The Daya Bay Reactor Neutrino Experiment

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Solvay workshop on "Beyond the Standard model with Neutrinos and Nuclear Physics" Nov 29 – Dec 01, 2017, Brussels, Belgium

Recent results from Daya Bay

- The Daya Bay Reactor Neutrino Experiment
- Recent oscillation results
- Absolute reactor anti-neutrino flux, spectrum, and their changes due to fuel evolution
- Search for a light sterile neutrino

Neutrino Oscillations

- Each flavor state is a mixture of mass eigenstates
- Described by a neutrino mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

The Maki-Nakagawa-Sakata-Pontecorvo Matrix

- A freely propagating ν_e will oscillate into other types
- In general, $|<\nu_{\mu,\tau}(t)|\nu_e(0)>|^2 \neq 0$

$$|<\nu_e(t)|\nu_e(0)>|^2 \approx 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

The Daya Bay Reactor Neutrino Experiment

F. P. An et al., Daya Bay Collaboration, NIM A **811**, 133 (2016); PRD **95**, 072006 (2017).

Reactor expt.: a clean way to measure θ_{13}

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

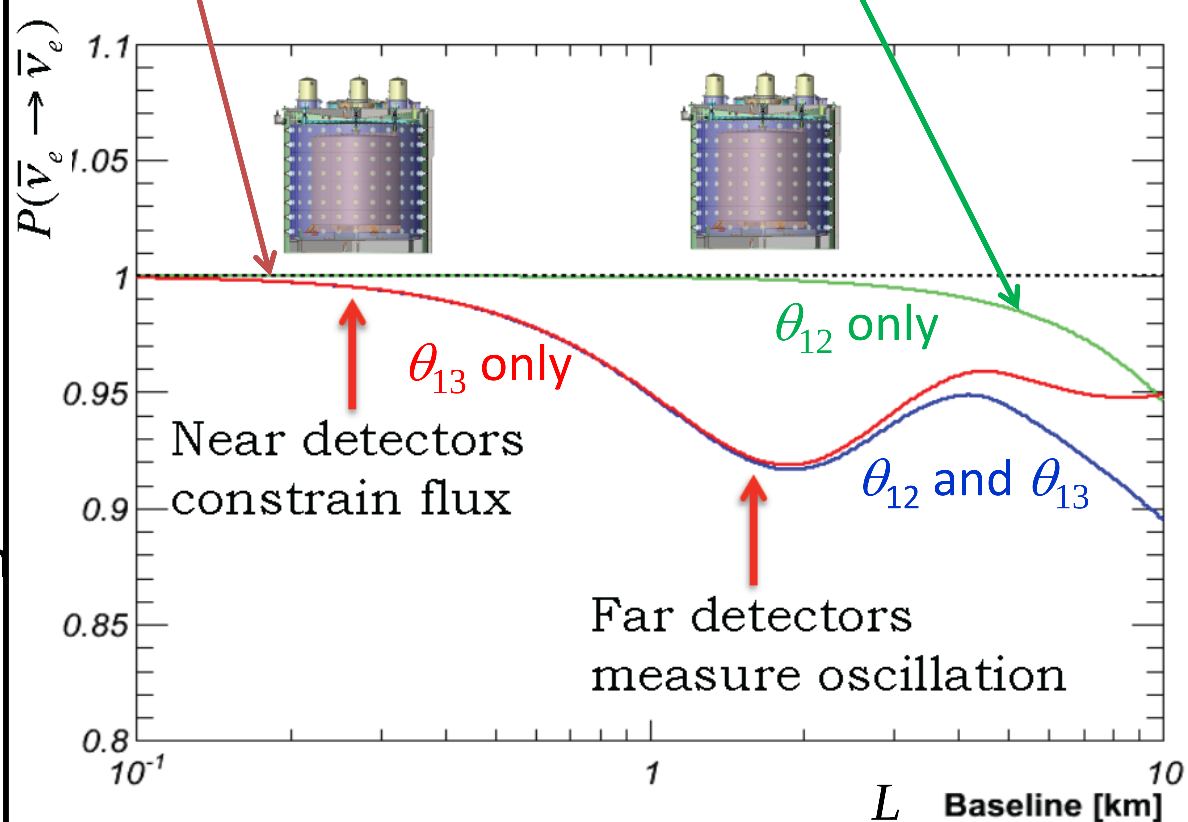
- Reactor: abundant, free, pure source of $\bar{\nu}_e$
- disappearance of $\bar{\nu}_e$ at small L depends only on θ_{13}

Near-far configuration

Near detectors: $\bar{\nu}_e$ flux and spectrum for normalization

Far detectors: near oscillation maximum for best sensitivity

Relative measurement: cancel out most systematics



Near/far Configuration

Minimize systematic uncertainties:

reactor-related: cancelled by near-far ratio

detector-related: use 'identical' detectors, careful calibration

$$\frac{R_{\mathrm{Far}}}{R_{\mathrm{Near}}} = \left(\frac{L_{\mathrm{Near}}}{L_{\mathrm{Far}}}\right)^2 \frac{N_{\mathrm{Far}}}{N_{\mathrm{Near}}} \frac{\varepsilon_{\mathrm{Far}}}{\varepsilon_{\mathrm{Near}}} \left[\frac{P_{\mathrm{surv}}(L_{\mathrm{Far}})}{P_{\mathrm{surv}}(L_{\mathrm{Near}})}\right]$$

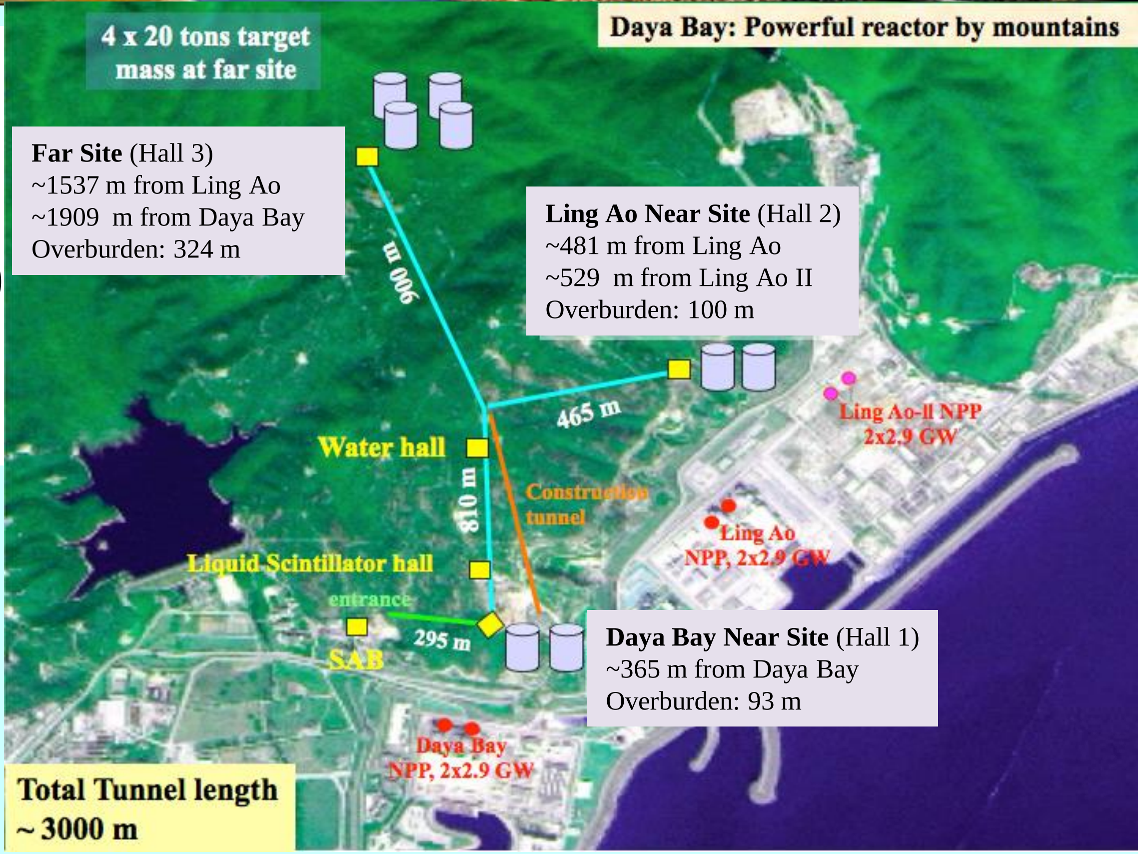
$\bar{\nu}_e$ detection ratio — $1/r^2$ — number of protons — detector efficiency — Survival prob. $\rightarrow \sin^2(2\theta_{13})$

Parameter	CHOOZ error	Near/far configuration
Reaction cross section	1.9 %	Cancelled out
Number of protons	0.8 %	Reduced to ~ 0.03%
Detection efficiency	1.5 %	Reduced to ~ 0.2%
Reactor power	0.7 %	Reduced to ~ 0.04%
Energy released per fission	0.6 %	Cancelled out
CHOOZ Combined	2.7 %	~ 0.21%

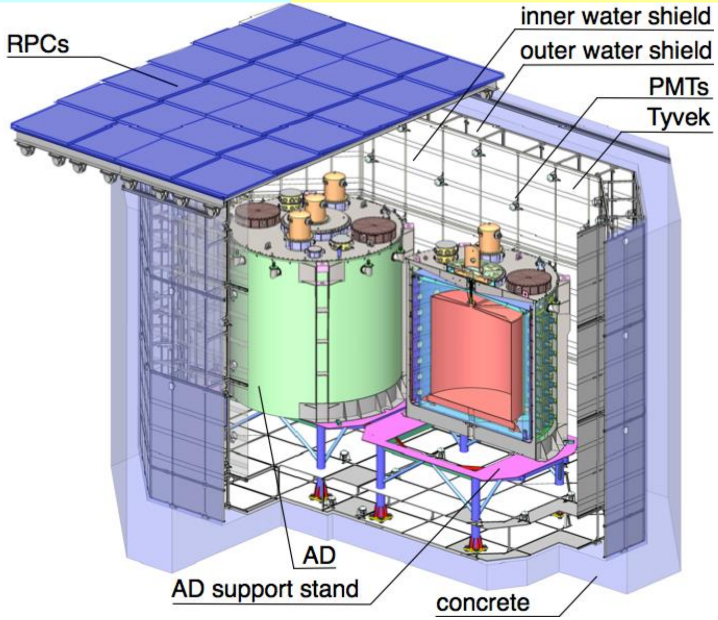
Daya Bay (China)

Daya Bay Experiment

- Top five most powerful nuclear plants (17.4 GW_{th})
→ large number of $\bar{\nu}_e$ (3×10^{21}/s)
- Adjacent mountains shield cosmic rays



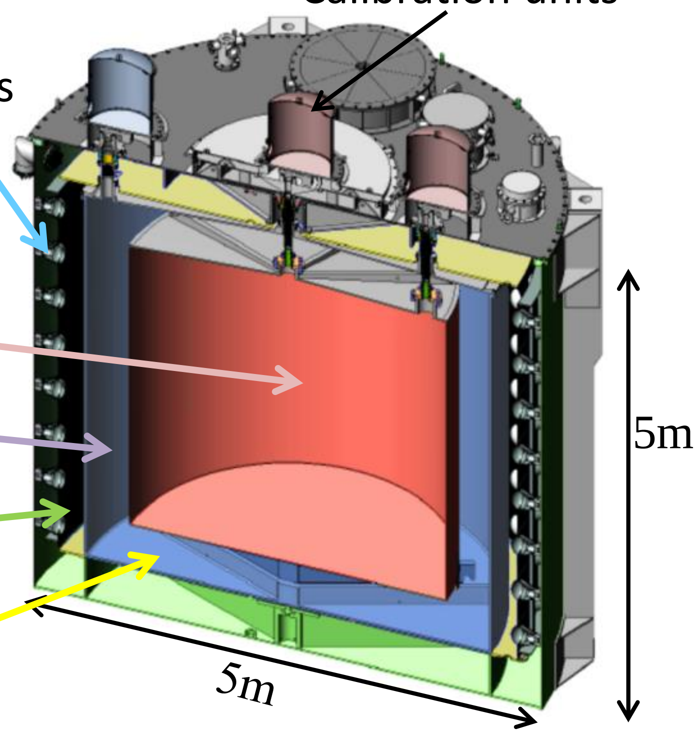
Daya Bay detectors



RPC : muon veto
Water pool: muon veto + shielding from environmental radiations (2.5m water)

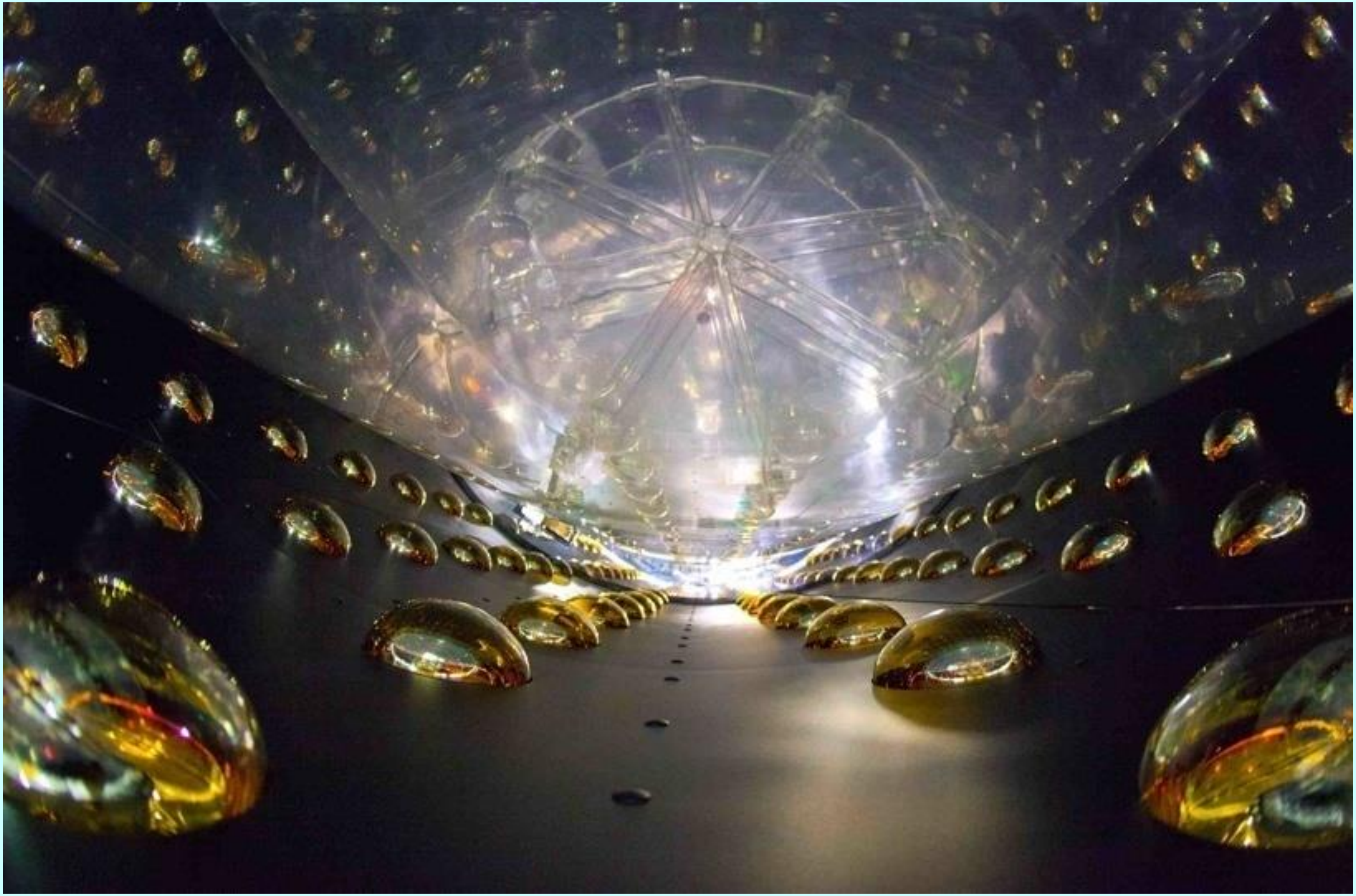
8 functionally identical anti-neutrino detectors (AD) to suppress systematic uncertainties

3 zone cylindrical vessels			
	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding



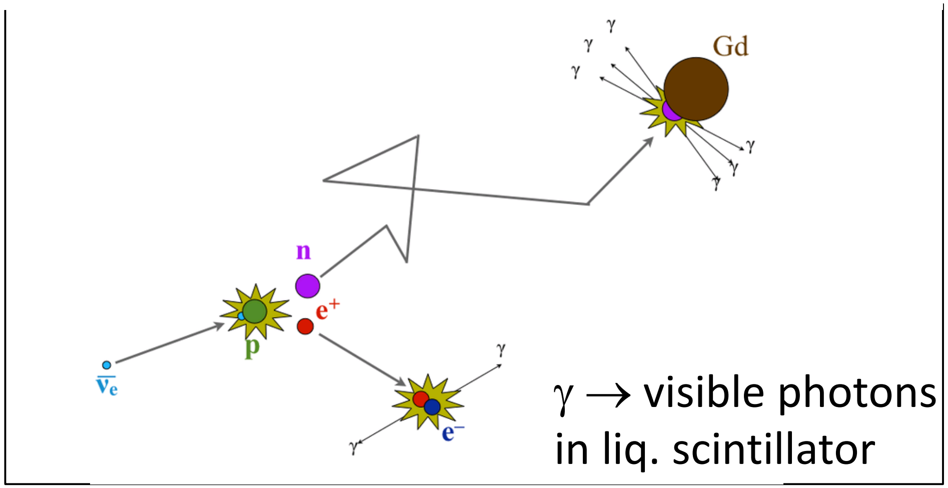
Top and bottom reflectors: more light, more uniform detector response

Interior of an AD



Anti-neutrino detection

$\bar{\nu}_e$ detected via inverse beta-decay (IBD):



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

$\rightarrow + p \rightarrow D + \gamma$ (2.2 MeV)   ~180μs

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

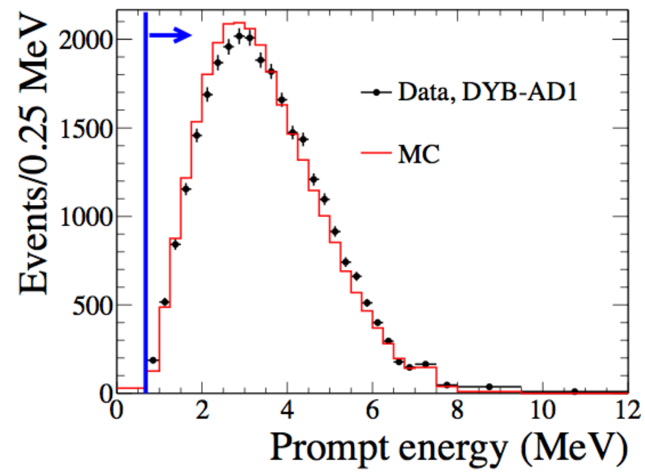
$\rightarrow Gd + \gamma$'s (8 MeV)

(delayed signal)

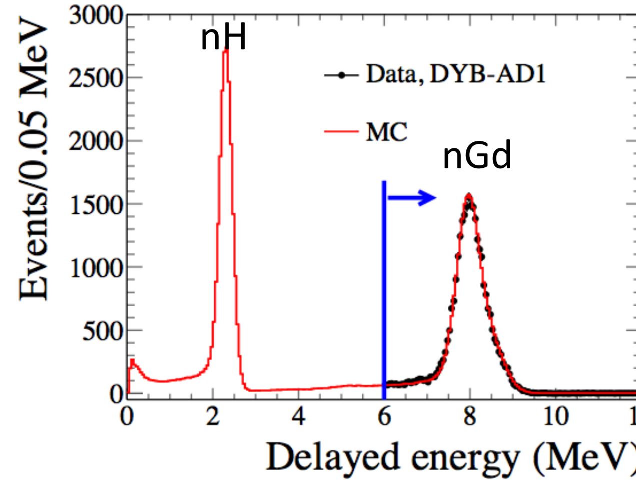
Powerful background rejection!

$$E_\nu \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8 \text{ MeV}$$

Prompt Signal



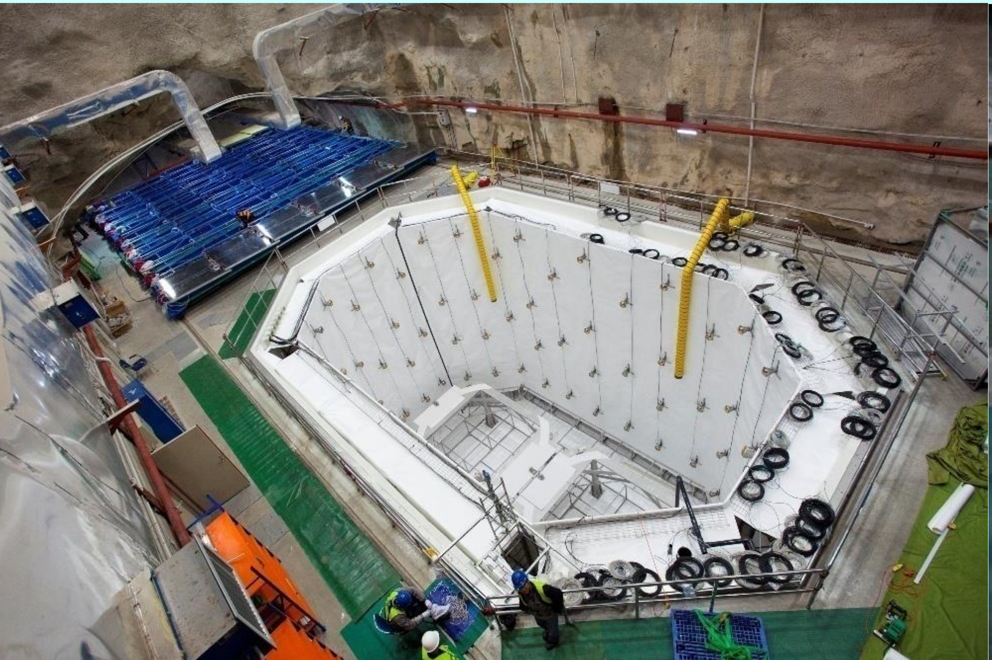
Delayed Signal

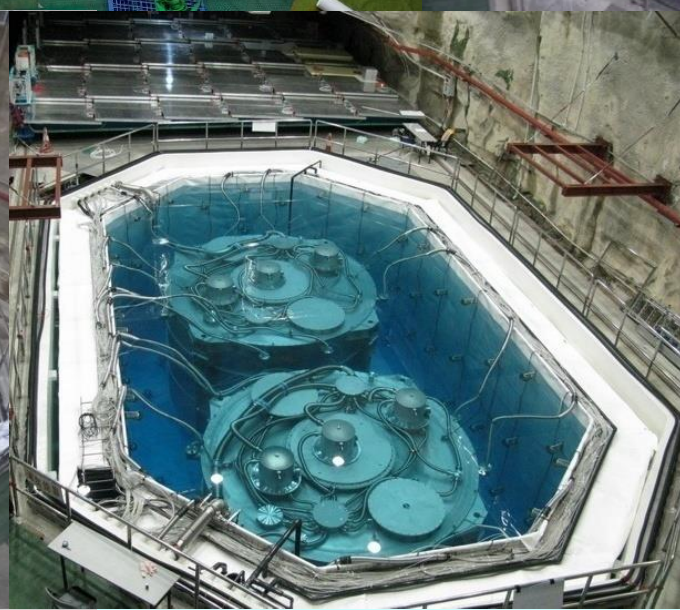


The Daya Bay Collaboration

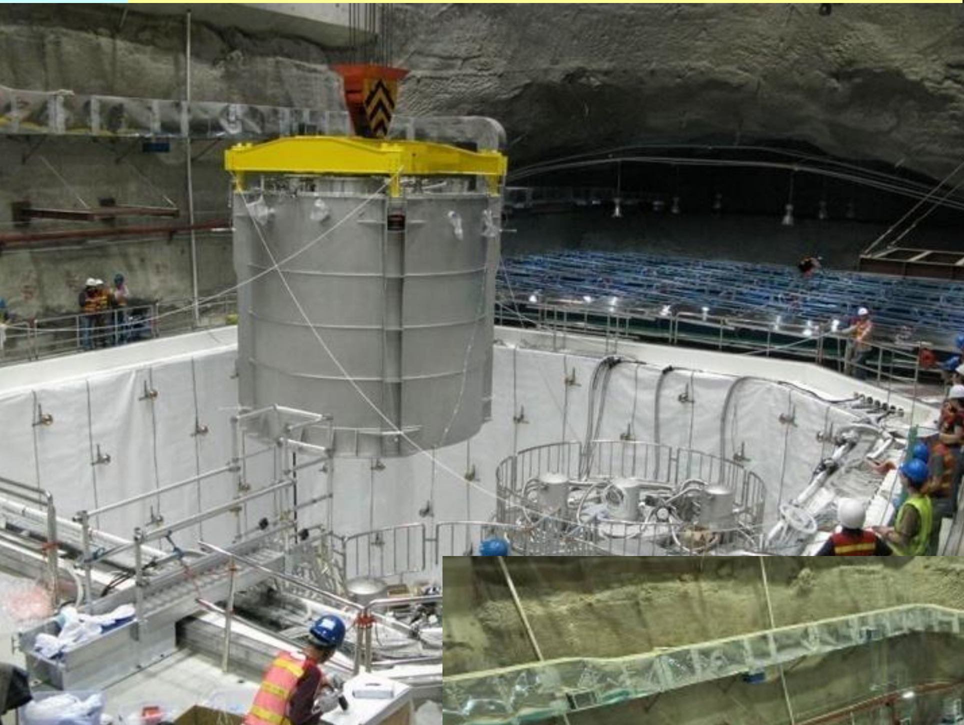
42 Institutes, ~ 203 collaborators from China, USA, Hong Kong, Taiwan, Chile, Czech Republic and Russia

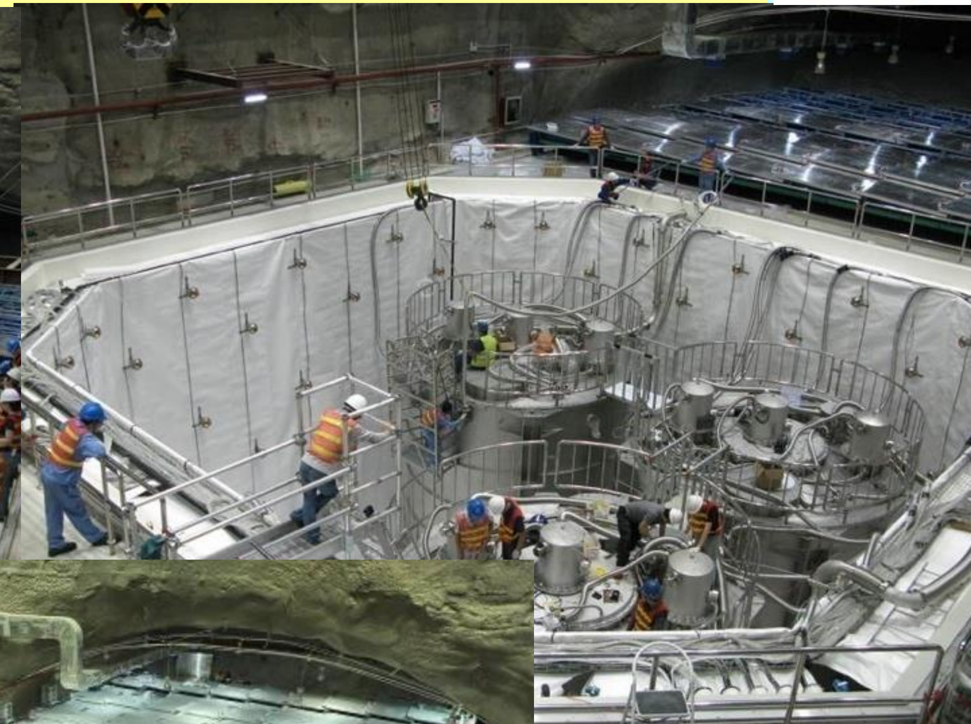
AD Installation - Near Hall





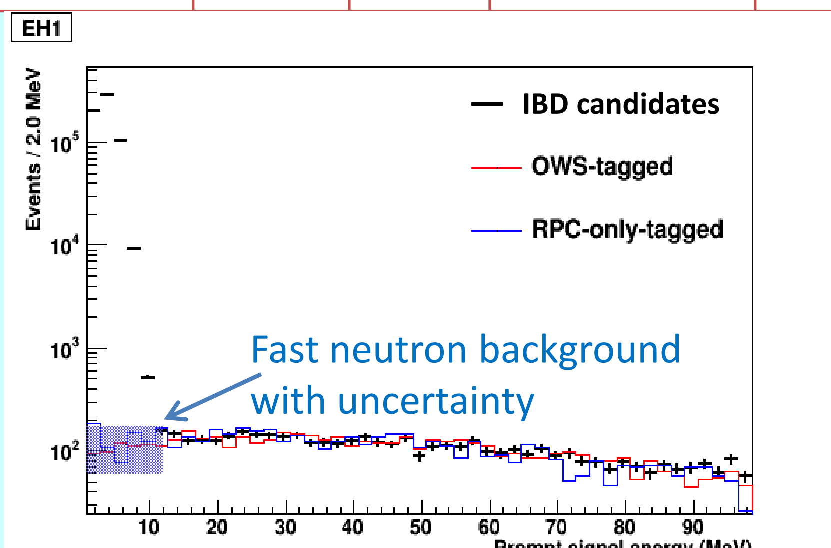
AD Installation - Far Hall

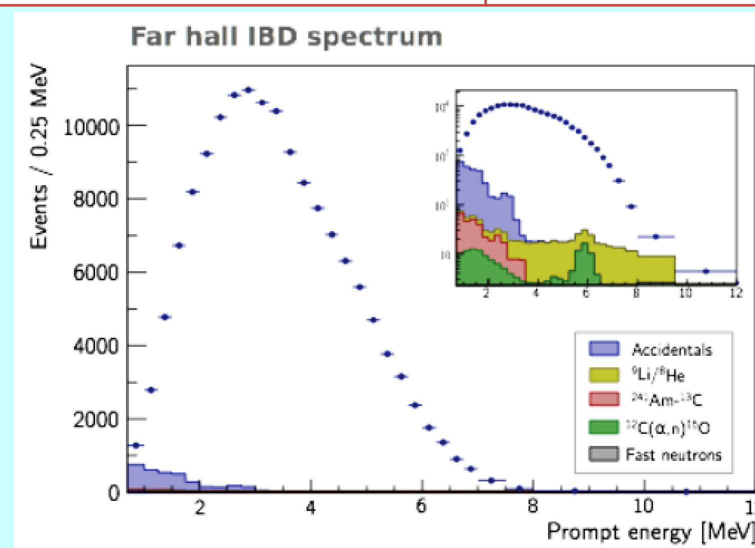




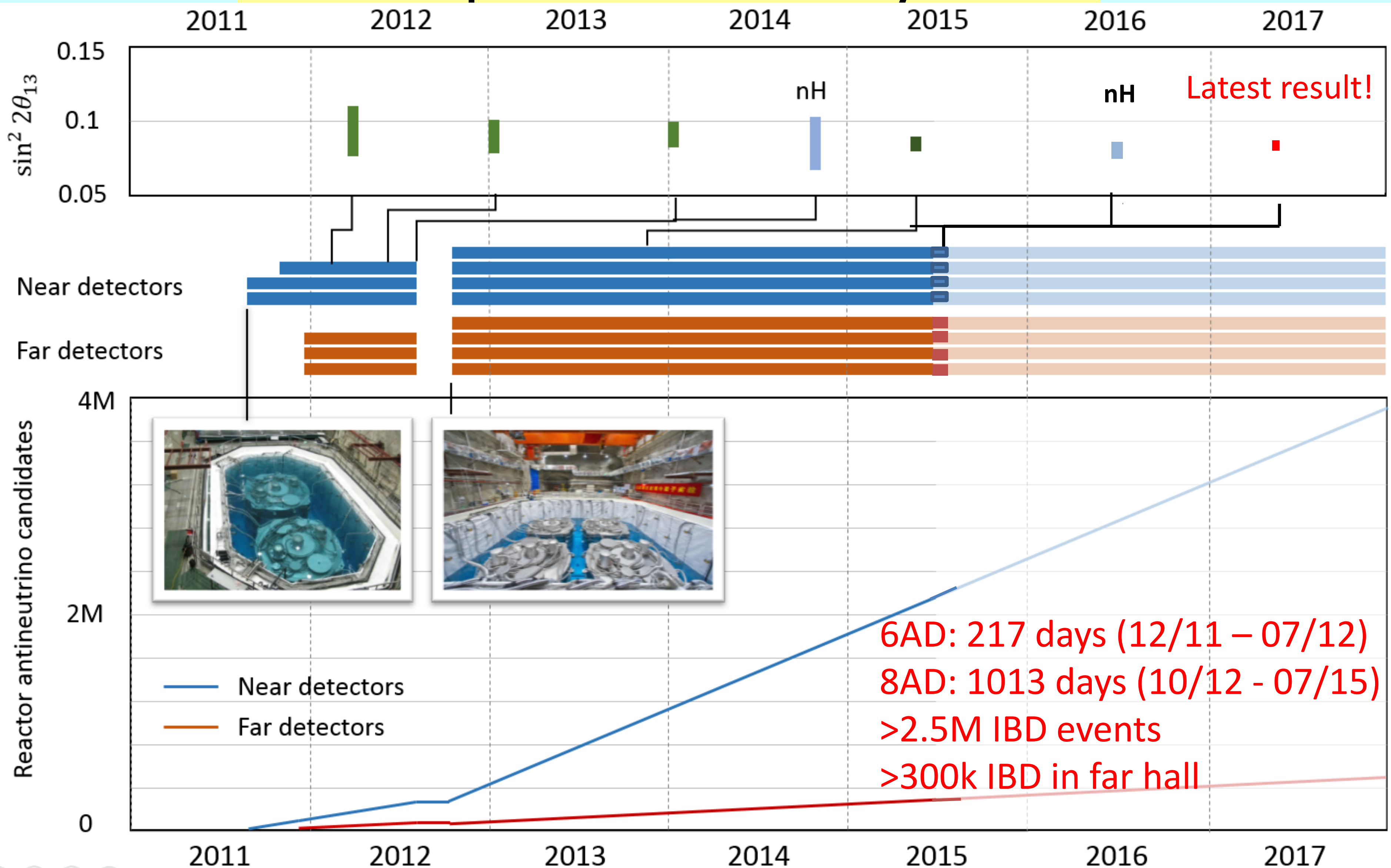
Background

Background	Near	Far	Uncertainty	Method	Improvement
Accidentals	1.4%	2.3%	~1%	Statistically calculated from uncorrelated singles	Extend to larger data set
$^{9}Li/^{8}He$	0.4%	0.4%	~44%	Measured with after-muon events	Extend to larger data set
Fast neutrons	0.1%	0.1%	~13%	Measured from RPC+OWS tagged muon events	Model independent measurement
AmC source	0.03%	0.2%	~45%	MC benchmarked with single gamma and strong AmC source	Two sources are taken out in Far site ADs
α-n	0.01%	0.1%	~50%	Calculated from measured radioactivity	Reassess systematics





Operation history



Signal and background summary

	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
ΔN_{p} [%]	0.00 ± 0.03	0.13 ± 0.03	-0.25 ± 0.03	0.02 ± 0.03	-0.12 ± 0.03	0.24 ± 0.03	-0.25 ± 0.03	-0.05 ± 0.03
	Selection A							
$\bar{\nu}_e$ candidates	597616	606349	567196	466013	80479	80742	80067	66862
DAQ live time [days]	1117.178	1117.178	1114.337	924.933	1106.915	1106.915	1106.915	917.417
ϵ_μ	0.8255	0.8221	0.8573	0.8571	0.9824	0.9823	0.9821	0.9826
$\bar{\epsilon}_{\mathrm{m}}$	0.9744	0.9747	0.9757	0.9757	0.9759	0.9758	0.9756	0.9758
Accidentals [day^{-1}]	8.46 ± 0.09	8.46 ± 0.09	6.29 ± 0.06	6.18 ± 0.06	1.27 ± 0.01	1.19 ± 0.01	1.20 ± 0.01	0.98 ± 0.01
Fast neutron [AD^{-1} day^{-1}]	0.79 ± 0.10		0.57 ± 0.07		0.05 ± 0.01			
^{9}Li, ^{8}He [AD^{-1} day^{-1}]	2.46 ± 1.06		1.72 ± 0.77		0.15 ± 0.06			
^{241}Am-^{13}C, 6-AD [day^{-1}]	0.27 ± 0.12	0.25 ± 0.11	0.28 ± 0.13		0.22 ± 0.10	0.21 ± 0.10	0.21 ± 0.10	
^{241}Am-^{13}C, 8-AD [day^{-1}]	0.15 ± 0.07	0.16 ± 0.07	0.13 ± 0.06	0.15 ± 0.07	0.04 ± 0.02	0.03 ± 0.02	0.03 ± 0.02	0.05 ± 0.02
^{13}C$(\alpha, \mathrm{n})^{16}$O [day^{-1}]	0.08 ± 0.04	0.07 ± 0.04	0.05 ± 0.03	0.07 ± 0.04	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03
$\bar{\nu}_e$ rate, $R_{\bar{\nu}}$ [day^{-1}]	653.03 ± 1.37	665.42 ± 1.38	599.71 ± 1.12	593.82 ± 1.18	74.25 ± 0.28	74.60 ± 0.28	73.98 ± 0.28	74.73 ± 0.30

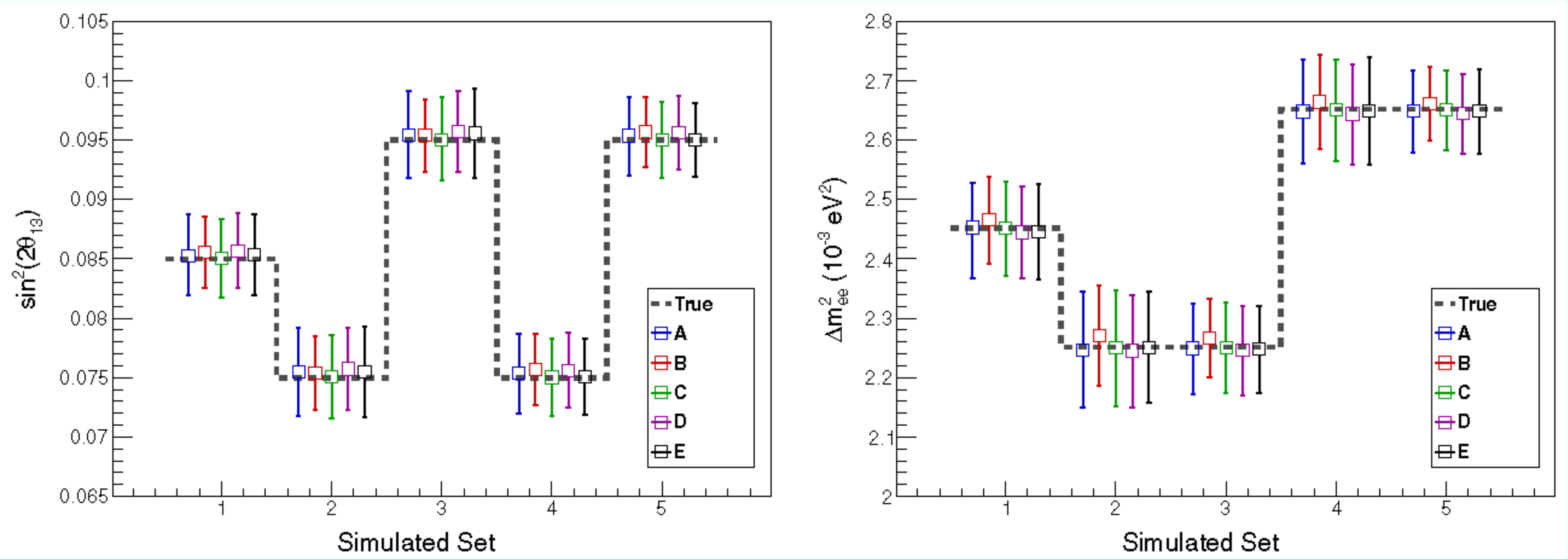
F. P. An et al., Daya Bay Collaboration, PRD **95**, 072006 (2017).

Recent Oscillation Results

F. P. An et al., Daya Bay Collaboration, PRD **95**, 072006 (2017).

Oscillation results

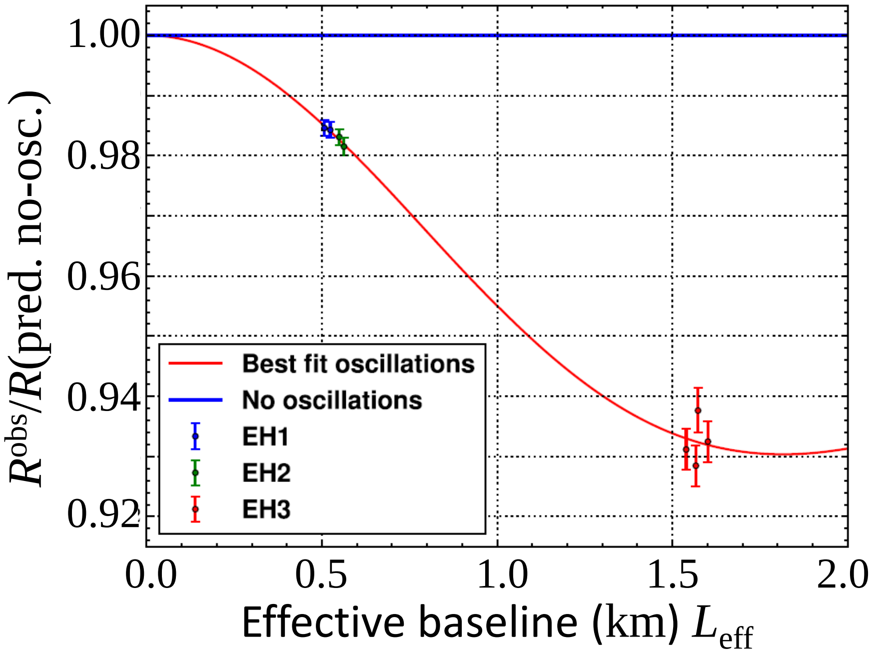
5 independent analysis methods, all consistent with each other and validated by simulated data generated with various $\sin^2 2\theta_{13}$ and Δm^2_{ee}

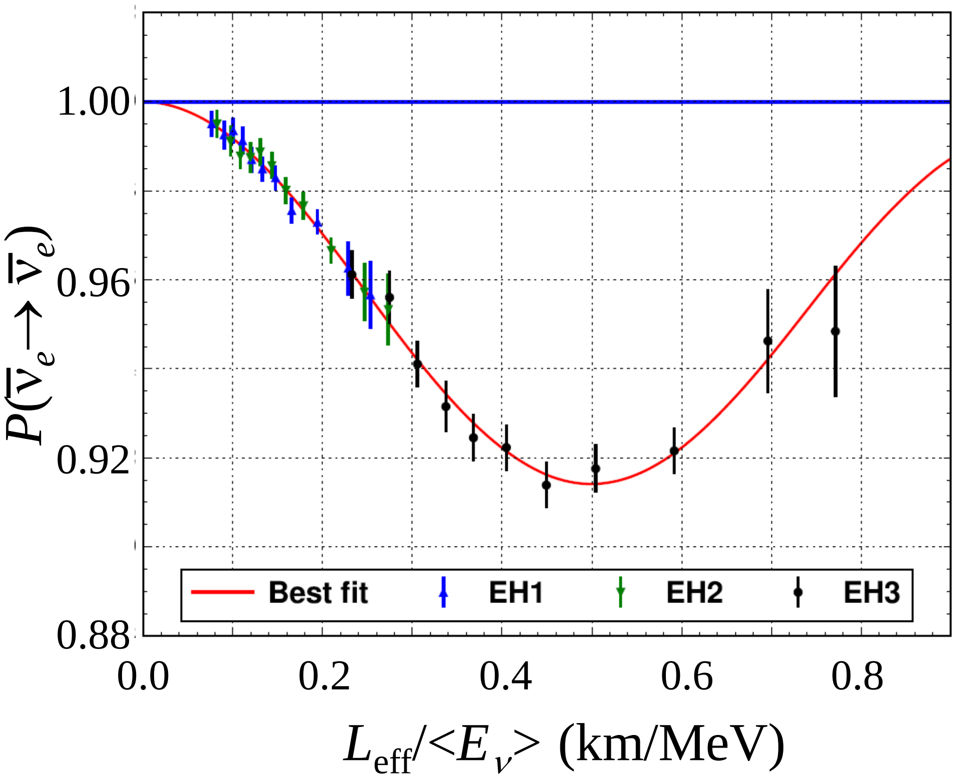


Oscillation results

$$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2(\Delta m_{ee}^2 L/4E_\nu) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2(\Delta m_{21}^2 L/4E_\nu)$$

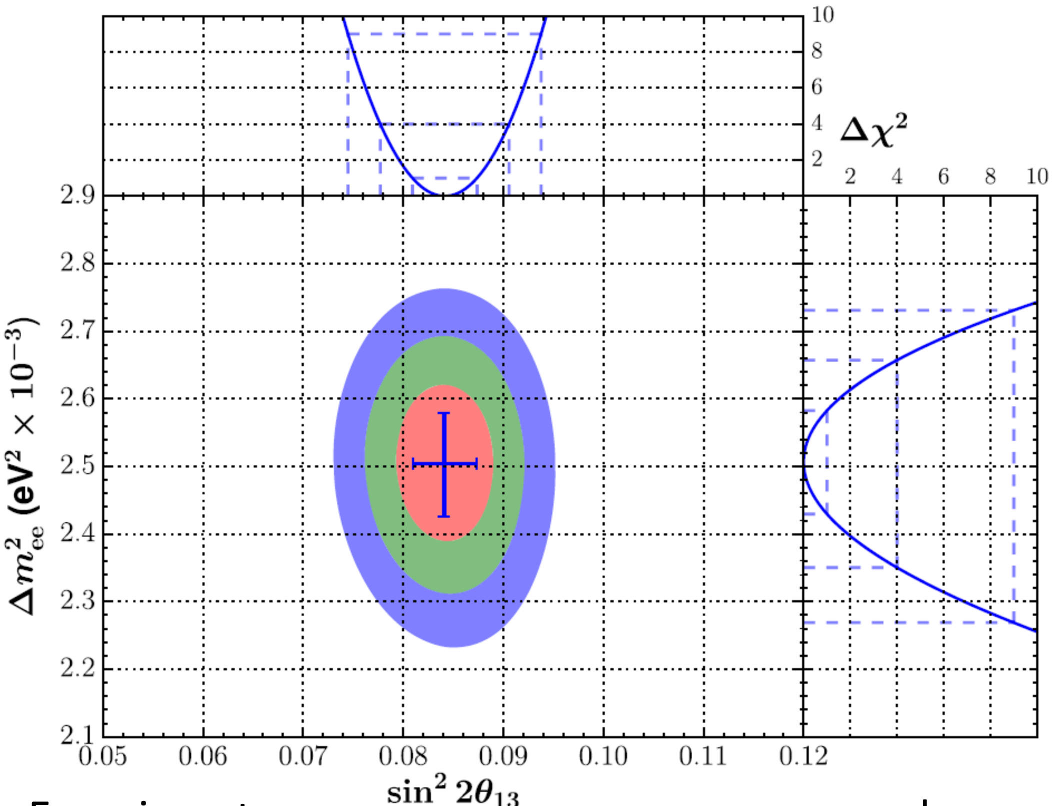
- Far/near relative measurement
- Oscillation parameters measured with rate + spectral distortion
- Both consistent with neutrino oscillation interpretation





F. P. An et al., Daya Bay Collaboration, PRD **95**, 072006 (2017).

Oscillation results



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

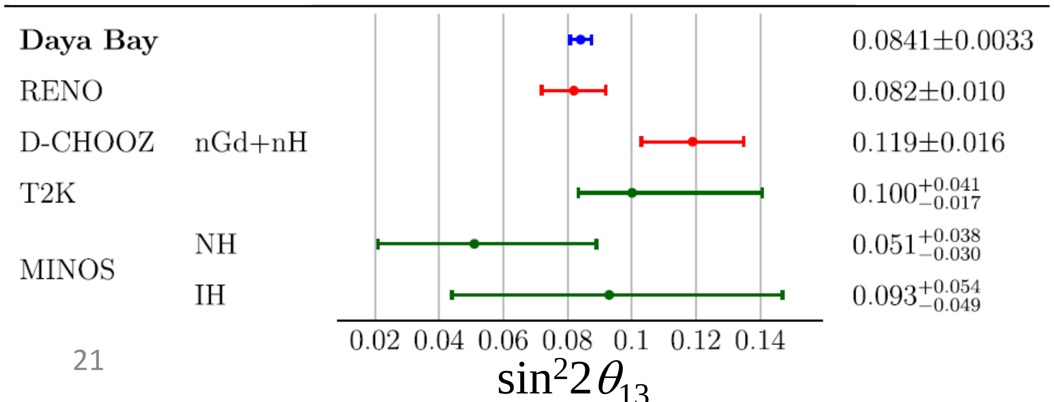
$|\Delta m^2_{ee}| = (2.50 \pm 0.06\ (\text{stat.}) \pm 0.06\ (\text{syst.}))\text{x}10^{-3}\ \text{eV}^2$

$\chi^2/\text{NDF} = 232.6/263$

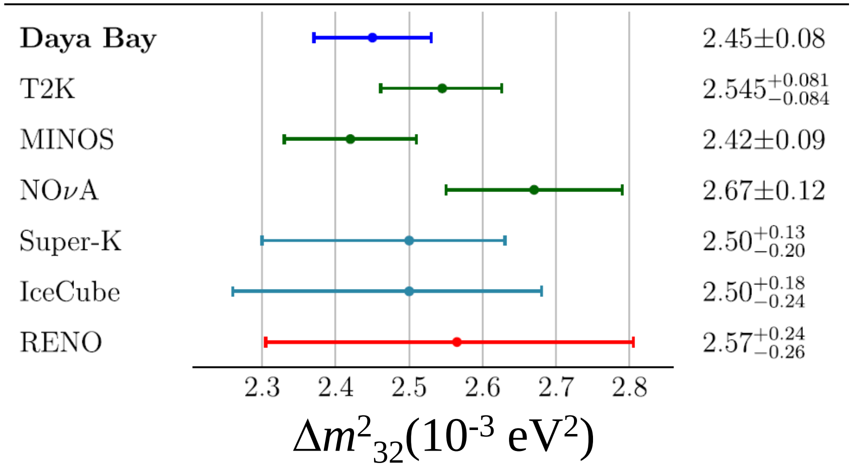
- Most precise measurement (< 4%) of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ $\rightarrow$

$\Delta m^2_{32} = (2.45 \pm 0.08)\text{x}10^{-3}\ \text{eV}^2$ (N.H.)
$(-2.56 \pm 0.08)\text{x}10^{-3}\ \text{eV}^2$ (I.H.)

Experiment value



Experiment N.H. value (10^{-3} eV^2)

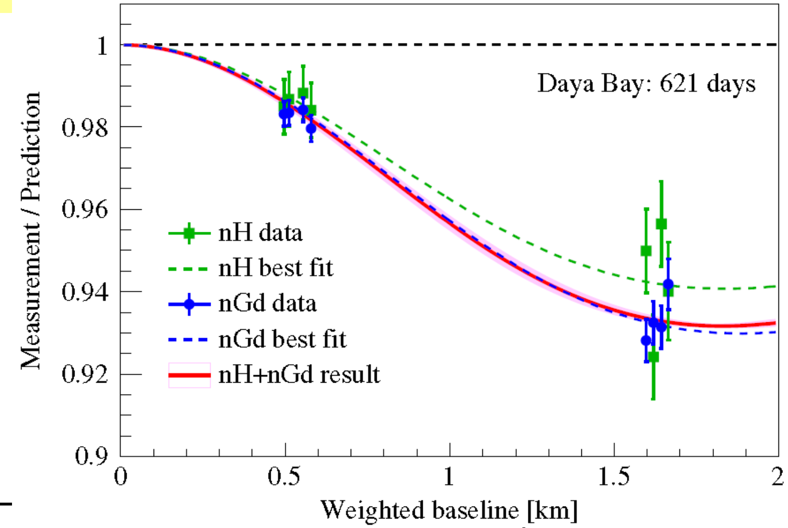


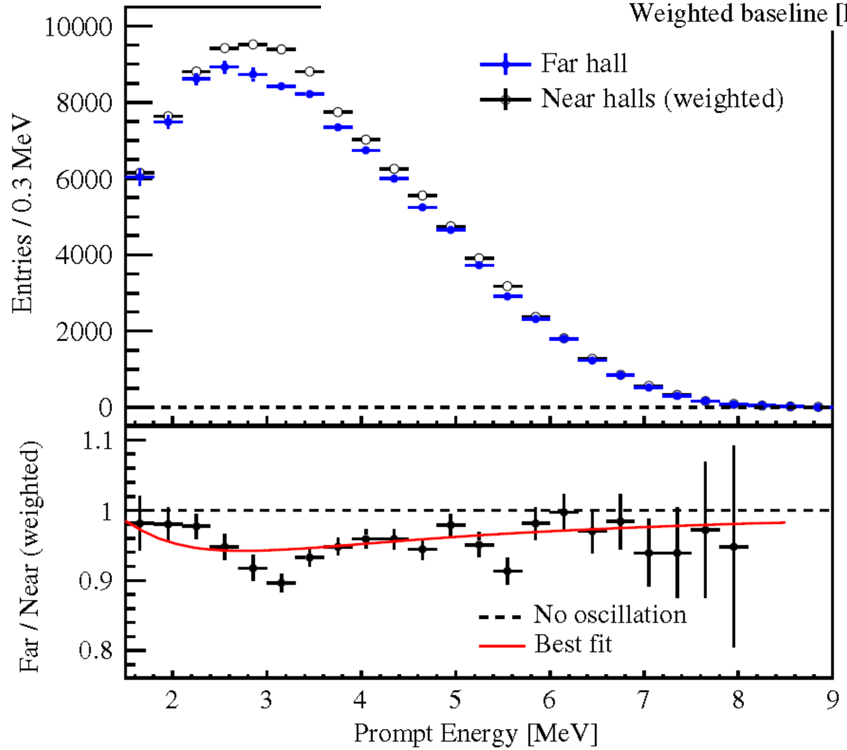
Independent θ_{13} measurement with nH

Daya Bay Collaboration, PRD**93**, 072011 (2016).

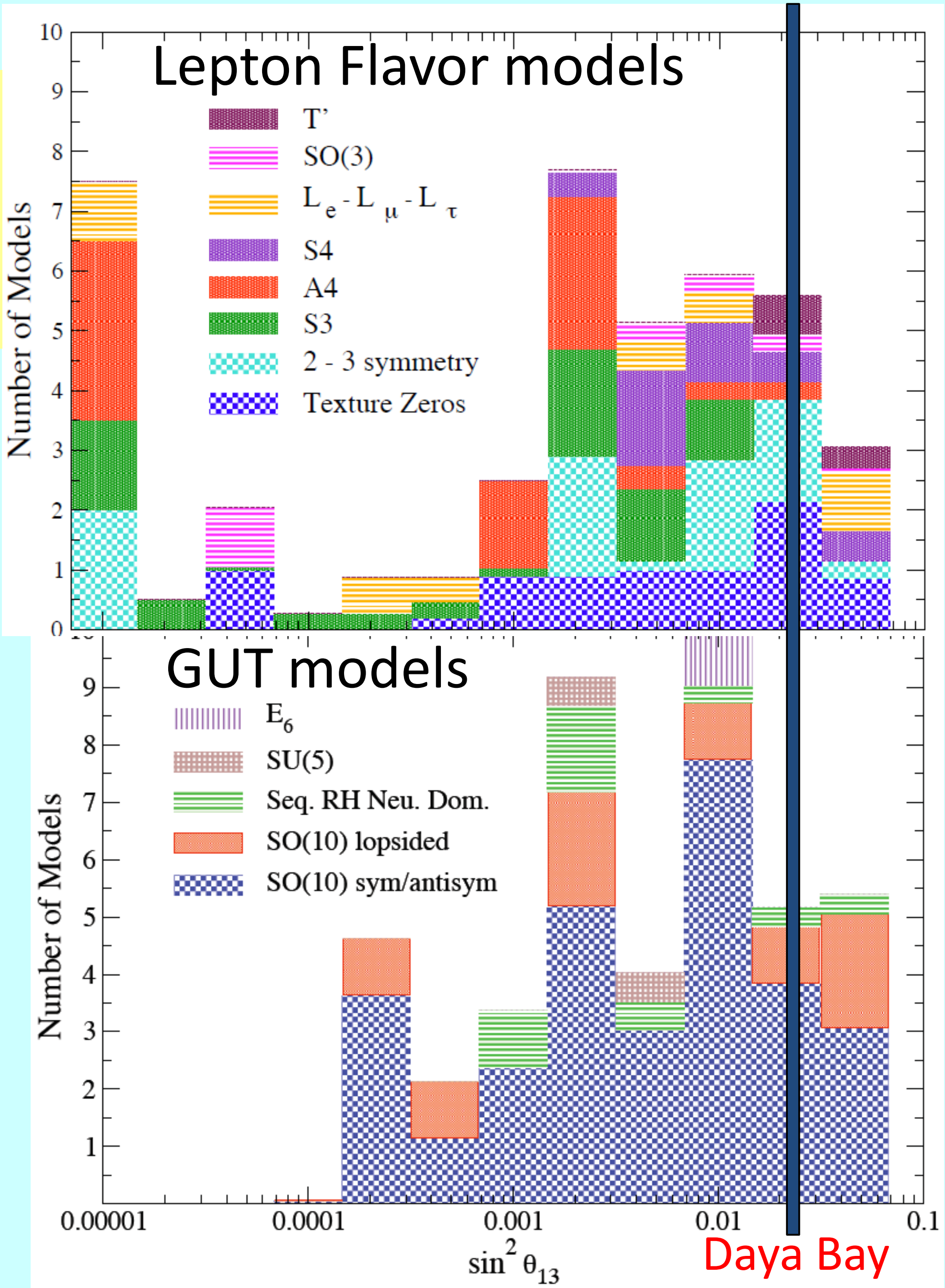
- Independent measurement, statistics, different systematics
- Longer capture time, lower delayed energy (2.2 MeV) $\rightarrow$high high accidental background
- $\rightarrow$ higher prompt energy cut ($>$ 1.5 MeV) + prompt-to-delay distance cut ($<$ 0.5 m)
- nH: $\sin^2 2\theta_{13} = 0.071 \pm 0.011$
- Combined nH + nGd:

  $\sin^2 2\theta_{13} = 0.082 \pm 0.004$
- 3rd world's most precise measurement of θ_{13} after Daya Bay nGd and RENO





θ_{13} selects Flavor/GUT models

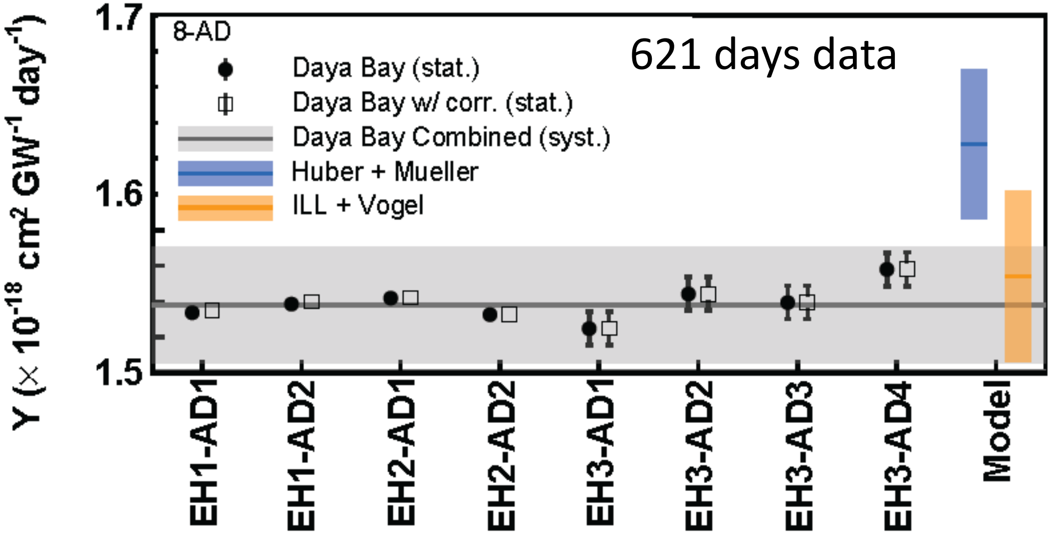


Taken from C. Albright, arXiv: 0905.0146

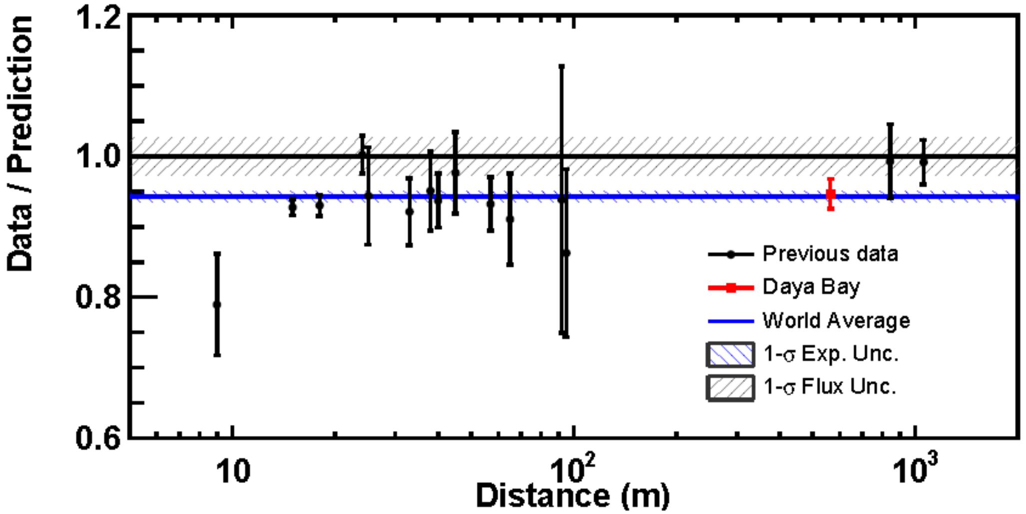
Absolute reactor anti-neutrino flux and spectrum

F. P. An et al., Daya Bay Collaboration, PRL **116**, 061801 (2016); Chinese Physics C **41**(1), 13002 (2017); PRL **118**, 251801 (2017).

Reactor anti-neutrino flux



Measured IBD events (background subtracted) in each detector are normalized to *cm²/GW/day* (***Y***) and *cm²/fission* (σ_f).



Global comparison of measurement and prediction (Huber+Mueller)

Daya Bay's reactor anti-neutrino flux measurement is consistent with previous short baseline expts.

4-AD (near halls) measurement

$$Y = (1.53 \pm 0.03) \times 10^{-18}\ \mathrm{cm^2 GW^{-1} day^{-1}}$$

$$\sigma_f = (5.91 \pm 0.12) \times 10^{-43}\ \mathrm{cm^2 fission^{-1}}$$

Compared to flux model

Data/Prediction (Huber+Mueller)

0.946 ± 0.020

Data/Prediction (ILL+Vogel)

0.992 ± 0.021

Effective baseline (near sites)

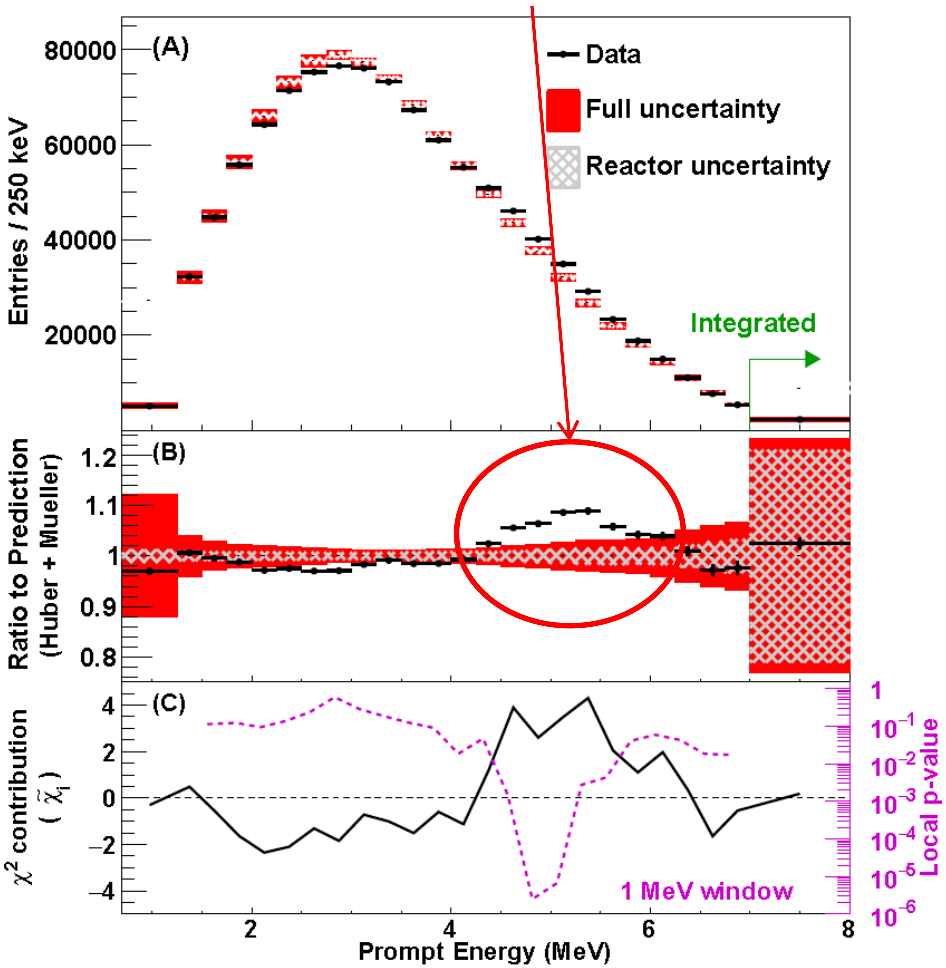
$$L_{eff} = 573\mathrm{m}$$

Effective fission fractions F_i

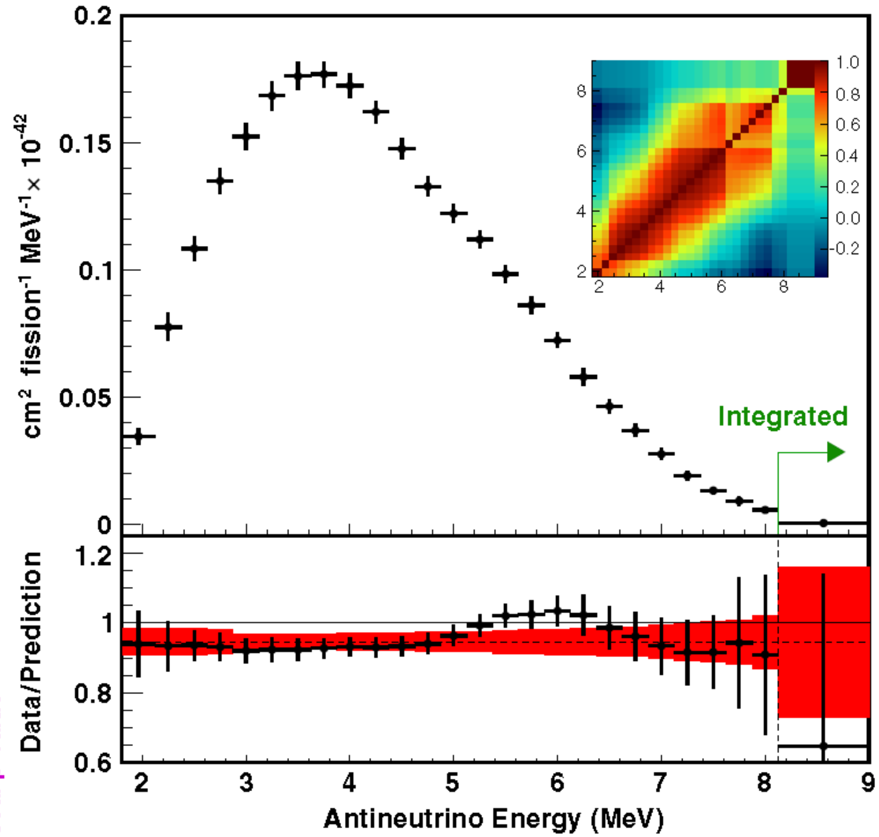
^{235}U	^{238}U	^{239}Pu	^{241}Pu
0.561	0.076	0.307	0.056

Reactor anti-neutrino spectrum

- Absolute positron spectral shape is NOT consistent with the prediction. A bump is observed in 4-6 MeV (4.4 σ).



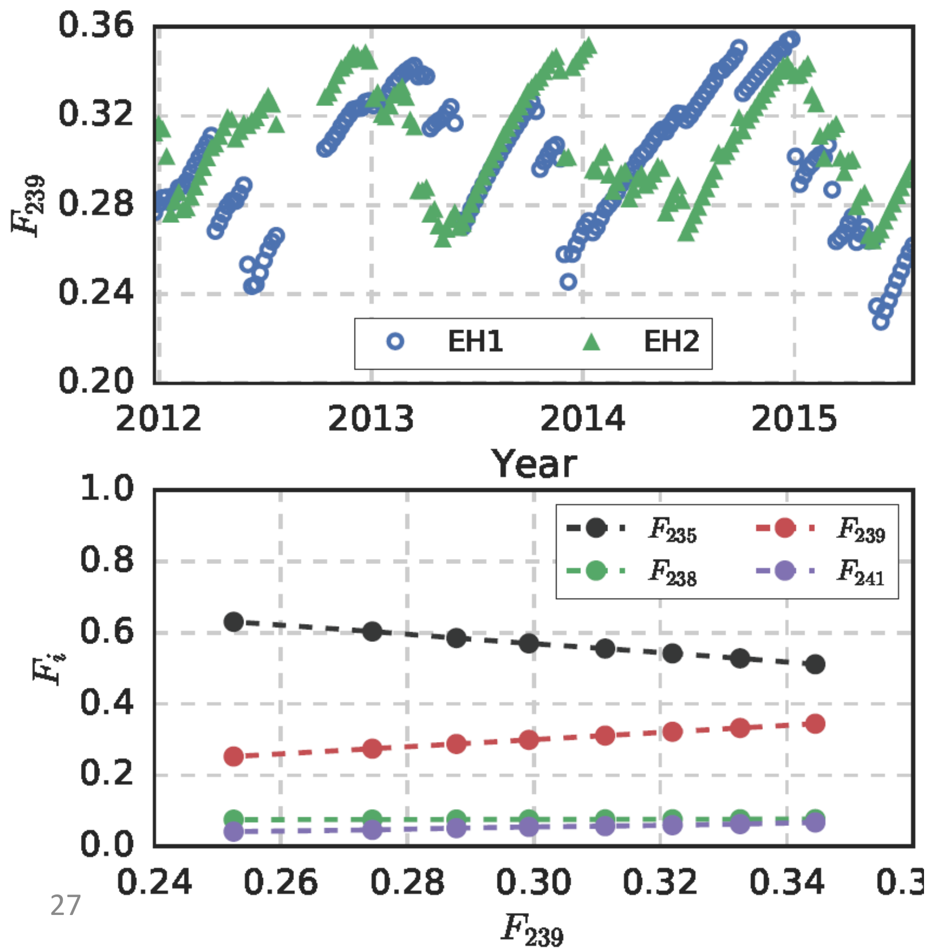
- Extract a generic observable reactor anti-neutrino spectrum by removing the detector response



Reactor anti-neutrino flux evolution

Effective fission fraction for i^{th} isotope changes in time as fuel evolves:

$$F_i(t) = \sum_{r=1}^{6} \frac{W_{th,r}(t)\bar{p}_r f_{i,r}(t)}{L_r^2 \overline{E}_r(t)} \Bigg/ \sum_{r=1}^{6} \frac{W_{th,r}(t)\bar{p}_r}{L_r^2 \overline{E}_r(t)}$$



$f_{i,r}(t)$ (fission fraction for i^{th} isotope in reactor r) and $W_{th,r}(t)$ (thermal power) obtained from reactor data, validated with MC.

$\bar{p}_r$ = survival probability

L_r = baseline

$\overline{E}_r$ = average energy per fission

$\sigma_f(t) = \Sigma_i\ \sigma_i F_i(t)$ also evolves

IBD yield $\quad$ i^{th} isotope

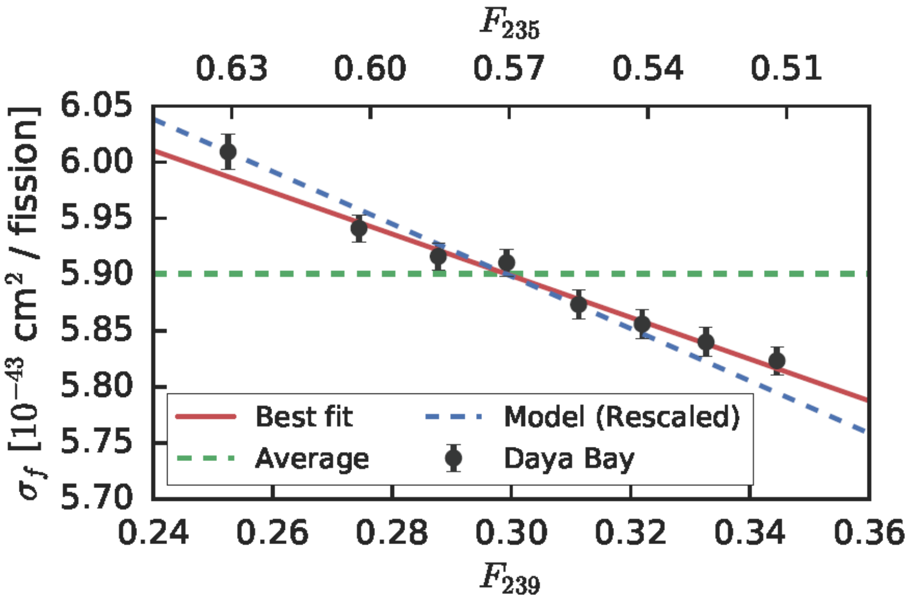
PRL **118**, 251801 (2017).

Reactor antineutrino flux and spectrum evolution

PRL **118**, 251801 (2017).

$\sigma_f(t) = \Sigma_i\ \sigma_i F_i(t)$ also evolves

IBD yield $\quad i^{\text{th}}$ isotope



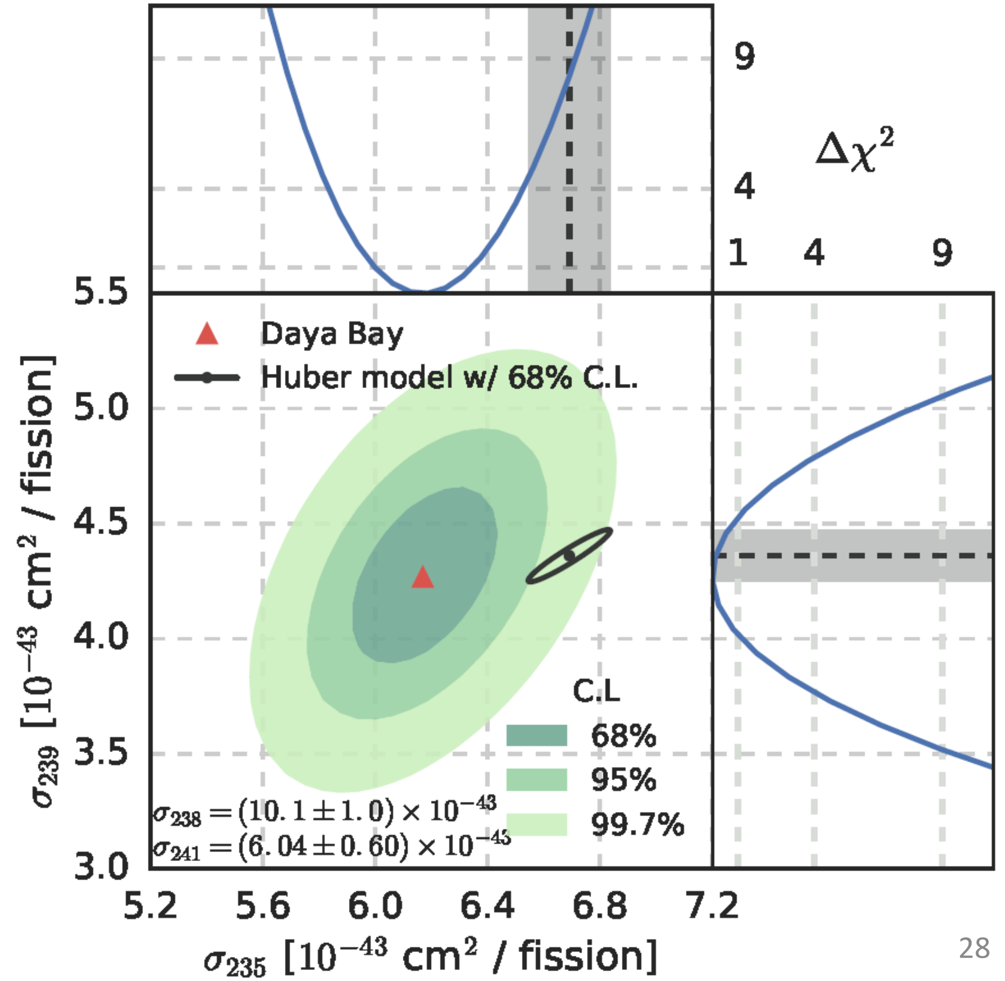
Slope differs from theory by 3.1σ

Sterile ν only ⇒ same fractional flux deficit for all isotopes: $(d\sigma_f/dF_{239})/\langle\sigma_f\rangle$ = theory

incompatible with data at 2.6σ

Best fit of $\sigma_f(t) = \Sigma_i\ \sigma_i F_i(t)$ to get σ_i

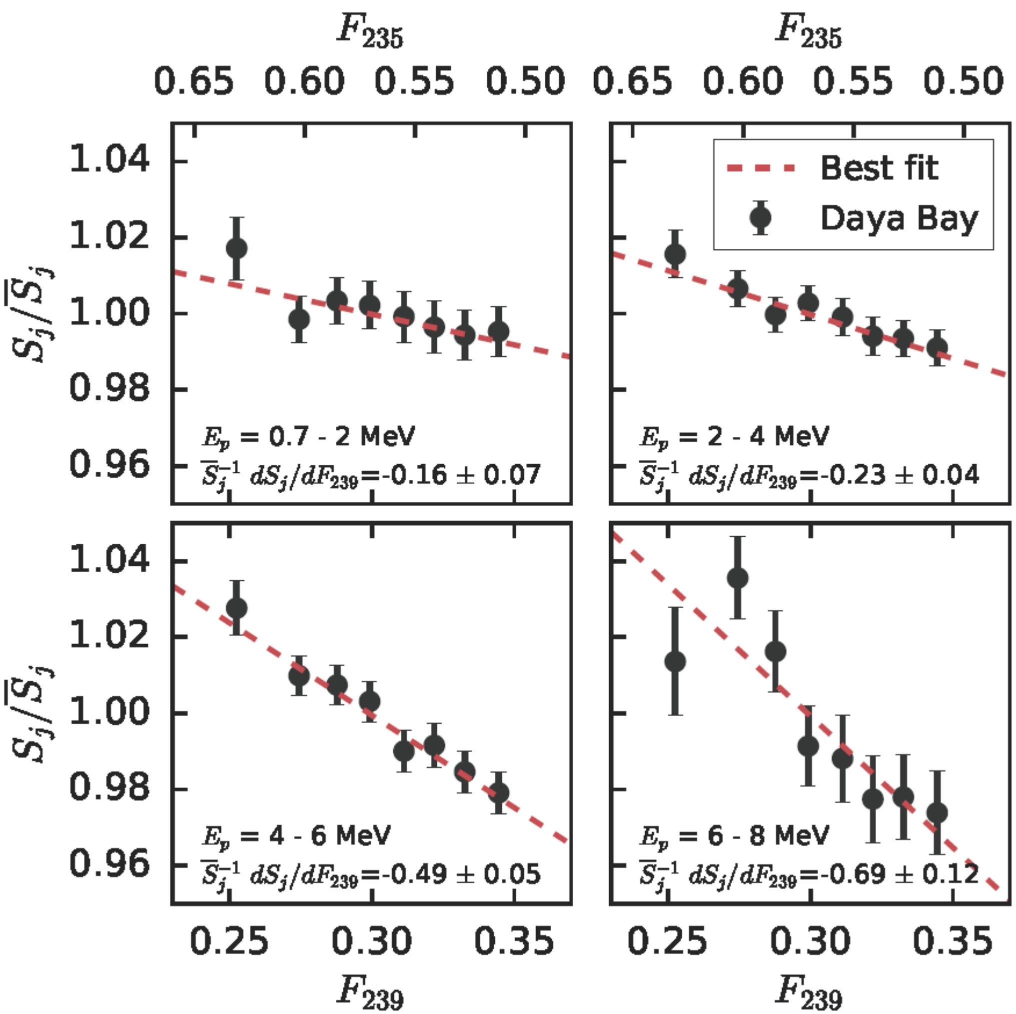
Favors: overestimation of ^{235}U yield

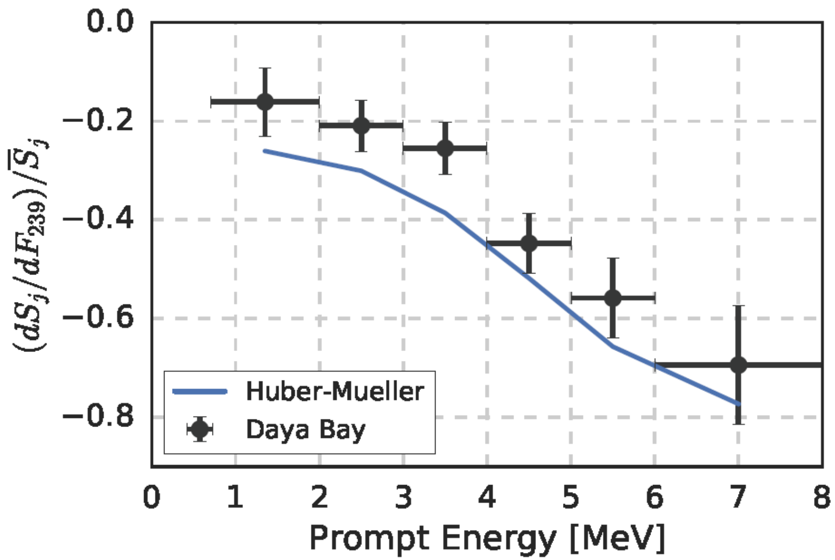


Reactor antineutrino spectrum evolution

S_j = observed IBD per fission in j^{th} energy bin

PRL **118**, 251801 (2017).





- First observation of change in IBD spectrum with F_{239} at 5.1σ
- Shape ~ theory
- Demonstration of neutrino monitoring of reactors

Search for a light sterile neutrino

F. P. An et al., Daya Bay Collaboration, PRL **117**, 151802 (2016); PRL **113**, 141802 (2014).
Daya Bay and MINOS Collaborations, PRL **117**, 151801 (2016).

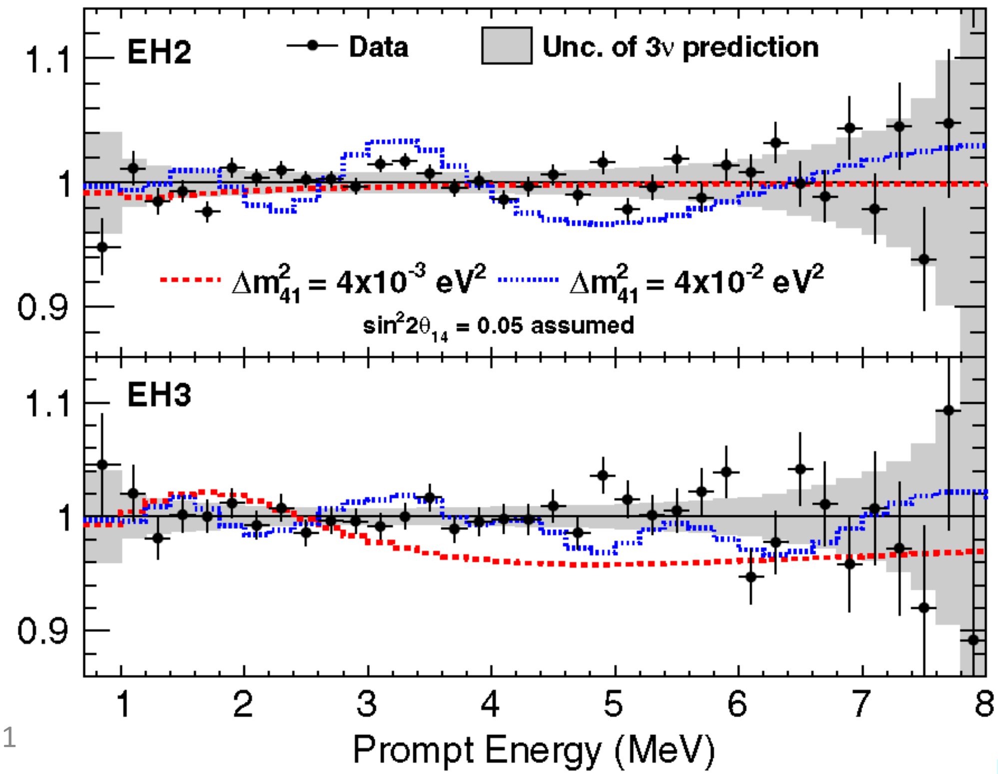
Search for a light sterile neutrino

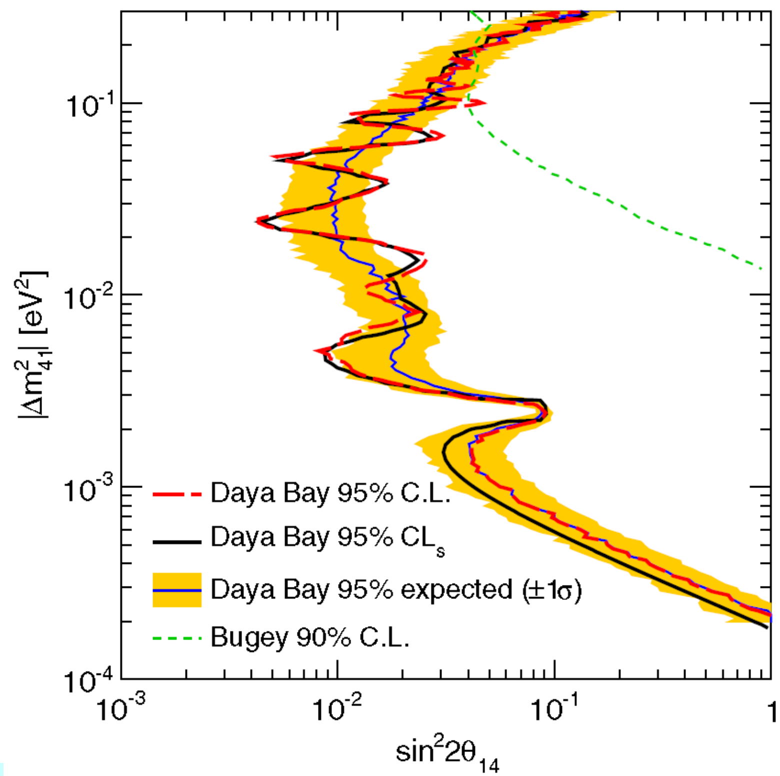
- Sterile neutrino: additional oscillation mode θ_{14}:

PRL **117**, 151802 (2016).

$$P_{ee}^{4\nu} \approx P_{ee}^{3\nu} - \sin^2 2\theta_{14} \sin^2(1.267\Delta m^2_{41} L/E_\nu)$$

- 3 expt. halls → multiple baselines
  - Relative measurement at EH1 (~350m), EH2 (~500m), EH3 (~1600m)
  - Unique sensitivity at 10^{-4} eV^2 < Δm^2_{41} < 0.1 eV^2
- most stringent limit on $\sin^2 2\theta_{14}$ for 2x10^{-4} eV^2 < Δm^2_{41} < 0.2 eV^2

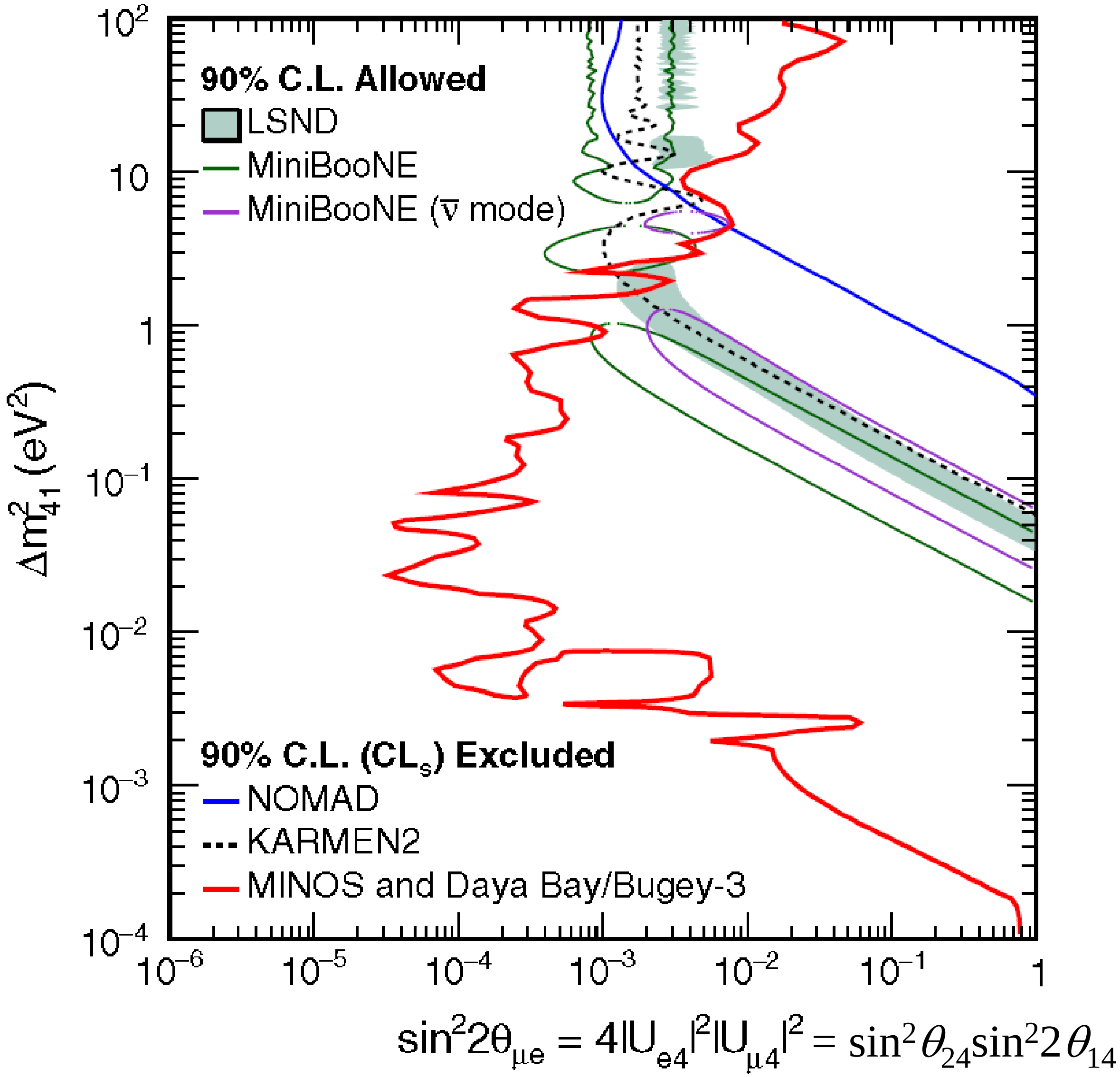




Search for a light sterile neutrino

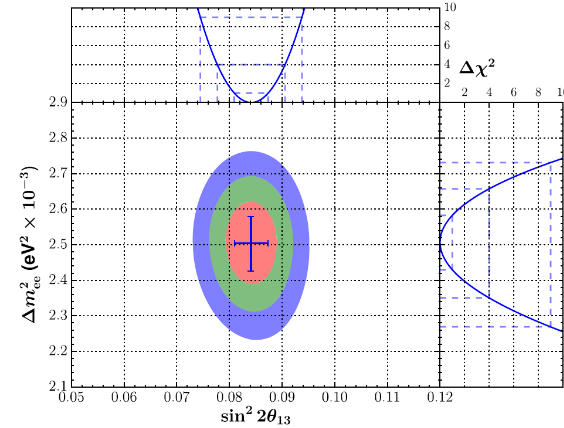
PRL **117**, 151801 (2016).

- Constrain $\nu_\mu \rightarrow \nu_e$ by combining constraints on $\sin^2 2\theta_{14}$ from $\overline{\nu_e}$ disappearance in Daya Bay and Bugey-3 with constraints on $\sin^2 2\theta_{24}$ from $\overline{\nu_\mu}$ disappearance in MINOS
- Set constraints over 6 orders of magnitude in Δm^2_{41}. Strongest constraint to date.
- Exclude parameter space allowed by MiniBooNE and LSND for $\Delta m^2_{41} < 0.8\ \text{eV}^2$.

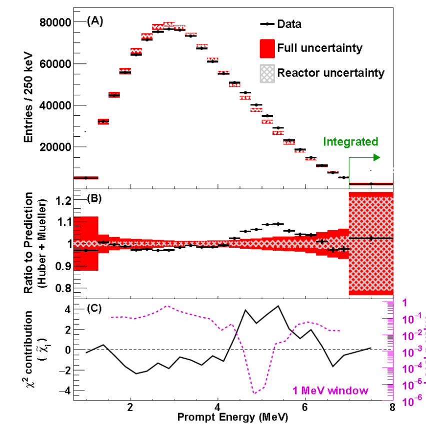


Summary

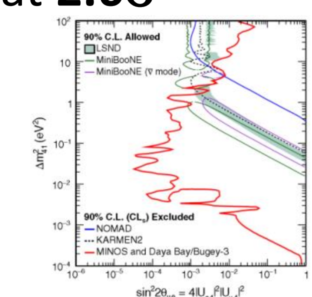
- Daya Bay **1230** days of data, **> 2.5M** IBD events
  - Most precision measurement of $\sin^2 2\theta_{13}$: **3.9%**
  - Most precision measurement of $\left|\Delta m^2_{ee}\right|$: **3.4%**
  - Oscillation results confirmed with independent nH rate measurement **(621 days)**

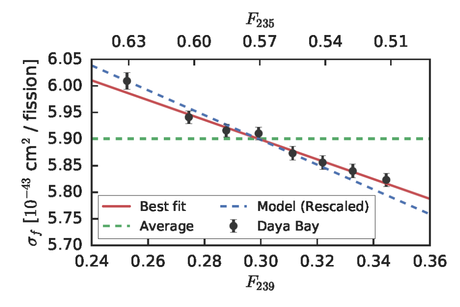


- Reactor antineutrino flux and spectrum
  - **Flux** : consistent with previous short baseline expts, but ~5% < theoretical prediction **(1.7σ)**
  - **Spectrum**: 4.4σ **deviation** from prediction in [4, 6] MeV prompt energy
  - **Evolution observed**. Favors overestimation of σ_{235}; disfavors equal contribution from isotopes at **2.6σ**



- Set **new limit** to light sterile neutrinos
- Will continue till 2020





More to come …

- Will continue until 2020 $\rightarrow$ 2.5x data, > 6M neutrino events
- Precision measurement of oscillation parameters $\sin^2 2\theta_{13}$, Δm^2_{ee}
- Precision measurement of spectral distortion:
  - neutrino decoherence
  - sterile neutrino mixing
  - CPT violation
- Precision measurement of neutrino rate:
  - sidereal modulation (CPT violation, …)
  - supernova neutrinos
- Search for gravitational-wave neutrino sources
- Other analyses

The Daya Bay Reactor Neutrino Experiment

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The Chinese University of Hong Kong, Hong Kong

On behalf of the Daya Bay Collaboration

Partial support: CUHK VC Discretionary Fund, RGC CUHK3/CRF/10R

Solvay workshop on “Beyond the Standard model with Neutrinos and Nuclear Physics” Nov 29 – Dec 01, 2017, Brussels, Belgium

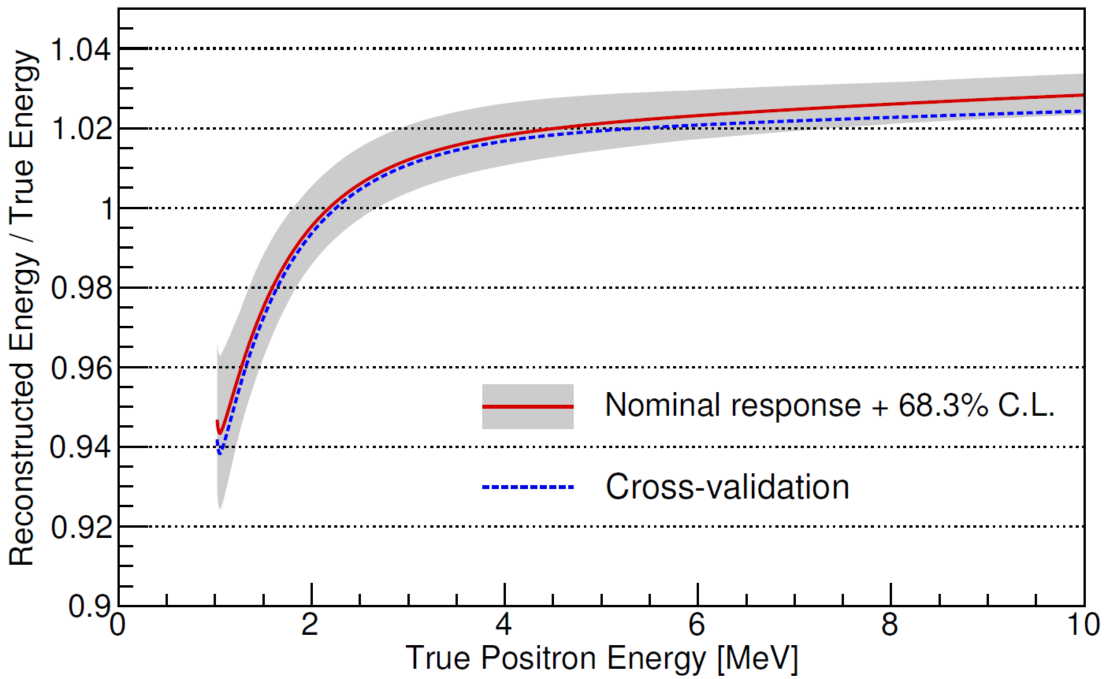
backup

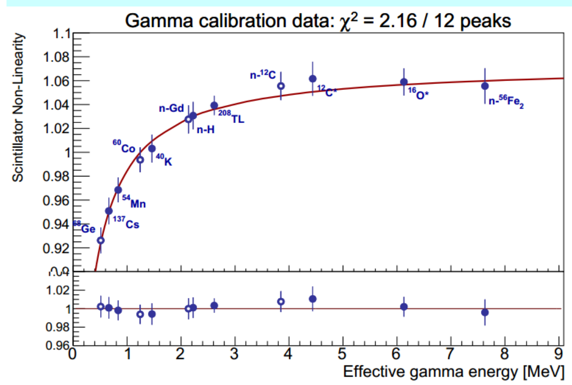
More searches

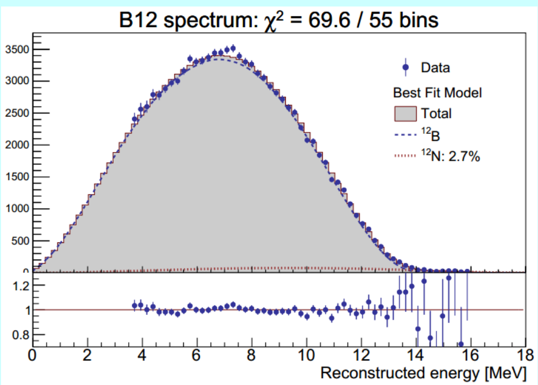
- Precision measurement of spectral distortion:
  - neutrino decoherence
  - sterile neutrino mixing
  - CPT violation/NSI
  - mass-varying neutrinos
- Precision measurement of neutrino rate:
  - sidereal modulation (CPT violation, …)
  - supernova neutrinos
- High energy events:
  - neutron-anti-neutron oscillation

Detector energy response model

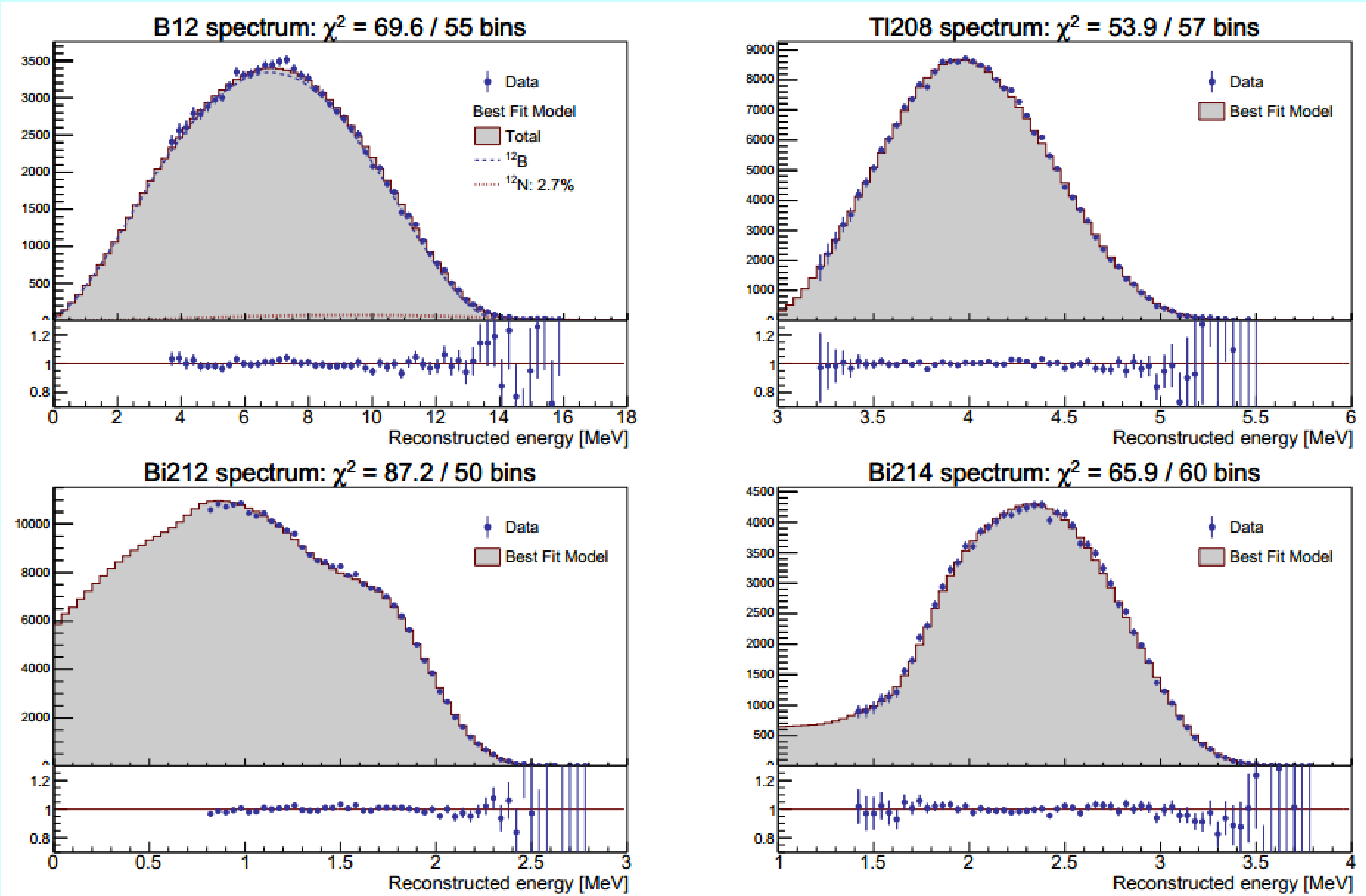
- Particle-dependent scintillator nonlinearity: modeled with Birks' law and Cherenkov fraction
- Charge-dependent electronics nonlinearity: modeled with MC and single channel FADC measurement
- Nominal model: fit to mono-energetic gamma lines and ^{12}B beta-decay spectrum
- Cross-validation model: fit to ^{208}Th, ^{212}Bi, ^{214}Bi beta-decay spectrum, Michel electron
- Uncertainty $< 1\%$ above 2 MeV





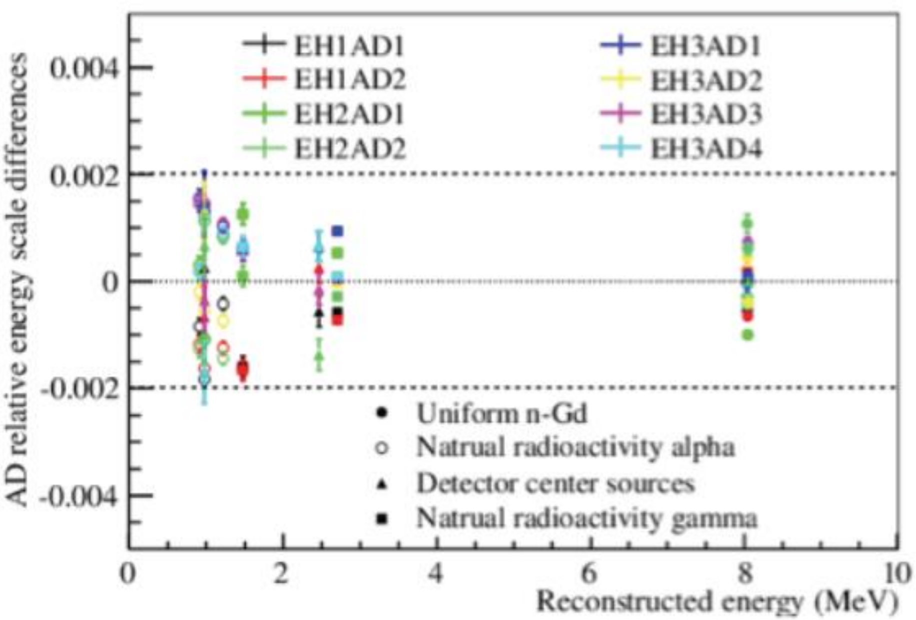


Detector energy response model

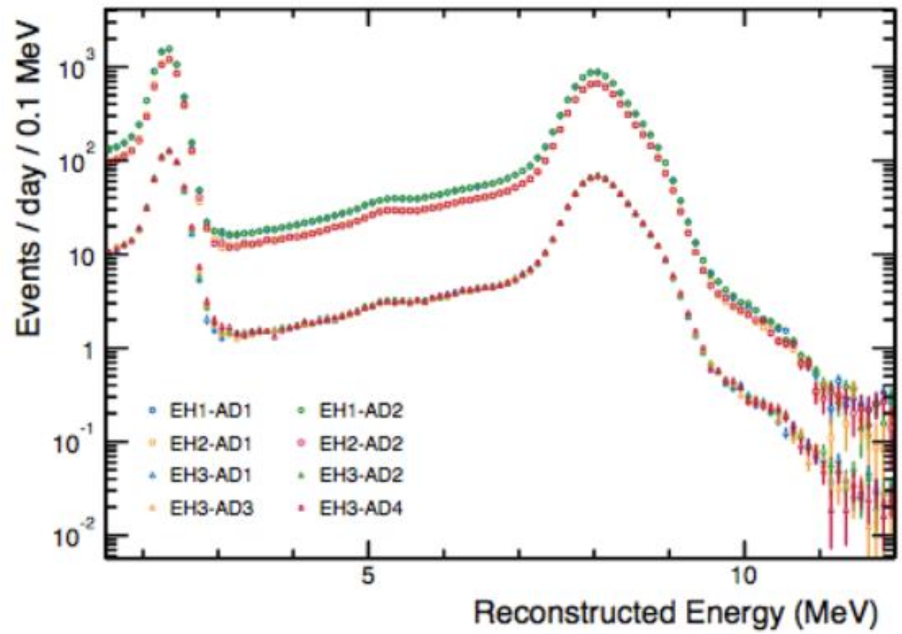


AD Calibration

ACU: ^{60}Co, ^{68}Ge, AmC
Spallation: nGd, nH
Gamma: ^{40}K, ^{208}Tl
Alpha: ^{212}Po, ^{214}Po, ^{215}Po



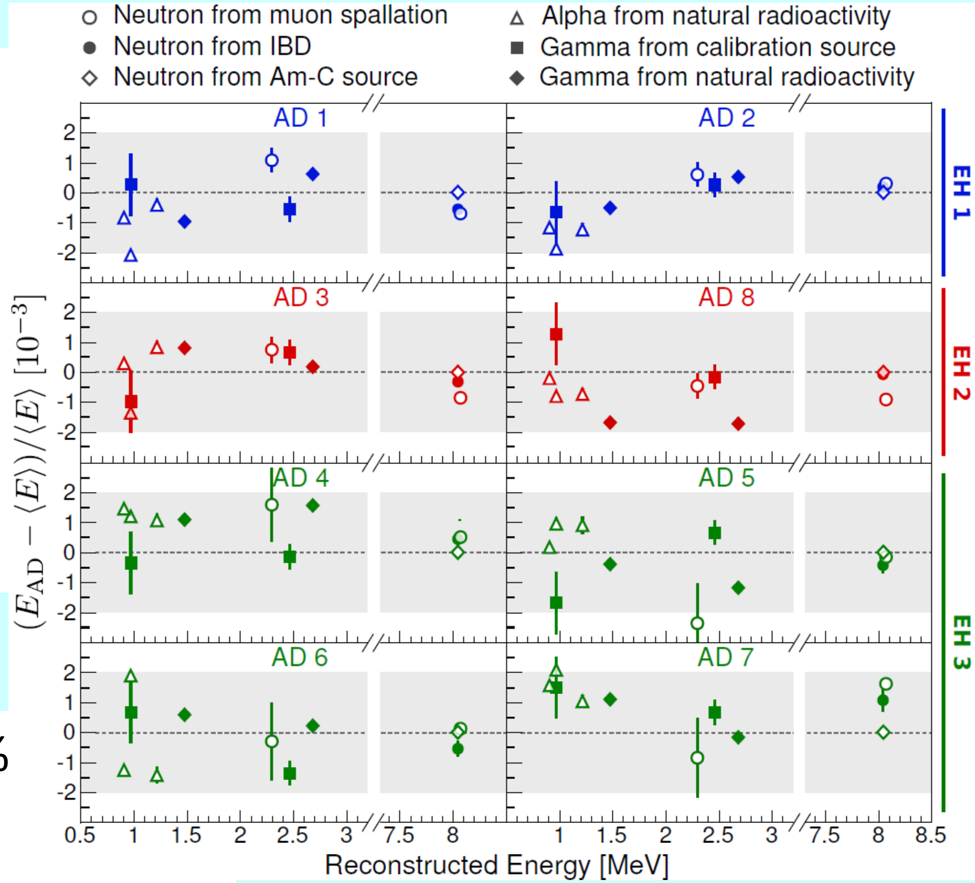
spallation neutron capture spectrum



Less than 0.2% variation in reconstructed energy between detectors.

Energy calibration

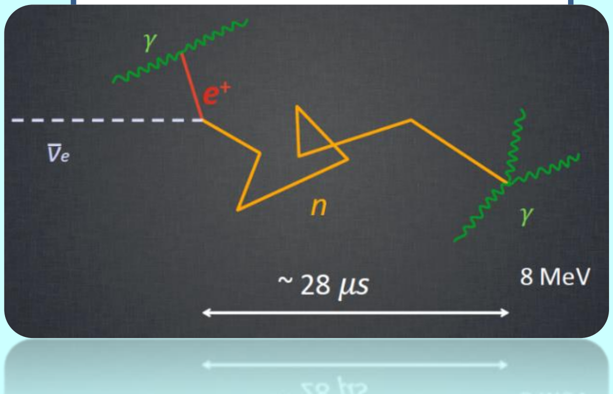
- PMT gain: Single electrons from photocathode
- Absolute energy scale: AmC at AD center
- Time variation: ^{60}Co at AD center
- Non-uniformity: ^{60}Co at different positions
- Alternative calibration: spallation neutrons

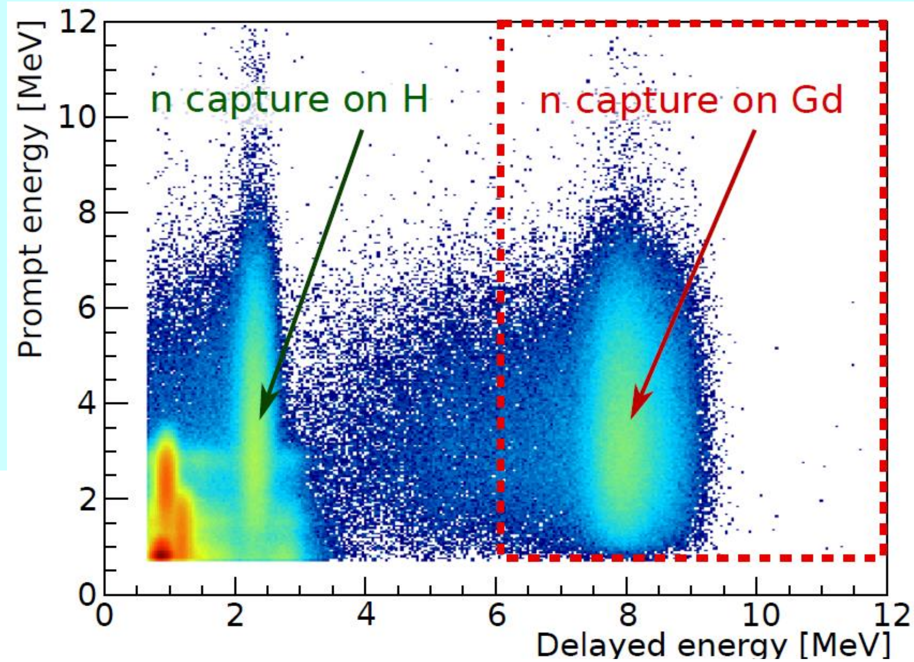


- Relative energy scale uncertainty: 0.2%
  - ^{68}Ge, ^{60}Co, AmC: detector center
  - nGd from IBD and muon spallation: Gd-LS region
  - α from polonium decay: Gd-LS vertex cut
  - ^{40}K, ^{208}Tl, nH: 1m vertex cut

Anti-neutrino candidates selection

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

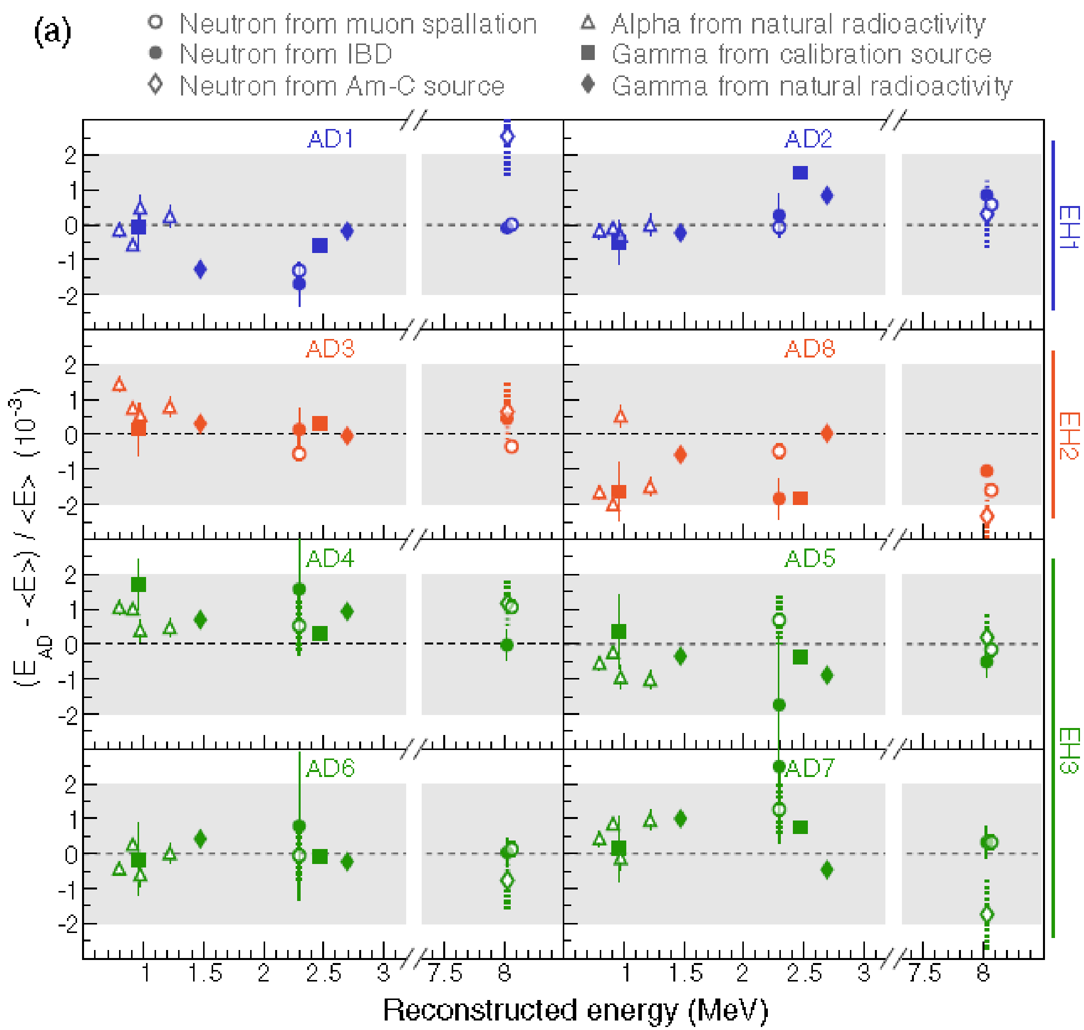




- Reject PMT flashers
- **Coincidence** in energy and time with multiplicity = 2
  - **- Energy**: $0.7\ \text{MeV} < E_p < 12.0\ \text{MeV}$, $6.0\ \text{MeV} < E_d < 12.0\ \text{MeV}$
  - **- Time**: $1\ \mu s < \Delta t_{\text{p-d}} < 200\ \mu s$
- Muon **anticoincidence**
  - - Water pool muon: reject 0.6 ms
  - - AD muon (>20 MeV): reject 1 ms
  - - AD shower muon (>2.5 GeV): reject 1 s

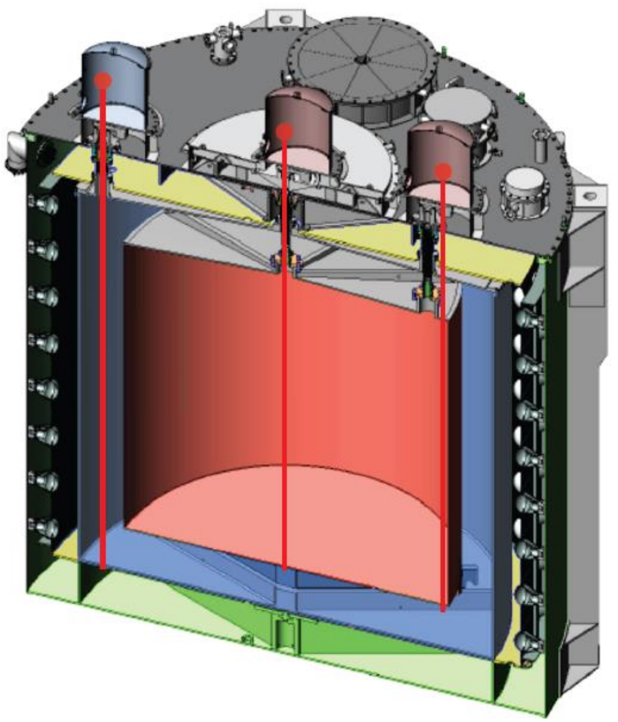
	Efficiency	Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.08%
Prompt energy cut	99.8%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Gd capture fraction	84.2%	0.95%	0.10%
Spill in	104.9%	1.00%	0.02%
Live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

Detector calibration

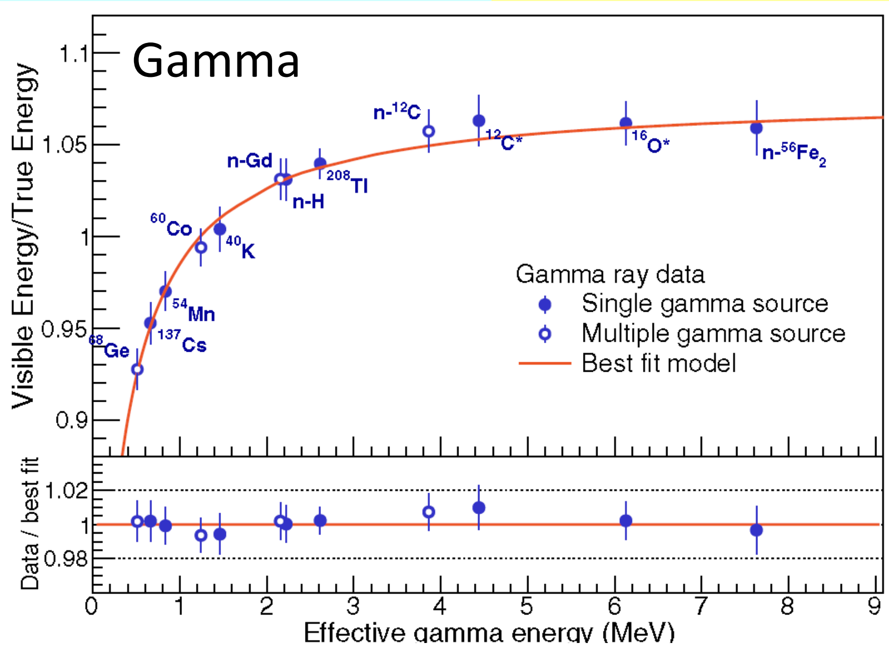


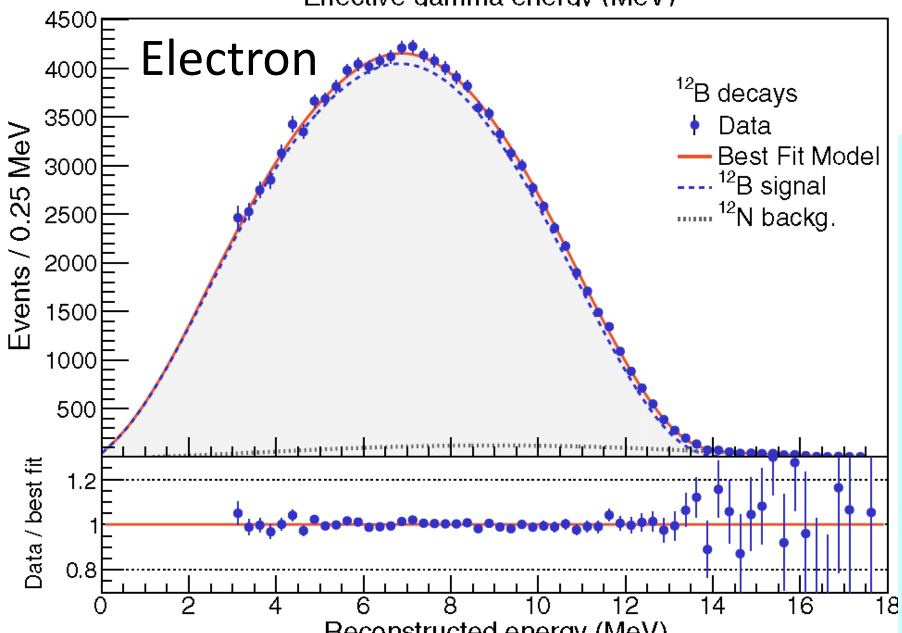
Relative energy scale uncertainty < 0.2%

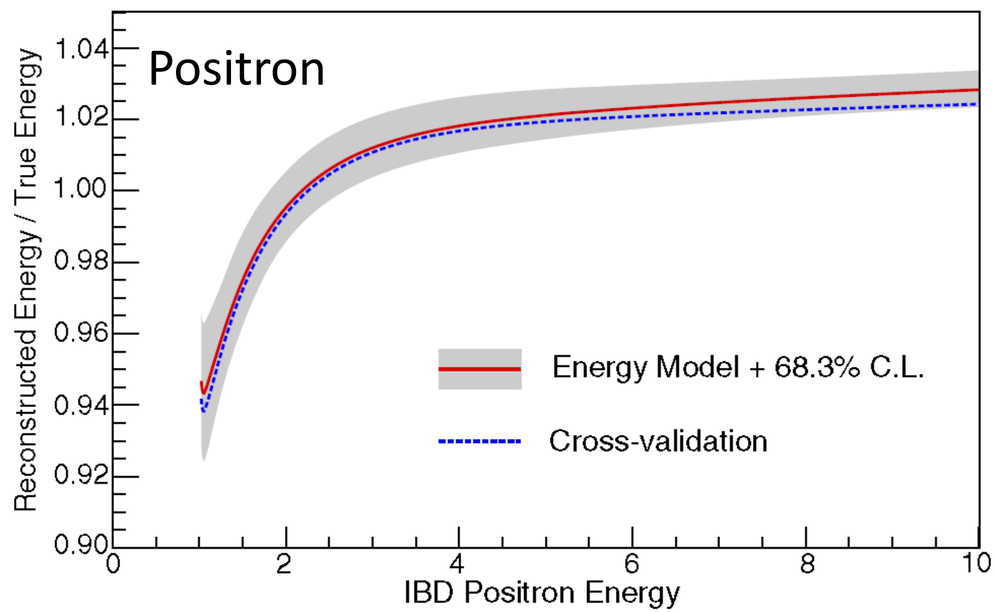
Calibration using ^{68}Ge (1.02MeV), ^{60}Co (2.5MeV), ^{241}Am-^{13}C (8MeV), LED, spallation neutrons



Energy non-linearity







- Measured γ and e responses
- Derive e^+ energy model from γ and e responses using simulation Uncertainty ~ 1% (correlated among detectors)

Systematics

Detector efficiency

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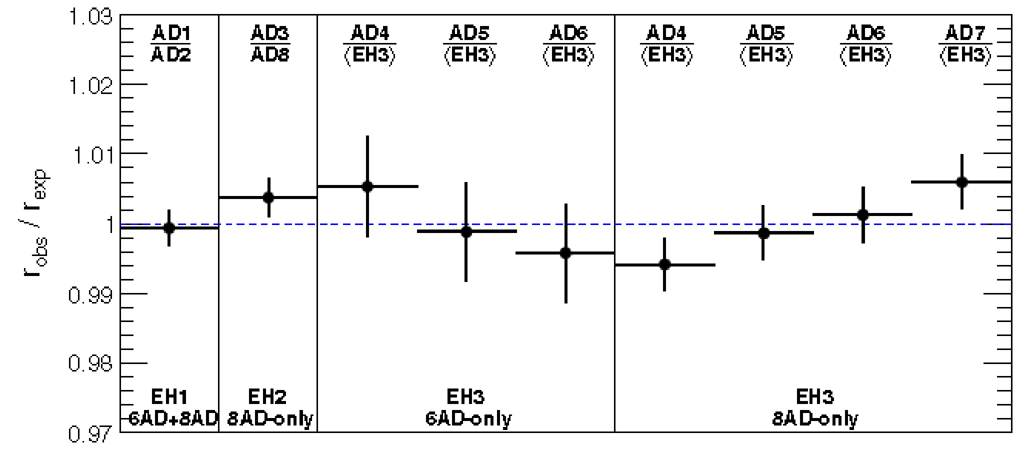
Correlated uncertainties cancelled out in relative measurement



Uncorrelated uncertainties cross-checked by multiple detectors in the same hall