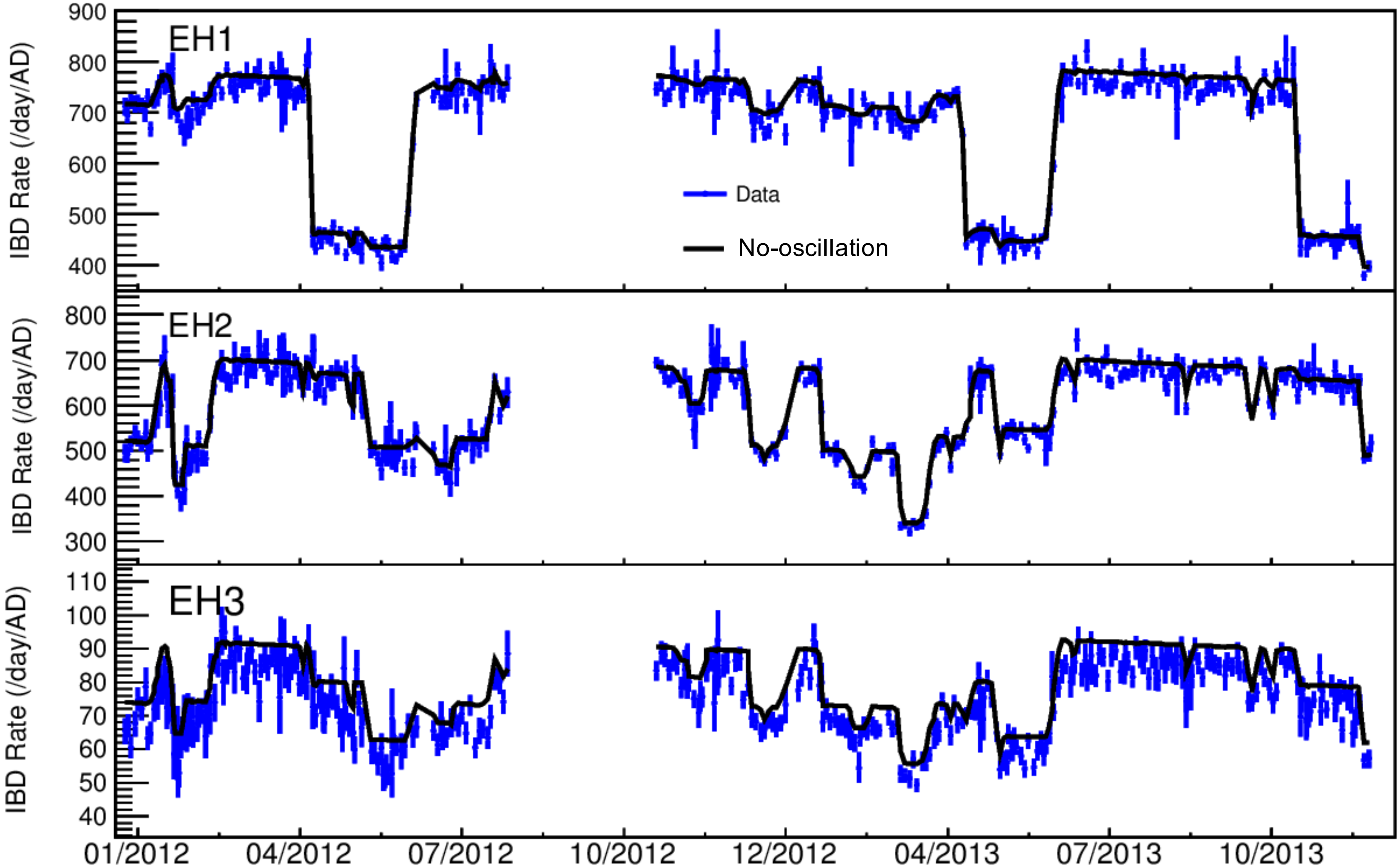
$1\ \mu s < t_{prompt-delayed} < 200\ \mu s$



Reject

- Muons tagged by either water Cerenkov detectors or AD
- Flashers: spontaneous PMT light emission
- Events with more than one coincidence (multiplicity cut)

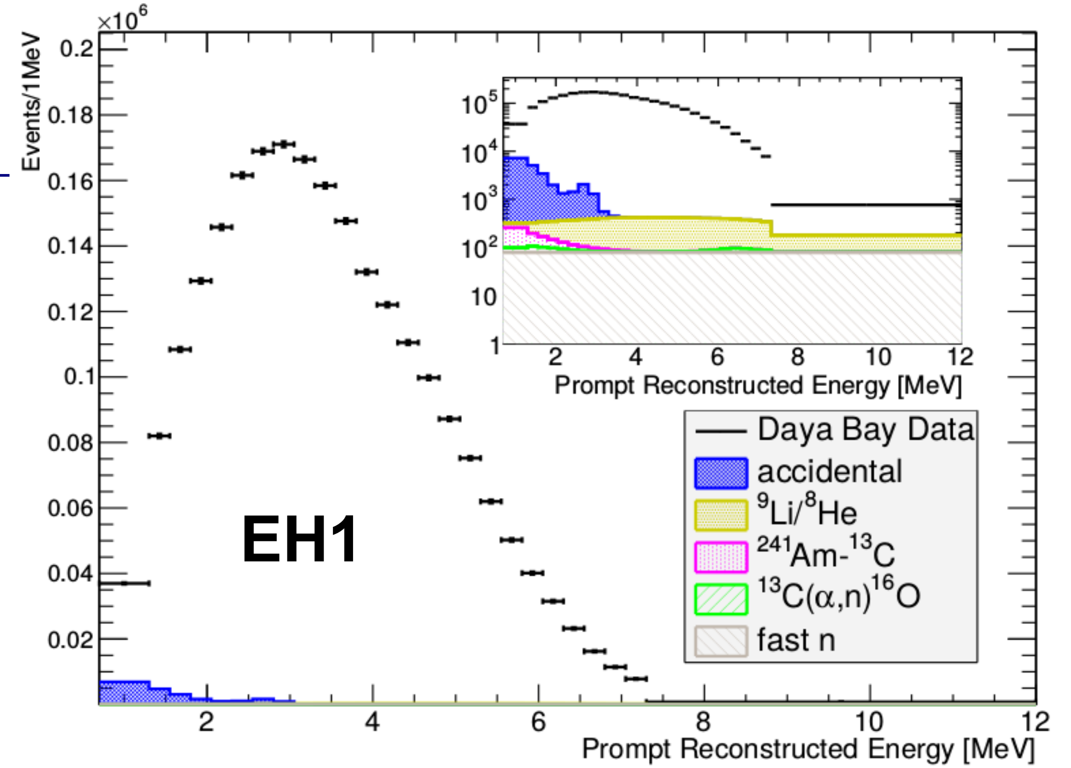
Event Rates

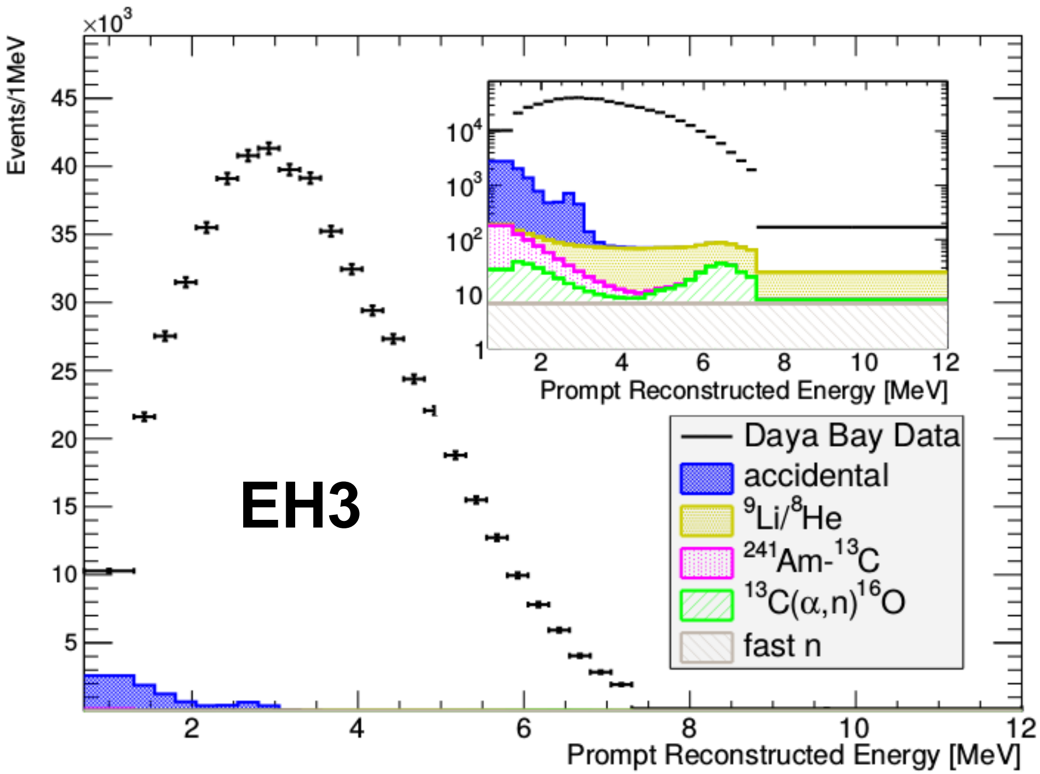


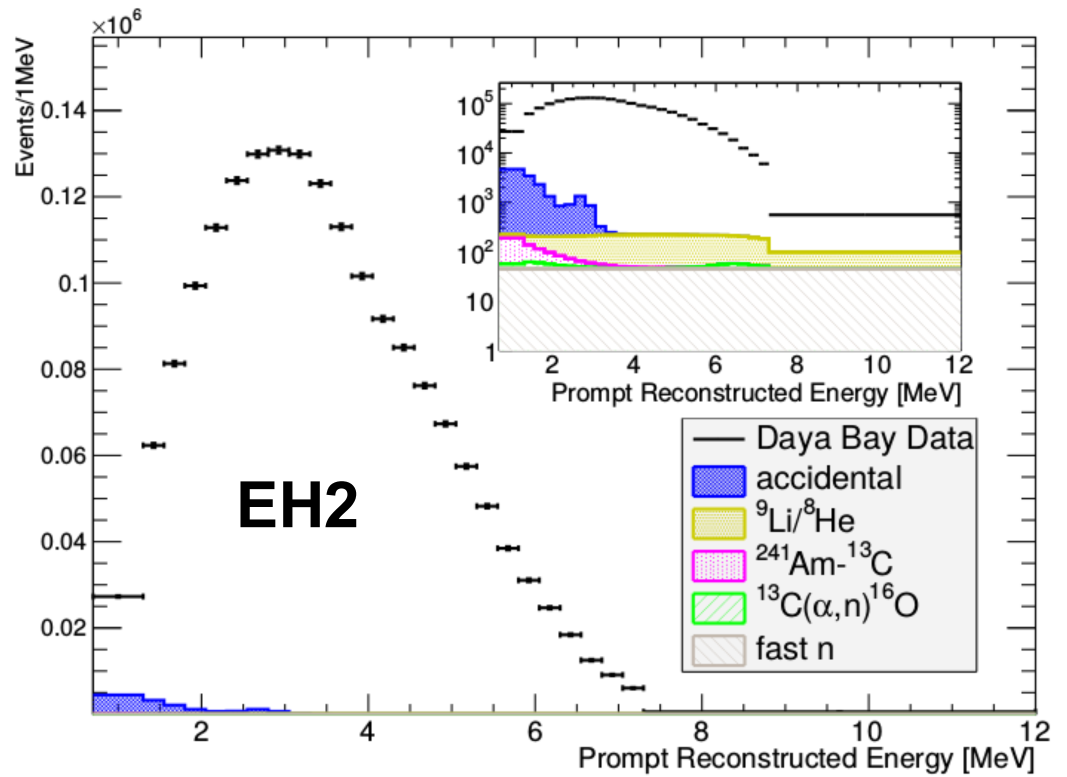
- **Event rates closely follow reactor power**
- **Rates at EH3 are clearly lower than no oscillation prediction**

Energy Spectrum

- Background rates at about 2% (3%) at near (far) halls
- Rate + Shape analysis is used







Backgrounds – Pairs Other than IBD

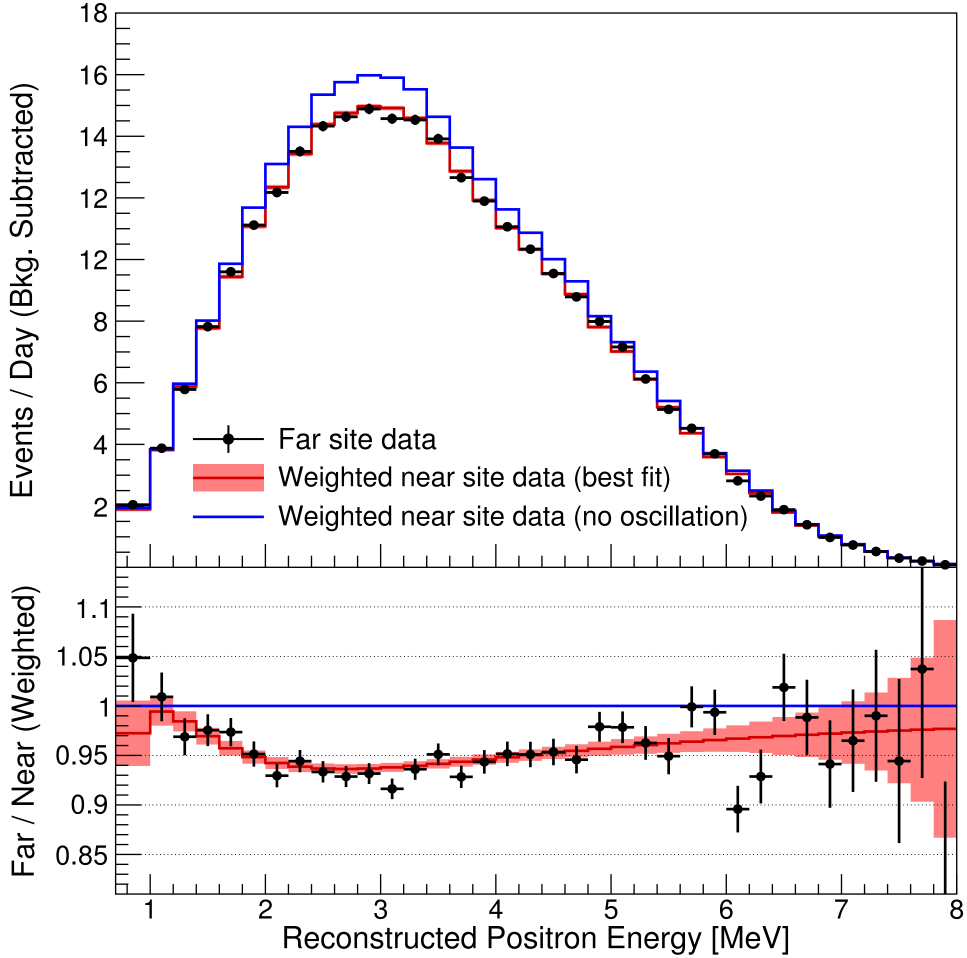
Backgrounds		Rates		Mimic process	
		Near	Far	prompt	delayed
Accidentals		1.2%	2.0%	Accidental two triggers	
Cosmic muons	$^{9}Li/^{8}He$	0.4%	0.4%	β-decay	Neutron Capture
	fast neutron	0.1%	0.07%	Neutron scatters in target	
Calibration source	AmC	0.04%	0.1%	Neutron inelastic scattering	
Intrinsic radiation	$^{13}C(\alpha,n)^{16}O$	0.01%	0.07%	Neutron scatters/ $^{16}O^{*}$ de-excitation	

Extracting $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$

- **Cross-checked between several fitters with different methods including**
  - **Full pull terms:** each systematic term is constrained by a pull term in the χ^2
  - **Full covariance matrix:** The correlation between each energy bin is calculated through MC simulation
  - **Pull terms + covariance matrix**
- **Data from 6AD and 8AD periods are carefully combined**
- **Consistent results**

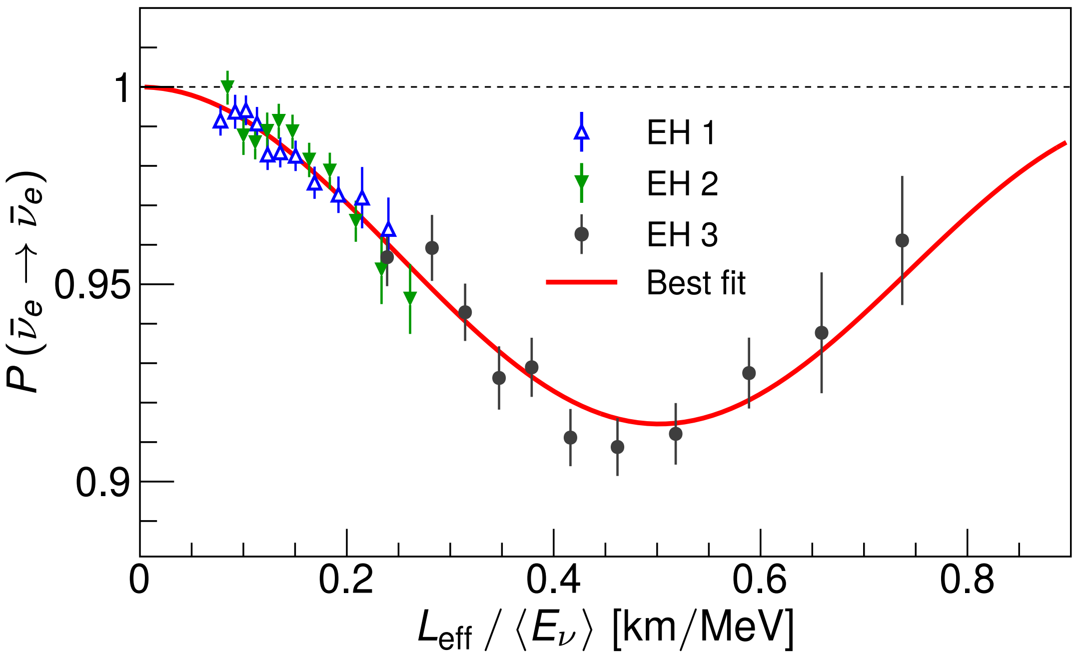
Results - Spectrum

Energy Spectrum at Far Site



Clear oscillation pattern appears in the far site

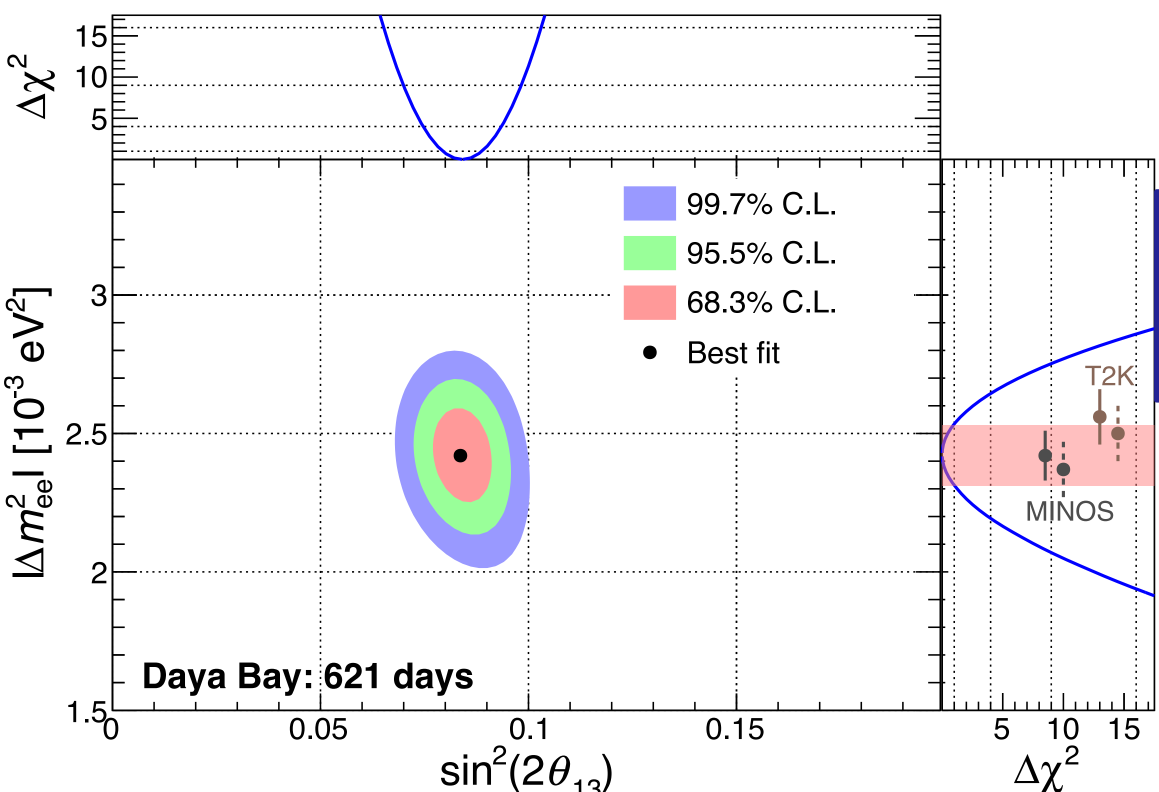
Oscillation Probability with respect to $L_{effective}/E_\nu$



The combination of near and far sites almost completes one oscillation cycle

Oscillation Results

- From 6AD to 6+8AD, the precision improves for
  - $\sin^2 2\theta_{13}$ from 9% to 6 %
  - $|\Delta m^2_{ee}|$ from 7% to 5%
- The measurement of Δm^2_{ee} achieve similar Δm^2 precision as the muon neutrino disappearance channel

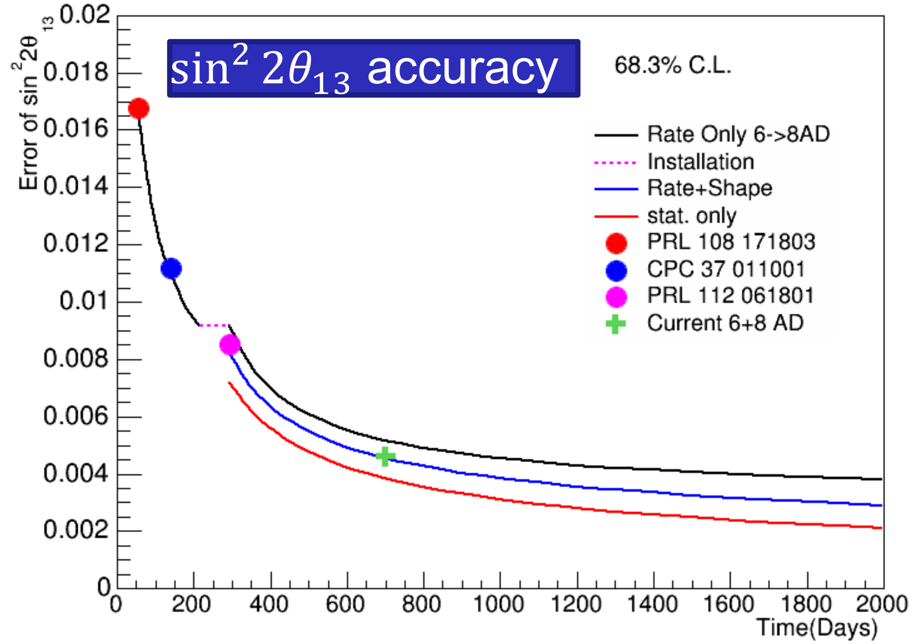


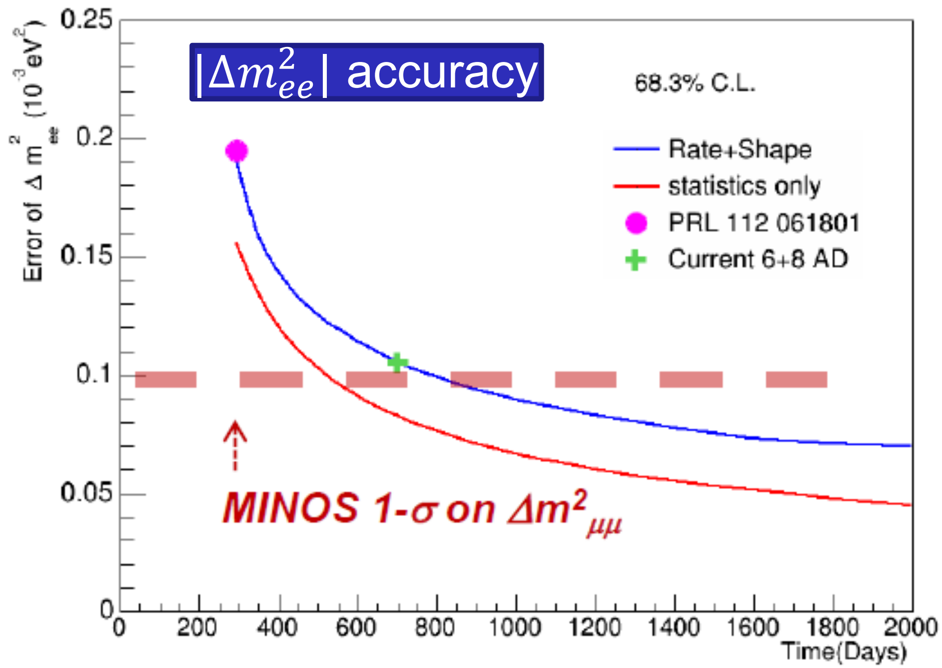
$\sin^2 2\theta_{13} = 0.084 \pm 0.005$
$|\Delta m^2_{ee}| = (2.42 \pm 0.11)\times 10^{-3}\ \mathrm{eV}^2$
$\chi^2/NDF = 134.7/146$

PRL 115, 111802 (2015)

Current Status and Future Prospect

- Continue data-taking until the end of 2017
- Currently still dominated by statistics
- Continue to improve systematics
- Anticipate ~3% precision for both $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$

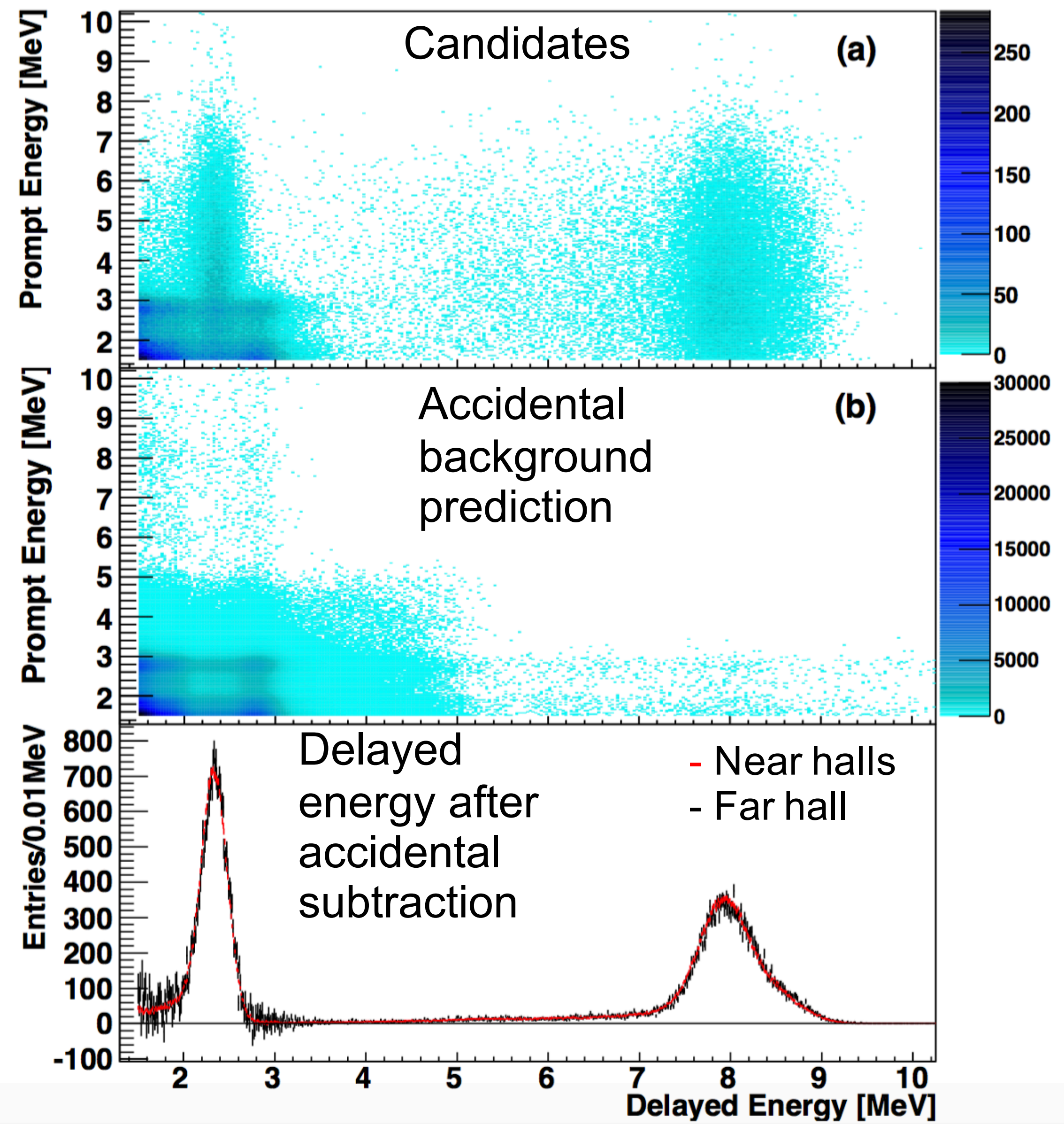




Hydrogen Capture

	H (2.2 MeV)	Gd (8 MeV)
dt	400 μs	200 μs
E_p	[1.5, 12] MeV	[0.7, 12] MeV
E_d	3 σ	[6, 12] MeV
Distance	50 cm	N/A

- **Longer capture time for hydrogen capture**
- **Raise prompt energy cut(0.7 to 1.5 MeV) and require prompt-delayed distance cut to remove accidental background**



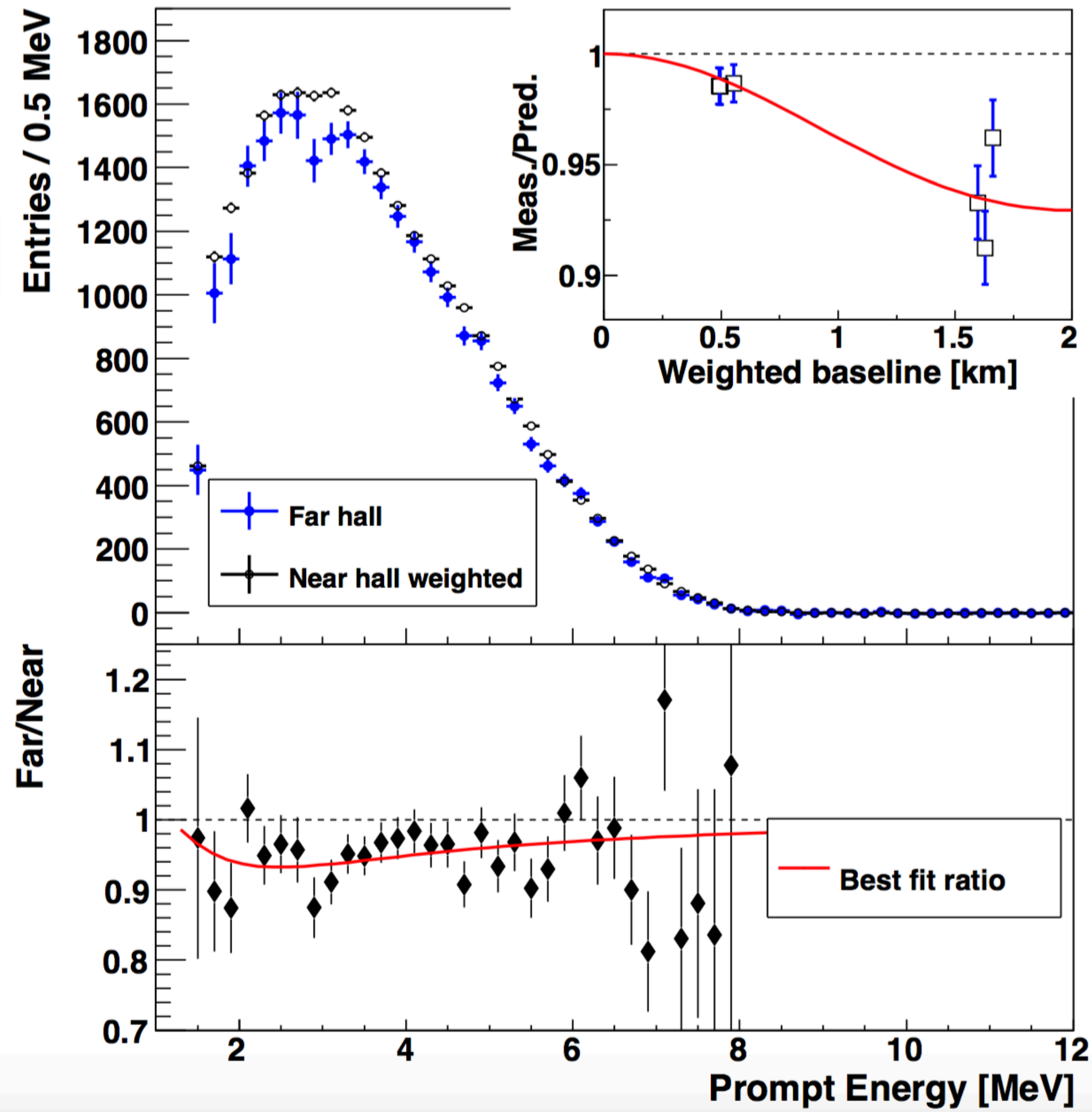
Hydrogen Capture

- **Rate analysis of 217 days of 6-AD data:**

$$\sin^2 2\theta_{13} = 0.083 \pm 0.018$$

Rule out null hypothesis **at 4.6σ level**

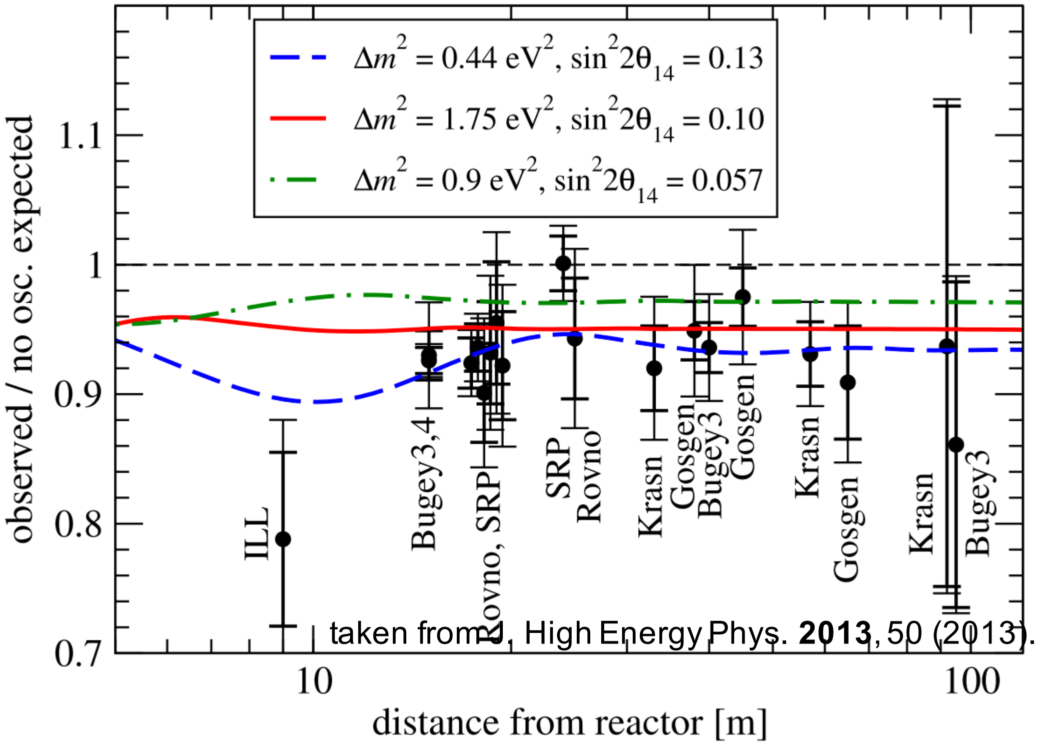
- **Independent statistics**
- **Different systematics**
- **Potentially improve the final precision of $\sin^2 2\theta_{13}$**



PRD 90, 071101 (R) 2014

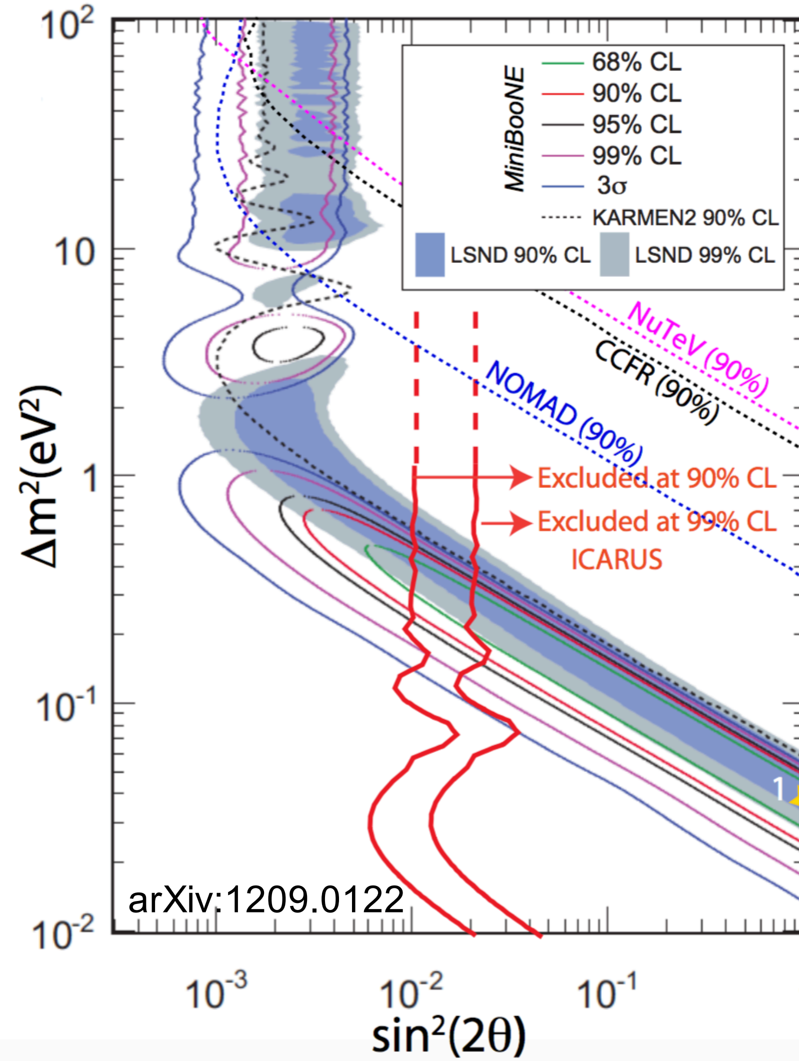
Sterile Neutrino?

Reactor Neutrino Anomaly



taken from J. High Energy Phys. **2013**, 50 (2013).

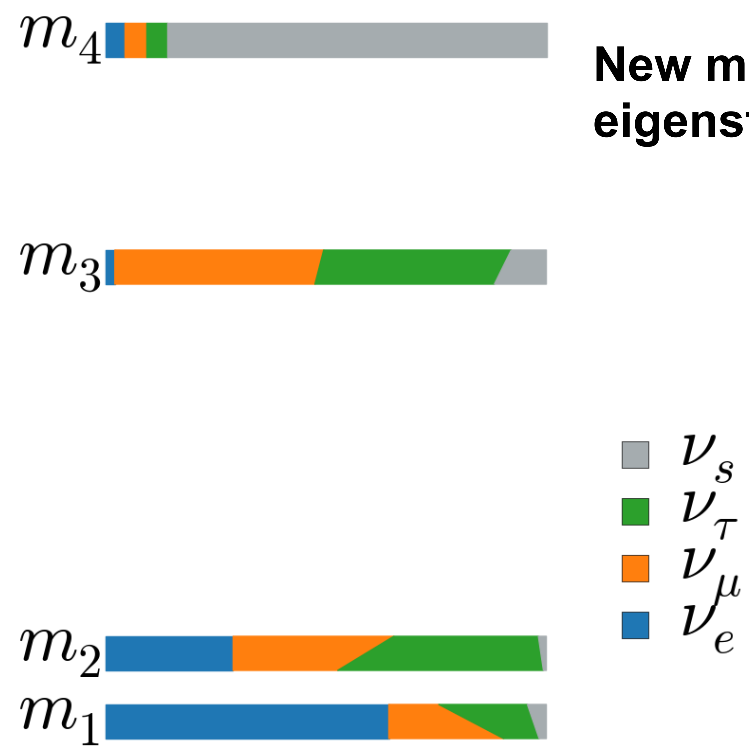
LSND & MiniBooNE



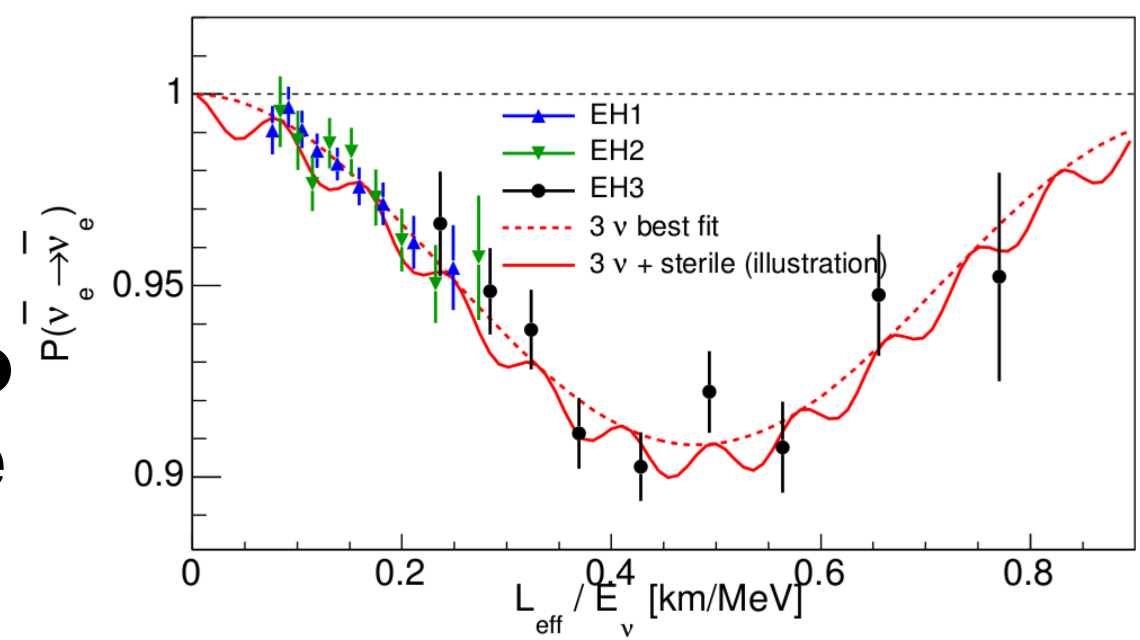
- Global average of the reactor neutrino rates is lower than the prediction without oscillation
- LSND & MiniBooNE observed excessive events for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$
- Both can be explained by the existence of sterile neutrino

Sterile Neutrino Search

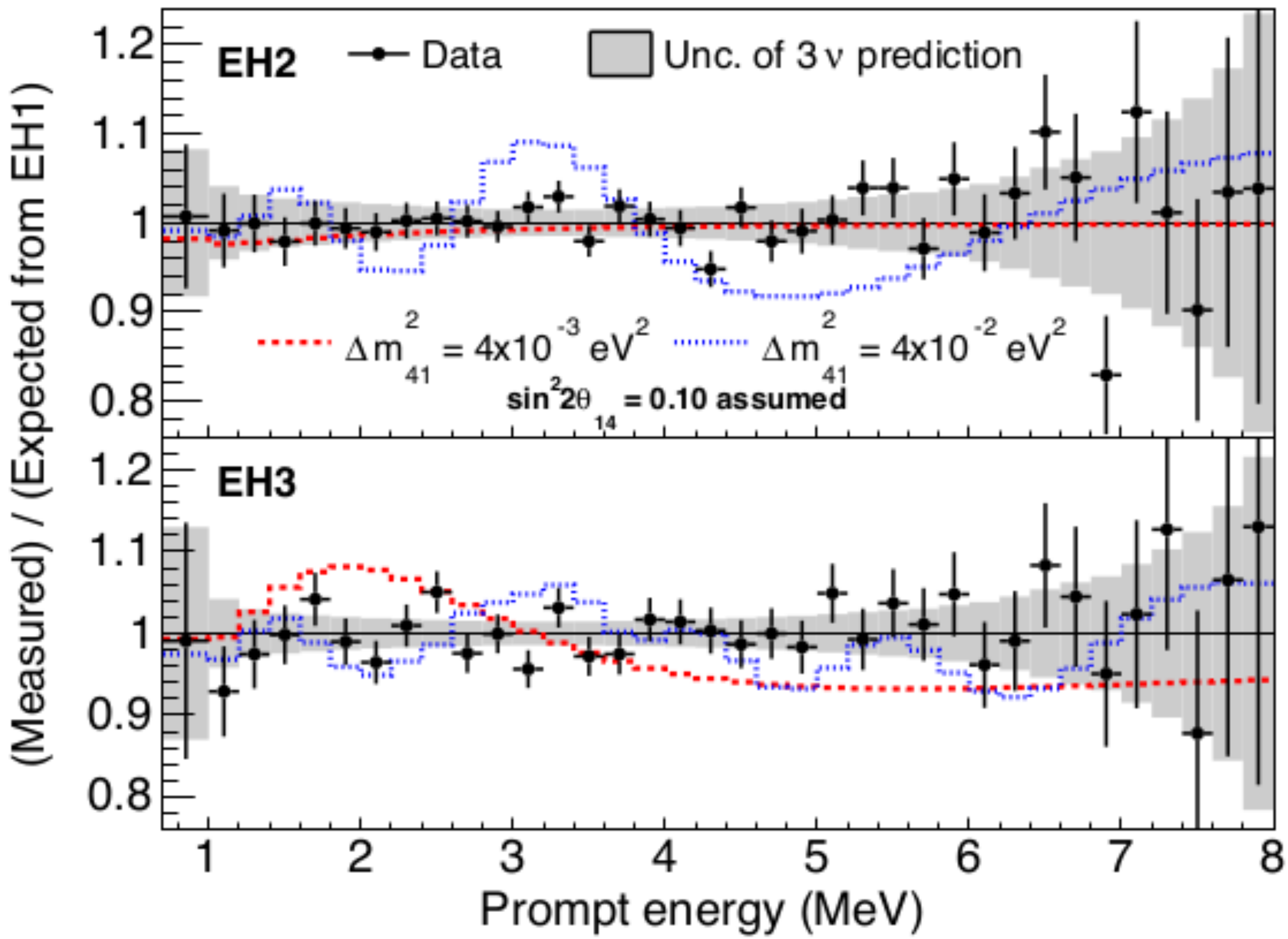
$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L) \approx 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee} L}{4E_\nu}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$



- **A minimum 3+1 extension of Standard Model is used**
- **Light sterile neutrino might distort relative energy spectrum**

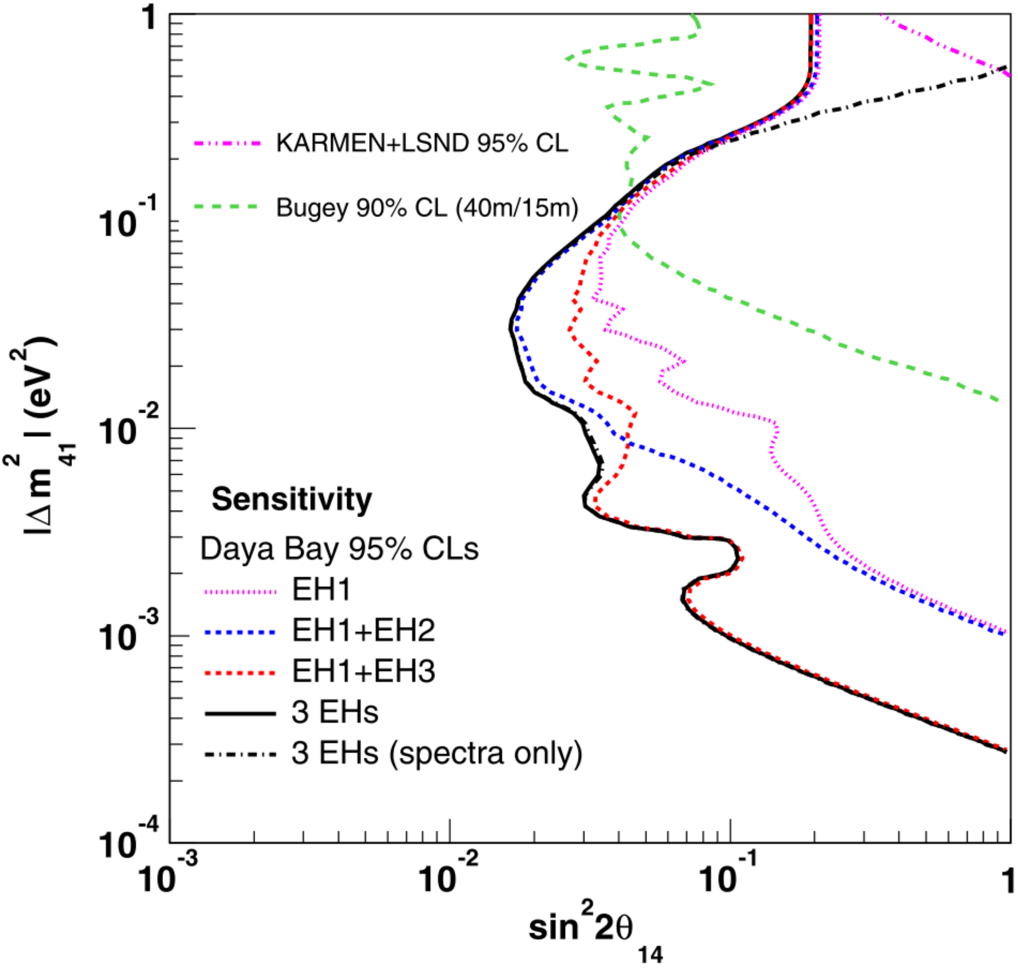


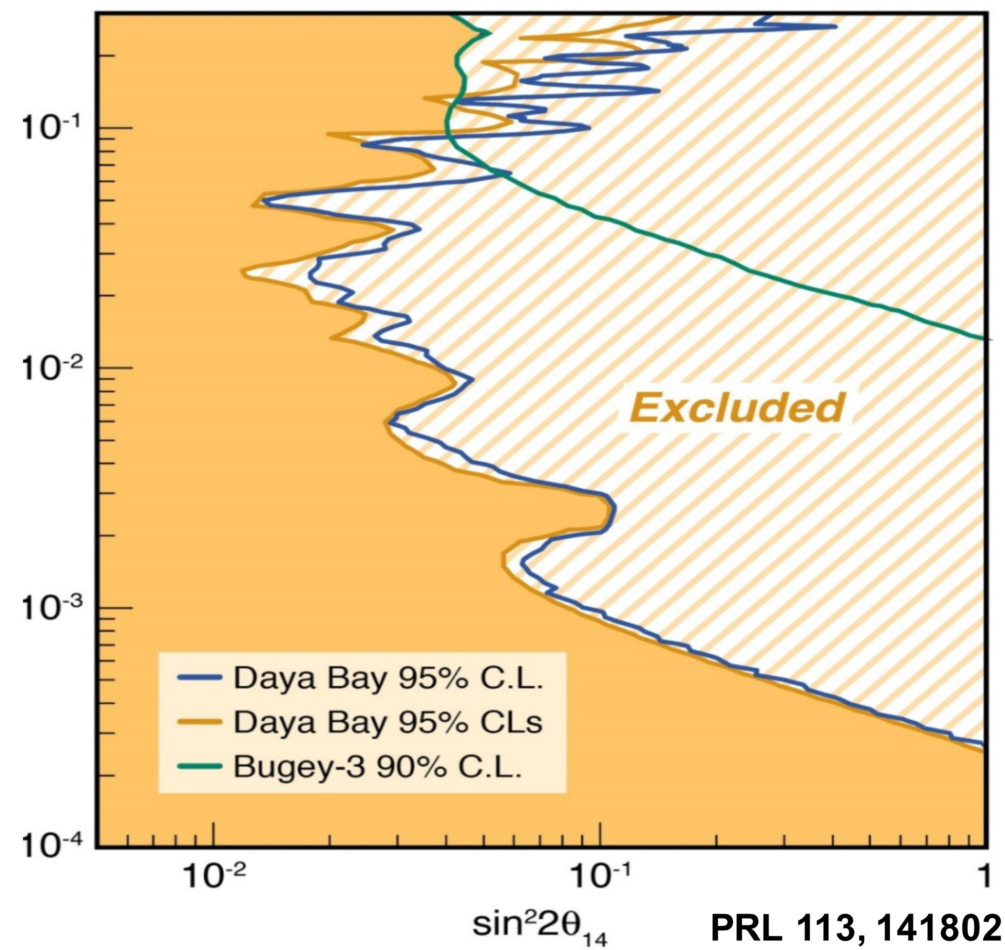
Sterile Neutrino Search



- **Daya Bay's unique configuration of multiple baselines allows to cover a large region of parameter space**

Exclusion Region (6AD)





PRL 113, 141802

- **Different baseline combinations provide sensitivities at different mass squared splitting range**
- **Best result in a previously unexplored region**
- **A factor of 2 improvement expected from 6 AD to 6+8 AD. Another factor of 2 improvement expected by the end of 2017**

Absolute Reactor Neutrino Flux

- **Measured Flux**

$$Y_0 = (1.55 \pm 0.04)\times10^{-18}\ \text{cm}^2\text{/GW/day}$$
$$\sigma_f = (5.92 \pm 0.14)\times10^{-43}\ \text{cm}^2\text{/fission}$$

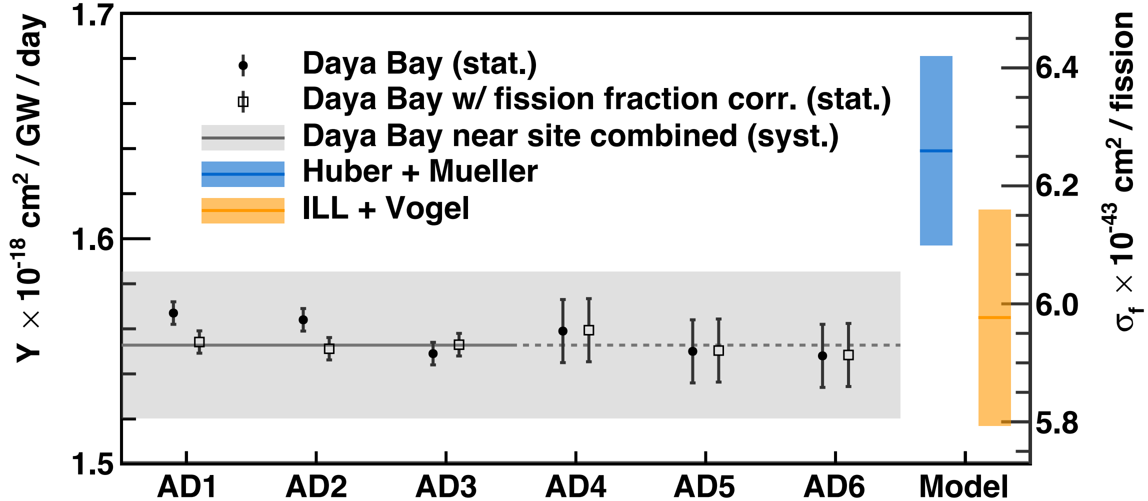
- **Measured flux is consistent with previous reactor experiments**

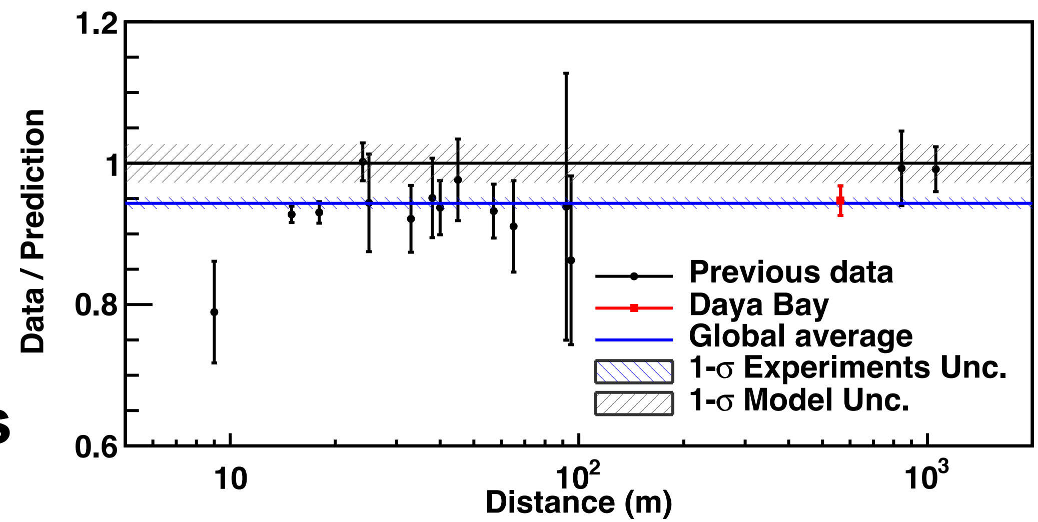
- **Data / Prediction:**

  R(Huber+Mueller)= 0.946 ± 0.022

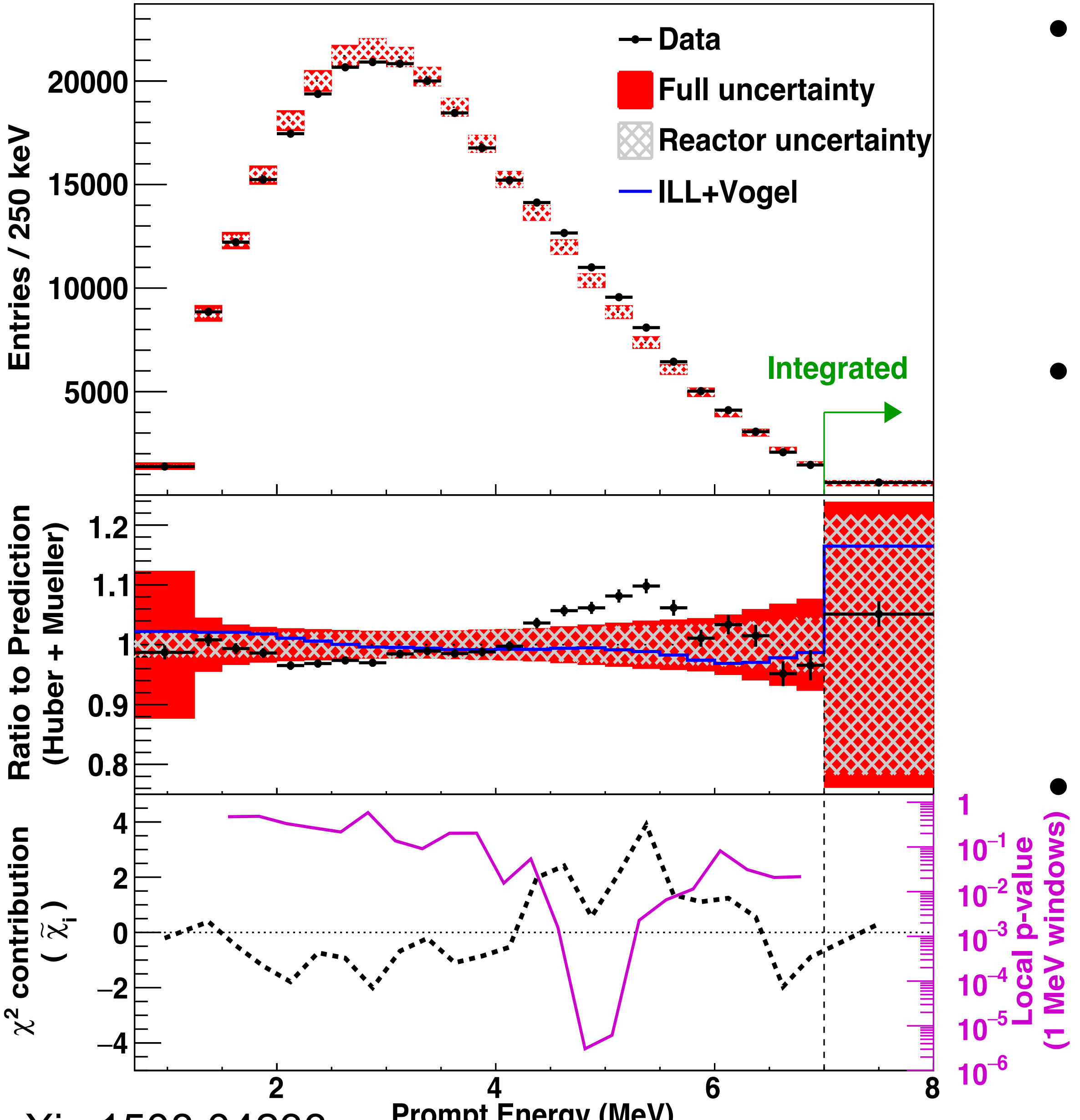
  R(ILL+Vogel) = 0.991 ± 0.023

- **Possible indication of the existence of sterile neutrinos with $\left|\Delta m^2_{41}\right| \gtrsim 0.5$ eV²**





Measured Positron Spectrum



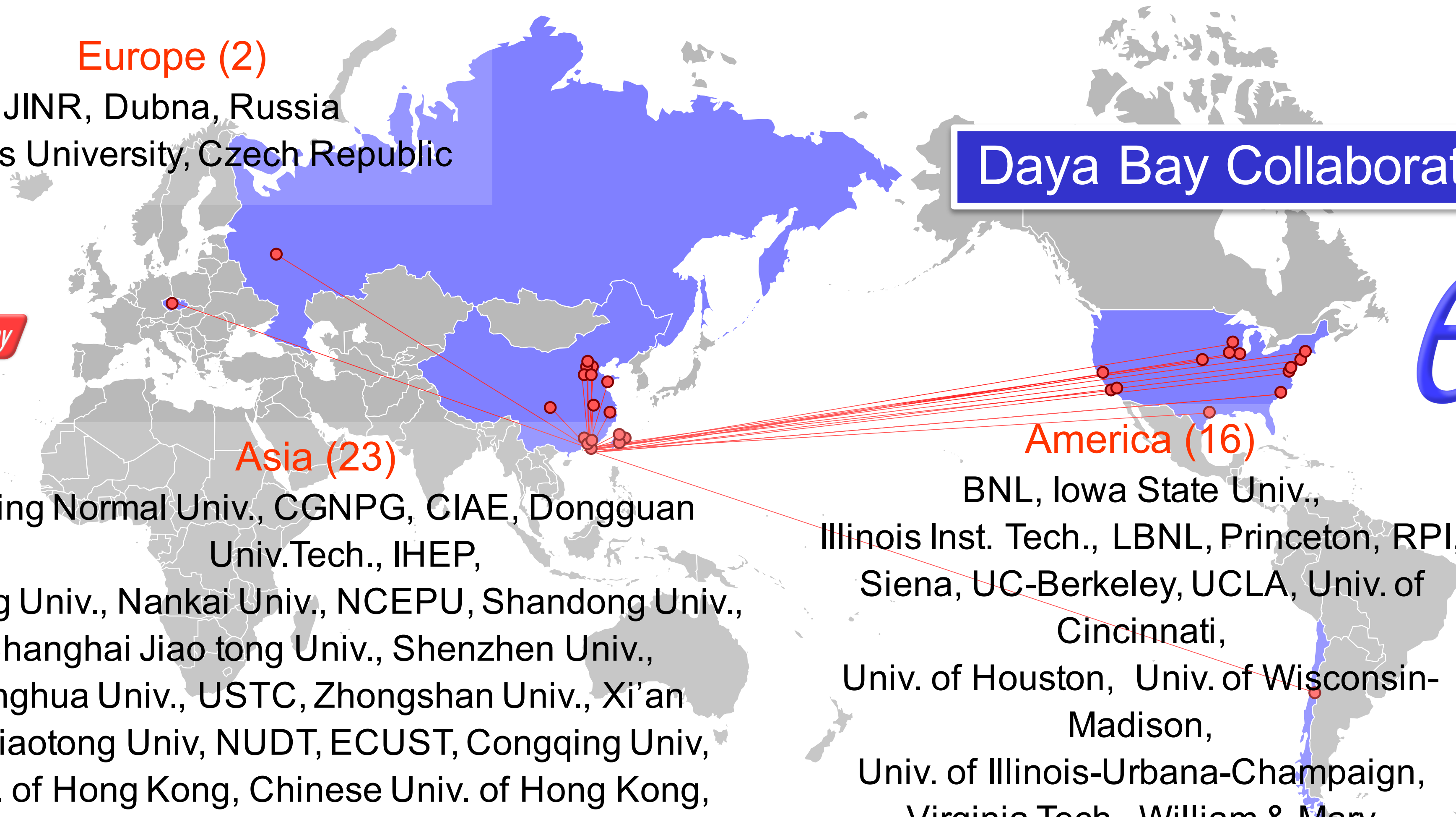
arXiv:1508.04233

- Prompt spectrum is compared with Huber+Mueller (ILL+Vogel) model
- For the whole energy range, the measured spectrum deviates from both models by $\sim 2\sigma$
- Between 4~6 MeV, the excess is up to $\sim 4\sigma$

Summary

- The precision of $\sin^2 2\theta_{13}$ in our new 6+8 AD measurement has reached 6% level
- The precision of $\left|\Delta m^2_{ee}\right|$ has reached 4% level, comparable to the results from T2K & MINOS
- The nH analysis gives an independent measurement of $\sin^2 2\theta_{13}$
- Daya Bay has the most stringent constraints on sterile neutrino for $10^{-3}\ \mathrm{eV}^2 < \left|\Delta m^2_{41}\right| < 0.1\ \mathrm{eV}^2$
- The rate and flux of reactor neutrinos are measured at Daya Bay. An excess up to 4σ is found at ~5 MeV

Thank You!



Daya Bay Collaboration

Europe (2)

JINR, Dubna, Russia
Charles University, Czech Republic

Asia (23)

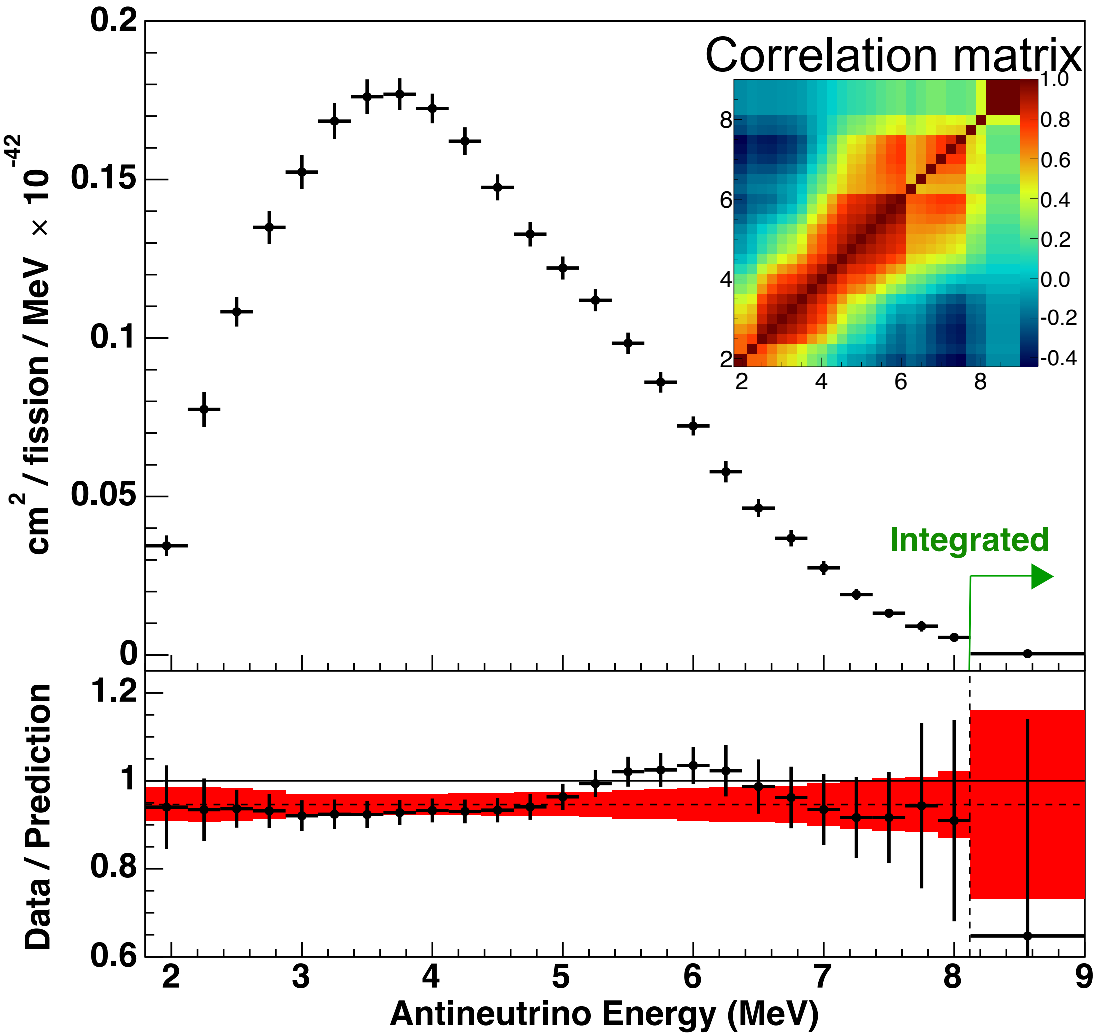
Beijing Normal Univ., CGNPG, CIAE, Dongguan Univ.Tech., IHEP,
Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ.,
Shanghai Jiao tong Univ., Shenzhen Univ.,
Tsinghua Univ., USTC, Zhongshan Univ., Xi'an Jiaotong Univ, NUDT, ECUST, Congqing Univ,
Univ. of Hong Kong, Chinese Univ. of Hong Kong,
National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

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
Catholic Univ, Chile

Backup

Reactor Antineutrino Spectrum



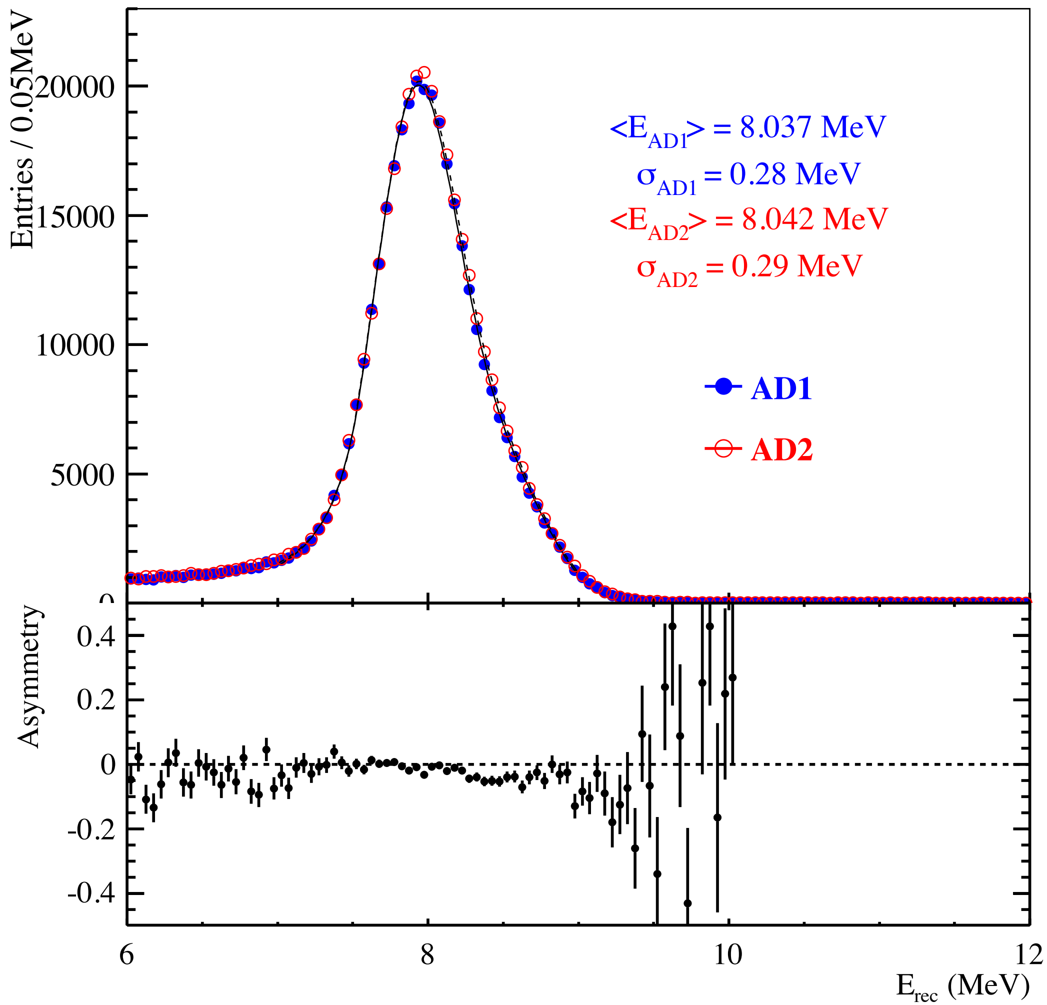
Reactor antineutrino spectrum is extracted by applying detector response model unfolding as a model-independent prediction

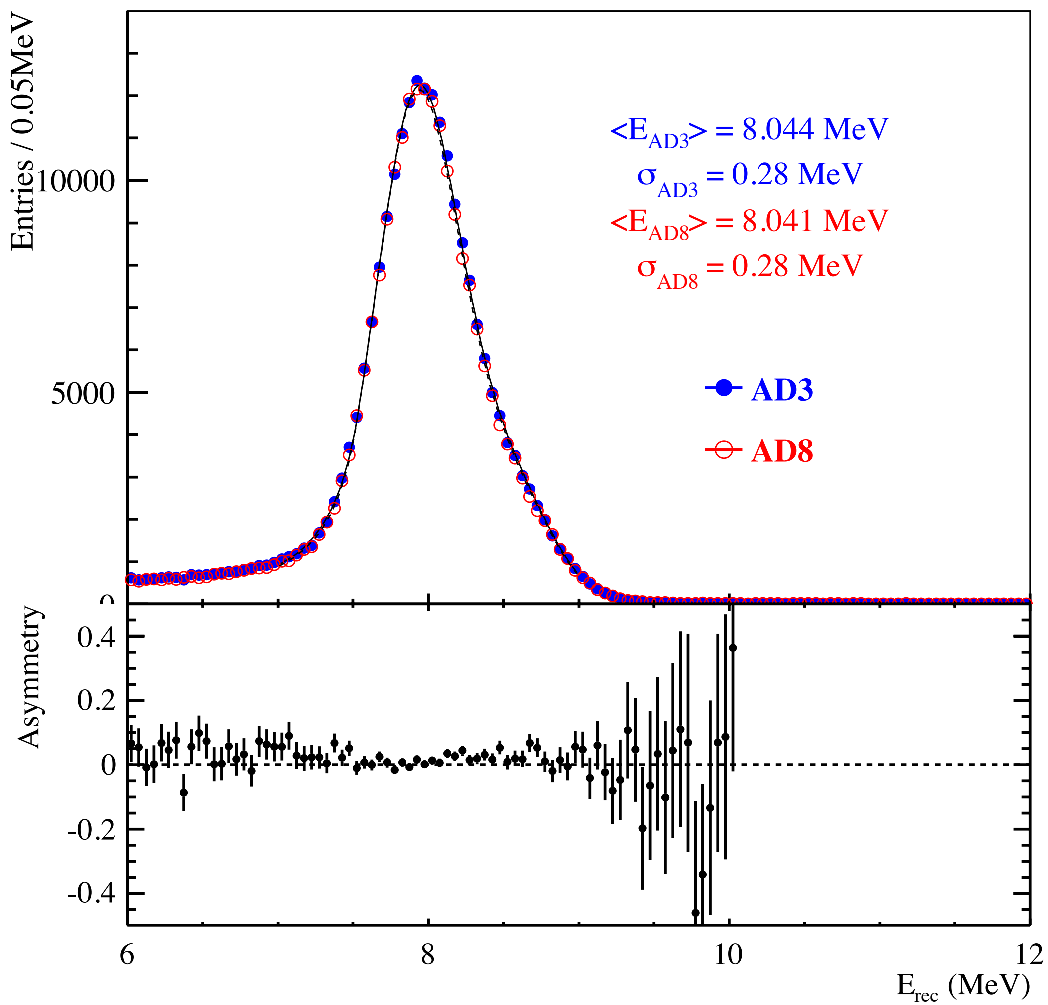
Correlation between nH and nGd Analysis

	Uncorrelated uncertainty	Coupled
$N_{p,\mathrm{GdLS}}$	0.03%	yes
$N_{p,\mathrm{LS}}$	0.13%	no
$N_{p,\mathrm{Acrylic}}$	0.50%	no
$\varepsilon_{ep,v}$	0.1%	yes
$\varepsilon_{ed,v}$	0.5%	no
$\varepsilon_{t,v}$	0.14%	yes
ε_{d}	0.4%	no
Combined	0.67%	

The correlation coefficient is found to be 0.05

Side by Side Comparison





Detectors function identically

Δm^2_{ee}

- **At Daya Bay, results are from fitting the data with the two-flavor approximation:**

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

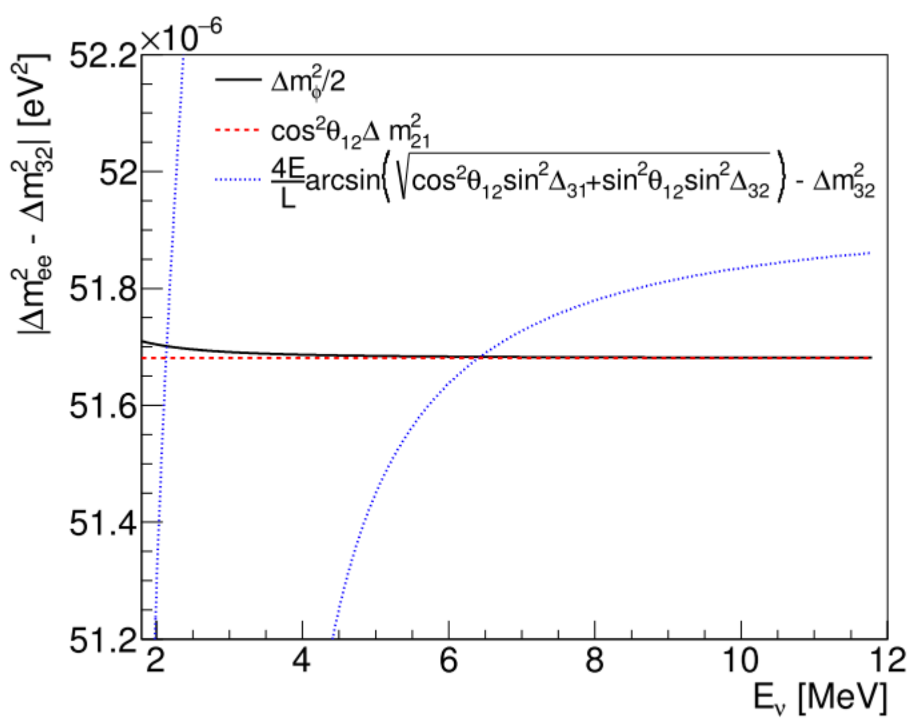
- **This enables to represent our result independent of mass hierarchy**

$$|\Delta m^2_{ee}| = |\Delta m^2_{32}| \pm \Delta m^2_{\phi}/2$$
$$= |\Delta m^2_{31}| \mp (|\Delta m^2_{21}| - \Delta m^2_{\phi}/2),$$

$$\Delta m^2_{\phi} = \phi \times \frac{4E}{L}.$$

$$\phi = \tan^{-1}\left(\frac{sin2\Delta_{21}}{cos^2\,\Delta_{21} + tan^2\,\theta_{12}}\right)$$

$$\Delta m^2_{\rm eff}|_e = \cos^2\theta_{12}|\Delta m^2_{31}| + \sin^2\theta_{12}|\Delta m^2_{32}|$$
$$= |\Delta m^2_{32}| \pm \cos^2\theta_{12}\Delta m^2_{21}.$$



Reactor Neutrino Anomaly

- At low energy ($E_\nu < 4$ MeV):
  - Implementation of Columb and weak magnetism interaction
  - Correction = $(0.65 \times (E_\nu - 4\ MeV)\ in\ \%)$
- At high energy ($E_\nu < 4$ MeV):
  - Sensitive to the charge Z of the nuclei
  - Old: mean dependence of Z is used
  - New: complete distribution is used

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